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Bioenergy & Sustainability: bridging the gaps

EDITED BY
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Foreword

SCOPE Bioenergy & Sustainability Contributors

Acknowledgments

Foreword

The development of modern high efficiency bioenergy technologies has the potential to improve energy security and access while reducing environmental impacts and stimulating low-carbon development. While modern bioenergy production is increasing in the world, it still makes a small contribution to our energy matrix.

At present, approximately 87% of energy demand is satisfied by energy produced through consumption of fossil fuels. Although the International Energy Agency (IEA) predicts that this share will fall to 75%, the total consumption of fossil fuels will continue to rise, adding another 6 Gt of carbon to the atmosphere by 2035. The consequences of this increase are worrisome.

Our oceans are being critically affected. Oceans are an important CO_2 sink and absorb 26% of the CO_2 emissions but due to accelerated acidification and rising sea surface temperatures, this capacity may be reduced. Never in the last 300 million years has the rate of ocean acidification been so high. In the last 150 years, acidity in oceans increased by 30%. The main cause are the emissions from fossil fuel burning, especially the release of CO_2.

Deforestation and land degradation also contribute to increased greenhouse gas emissions. The world's total forest area in 2010 was just over 4 billion hectares, which corresponds to an average of 0.6 ha per capita. Each year, between 2000 and 2010, around 13 million hectares of forestland were converted to other uses or lost through natural causes. The production of timber for housing or the need to make land available for urbanization, large-scale cash crops such as soy and oil palm, subsistence agriculture and cattle ranching induce deforestation. Forests are also degraded or damaged due to the soaring demand for fuelwood and charcoal for cooking and heating in developing countries that suffer from low levels of access to modern energy services. Most of the world's bioenergy is presently derived from wood burning for cooking and heating in developing countries. Such traditional uses of biomass are low in cost to the users, but their technical inefficiency results in considerable health and environmental costs while providing only low quality energy services. Many countries demonstrate that a much higher efficiency can be obtained in traditional uses commercially with sustainably managed feedstock supplies. Since bioenergy systems often operate at the interface between agriculture and forestry, they are also closely connected to the planning and governance of these sectors and of policy to conserve and manage forests. Consequently, interdisciplinary and cross-level or horizontal studies are needed in order to define the best routes through which achieve a sustainable energy matrix.

Can modern bioenergy make a significant contribution to our energy matrix with positive contributions to the environment? What are the social, environmental and economic implications of the expansion of bioenergy in the world? How does expansion of bioenergy perform in the context of the food, energy, climate, development and environment nexus? Which are the most significant potential benefits of bioenergy production and use and how can we design implementation platforms and policy frameworks to ensure that such benefits are realized and widely replicated? What are the scientific research needs and technological development requirements needed to fill in the gaps?

To answer some of these questions, FAPESP BIOEN, Climate Change and BIOTA Research Programs led, in December 2013, a group of 50 experts from 13 countries convened at UNESCO in Paris, France, for a rapid assessment process on “Bioenergy and Sustainability” under the aegis of SCOPE. Background chapters commissioned before the workshop provided the basis for this international consultation during which crosscutting discussions focused on four themes: Energy Security, Food Security, Environmental and Climate Security, Sustainable Development and Innovation.

The resulting synthesis volume has the contribution of 137 researchers from 82 institutions in 24 countries.

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BIOEN

BIOEN, the FAPESP Bioenergy Research Program, aims at articulating public and private R&D, using academic and industrial laboratories to advance and apply knowledge in fields related to bioenergy in Brazil. Research ranges from biomass production and processing to biofuel technologies, biorefineries, sustainability and impacts.

RPGCC

The FAPESP Research Program on Global Climate Change (RPGCC) aims at advancing knowledge on Global Climate Change and guide decisions and policy in the field.

BIOTA

The BIOTA-FAPESP Program (FAPESP Research Program on Biodiversity Characterization, Conservation, Restoration and Sustainable Use), aims not only at discovering, mapping and analyzing the origins, diversity and distribution of the flora and fauna of the biomes of the state of São Paulo, but also at evaluating the possibilities of sustainable exploitation of plants or animals with economic potential and assisting in the formulation of conservation policies on remnants of native vegetation.

SCOPE

The Scientific Committee on Problems of the Environment is an international nongovernmental organization founded in 1969. SCOPE is a cross-sectoral and trans-disciplinary network, connecting experts and institutions around the world. It is recognized for its authoritative, independent and influential scientific analyses and assessments of emerging environmental issues that are caused by or impact humans and the environment. It collaborates with inter-governmental agencies such as UNESCO and UNEP and with other partners in the development of its scientific program and outreach activities.

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section II

Summaries

Executive Summary
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SCOPE Bioenergy & Sustainability

Executive Summary

***Bioenergy & Sustainability* is a collective effort with contributions from more than 130 experts from 24 countries.**

Scientific studies were developed that assess topics ranging from land use and feedstocks, to technologies, impacts, benefits and policy.

They consider how bioenergy expansion and its impacts perform in the energy, food, environmental and climate security, sustainable development and innovation nexus in both developed and developing regions.

Authors also highlight numbers, solutions, gaps of knowledge and suggest the science needed to maximize bioenergy benefits.

http://bioenfapesp.org/scopebioenergy

One approach to solving today's energy challenges is to use modern bioenergy practices to harness the solar energy captured by photosynthesis. Bioenergy derived from plants can play an essential role in satisfying the world's growing energy demand, mitigating climate change, sustainably feeding a growing population, improving socio-economic equity, minimizing ecological disruptions and preserving biodiversity. There is broad consensus that modern bioenergy will be necessary to achieve a low-carbon future. The idea that the large-scale use of bioenergy compromises efforts to meet these challenges is unsupported by the current scientific evidence when bioenergy practices are implemented properly.

So says the new report "Bioenergy & Sustainability", a SCOPE series assessment, led by researchers associated to the São Paulo Research Foundation (FAPESP) Programs on Bioenergy, Biodiversity and Climate Change, and developed under the aegis of the Scientific Committee on Problems of the Environment (SCOPE) and a Scientific Advisory Committee.

This report combines a comprehensive analysis of the current bioenergy landscape, technologies and practices with a critical review of their impacts. Experts from over 80 institutions contributed to the extensive evaluation of the current status of bioenergy resources, systems and markets and the potential for sustainable expansion and wider adoption of this renewable resource.

What "Bioenergy & Sustainability" proposes is not only improving energy security for over 1.3 billion people with no access to electricity and lifting rural areas out of poverty, but ultimately securing a sustainable and equitable future.The resources and technologies for the transition from fossil to renewable energy are within our reach, but achieving the critical contributions needed from modern bioenergy call for political and individual will.

The report finds that land availability is not a limiting factor. Bioenergy can contribute to sustainable energy supplies even with increasing food demands, preservation of forests, protected lands, and rising urbanization. While it is projected that 50 to 200 million hectares would be needed to provide 10 to 20% of primary energy supply in 2050, available land that does not compromise the uses above is estimated to be at least 500 million hectares and possibly 900 million hectares if pasture intensification or water-scarce, marginal and degraded land is considered. As documented in the 21 chapters of the report, the use of land for bioenergy is inextricably linked to food security, environmental quality, and social development, with potentially positive or negative consequences depending on how these linkages are managed.

Building on over 2,000 scientific studies and major assessments, this 700-page e-publication outlines how:

- Development of bioenergy can replenish a community's food supply by improving management practices and land soil quality
- New technologies can provide communities with food security, fuel, economic and social development while effectively using water, nutrients and other resources
- The use of bioenergy, if done thoughtfully, can actually help lower air and water pollution
- Bioenergy initiatives monitored and implemented, hand in hand with good governance, can protect biodiversity, and provide ecosystems services
- Efficiency gains and sustainable practices of recent bioenergy systems can help contribute to a low-carbon economy by decreasing greenhouse gas emissions and assisting carbon mitigation efforts
- With current knowledge and projected improvements 30% of the world's fuel supply could be biobased by 2050

The report's authors see both practical and ethical imperatives to advance bioenergy in light of its potential to meet pressing human needs not easily addressed by other renewable energy sources. At the same time, they acknowledge that just because bioenergy can be beneficial does not mean that it will be. Research and development, good governance and innovative business models are essential to address knowledge gaps and foster innovation across the value chain. With these measures, the report argues, a sustainable future is more easily achieved with bioenergy than without it, and not using the bioenergy option would result in significant risks and costs for regions, countries and the planet.

chapter 1

SCOPE Bioenergy & Sustainability

Technical Summary

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SCOPE Bioenergy & Sustainability is a collective effort with contributions from 137 researchers of 82 institutions in 24 countries[1].

The volume is the outcome of an assessment that included a meeting held at UNESCO, Paris, in December 2013. Fifty experts discussed bioenergy sustainability across its whole lifeline and crosscutting aspects including energy security, food security, environmental and climate security, sustainable development and innovation.

This is a technical summary of one of the outcomes of this effort, the Bioenergy & Sustainability Synthesis of Knowledge volume. Additional facts and numbers that substantiate some of the key findings reported here can be found in Chapter 2 (Bioenergy Numbers)[2] or in the SCOPE Bioenergy & Sustainability background chapters (as referred throughout this summary)[3].

Background chapters were commissioned to provide context, raise issues, and report on status and technological developments for bioenergy expansion. Background themes were chosen so that the report would range from land use and feedstocks, to technologies and impacts. They represent a selection of topics authors considered the most relevant to enlighten decision-making based on current scientific knowledge on bioenergy. They created the basis to consider how bioenergy expansion and its impacts performed in the energy security[4], food security[5], environmental and climate security[6], sustainable development and innovation[7] nexus. And most importantly authors highlighted important gaps of knowledge and suggested the science needed to fill them.

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[1] (http://bioenfapesp.org/scopebioenergy/index.php/project-overview/roster-of-experts/)

[2] (Chapter 2)

[3] (also consult Background Chapters 8 to 21, this volume)

[4] (Chapter 3)

[5] (Chapter 4)

[6] (Chapter 5)

[7] (Chapter 6)

Scientific evidence was evaluated on the impacts and constraints for bioenergy expansion from data reported in over 2,000 references and major assessments. The report was subjected to an extensive internal and external peer-review process.

When assessing important drivers for bioenergy expansion, such as sustainable development and Innovation and global climate change the group addressed some of the perceived “showstoppers”:

- the need for integrated policy to maximize bioenergy benefits and positive synergies;
- the concern that at the scales needed cannot be attained;
- the high costs and technological complexities of developing sustainable biorefinery systems;
- bioenergy governance;
- bioenerg certification and social aspects;
- financing the bioenergy effort;
- bioenergy trade expansion;
- competition with food production;[8]

Bioenergy science and technology is being developed that improve economics, land use, biomass production, environmental benefits and livelihood

Over the last 5 years plentiful improvements on producing and using bioenergy have been documented and much is already commercially available.

The report offers solution oriented scientific recommendations to maximize bioenergy benefits[9] and highlights practices that can contribute to the modernization of agriculture, the recuperation of degraded land, increasing of soil carbon, the improving of soil quality and ecosystem services as well as its contribution to improving human health.

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[8] (Box 1.2 - The food vs. biofuels land competition issue)

[9] (Box 1.1)

Box 1.1. Maximizing bioenergy benefits

Bioenergy benefits can be expanded by[a]:

- promoting high yielding bioenergy crops with positive attributes with respect to water use and soil impacts
- increasing the share of bioenergy derived from wastes and residues
- integrating bioenergy production with crop production systems and in landscape planning
- increasing crop land productivity especially in developing countries, freeing up crop land for bioenergy crops, with a particular focus on pasture intensification for livestock production
- deploying marginal or degraded lands together with breeding of crops that can maintain productivity on marginal land
- using co- and by-products
- removing the correct amount of plant material to avoid reducing soil fertility, cause loss of organic matter or predispose the soil to erosion
- avoiding deforestation by promoting agroecological zoning
- adopting voluntary market-based incentives for appropriate resource management
- considering externalities, giving value to clean water, clean air, and other ecosystem services to encourage their protection
- establishing financial incentives to reduce carbon emissions
- integrating bioenergy production into existing activities (forest products, buffer strips, perennial rotations)
- producing bioenergy in land that makes a small contribution to food production, which includes the huge quantity of global pasture land
- using excess agricultural capacity for energy production to bring additional value and resilience into agricultural economies and the human communities that depend on them

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[a] (Chapter 5, Chapter 16, Chapter 6)

1.1 Introduction

Our understanding of the challenges and opportunities associated with bioenergy production has evolved considerably in the last 5 years. The contribution of bioenergy expansion to increased food prices was considerably smaller than initial predictions [10]. The potential negative environmental effects associated with indirect land use change (iLUC) have turned out to be subjective and uncertain[11]. Several high yield feedstock options are available. Sugarcane, maize, miscanthus and other perennial grasses, eucalyptus, willow, and other woody species, oil palm, agricultural residues and wastes, to name a few[12], are all options that together contribute to provide biomass supply in many regions of the world. New energy crops are being developed, with greatly increased yields and tailored for advanced biofuels that open the path for expansion with different technological options on many fronts[13]. Data on land availability[14], required infrastructure and costs for a reliable supply of biomass in many countries and scenarios are available[15]. Ethanol, biodiesel, renewable diesel, and wood pellets trade created an international market, spurred by policy efforts. At the same time, a number of voluntary schemes for certification of biomass, biofuels, and bioenergy production according to criteria and principles set by the specific sustainability schemes emerged, with the aim to increase the sustainable production and logistics of supply of biomass to conversion processes making fuels, energy, and products based on economic, environmental, and social considerations. Several voluntary sustainability schemes already existed for forest products and agriculture but without climate or energy specific criteria. Multiple standards and more stringent sustainability criteria are developing[16].

One of the main motivations for increasing the use of biomass to generate energy is that under the correct conditions greenhouse gas (GHG) emissions are reduced[17]. Decreasing emissions is critical and urgent to avoid serious interference with the climate system as reported by the IPCC 5th Assessment Report[18]. At the same time, more than 2 billion people lack access to modern energy services, which are a fundamental prerequisite for poverty reduction and human development. To transition into a sustainable energy matrix the United Nations has launched the SE4ALL initiative to achieve three global interlinked energy policy objectives by 2030: 1) ensuring universal access to modern energy services; 2) doubling the global rate of improvement in energy efficiency; and 3) doubling the share of renewable energy (RE) in the global energy mix by 2030[19]. IRENA summarizes the bioenergy situation: “Biomass currently

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[10] (Chapter 8)

[11] (Chapter 9) (Chapter 17) (Bioenergy Numbers 2.3.6, Bioenergy Numbers 2.2.2, Bioenergy Numbers 2.2.4, Bioenergy Numbers 2.3.1)

[12] (Chapter 9, Chapter 10, Chapter 12)

[13] (Chapter 10)

[14] (Chapter 9)

[15] (Chapter 11, Chapter 12)

[16] (Chapter 19)

[17] (Chapter 5, Chapter 6, Chapter 17, Chapter 1 Box 1.2)

[18] IPCC 5th Assessment Report (http://www.ipcc.ch/report/ar5/)

[19] Sustainable energy for all - A Global Action Agenda. (2012). United Nations. http://www.un.org/wcm/webdav/site/sustainableenergyforall/shared/Documents/SEFA-Action Agenda-Final.pdf

makes up 75% of the total renewable energy consumption, with traditional biomass use accounting for more than 50% of all the renewable technologies. Not all traditional biomass used today is sustainable. As the use of traditional biomass decreases, the shares of modern renewables will more than triple. As energy demand continues to grow, this requires a quadrupling of modern renewables in absolute terms. Technology costs have fallen significantly and will continue to decline through technology innovation, competition, growing markets and regulatory streamlining"[20]. These are very ambitious goals considering that the tripling of modern bioenergy in a short period has only been achieved by the US dry mill corn ethanol industry[21]. In order to achieve the desired climate effects, and reach more than double of bioenergy, intensified research, development and deployment (RD&D) policies are needed[22]. Moreover there is an accompanying requirement for standards, quality control, technology co-operation and project development capacity together with sustainability considerations and research throughout development, implementation and monitoring. More recently the New Climate Economy report of the Global Commission on the Economy indicated that it is possible to finance a reduction of 50% GHG emissions, with investments in renewables including modern bioenergy technologies partially compensated by reduced costs for conventional energy and savings from efficiency[23].

Our report considers the constraints, best options and science for bioenergy to realize its potential. The goals of this SCOPE Bioenergy & Sustainability project is to assess and communicate the complex nuances and opportunities of this key issue, to integrate scientific research and help inform the policy process, indicating options for the sustainable expansion of bioenergy use and production around the world.

1.2 Sustainable Development and Innovation

Different drivers motivated adoption of bioenergy options in different regions of the world including energy security, economic development and environmental concerns. One of the most important is the role it can play in facilitating sustainable development: meeting society's needs without jeopardizing the welfare of future generations by exceeding the carrying capacity of natural systems.

Improvement of universal, affordable access to clean energy that minimizes local pollution and health impacts[24] as well as mitigates global warming is of global concern.

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[20] REmap 2030 - A Renewable Energy Roadmap (2014). International Renewable Energy Agency. http://irena.org/remap/REmap Summary of findings_final_links.pdf

[21] (Chapter 12)

[22] (Chapter 7)

[23] The New Climate Economy Report (2014). http://newclimateeconomy.report

[24] (Chapter 2 section 2.4.3)

It is important to recognize the potential role of bioenergy in an *integrated* policy framework[25] that meets the 2030 UN SE4ALL goals referred to earlier. Modern bioenergy is naturally an integrating energy resource, linked to improving health[26], livelihoods and education[27] when properly designed and implemented. Modern bioenergy can be promoted from small-scale local use in stand-alone applications or mini-grids[28] as well as large-scale production and commoditization[29], through automotive biofuels[30] and bioelectricity[31], with a large capacity to substitute for the inefficient traditional burning of biomass largely used in the developing world[32]. Sustainable bioenergy production promotes more efficient uses of agricultural and woody biomass, reducing deforestation by replacing the overuse of natural forest firewood, reducing land degradation that is associated with low-productivity agriculture, fuelwood or charcoal use[33].

The potential for sustainable bioenergy development is dependent on the needs, available resources and infrastructure of particular countries and regions. IPCC 5th Assessment Report[34] points out that: "infrastructure and integration challenges vary by mitigation technology and region. While these challenges are not in general technically insurmountable, they must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply". Technological development in biomass supply and transformation is reducing costs, generating new business models, driving innovation in science and technology, and supporting continuous improvement of infrastructure and extension services. A number of examples exist, where innovation has given rise to new business models[35]. The production of multiple outputs (energy, food, feed, material products, and use of co- or by-products) is an example where different business opportunities have been combined. Innovation in feedstock production[36], biomass processing and utilization[37], development of new biorefinery systems[38], and advanced biofuels[39] are scale and context dependent technologies for different countries and regions, both developed and developing, and have the potential to enable the advancement of a bioeconomy generating abundant jobs and promote economic development[40]. These innovation efforts should be incorporated in the Millennium[41] and Sustainable Development[42] policy goals.

1.3 Global Climate Change

Integrated studies of the energy sector show that bioenergy is an essential component of GHG reduction technologies displaying a critical role for environmental security

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[25] (Chapter 7)

[26] (Chapter 2 section 2.4.3)

[27] (Chapter 2 section 2.4.4)

[28] (Chapter 2 sections 2.2.3.10, 2.2.4, Chapter 21)

[29] (Chapter 2 sections 2.2.3.1, 2.2.3.3, 2.3.8)

[30] (Chapter 2 sections 2.2.3.2, 2.2.3.3)

[31] (Chapter 2 section 2.2.3.9)

[32] (Chapter 2 Box 2.1)

[33] (Chapter 6, Chapter 21)

[34] IPCC 5th Assessment Report (http://www.ipcc.ch/report/ar5/)

[35] (Chapter 6, Chapter 11, Chapter 12, Chapter 14)

[36] (Chapter 2 Box 2.7)

[37] (Chapter 2 section 2.3.2)

[38] (Chapter 2 Box 2.4)

[39] (Chapter 2 sections 2.2.3.5, 2.2.3.6)

[40] (Chapter 6, Chapter 15)

[41] United Nations Development Goals (http://www.un.org/millenniumgoals/)

[42] United Nations Sustainable Development Goals (http://sustainabledevelopment.un.org/?menu=1300)

and climate change mitigation. Global warming levels greater than 2 °C will lead to significant adverse impacts on biodiversity, ecosystem services, natural ecosystems, water supply, food production and health. Any potential impacts of bioenergy should be viewed in this context[43], but not exclusively since there are multiple benefits described for well-executed projects and potential trade-offs.

At present, approximately 87% of energy demand is satisfied by energy produced through consumption of fossil fuels[44]. Although the IEA predicts that this share will fall to 75%, the total consumption of fossil fuels will continue to rise, adding another 6 Gt of carbon to the atmosphere by 2035[45]. Global surface temperatures are increasing and the rate of ocean acidification has not been this high in 300 million years, having increased by 30% over the last 150 years. The main cause is emissions from fossil fuel burning, especially the release of CO_2. The oceans are an important CO_2 sink absorbing 26% of the CO_2 emissions, but due to accelerated acidification and rising sea surface temperatures, this capacity may be reduced[46].

As awareness of the evidence that combustion of fossil fuels is causing climate change has expanded, bioenergy has come to be seen as a mechanism for decreasing the carbon cost of energy use[47]. In the transport sector, biofuels offer a climate-compatible approach that also supports agricultural development; approximately 50 countries, including many developing countries, now have biofuels mandates, some driven by climate security efforts other by energy security or other reasons[48].

1.4 Planning the Expansion of Bioenergy

Bioenergy has evolved to a comprehensive role for heat, power, and transportation fuels at a range of scales from households to nations. Further, bioenergy can play a significant role in policy decisions if evaluated as an important option for increasing energy security[49]. In several scenarios (IPCC/SRREN or AR5, IEA, GEA, WWF and Greenpeace) bioenergy will grow to an average of 138 EJ by 2050 with a low of 80 EJ and a high of 180 EJ. These absolute amounts of biomass-derived energy correspond to a range of 14 percent to over 40 percent of the primary energy projected supply[50]. IRENA in its recent REmap2030 report[51] proposes that if all the technology options envisaged in the REmap analysis are deployed, biomass use could reach 108 EJ worldwide by 2030, double the current level, and could account for 20% of total primary energy supply and 60% of final renewable energy use. There are three major land classes that can grow terrestrial biomass: cropland (~1.5 Bha), forestland (~4 Bha)

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[43] (Chapter 8, Chapter 5)

[44] (Chapter 2 Figure 2.1)

[45] (Chapter 8)

[46] (Chapter 5)

[47] (Chapter 2 section 2.2.4)

[48] (Chapter 3, Chapter 20)

[49] (Chapter 3)

[50] (Chapter 9 Figure 9.1)

[51] REmap 2030 - A Renewable Energy Roadmap (2014). International Renewable Energy Agency. http://irena.org/remap/REmap Summary of findings_final_links.pdf

and pastureland (~ 3.4 Bha)[52]. IPCC[53] reports that land availability will depend on the extent to which bioenergy can be grown on areas with little current production and that considerations of trade-offs with water and biodiversity are crucial to avoid adverse effects. Around 0.9 Bha of global land complies with the above points being interpreted as rainfed land that is being either unused in economic terms or pasturelands, which are lightly used and thus could accommodate other options. To grow bioenergy crops to generate 100-200 EJ/year of bioenergy by 2050 around 50 to 200 million rainfed hectares would be needed. This corresponds to the use of 0.4 to 1.5% of total global land to provide a share of 10-20% of total primary energy with modern bioenergy or 5-20% of the available rainfed unused or poorly used land. This calculated bioenergy land of 50 to 200 million ha needed excludes the land needed for food crops, native and planted forests, and urban and other protected landscapes[54].

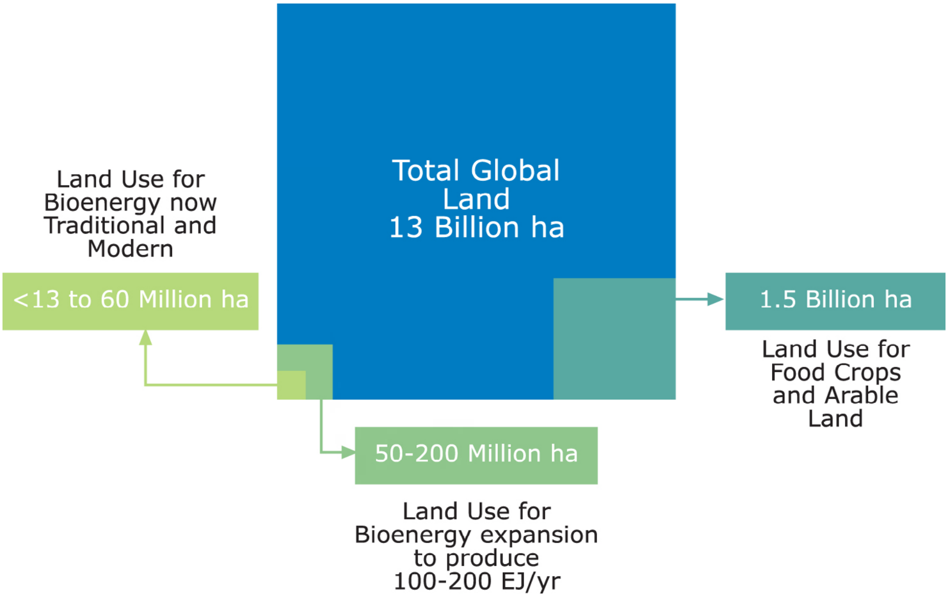

Figure 1.1. Global land use for bioenergy. Approximate numbers.

When properly planned and managed, bioenergy may have positive synergies with other policy priorities such as water and food security, as well as supporting energy access, economic development, growth, stability and environmental goals[55]. As efforts to adapt to and mitigate climate change increase, and the realization that fossil fuels may no longer be an option becomes clearer, bioenergy is expected to be increasingly important to energy security issues because of the relatively low carbon intensity of bioenergy

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[52] (Chapter 9 Table 9.15)

[53] IPCC 5th Assessment Report (http://www.ipcc.ch/report/ar5/)

[54] (Chapter 9)

[55] (Chapter 8, Technical Summary Box 1.1)

compared to fossil fuels. Greater utilization of lignocellulosic materials, enabled by technology advancements ranging from improved cooking stoves for underdeveloped regions to the production of lignocellulosic biofuels, can significantly increase the useful resource base globally and alter the geopolitical landscape due to different national resource endowments[56]. Land availability in global terms is not a constraint but availability is expected to be concentrated in two main regions: Latin America and Africa[57].

1.4.1 Integrated Policy to Maximize Bioenergy Benefits and Positive Synergies

Integrated policy frameworks for bioenergy are desirable at several levels including the management sectors (agriculture, forestry, energy, transportation, for instance), across physical landscapes (such as in the establishment and monitoring of agroecological zoning) and across financing schemes to consider technological options and multiple potential benefits. Making bioenergy an integral part of sustainable development strategies requires a systems approach in developing assessments, policies, strategies and business models.

To avoid reliance on staple food crops and to avoid excessive reliance on productive agricultural lands for bioenergy, several options exist that could be stimulated such as using degraded lands, expanding coproducts, practicing integrated land use management, and promoting advanced biofuel technologies that use multiple feedstocks[58]. On the utilization side, promoting improvements on the conversion efficiency of biofuels in vehicles and power generation can increase the positive impacts of the whole chain[59].

Political leadership, providing long-term, consistent policy, legal, and institutional frameworks are necessary to leverage the necessary investment in innovation and scale up of the existing and emerging examples of good practices[60].

Integrated resource assessment is at the heart of any decision-making process, particularly in integrated water management and land use planning. Furthermore, projected energy, food and materials needs should be accounted for as part of assessments. Policies need to be long-term, providing investor security, and have to be consistent with climate, rural and industrial development, energy and food security policies[61].

As we look toward the future, it is clear that global policy frameworks should more explicitly address bioenergy production and provide appropriate incentives for sustainable integration with food and timber production. Such policies must have the flexibility to adapt to local social and biophysical circumstances, yet also drive management practices that achieve global greenhouse gas (GHG) reduction goals. There are many strategies that can be used to achieve that integration, providing large quantities of fuel while enhancing ecosystem services and addressing socioeconomic needs. Central to all of these strategies are embedded concepts of multifunctional landscapes, integrated landscape design, and resilience in the

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[56] (Chapter 3)

[57] (Chapter 2 Box 2.5)

[58] (Chapter 4)

[59] (Chapter 2 Box 2.2)

[60] (Chapter 6)

[61] (Chapter 6)

face of changes yet to come[62]. In this sense, adaptive approaches that account for changing resource endowments, natural conditions, technology advancements, and geopolitical change are needed[63] as well as monitoring of these areas to continuously improve practices.

A careful analysis is required when policy and regulatory approaches are applied for bioenergy production, conversion, and use. Policy measures can enable or inhibit positive synergies being more site-specific than other energy sources [64]. Bioenergy deployment in several countries has shown different outcomes, even for apparently similar situations, that are strongly influenced by the local context and supporting policies. In the case of ethanol production in Brazil and Thailand, technology development and management practices evolved slowly in the former, to make it the largest sugarcane ethanol producer in the world, and they served as starting point to the latter, being adapted to the local conditions. Strong and adequate policies were the key factor for the success of both cases[65] and also for downfall as the recent stress on the Brazilian bioethanol industry caused by policy that lower fossil fuel prices exemplifies[66].

In terms of implementation, policy measures and investment in research, pilots and business development will be required[67]. A lesson learned is that sufficient time of operations of pilot plants is extremely important to minimize future development risks and costs[68]. Attention must also be given to technical support for farmers, land tenure schemes and development of cooperatives for sustainable agriculture[69]. Policy instruments specific to biofuels have been put in place in several countries, but they still need to be linked to wider country-level objectives on food production, coproduction of chemicals, education and land use planning[70].

Box 1.2. The food vs. biofuels land competition issue[b]

Concerns on the production of bioenergy based on global land availability and linking biofuels production to increased food prices are unfounded.

The overall land required to meet bioenergy demand has been estimated as ranging from 50 Mha to 200 Mha in 2050 with biofuels being the most land intensive sub-sector. Between 40 and 50 Mha is required to grow the feedstocks for conventional biofuels, providing between 7% and 17% of primary energy in 2050. The remaining 10 to 150 Mha of land demand is for lignocellulosic biomass from energy crops and could be met from a combination of rainfed agricultural land and pastureland arising from pasture intensification. Additional feedstocks and land for bioenergy could effectively be made available from forestry activities. A small (0% to 11%) portion of potentially available land considered suitable for rainfed agriculture is required for energy crops.

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[62] (Chapter 13)

[63] (Chapter 3)

[64] (Chapter 3)

[65] (Chapter 14)

[66] (Chapter 8)

[67] (Chapter 7)

[68] (Chapter 12)

[69] (Chapter 4)

[70] (Chapter 15)

[b] (Chapter 9, Chapter 4, Chapter 2 section 2.3.1)

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Irrigation should not be excluded per se from considerations of biomass supply where water is available. Efficiency is almost always greater in irrigated systems, including for bioenergy.

That said, it is important to mention that there is enough land available that does not require irrigation. Potentially available land for rainfed agriculture is estimated to be in the range of 900 Mha in 2050. Based on population and dietary trends, the FAO projects a net increase in land used to grow food crops by 2050 of about 70 Mha resulting from an increase in land area under agriculture in developing countries of 130 Mha and a decrease of over 60 Mha in developed countries. By 2050, 1.2 Bha of land could be considered as available for uses other than food/feed including bioenergy feedstock production[c]. Forestry, protected lands and urban demands account for a further 1.8 Bha. Approximately 0.6 BHa of land that has been farmed in the past but is not currently farmed is available worldwide.

At a global level, land is not a constraint but availability is concentrated in two main regions, in Latin America and Sub-Saharan Africa, and is currently used predominantly for low intensity animal grazing. Developed countries also have land available but agricultural area in those regions is expected to remain stable.

The projected rate of increase in global food demand (2.4% per year) is now outstripping the increases in production. However, malnourishment is not primarily a problem of food production, but also of downstream factors and disposable income. Roughly 20-30% of people with food insecurity (180-270 million) live in urban areas and are mainly affected by high food prices. However, 70-80% (630-720 million) of food insecurity problems occur in rural areas where energy insecurity or energy poverty is also concentrated. Positive synergies can thus be obtained between expanded food AND energy production, by offering new sources of income for farmers and new sources of energy in rural areas. Together with increased agricultural and rural development, local and national economies will be boosted.

In defining bioenergy policies it is important to manage risks of food insecurity and climate change in ways that take into account persons who are underrepresented because they are poor or unable to look after themselves. Since food insecurity, lack of energy access and low life expectancy go together, there is often a cycle of negative environmental impacts with little or no economic return, such as the traditional, unhealthy practice of using fuelwood or dung for cooking. In stimulating development that benefits rural communities, bioenergy has a clear potential to help achieve food security and other aspects of human development, and should be considered as a viable option for investment schemes.

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[c] (Chapter 9 Table 9.5)

1.4.2 Sustainable and Reliable Biomass Supply

Considerable advances have been made in the improvement of crop yield[71], in the understanding of the key criteria that need to be met for sustainable production, which crops best meet these criteria, the changes needed to further improve sustainability and the impact of climate changes on productivity[72]. The quantity of dedicated energy crops and their yields are important determinants of land needed[73]. The challenges of meeting biomass supply through yield improvement and expansion of feedstocks in sustainable ways can be met[74], but only with secure and prolonged support and sensible, easily adoptable policies that recognize the environmental as well as the economic goals. Policies are needed so that strategies for increasing feedstock production in sustainable ways can be implemented immediately[75] to meet the ambitious goals of SE4ALL, for instance. Crop breeding and the development of suitably adapted varieties of energy crops is a long-term process. Nearly all of the 100 billion liters of biofuels used today consist of ethanol and biodiesel produced using maize, sugarcane, rapeseed and soybean[76] that were expanded using intensification and thus requiring very little additional land, approximately 13.5 Mha[77]. These crops have been bred for many decades to achieve their current high yields[78]. Maize yields 72.8 GJ/ha and sugarcane yields 156.8 GJ/ha (3900 L/ha and 7200 L/ha ethanol respectively)[79]. There is consistent evidence of many potential bioenergy feedstock options[80] including the use of residues, sugarcane bagasse, corn stover, other energy grasses or woody plants such as eucalyptus that can double the energy output through the use of advanced biofuel technologies, current high efficiency thermal cycles commonly in cogeneration schemes, direct combustion or power generation[81]. Measures for their immediate deployment and development are needed to release this potential in time to fight global climate change[82].

Emerging perennial crops and woody feedstocks that may be grown on marginal land, i.e. land unsuited to arable crop production or semi-arid land could allow large-scale replacement of fossil fuels[83]. Pasture intensification will be an important tool to contemplate land demand. However, this will require the implementation of policies that favor these new land uses and policies that support the realization of the potential of producing cellulosic fuels. Acceptance of biotechnology for bioengineered crops will be important since crop yields in marginal lands are low and could benefit from more rapid improvement made possible with the use of biotechnological tools[84].

Cropping intensification[85] and agro-forestry integration are additional ways to increase yields and decrease land demand[86]. Harmonizing forestry and agriculture policies is

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[71] (Chapter 10)

[72] (Chapter 2 section 2.3.4)

[73] IPCC 5th Assessment Report (http://www.ipcc.ch/report/ar5/)

[74] (Chapter 2 section 2.3.2)

[75] (Chapter 10)

[76] (Chapter 2 Figure 2.1)

[77] (Chapter 2 section 2.2.2)

[78] (Chapter 2 section 2.2.1)

[79] (Chapter 2 Figure 2.1)

[80] (Chapter 10 Table 10.1)

[81] (Chapter 2 section 2.2.3)

[82] (Chapter 10)

[83] (Chapter 9, Chapter 10)

[84] (Chapter 10)

[85] (Chapter 9)

[86] (Chapter 13)

fundamental for the implementation of integrated approaches to sustainable production and supply of bioenergy. Regulations that ensure the sustainability of biofuel-specific agriculture and forestry practices have not yet been developed in many countries. The necessary legal and institutional frameworks are also lacking particularly those related to tenure, and the customary land rights[87].

It is not clear how biomass supply will be affected by climate change[88]. Yield reductions of zero to -2.5% appear small in relation to historic rates of yield improvement per decade in maize and wheat. For rice and soybean no reductions are indicated. But extreme weather events may alter rainfed crop performance, pest and disease incidence. Field experiments with crops under CO_2 2050 predicted levels increased the yield of rice, wheat and soybean by 15%, but did not affect maize yield, however effects may not be globally uniform[89]. It will be important to better understand the impacts and interactions of climate change on bioenergy crops for sustainable feedstock production in an uncertain future.

1.4.3 Developing Sustainable Biorefinery Systems

Biomass has the unique capability among all energy sources of providing solid, liquid and gaseous forms of energy carriers that can be transformed into analogues provided by the fossil fuels industry[90]. IPCC[91] considers that land demand for bioenergy depends, among other things, on the share of bioenergy derived from wastes and residues. The design of new biorefinery systems can contribute to decreased land use by optimizing the use of biomass resources alongside water, land and other factors of production. Integrated biorefineries will minimize losses by using wastes and residues for bioenergy and non-energy products[92], while addressing long-term soil quality through recycling of nutrients[93]. Recently, 250 projects related to the industrial development of advanced biofuels and renewable materials based on innovative technological paths have been described[94]. This wide array of technological pathways in hundreds of chemical and energy industries is expanding and maturing. Almost half of the projects are in the US and Brazil, with initiatives also underway in Germany, The Netherlands, Canada and the UK. In Scandinavian countries a significant intensification of use of biomass for bioelectricity and heat is observed. As the bioeconomy is a promising but infant industry in most of the world, policies should stimulate its development. Technological change that reduces costs and stimulates full biomass utilization for food, feed, energy, materials and chemicals might improve its competitiveness in relation to the fossil fuels industry. The development of more efficient biomass conversion routes, especially routes that can convert lignocellulosic

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[87] (Chapter 13)

[88] (Chapter 2 section 2.3.4)

[89] (Chapter 4)

[90] (Chapter 2 section 2.2.3)

[91] IPCC 5th Assessment Report (http://www.ipcc.ch/report/ar5/)

[92] (Chapter 12)

[93] (Chapter 2 section 2.4.2, Chapter 18)

[94] World Directory of Advanced Renewable Fuels and Chemicals. 2014. Elabora. http://www.elaboraeditora.com.br/world-directory-of-advanced-renewable-fuels-and-chemicals

biomass into biofuels and biochemicals[95], will accelerate the transition towards a competitive biobased economy[96].

Development and commercialization of lignocellulosic technologies have been moving at a slower pace than anticipated by governments or by the private sector for many reasons but, now, it seems to be accelerating. The industry had to develop biomass production, logistics for biomass collection, storage, and delivery to the conversion facility for biofuel manufacture with agreements of purchase for fuel distribution and use, and had to reach fuel product acceptance. Significant improvement is possible to bring the cost of these technologies down in both the enzymatic hydrolysis and thermochemical lignocellulosic ethanol pathways[97]. Initial industrial scale operations of several lignocellulosic ethanol processes as first-of-a-kind plants started in 2013-2014[98]. The positive outlook of advanced biofuels is conditional on accelerated deployment of whole supply chains. This would help achieve: process stability, reliability, and availability that can lead to production costs falling to competitive levels[99].

Bioenergy is part of a larger transition to a bioeconomy in which bioproducts will be competing ultimately by means of efficiency and price. Policies and energy prices are key drivers for current bioenergy and the emergent bioeconomy. Technological change and full biomass utilization might create a competitive industry. A coherent temporary policy package can stimulate an immature industry and regulation can deal with the indirect effects[100].

Although the policy focus in support of bioenergy has an understandable focus on energy and climate, sustainable technology development requires attention to other environmental impacts as well. Significant advances have occurred in water recovery and recycling to reduce water requirements for conversion processes as well as effluent production that justify policy efforts to stimulate emerging sustainable bioenergy practices[101]. Feedstock production and conversion stages can, in some cases, be integrated to use resources more effectively and support good land and water management. Examples include the recirculation of sludge to willow plantations, vinasse application to sugarcane fields, the use of perennials to reduce erosion and nutrient runoff[102], and possibly, the use of biochar as a soil amendment[103]. More work is needed to integrate all the elements of the value chain, including assessments of environmental performance and overall system sustainability (environmental, social, and economic)[104].

Lignocellulosic biofuels may show higher GHG mitigation potential than current biofuels, but the exact potential of the new processes is still to be verified when in commercial scales.

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[95] (Chapter 7)

[96] (Chapter 20)

[97] (Chapter 12, Figure 12.21)

[98] (Chapter 8, Chapter 12)

[99] (Chapter 12, Chapter 2 section 2.3.3)

[100] (Chapter 20)

[101] (Chapter 12)

[102] (Chapter 2 section 2.4.2)

[103] (Chapter 18)

[104] (Chapter 12)

1.4.4 Bioenergy Governance

Adequate governance schemes need to be in place to ensure that bioenergy sustainability is achieved and that its benefits are distributed equally. There is enough suitable land available to accommodate both increased food demands and a considerable contribution to energy production but it is important to study and monitor bioenergy expansion to maximize benefits ensuring positive impacts and sustainable agricultural practices[105]. Sustainable implementation of bioenergy options requires strengthening institutions and governance at all scales, from local to global[106]. Governments worldwide can influence the deployment of sustainable bioenergy using appropriate assessment practices and policies[107]. Even in developed countries capacity is lacking with regard to implementation of certain elements of sustainability certification. Thus, the assumption cannot be automatically made that existing policies in those countries eliminate the need for verification, and that only underdeveloped countries lack the governance structures and warrant oversight[108]. Good governance, strong institutions, market based voluntary certification, and access to information about appropriate management strategies and tactics all support sustainable resource use and management that can benefit biodiversity and ecosystem services. Developing such management strategies around the world represents a long-term undertaking that is connected to improving agricultural and forest management[109].

Governance is especially important regarding the issue of biodiversity and ecosystem services protection. The negative effects of bioenergy and biofuel production on biodiversity and ecosystem services can be avoided or reduced and positive effects enhanced by attention to three guiding principles: (1) identification and conservation of priority biodiversity areas; (2) identification of effects of biofuel feedstock production on biodiversity and ecosystem services that are context specific; and (3) implementation of location-specific management of biofuel feedstock production systems to maintain biodiversity and ecosystem services[110]. Governance policies are needed that are especially designed to avoid the implications of unsustainable exploitation of natural forests for biofuels, which frequently lead to “exporting” deforestation to other regions in the same country or to other countries as well as encouraging illegal logging and trade in wood and non-wood forest products[111]. Participatory governance that engages the general public and key stakeholders in an open and informed dialogue is required for a broad public support of bioenergy[112]. Negative indirect effects of bioenergy are better addressed by policy directly supporting sustainable land use, food security, education, health care, and ecosystems supportive of public health. Policy should focus on public governance failures, and recognize the limitations of private, third party sustainability certification to address community-level issues[113]. The application and enforcement of Agroecological Zoning (AEZ) principles is of paramount importance to avoid the

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[105] (Chapter 3, Chapter 4, Chapter 5, Chapter 6)

[106] (Chapter 13)

[107] (Chapter 5)

[108] (Chapter 19)

[109] (Chapter 16)

[110] (Chapter 5) (Chapter 16)

[111] (Chapter 5)

[112] (Chapter 20)

[113] (Chapter 19)

conversion of ecologically significant and sensitive areas. As a highly innovative industry, biofuels can be part of the solution to environmental development[114].

1.4.5 Bioenergy Certification and Social Aspects

If “sustainability” is to have real meaning, government policy (and third party certifiers) must evolve from being theoretical to a more applied consideration of the technical and economic requirements needed for measurement and the capacity necessary to transform aspirational standards to on-the-ground results. Case studies demonstrate that even in developed countries, where some programs and tools already exist, gaps remain[115]. Technical capacity problems are likely magnified for developing and underdeveloped countries. Bioenergy policy, therefore, must provide scientific, educational and technical support to producers to ensure fulfillment of certification requirements. International efforts should consider implementing support mechanisms for building knowledge networks that translate skill sets and lessons learned to those charged with implementing sustainability practices and outcomes locally[116]. Examples of efforts in this direction are those led by GBEP and RSB[117].

In the context of equitable development, energy solutions that reduce health impacts and provide higher quality energy services at reasonable costs are preferred. Social aspects should be included in bioenergy policy and certification schemes especially considering education benefits and job generation[118]. Women and children disproportionally bear the ill effects of inefficient bioenergy use ranging from the hard labor of biomass collection to indoor air pollution issues[119]. Gathering fuelwood for traditional stoves to cook and heat homes occupies young women with provisioning for energy at the cost of formal education [120]. Transitioning away from traditional biomass use to modern energy services can reduce the time needed to collect water and firewood, which means that many women and children have more time to study or for income generating activities[121]. Additionally, women play a significant role in agriculture and various forms of land rights in developing countries have frequently discriminated against women. Educating communities, and particularly women about their own land rights is crucial[122].

1.4.6 Financing the Bioenergy Effort

Studies indicate that it is possible to finance a reduction in GHG emissions of 50-90% of what is needed by 2030 to avoid the 2^{o}C global warming [123] at lower cost than is currently used to subsidize fossil energy. A significant challenge to transition to a low carbon economy is that the petroleum industry invests based on internal rates of return of about

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[114] (Chapter 16)

[115] (Chapter 14)

[116] (Chapter 19)

[117] (Chapter 19)

[118] (Chapter 2 section 2.4.4)

[119] (Chapter 3)

[120] (Chapter 3, Chapter 15, Chapter 6)

[121] (Chapter 6)

[122] (Chapter 15)

[123] (Chapter 2 section 2.3.7)

15% per annum, a number that is difficult to obtain with most types of unsubsidized bioenergy[124]. To correct for market failures, extensive research, development and demonstration (RD&D) programs relating to renewable energy are present in rich countries. According to the International Energy Agency they spent at least USD 4.1 billion on RD&D related to renewable energy in 2011[125]. Even though these policy instruments may boost returns for bioenergy to an acceptable level in the short-term, uncertainty about the duration of policy support for bioenergy may preclude long-term capital investment. In particular, capital investments may be based on approximately 30-year lifetimes. Thus, there is a need for long-term stability of regulatory mechanisms[126].

1.4.7 Bioenergy Trade Expansion

As international trade expands, bioenergy issues will play an increasingly larger role in the geopolitical dialogue, including the complexities across multiple energy segments and the interconnectivity with other geopolitical issues including food, water, trade, human rights, and conflict[127]. All commercial biofuels have been increasingly traded internationally as have solid biomass pellets and other densified materials, which enable transport at longer distances to supply a variety of markets, such as power generation and cogeneration for district heating and power[128]. Many biofuels and feedstocks were exported and received sustainability certification according to criteria and principles defined by several sustainability schemes accepted by the EU Renewable Energy Directive[129]. International harmonization efforts must account for unique regional and local socio-environmental conditions; certification should not lead to north-south trade barriers[130].

1.5 Conclusions

SCOPE Bioenergy & Sustainability provides a guide to bioenergy possibilities, paths for sustainable expansion and recommendations for realizing its techno-economic potential. It shows there is probably no one-size-fits-all solution for bioenergy development with different paths available for adoption depending on resources endowment, technology suitability and appropriate policy frameworks. It also highlights the gaps in knowledge and proposes the science and technology needed for bioenergy to realize its maximum benefits. Enough land is available, that need not pose a threat to food security, biodiversity and ecosystem services, and the improvements this industry has been attaining (improving soils, integrated chains, use of co-products, improved conversion technologies) add up to reach climate mitigation much more effectively while improving economic performance to benefit broader societal needs.

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[124] (Chapter 3)

[125] (Chapter 20)

[126] (Chapter 3, Chapter 6 Figure 6.2)

[127] (Chapter 3)

[128] (Chapter 2 section 2.3.8)

[129] (Chapter 12)

[130] (Chapter 19)

Bioenergy science and technology is bringing solutions that improve economics, land use, biomass production, environmental benefits and livelihoods. For additional information visit Boxes on Chapter 2[131].

Bioenergy Numbers - Box 2.1 – to decrease pollution

Bioenergy Numbers - Box 2.2 – to increase efficiency for competitive deployment

Bioenergy Numbers - Box 2.3 – to decrease costs

Bioenergy Numbers - Box 2.4 – to establish the cellulosic ethanol industry

Bioenergy Numbers - Box 2.5 – to recuperate soils

Bioenergy Numbers - Box 2.6 – to protect biodiversity and ecosystem services

Bioenergy Numbers - Box 2.7 – to increase crop yields

Bioenergy Numbers - Box 2.8 – to decrease water use

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[131] (Chapter 2 Boxes)

chapter 2

Bioenergy Numbers

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2.1 Introduction

Substantive evidence exists that many bioenergy cropping systems can bring multiple benefits and off-set environmental problems associated with fossil fuels, intensive food production and urbanization[1]. As for any other developmental change, however, this does not mean that bioenergy does not present any risks, but rather that such risks can be managed through the adoption of appropriate policies, promotion of suitable energy feedstocks, and management practices. In this chapter we present a summary of numbers regarding current use and expansion of bioenergy as well as aspects that constrain the realization of its multiple benefits.

This chapter is part of the synthesis of the SCOPE Bioenergy & Sustainability volume and includes the contribution of its editors, scientific advisors, background and crosscutting chapter authors. SCOPE Bioenergy & Sustainability includes the contributions of 137authors from 82 institutions in 24 countries. The Bioenergy Numbers section is a selection of some of the key numbers that substantiate the Key Findings of SCOPE Bioenergy & Sustainability volume. For additional details refer to the synthesis volume chapters (http://bioenfapesp.org/scopebioenergy/index.php).

2.2 Bioenergy Production Now

Total global primary energy use is around 550 EJ. Biomass as a source of energy currently contributes to approximately 10% of primary energy used - 62 EJ. Traditionally, bioenergy production is mostly wood-based, and is generated by direct inefficient combustion (burning), although other crop wastes and residues are also used[2]. In 2010, traditional bioenergy amounted to around 40 EJ/yr[3] primarily used for household cooking. More efficient conversion processes are increasingly being implemented using wood pellets[4].

Liquid biofuels have been used for transportation fuel, direct heating and lighting. In some countries, biofuels have become an important contribution to the energy matrix but globally, they currently make a small contribution (4.2 EJ). Biofuels are expected to play a more important and larger role in the world's fuel supply, increasing from just under 2% of oil equivalent for the globe as a whole today to as much as 30% by mid-

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[1] (Chapter 3, Chapter 4, Chapter 5, Chapter 6)

[2] (Chapter 10)

[3] (Chapter 9)

[4] (Chapter 13, Chapter 14, Chapter 17)

century[5]. Current world production of biofuels is over 100 billion L (88 Gl ethanol and 20 Gl biodiesel). The leading producer in 2012 was the USA, followed by Brazil, China, the EU and Canada. Lignocellulosic biofuels production has advanced but with a few plants worldwide represents a small share (0.2% of total global biofuel production).

Global demand for wood has been increasing by 1.7% annually[6]. Non-traditional biomass is expected to grow from 526 mega metric tons of oil equivalent (Mtoe) in 2010 to nearly 1200 Mtoe by 2035, growing at a rate of 3.3% per year[7]. Between 2005-2013, there was a three- and four-fold increase in production of wood pellets for electricity, heat, or combined heat and power (CHP), and of liquid fuels for transport. Gaseous biofuels had an average growth rate of 15% per year while liquid biofuels grew at a 12% annual rate between 1990 and 2008[8]. Today bioethanol represents the fastest growing renewable fuel substituting for almost 10% of the volume of gasoline used in vehicles in the USA and about 40% in Brazil. The role of biomass in bioelectricity, heating and cooling is also expected to grow considerably in the future[9]. Brazil's sugarcane industry-wide electricity generation nearly doubled since 2006-2009[10].

2.2.1 Current Feedstocks

Today, the world produces more maize than any other grain or seed. Maize as feedstock accounts for more than 95% of fuel ethanol production in the USA providing more than half of all of the fuel ethanol produced in the world. US production of maize grain from 2006-2010 averaged 311 Mt yr^{-1}, of which 94 Mt yr^{-1} was used for ethanol production and 54 Mt yr^{-1} exported. Globally, research and development (R&D) boosted maize yields per hectare by 30% over the past decade of which the introduction of genetically modified (GM) traits accounted for one-third of the increase. Innovation in maize production and processing improved ethanol greenhouse gas (GHG) benefits versus fossil fuels by 35%, reduced fossil energy use in ethanol production by 30%, and process water use by a factor of 2[11]. Of the global 880 Mt of maize production, the USA accounts for just over 40%, yet is grown on just 20% of the land planted to this crop globally. In the USA whereas an acre of maize farmland produced an average 138.2 bushels in 2001, the average yield was 152.8 bushels per acre in 2010. The average annual increase in maize yield in the USA between 1983 and 2013 was 0.17 t ha^{-1} yr^{-1} [12].

Sugarcane has a well-established agricultural production system and processing infrastructure to make it among the most advanced feedstocks for bioenergy. Sugarcane is a major crop grown in the tropical and subtropical regions of the world. Nearly 1.8 billion metric tons of sugarcane biomass were produced in 2012 in more than 100 countries. The calculated average energy content of the total above ground biomass is 7,400 MJ t^{-1} of cane for an average crop of around 70 t ha^{-1} yr^{-1} (more than 500 GJ ha^{-1} yr^{-1}). Sugarcane is planted once

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[5] (Chapter 8)
[6] (Chapter 10)
[7] (Chapter 20)
[8] (Chapter 12)
[9] (Chapter 9)
[10] (Chapter 12 Figure 12.11)
[11] (Chapter 10)
[12] (Chapter 10 Figure 10.2)

Box 2.1. Improving use of wood to decrease pollution

Approximately 30 EJ of traditional biomass was derived from direct biomass burning, 3EJ from charcoal and only 1EJ from modern solids (pellets and chips) as recently as 2007[a]. In developing regions about one-third of traditional biomass energy was estimated to be supplied from forests, with two-thirds from trees interspersed in agricultural cropland and grasslands, as well as livestock manures and crop residues[b]. Around 2.8 billion people in the world rely on solid fuels for cooking and heating[c], whose consumption causes respiratory illnesses and close to 1.6 million deaths per year, of mainly women and children[d]. In India solid fuels account for about 63% of the total household energy consumption with significant contributions to both CO_2 emissions and indoor air hazards, Cambodia, with 1,304 deaths per million people in 2004 and India with 954 deaths, occupy the top two positions in deaths due to indoor pollution, one of the top causes of death in the world[e].

Increasingly, bioenergy production from wood is being improved. Wood represents an important share of total primary energy supply in some industrialized countries using efficient steam power systems, generally in co-generation schemes (e.g. Finland (28%), Latvia (28%), Sweden (27%), Denmark (19%))[f]. The use of bioenergy has increased steadily in Scandinavia and has reached about 20% of the total energy supply in Sweden. Most of Scandinavian bioenergy comes from the forests[g]. Wood pellet production as of 2011 has grown to 22 million metric tons or some 350 PJ[h]. Estimated consumption of wood pellets in EU alone was 12 million t/year, in 2012[i].

and harvested repeatedly after 12 to 18 months of growth for 5 to 6 years. Approximately one-third of the total energy in the above-ground biomass of today's sugarcane cultivars, is captured as the sucrose fraction present in the stalk while another third is present in the bagasse and the last third is the straw left in the field after mechanical harvesting. Currently, sugarcane provides 17.5% of Brazilian primary energy supply. In 2010, Brazil supplied 25 billion liters of ethanol using sugarcane as feedstock and 2.5 billion liters of biodiesel from soy oil, totaling 25% of global biofuels (0.62 EJ biofuel out of 2.5 EJ global)[13]. Today there is an increasing awareness that sugarcane can be used for many applications, not only as a biomass feedstock for energy production but also for bioprocessing in a biorefinery into a wide range of chemicals including a variety of polymers. Life cycle analyses indicate that sugarcane would be highly competitive with other crops as a preferred feedstock for a biomass-based industry[14].

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[13] (Chapter 10)
[14] (Chapter 10)
[a] (Chapter 10)
[b] (Chapter 13)
[c] (Chapter 21)
[d] (Chapter 15)
[e] (Chapter 3)
[f] (Chapter 8)
[g] (Chapter 14)
[h] (Chapter 14)
[i] (Chapter 17)

In Europe, ethanol production uses multiple feedstocks such as wheat, corn, barley, rye, and sugar beet derivatives; the total weight of grain feedstocks is the same as that for beet derivatives used for a total production of about 4.5 billion liters of ethanol or about 5% of EU gasoline use.

There are around 350 oil-bearing crops identified as potential feedstocks for biodiesel production in the world. Soybean, rapeseed/canola and oil palm are the main products processed commercially.

Oil palm is the most productive source of oil for biodiesel. The high yield of oil palm means that the current global output of 65 Mt palm oil requires cultivation of only 15 Mha, which contrasts dramatically with the 194 Mha needed to produce just 87 Mt oil from temperate annual oilseed crops such as soybean, rapeseed and canola. Therefore, in terms of total oil yield (kernel + mesocarp oil) per hectare, oil palm is already more than 6.5-fold more efficient than the average combined yields of the temperate oilseed crops such as soybean, rapeseed and canola. Despite this high productivity level only 1 Gl of biodiesel was produced from oil palm (Indonesia and Malaysia) in 2010.

Soybean is now widely processed to extract oil for biodiesel whilst co-producing soymeal for animal feed. The USA and Brazil together planted 55 Mha of soybean in 2010 producing 4 Gl of biodiesel. In practice, biodiesel production from soybean remains a by-product of the animal feed industry but as the demand for soybean as animal feed is predicted to grow strongly, biodiesel production from this source is also likely to increase.

Jatropha cultivation has been stimulated in many regions but there are doubts about its economic feasibility due to low yields.

The main raw material for wood pellets is sawdust but availability of traditional sawmill residues has decreased and difficulties in sourcing feedstock at competitive prices has resulted in a lower utilization by many pellet mills. Pellet producers have begun to source alternative woody feedstock, including wood chips from saw mills, round wood, residues, bark, used wood and wood from managed plantations. Demand for wood is currently met from around 30% of the world's natural forest area. Many tree species are grown in managed plantations for bioenergy. Depending upon geographic location, primary softwoods include pines, firs and spruce whilst the main hardwoods are eucalypts, poplars and willows[15].

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[15] (Chapter 10)

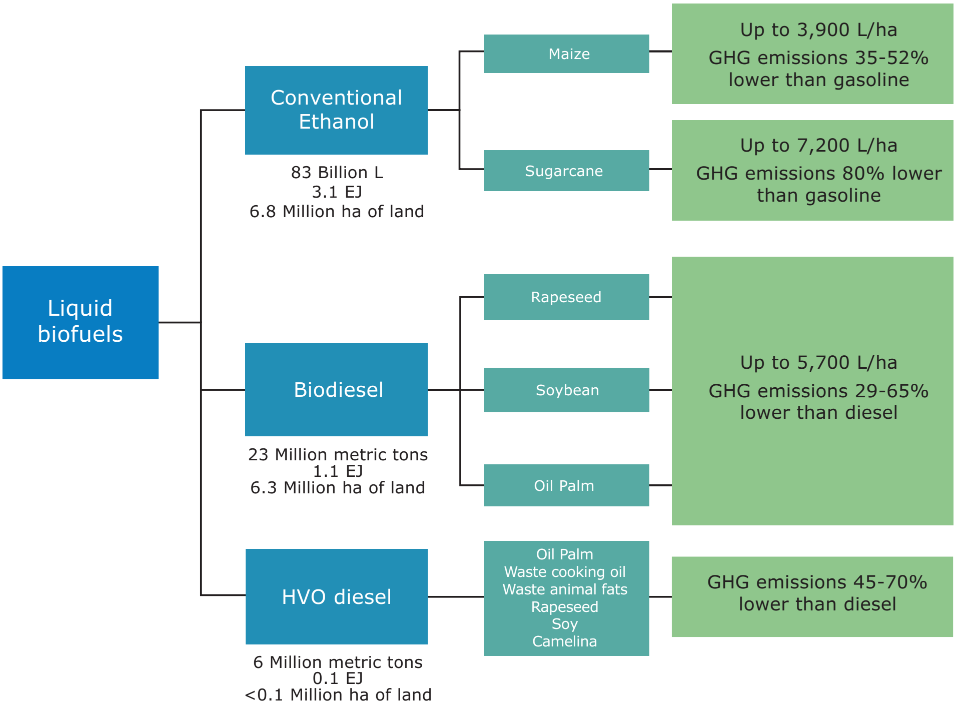

Figure 2.1. Current feedstocks and biofuels. Approximate numbers.

2.2.2 Current Land Use

Between 2000 and 2010 the net ‘increased area’ (net of co-products) associated with biofuels was 13.5 Mha (24.9 Mha of which 11.4 was associated with co-products, hence approximately 13.5 Mha were required for biofuels production). This was allocated between bioethanol (6.8 Mha) and biodiesel (6.7 Mha). The additional area assigned to co-products is roughly 6 Mha for bioethanol (almost all dried distillers grains with solubles (DDGS) in the USA) and 5.4 Mha with biodiesel (mostly EU rapeseed and then US soy)[16].

2.2.3 Current Conversion Technologies

2.2.3.1 Conventional Ethanol

Currently, 13.8 million ha of crop and around 200 mills comprise the maize ethanol system in the USA where dry milling is the dominant production process. The dry milling of maize grains allows enzymes’ easier access to starch for hydrolysis,

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[16] (Chapter 9)

Box 2.2. Improving vehicle efficiency and fuel distribution logistics is needed for competitive deployment of bioenergy

The main competitive issues between bioanalogues and the corresponding fossil fuels are production costs, distribution logistics and end-use efficiency. Some forms of bioenergy carriers can be more competitive than others depending on regional conditions. From a global point of view, liquid hydrocarbon “drop-in” biofuels are very attractive in terms of distribution logistics and existing equipment for end-use, but their energy cost is higher than that of their oxygenated precursors. In the past, the energy efficiency of ethanol vehicles was 16% higher than gasoline vehicles. Nowadays, the common technology applied to FFVs which are currently consuming about 15% of the available ethanol, is not fully exploring ethanol properties to avoid impairing gasoline operation. R&D combining direct-injection-downsized engines with turbocharging and variable transmissions has shown ethanol energy efficiency improvements of more than 10% over that of gasoline, for the same vehicle performance and without harming gasoline operation. The automotive industry and the fuel distribution infrastructure should both be stimulated to improve efficiency of ethanol use[j].

producing glucose that is fermented by yeast to ethanol. Hydrolysis and fermentation can be conducted simultaneously allowing for increased efficiency. In the nineties most conversion plants were designed for beverages with 35 million L/yr capacity. Plant size doubled by 2005 and more than doubled again since 2005 resulting from efficiencies of scale and better integrated designs[17]. Current average corn ethanol production is around 4,000 L/ha[18]. Corn average yield in the USA is 9.9 ton/ha of grain standardized to 15.5% moisture [19].

Around 4.8 million ha of sugarcane for ethanol and over 400 mills comprise the sugarcane ethanol system in Brazil where most commonly, a mixture of juice and molasses is used. The majority of mills are sugar mills coupled to distilleries, an operational synergy that allows for the easy switch from sugar to fuels production when necessary. Fermentation improvements have been attained in juice treatment, beer centrifugation, microbiological control, yeast treatment and recycling, and use of selected yeasts in fermentation. The prevailing system includes fed-batch fermentation with yeast recycling even though some continuous fermentation systems are in use[20]. Today, the average yield of the process is around 82 L of ethanol per wet metric ton of cane[21]. Current average sugarcane ethanol production is 7200 L/ha[22]. Sugarcane average yield in Brazil is 79.5 ton/ha fresh weight[23]. Using first-generation (1G) biofuel

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[17] (Chapter 12)

[18] (Chapter 9)

[19] (Chapter 10)

[20] (Chapter 12)

[21] (Chapter 10)

[22] (Chapter 9)

[23] (Chapter 9)

[j] (Chapter 12)

technologies, much less land is required to produce the same amount of ethanol when sugarcane is used as a feedstock as opposed to corn.

2.2.3.2 Ethanol and Flexible Fuel Vehicle Engines

The world fleet of 800 million LDV (Light Duty Vehicles) in 2010 is expected to reach a range of 1.7 to 2.1 billion cars in 2050[24]. The use of ethanol as a transportation fuel is currently concentrated in USA and Brazil, but blends of 10-20% ethanol in gasoline have proven feasible in many countries and advanced automotive technology has expanded the conditions for using ethanol.

Currently, more than 75% of ethanol consumption in transportation worldwide is in the form of a low-level blend, limited usually to E10 that is used in gasoline vehicles. Mid-level blends (E10<EX<E40) represent approximately 10% of ethanol consumed in transportation worldwide.

Flex-fuel vehicles (FFVs) currently represent approximately 90% of sales of new cars in Brazil, and pure ethanol can be used nowadays by 23.8 million Brazilian vehicles (mostly cars with flex-fuel engines), which represent approximately 71% of the national fleet of light road vehicles. The US fleet included 14 million FFVs in 2013, of which more than 10% were using E85 (blends containing 51% to 83% ethanol, as lower levels are used during winter months to ensure cold starting)[25].

2.2.3.3 Biodiesel

In 2011, 11.2 million hectares of land were used to produce biodiesel (6.7 Mha discounting the land used for co-products)[26]. Biodiesel is produced from oil seed crops like soybeans, rapeseed, canola, or from trees such as oil palm or jatropha through a transesterification process, by combining plant oil with a large excess of methanol and a catalyst (sodium or potassium hydroxide) to produce glycerol and a mixture of fatty acid mono-alkyl methyl esters (FAME) that is designated as biodiesel. About 50% of the biodiesel plants are smaller than 35 million liters per year capacity using a variety of waste feedstocks (e.g., used cooking oil, greases), while the other half ranges in size from 40 million to more than 150 million liters per year of capacity, using oil seed feedstocks, with the larger sizes being of integrated soybean production and biodiesel plants (e.g., Indiana, USA). European plants size tends to be smaller than in the USA because of feedstock availability. Current average rapeseed biodiesel production is 1300 L/ha. Rapeseed average yield in the EU is 3.1 ton/ha. Current average oil palm production is 4200 L/ha. Palm oil average yield in Malaysia is 18.4 ton/ha.

Globally, a large number of suppliers of smaller size production capacities range from one t/day to 500 times that, using various waste feedstocks such as animal fat, waste cooking oils and greases, and some of the non-food oils. Methanol as a reactant is one of the safety issues of production, principally in small-scale production where industrial

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[24] (Chapter 8)

[25] (Chapter 12)

[26] (Chapter 9)

standards for safety training may not exist. Biodiesel and customized oil compositions can also be made from sugars, using modified organisms including heterotrophic algae. Microalgae and cyanobacteria can generate fatty acids using sugars as feedstock from which biodiesel or other hydrocarbons can be derived. Ongoing research with these organisms aims to use brackish waters and land that does not conflict with food production, but will require improvements in engineering and reduction of costs before economically viable and sustainable systems are commercialized[27].

2.2.3.4 Biodiesel Vehicle Engines

Biodiesel is primarily used as a 2% to 20% by volume blend with petroleum diesel. Biodiesel in blends will not separate or partition into water. In most vehicles, B5 and lower blends are approved, as long as the biodiesel meets D6751 and/or EN14214, the European biodiesel specification. The ASTM specification for conventional diesel fuel, D975, allows up to 5% biodiesel in conventional diesel fuel. A separate specification, D7467, describes the required property limits for B6 to B20 blends. Blends of B20 or higher are now accepted by most Original Equipment Manufacturers[28].

2.2.3.5 Lignocellulosic Ethanol

The production of ethanol using lignocellulose as feedstock can use biochemical or thermochemical conversion approaches. In the biochemical route a pre-treatment of biomass is performed to separate the durable polymeric matrix of sugar-derived cellulose and hemicelluloses, and lignin, an alkyl-aromatic polymer, thus more difficult to process than grains or sugar crops. There are several leading pre-treatment options. Ethanol concentrations and rates vary depending on catalysts, temperature, and time, as well as reactor selection and process integration conditions. Additionally, pre-treatment optimization conditions vary from one feedstock to another, thus generating many technology options and need for optimization. Various competing routes are under development. Considerable technical progress has been made and scaling up to commercial scales is underway but no industrial plant has operated yet at capacity. Energy balance and costs need to be improved. Integration of second generation (2G) with 1G ethanol production provides an option for fully renewable production of energy without the use of natural gas for thermal processes such as pre-treatment.

Biomass pre-treatments alone or in combination with hydrolysis lead to sugars that can be fermented to ethanol and other products. The most common application for the lignin is to process heat and electricity but additional products are being developed. Other biofuels that are also undergoing parallel technology development include other alcohols, syngas derived compounds obtained through gasification, microbial products using tools of synthetic biology, or fatty alcohols via heterotrophic algae in dark fermentation[29].

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[27] (Chapter 12)

[28] (Chapter 12)

[29] (Chapter 12)

2.2.3.6 Aviation Biofuels

Aviation biofuels have to be designed as drop-in fuels to be used with existing equipment and infrastructure that is highly regulated regarding safety and reliability. Other alternatives that imply novel power developments are not viable due to much higher costs.

International standards are in place and several pathways to aviation biofuels have been certified, but significant national, regional, and global level efforts will be required until technical confidence in a more diverse range of feedstocks and pathways for aviation biofuels is obtained. Multiple partnerships of airlines, airports, aircraft manufacturers, governments, biomass and biofuel producers and suppliers, and sustainability certification groups are leading these efforts.

The biomass gasification and catalytic Fischer-Tropsch upgrading pathway to synthetic paraffin kerosene received the first approval, because it is substantially identical to the commercial product based on coal gasification. HEFA (hydroprocessed esters and fatty acid) was approved for blends up to 50%. Since 2011, airlines collectively performed over 1500 commercial passenger flights with blends of up to 50% jet biofuel from used cooking oil, jatropha, camelina, and algae. A six-month commercial flight use study did not show adverse effects in the engines. The microbial pathway to farnesene was approved in 2014 for up to 10% blend. Other processes undergoing approval for commercial flights are in preparation and have produced sufficient fuels to start testing properties on the way to commercial flights[30].

2.2.3.7 Renewable Diesel

Renewable diesel is a commercial hydrocarbon biofuel introduced in 2007 that reached 10% of biodiesel production by 2013. It is also referred to as "green diesel," and includes HEFA, Hydrogenated Vegetable Oil (HVO) produced from fatty acids (fats, oils, and greases) or vegetable oils, or tall oil from trees. Current thermochemical technologies include hydroprocessing and hydroisomerization technology used in petroleum refineries, although various biochemical strategies are under investigation. The products consist predominantly of isoparaffins with some residual normal paraffins and proportions can be adjusted for diesel fractions or jet fuel fractions. Technoeconomic analyses and size of production are different depending on the feedstock and co-products[31].

2.2.3.8 Bioelectricity

Electricity can be generated from biomass through direct combustion or conversion into gaseous or liquid fuels, such as biogas, syngas and bio-oil, which are subsequently combusted. The total contribution of bioelectricity represented nearly 83 GW of capacity, and 350 TWh of generated electricity in 2012. The contribution of bioelectricity in global renewable energy systems is expected to continue to grow from today's annual 19%

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[30] (Chapter 12)

[31] (Chapter 12)

to 23% by 2035[32]. Currently, roughly half of bioelectricity is used industrially and half is generated for municipal or residential use.

The introduction of advanced thermal cycles can increase the current efficiency (of co-generation processes) and almost double the amount of electricity produced[33]. One of the main barriers to co-generation projects is connection to the national grid. In Brazil, the connection cost has to be paid in full by the bioelectricity supplier and, in some cases, it represents 30% of the total project investment. In order to reach the potential, the country needs to establish a free or co-shared cost policy for building the bioelectricity transmission system[34].

In 2012, bioelectricity from sugarcane was responsible for almost 3% of the total consumption of electricity in Brazil. The sugarcane and bioelectricity sectors need a long-term policy to stimulate investment in this power source[35]. The efficiency level could be higher, but at the expense of significant increases in costs[36]. The implementation and evolution in cane straw recovery will eventually lead to much higher levels of surplus electricity. However, there is a potential to reach 18% by 2020-2021. On average, the current levels of electricity surplus are around 10 kWh/t sugarcane and are expected to increase rapidly in the next years[37].

In 1957, Mauritius was the first country where a sugar factory started to export bioelectricity to the grid (0.28 GWh). Since then, the amount of electricity co-generated by sugar factories from bagasse has been in constant progression.

2.2.3.9 Biogas

Biogas, a clean gaseous fuel, is an important clean-burning energy source for both developed and developing regions. Rural communities lacking access to conventional energy distribution specially benefit from biogas initiatives. Biogas is a mixture of methane and CO_2 produced by anaerobic bacteria using organic waste (urban, agricultural or industrial) as feedstock. Biogas is about 60% methane and 40% carbon dioxide and the digester effluent has greatly reduced pathogens. Conversion to gas in family-size biogas plants allows 24% of the energy content in the dung and crop residues to reach the cooking vessel, while >90% of the nutrients and >80% of the humus are returned to crop-land[38].

In the BRIC nations, China and India have embraced biogas, while Brazil and Russia have not. China has over 50,000 medium- to large-scale digesters and over 40 million household digesters. India has over 4 million household digesters and several large-scale projects. In both cases, government was critical to biogas adoption, lowering financial barriers and promoting usage[39]. In Brazil, with clean, centralized hydroelectricity, and Russia, with large supplies of natural gas, there has been little incentive to invest in biogas. Brazil has 22 biogas facilities. While there are plans to build biogas in Brazil and Russia, the projects face tough economics without clear policy supports[40]. The status of

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[32] (Chapter 3)

[33] (Chapter 8)

[34] (Chapter 14)

[35] (Chapter 14)

[36] (Chapter 12)

[37] (Chapter 14)

[38] (Chapter 21)

[39] (Chapter 14)

[40] (Chapter 14)

Box 2.3. Decreasing lignocellulosic biofuel costs and commercialization are underway

Multiple industrial-scale plants utilizing various configurations of biochemical conversion of lignocellulose into ethanol are being constructed and coming online worldwide. The higher costs, compared to corn or sugarcane ethanol, are typically related to pre-treatment and enzymatic hydrolysis processes due to high cost of enzymes. Alternatives that could eliminate the need for enzymes such as ionic liquids pre-treatments can be expensive and require very high recovery efficiency for low cost products. Enzyme costs though are being reduced. Wastewater treatment when acid or base catalysts are present can also increase cost. Some pre-treatments require corrosion resistant materials, thus increasing capital costs. The conversion of soluble sugars to ethanol is limited by the tolerance of fermentative organism against inhibitors (e.g., furfural or 5-hydroxymethylfurfural) produced during pre-treatment and by contaminating organisms. The discovery of new detoxification methods and the development of more robust fermentative organisms are addressing this problem. In one pilot-scale example, performance evaluation was conducted of various commercial cellulase and hemicellulase enzyme cocktails with organisms that can ferment both five and six carbon sugars. In industrial conditions, current enzymes costs contribution to lignocellulosic ethanol is seven- to ten-times higher than in the mature starch ethanol production. Costs are expected to decrease with increased operational time of industrial-scale plants and continued improvements in cocktails by enzyme manufacturers. Consolidated bioprocessing options are also in development[k].

biogas in Germany, California, and the U.K., three regions with similar per capita GDP and energy use, is informative. All three regions began implementing agricultural biogas in the 1970s. Today, Germany has over 7,500 medium- to large-scale plants, more than three times the rest of the EU combined and nearly 40 times the U.S. Germany's success can be traced largely to a steady drip of policy supports that started in 1991. Despite similar biogas potentials, California and the U.K. trail Germany with a little more than 1% of its capacity. Recent E.U. Directives, a desire to limit landfill, and a steady decline in offshore natural gas production have spurred the U.K. to begin biogas investment, establishing a feed-in tariff and other incentives[41]. While the California Energy Commission had assisted on-farm biogas installations in the past, changes in NO_x emissions standards forced many to shut down, leaving farmers reluctant to reinvest. As a result, less than 1% of the state's 1,600 dairies recover biogas from their herds[42].

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[41] (Chapter 14)

[42] (Chapter 14)

[k] (Chapter 12)

2.2.3.10 Biogas Vehicles

Worldwide, there are about 17 million natural gas vehicles that could use upgraded biogas, including 1.7 million in Brazil, 1.5 million each in India and China, and 2.2 million in Argentina. In 2012, the International Energy Agency (IEA) projected a possible six-fold increase in use of natural gas in transportation by 2035[43]. Because of the potential for fugitive and exhaust emissions of methane, these increases should be coupled with improved engine designs and emission controls.

2.2.3.11 Heat

Modern plants can provide heat to some 10,000 persons and local institutions using municipal waste, wood chips or bio-oil. In Norway, one such example has a power of 8 MW and the heat in the flue gas is recovered through condensing the water vapor, thus making each furnace effectively 10 MW. There are cleaning systems for the flue gas and the ash is collected from the bottom of the combustion chamber. The furnaces are used for base load and not operated during summer months when the demand is low. Three bio-oil burners, each 13 MW, use mainly imported bio-oil from rapeseed to cover peak demand during winter and low demand during summer. A gas burner, 1.5 MW, burns the gas that is piped down from the landfill but the gas has a low caloric value and the methane and CO_2 content is rather low. The plant is also equipped with some 10,000 m^2 of solar thermal collector panels for 7 MW additional capacity. In combination with a water accumulation tank, this heat can be stored for later use[44].

More efficient cookstoves for solid biomass (e.g. wood or charcoal) are in development. It is important to recognize the need for a balance between efficiency and acceptability. While cookstove technologies now exist that are up to 90% efficient (in laboratories), they have a narrow tolerance to fuel size and moisture and thus generally require special care or pre-processing[45].

2.2.4 Emissions

Acceptable bioenergy systems are those that lead to significant GHG emissions mitigation, while minimizing other environmental and social impacts. In the last five years, a deeper understanding of the life cycle analysis (LCA) issues in the evaluation of GHG net emissions from biofuels led to improved models and the search for better data (carbon stocks, iLUC, coproducts treatment, N_2O emissions), changing significantly some earlier results (e.g., iLUC estimates). The complexity involving different feedstocks, regions, soils, local land use contexts, and conversion processes requires more data and still better analyses to provide sound support for policies[46]. Yet, there is strong evidence that when well managed, bioenergy can significantly contribute to climate change mitigation[47].

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[43] (Chapter 8)

[44] (Chapter 14)

[45] (Chapter 21)

[46] (Chapter 17)

[47] (Chapter 5)

Box 2.4. Evidence increasingly indicates the need for value-added co-products to establish the cellulosic ethanol industry

Traditional lines between biochemical and thermo/chemical catalytic conversion will continue to be significantly blurred with the development of processes combining aspects of biological, catalytic, and thermal treatments of biomass to produce renewable transportation fuels. Industrial development utilizing genetically modified yeast and bacteria to convert cellulosic biomass into high-value end products in a single step that combines hydrolysis and fermentation is underway. Development of fuel and chemicals as applications for antibiotics and other medical uses is continuing. Lignin conversion to chemicals and materials also offers potential additional value streams for an integrated biorefinery, with a range of possible renewable aromatics, which are common building block molecules produced currently from fossil fuels. If high throughput plants can be mass produced at small to medium scales, their environmental footprints could become smaller and the cost may be reduced sufficiently for chemicals applications. Supercritical water processing to rapidly solubilize in two stages five-carbon sugars from six-carbon sugars is being tested at small scales. This thermo/chemical pre-treatment can be coupled with a variety of chemical catalysts to produce drop-in hydrocarbon fuels. Integrated catalytic upgrading can lead to hydrocarbons in the jet, diesel, and gasoline range in addition to other chemicals also undergoing development and commercialization[l].

As awareness of the evidence that combustion of fossil fuels is causing climate change has expanded, bioenergy has come to be seen as a mechanism for decreasing the carbon intensity of energy use. Approximately 50 countries now have biofuels mandates driven by their need to reduce emissions[48]. When done right, biofuels can contribute to significant decreases in emissions relative to fossil alternatives. Emissions should be calculated in an integrated framework that considers all mass flows including co-products. A recent and highly detailed well-to-wheels analysis of life cycle GHG emissions concluded that relative to the use of petroleum, ethanol from maize grain, sugarcane, maize stover, switchgrass and Miscanthus would reduce emissions by 19–48%, 40–62%, 90–103%, 77–97% and 101–115%, respectively[49]. Biodiesel provides 30–60% mitigation (no LUC considered).

LUC GHG emissions of oil seeds based biodiesel are subject to great debate, varying from 34 to 62 g CO_2e/MJ[50]. The iLUC effects are usually calculated through

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[48] (Chapter 3, Chapter 20)

[49] (Chapter 10, Chapter 17)

[50] (Chapter 17)

[l] (Chapter 12)

the use of economic market equilibrium models. With respect to corn ethanol production, the initial LUC effect of US corn ethanol was proposed as 104 g CO_2-equivalent (CO_2e) per megajoule (MJ) (for reference purposes, the emission factor of gasoline is 92 g CO_2e/MJ). Various model improvements re-estimated LUC related GHG emissions that decreased to 32 g CO_2e/MJ and more recently to 15 g CO_2e/MJ. Significantly lower values for corn ethanol (e.g. 7 g CO_2e/MJ) have also been found[51].

Because of methane's high GHG multiplier (CO_2e = 34 over 100 years; 86 over 20 years[52]), fugitive methane emissions can also be a problem in biogas systems[53]. In addition to possible leaks in collection and transmission, when the gas is used in lean burn internal combustion (IC) engines for transportation or electricity generation, the combustion kinetics allow two to three percent of the methane to escape in the exhaust[54]. These methane emissions are often not regulated for stationary sources. If the IC engines operate with stoichiometric air/fuel mixture, methane presence in the exhaust is not significant.

2.3 Bioenergy Expansion

2.3.1 Land Availability

Is there enough land available to sustainably produce food, feed and biomass for energy for a growing population? Some argue that due to anticipated low rates in yield improvements food demand will outstrip production by 30% over the coming 35 years, requiring an additional 130-219 Mha of agricultural land. Estimates of net land demand for biofuels based on observation of the 34 largest biofuel producing countries, which accounted for over 90% of global production in 2010, indicate that the increase in biofuel production (2000 to 2010) resulted in a gross land demand of 25 Mha out of a total of 471 Mha arable land. However, nearly half the gross biofuel land area was associated with commercial co-products (primarily animal feeds, e.g., distillers dry and wet grains, soy and rape meal) leaving a net direct biofuel land demand of 13.5 Mha (2.4% of arable land area). Despite this increased demand for land for biofuel feedstock production, overall there was a decline in agricultural land area of 9 Mha in the countries evaluated. Increasing cropping intensity was found to have more than compensated for the decline[55].

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[51] (Chapter 20)

[52] (IPCC 2013)

[53] Flesch, T.K., R.L. Desjardins and D. Worth. 2011. Fugitive methane emissions from an agriculture biodigester. Biomass and Bioenergy 35(9):3927-3935

[54] Nielsen, M. and J.B. Illerup. 2004. Danish emission inventories for stationary combustion plants: Inventories until year 2002. Research Notes from NERI No. 200, National Environmental Research Institute, Ministry of the Environment, Denmark and Environmental Protection Agency (EPA, USA).

[55] (Chapter 9)

A gross land demand for modern bioenergy was estimated at between 50 Mha and 200 Mha by 2050. Whilst highly uncertain, this scale of land use would deliver between 44 and 135 EJ/yr of modern bioenergy in 2050. Approximately 0.7 EJ per Mha is a reasonable ballpark land use intensity for production of modern bioenergy at this scale in the 2050 timeframe[56].

Potentially available land for bioenergy expansion is exclusive of anticipated demands for cropland, natural forests and forest plantations, urban land (including allowance for expansion), and increased land for biodiversity. One major opportunity to compensate for growth in biomass resource use is to intensify the use of low productivity pastureland and make use of (part of) the available area of pasture, which is estimated to be around 950 Mha, for multipurpose agriculture. Pastureland makes a small contribution to global supplies of dietary protein and calories, and in many regions productivity is low due to lack of management and inputs. In such locations, pasture intensification to generate surplus land for bioenergy may be much simpler and offer comparatively greater benefits than the conversion of cropland. For sustainability reasons it is also recommended to use marginal, low productivity lands coupled with bioenergy crops that can adapt to poorer soils and rainfed conditions.

At a global level, land is not a constraint.

Land available for rainfed agriculture is estimated to be 1.4 Bha of ‘prime and good’ land and a further 1.5 Bha of marginal land that is ‘spare and usable’. Around 960 Mha of this land is in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha) with much, if not all of it, currently under pasture/rangeland[57]. There is also a sizable potential in the US[58,59]. The critical question is not one of managing a competition for land between energy and food, but rather whether and how bioenergy production can be gracefully incorporated into human and natural systems.

These current estimates for the land demand of bioenergy are lower than other estimates because of the inclusion of key factors supported by recent analysis: (1) the ability of bioenergy to recycle biomass through the use of wastes and residues, (2) crop yield growth supported through investments in infrastructure and (3) development of capacity in agriculture and forestry. Furthermore, the potential to use alternative crops and in particular to increase the area of perennial cropping will diversify agricultural landscapes and provide novel and productive tools to manage and ameliorate the impacts of intensified food cropping[60].

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[56] (Chapter 9)

[57] (Chapter 9)

[58] (Chapter 8)

[59] (U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry - 2011 BT2 (U.S. Department of Energy)

[60] (Chapter 9)

2.3.2 Biomass Production Potential

While traditional bioenergy is derived from a wide variety of tree species and crop residues, currently only a few crops supply the bulk of biofuel production globally. Of the four largest sources of biofuels, maize and sugarcane (bioethanol), soybean and rapeseed (biodiesel), sugarcane appears to be best poised for substantial growth in the future. Many other areas of the globe would be suited to replicate Brazil's success in developing an environmentally and economically sustainable sugarcane bioethanol industry. Because of projected increases in demand for food, the continued use of maize for biofuel may depend, in the long-run, on the rate of yield improvement for regions in the world outside the USA[61].

Taking account of the need to protect the Amazon, conserve biodiversity and avoid conflict with food production, the Brazilian government has mapped 63.5 Mha suitable for sugarcane production. This would not require the clearance of natural ecosystems, but would require significant expansion onto pasturelands, largely in the Cerrado region, with low stocking density. This would need to be compensated by improvement of the remaining pasture to support an increase in the number of head per hectare. This land area could allow the production of 800 Bl of ethanol by 2030, which in energy terms would be equivalent to 15% of total global liquid fuel use in 2009, while the bagasse could provide 30 GW of electricity. This expansion of sugarcane production is likely to be incentivized by the uncertainties in petroleum prices and by climate change driving a demand for biofuels with low net GHG emissions. However, it will require the development of new varieties capable of production under marginal, warmer and drier environments, as well as substantially different soils. Maintaining yield in these new areas will be important to minimizing land demand[62].

Many crops and even as yet undomesticated plants, have the potential to become important feedstocks. Lignocellulosic biomass in the form of energy crops, agricultural wastes and forest residues represents the most abundant source of renewable biomass with production of 10^{10} metric tons on an annual basis, which is about half of the biomass produced in the world. This resource is widely recognized as the primary future feedstock for the biofuel and bio-based industry; it could produce up to 442 billion liters of bioethanol per year due its high diversity around the world[63]. Although many plant species can be used for production of lignocellulosic fuels, Miscanthus, a C4 perennial grass, and a close relative of sugarcane, has attracted particular interest as a promising resource for use as both solid combustion fuel and as a feedstock for liquid fuels given its high yield potential, low requirements for soil tillage, weed control and fertilization as well as the long crop cycle of up to 25 years[64].

While it is anticipated that a range of herbaceous perennials could become viable sources of biomass on land unsuited to food crops, this is already an established

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[61] (Chapter 10)

[62] (Chapter 10)

[63] (Chapter 11)

[64] (Chapter 11)

Box 2.5. Recuperating soils with bioenergy

There is enough land available for substantial bioenergy production and increased food demand, considering impacts of global change affecting crop production, yield increase predictions, and preservation for urban areas, forestry and protected land. This land is concentrated in Latin America and Sub-Saharan Africa (over 900 Mha rainfed land available), and presently used predominantly for low intensity grazing. Developed countries also have land available but the agricultural area is expected to remain stable. In addition, there is about 607 Mha of farmland available that have become degraded. Not only can degraded and marginal land be used for bioenergy feedstock production, but in doing so, the land can be rehabilitated and improved, providing a positive impact on soil quality[m], soil carbon[n], productivity and again on food security. Long before the world reaches any significant fraction of 200 Mha devoted to modern bioenergy, we will have ample opportunity to be guided by experience rather than projection[o].

fact for the many pulp and round wood supply operations that meet ISO 14001 sustainability standards[65].

In 2006, global production of wood pellets was between 6 and 7 Mt worldwide (not including Asia, Latin America and Australia). In 2010, it reached 14.3 Mt or 0.26 EJ (including these countries) while consumption, predominantly for biopower, was close to 13.5 Mt, representing an increase of more than 110% in 4 years. Production capacity from pellet plants has also increased worldwide reaching over 28 Mt yr^{-1} in 2010. The European Union is the main market for wood pellets, but the gap between European production and consumption has grown to become 8 fold[66].

Organic post-consumer waste and residues and by-products from the agricultural and forest industries, which contribute a major part of biomass for energy today, will not suffice to meet the anticipated levels of longer term biomass demand. Thus, much of the bioenergy feedstock will have to come from dedicated production. Meeting future demands of wood will require investment in energy tree breeding and enabling policies that tackle the environmental concerns surrounding forest management, new plantings and residue removal. The claims that large-scale microalgae production will meet future energy needs have not been substantiated[67].

Meeting future energy needs with high productivity perennial feedstocks, both woody crops and grasses, will require expansion of agronomic research and breeding

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[65] (Chapter 10)

[66] (Chapter 10)

[67] (Chapter 10)

[m] (Section 2.4.2)

[n] (Section 2.4.3)

[o] (Chapter 9)

trials on marginal land and land unsuited for food crop production. A broader conceptualization of multipurpose agriculture will also require an improved definition of land suitability classes, including land unsuited to food crop production[68].

While much of the focus of feedstock research has been on biomass crop production, cost effective delivery of feedstocks also requires improved logistics. Biomass harvesting, collection, baling, transport, drying, storage and pre-treatment should all be efficiently and cost-effectively designed to enhance the overall sustainability of bioenergy projects. Except for some large-scale commercial crops such as sugarcane or corn, biomass supply chains for bioenergy production are currently underdeveloped. Significant improvements could be achieved by modernizing the logistic operations to make them more efficient. Capitalization, replication or adaptation experiences could be derived from the existing commercial biomass supply chains. Modern biomass supply chains offer significant possibilities for gathering all types of biomass and synergizing their physico-chemical properties with subsequent energy conversion processes[69].

2.3.3 Bioenergy Costs

Cost trends of commercial biofuels and bioenergy were reviewed for many countries and expressed as levelized cost of biofuel—a function of feedstock cost. For biodiesel, the oil feedstock costs contribute 80% to 90% of the estimated production cost, unless derived from wastes. For ethanol from corn and sugarcane, the feedstock contributed 60% to 80% of the cost[70]. Multi-biomass utilization costs (biomass co-firing or co-combustion) for simultaneous use of straw and reed canary grass was investigated and a 15–20% cost reduction was obtained simply by using the two biomass sources instead of one[71].

The 2012 ethanol prices in Brazil and U.S. are shown[72]. The Brazilian government has held the gasoline price at the refinery gate (ex-taxes) at approximately 70 US$/barrel for the last 5 years, significantly below the international parity prices formerly adopted. In Brazil, taxes have historically represented more than 40% of the final price of gasoline[73].

The capital costs of advanced biofuel conversion technologies are currently estimated at factors of 4 to 5 higher than commercial ethanol plants, so capital cost will contribute more to the cost of advanced biofuel production cost, depending on the conversion plant size, among other factors[74]. Stable policies become even more important when capital costs are a large part of the fuel price.

Projections from linked models of feedstock production, logistics with pre-processing, and conversion techno-economic analysis of advanced conversion for the nth plant indicate a decrease in the minimum ethanol selling price of around 10% as a refinery

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[68] (Chapter 10)

[69] (Chapter 11)

[70] (Chapter 12)

[71] (Chapter 11)

[72] (Chapter 12 Figure 12.7)

[73] (Chapter 8)

[74] (Chapter 12)

scales up from 2000 to 10000 Mg/day, while increasing the GHG emissions intensity by about 16% for corn stover. Estimates of economies of scale for switchgrass indicate similar decreases for that feedstock[75].

Biofuels costs were estimated for 2012, projected for 2020 and compared to fossil fuel costs in an analysis of more than 15 lignocellulosic biofuel plants planned to be online within the next few years[76]. Compared to today's estimated production costs, significant improvement is possible in both the enzymatic hydrolysis and thermochemical lignocellulosic ethanol pathways. By 2014, in industrial conditions, enzymes cost contribution to lignocellulosic ethanol is described by industry as seven- to ten-times higher than in the mature starch ethanol production; costs are expected to decrease with increased operational time of industrial-scale plants and continued improvements in cocktails by enzyme manufacturers. Similarly, the thermochemical routes for hydrocarbon fuels are also expected to reduce their costs[77].

2.3.4 Biomass Supply in the Face of Climate Change

The median of studies[78] indicate that climate change will cause a 0 to -2.5% decline in maize and wheat yields per decade and none in rice and soybean. This appears small in relation to historic rates of yield improvement per decade in these crops. But there are several caveats in relation to a range of conditions that may on balance become more common, like extreme weather events and altered pest and disease incidence. Tropospheric ozone, which is today some ten times pre-industrial levels, is already estimated to cause yield losses of around 10% in these crops and levels may increase by increasing temperatures and nitrogen oxide emissions, especially in Southeast Asia. By contrast empirical field scale enrichment of CO_2 to anticipated 2050 levels increased the yield of rice, wheat and soybean (C3 crops) by about 15%, but did not affect maize (C4) yield[79]. The development of perennial grasses and coppice systems could provide resilience for regions facing heavier rainfall and erosion under climate change. Similarly, exploration of alternative energy crops for semi-arid regions could improve the adaptive capacity of bioenergy systems.

2.3.5 Impacts of Bioenergy Expansion on Biodiversity and Ecosystems

The effects of biofuel feedstock production on biodiversity and ecosystem services are context specific, and need location-specific management[80]. Policies addressing environmental impacts of bioenergy should be informed by assessments specific for the location, rather than relying on average/generic data and simple footprints and efficiency metrics[81].

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[75] (Chapter 12)

[76] (Chapter 12 Figure 12.21)

[77] (Chapter 12 Figure 12.21)

[78] reviewed by the IPCC (2013)

[79] (Chapter 4)

[80] (Chapter 16)

[81] (Chapter 18)

Box 2.6. The use of pastureland marginal lands provides an important economic potential

Increasing animal stocking densities to currently-attainable, climate appropriate levels, would allow existing pastureland to support 3.8 fold more animals. Bringing the poorest-performing pastures up to 50% of their maximum attainable density would more than double the global stock of grazing animals[p]. Actions to improve pasture conditions, along with livestock production intensification, can effectively make large amounts of land available for alternative uses[q]. Gross estimates of the potential for energy crops on possible surplus good quality agricultural and pasturelands range from 140 to 290 EJ/yr (surplus 'Very Suitable' and 'Suitable' land at 10 and 20 odt ha^{-1} yr^{-1})[r].

The potential contribution of water-scarce, marginal and degraded lands could amount to 80 EJ/yr ('Moderately' + 'Marginally Suitable' Land; 5 odt ha^{-1} yr^{-1})[s]. For example, saline soils could support as much as 50 EJ of biomass for energy[t]. Arid lands cover 30% of the Earth's land surface and could be used to produce agave for ethanol production[u].

Sustainable biofuels and biodiversity management requires cross-sectoral integrated planning and regular monitoring of selected, cost effective and policy relevant indicators. Cost effective, landscape-level biodiversity indicators are in development but await application over most of the developing world[82].

Conservation of priority biodiversity is paramount; management practices in biofuels production should aim to minimize threats[83].

Much attention has been given to the use of biodiverse systems for expansion of bioenergy production, with the concept that they could serve both biodiversity and production. However, analysis of this land sharing concept finds that because of the large areas required by these less productive systems, for most areas of the globe, high productivity monocultures are ironically more effective for biodiversity by sparing land through high productivity. For example, mixed-grass prairie would require 6x the land area of an unfertilized Miscanthus system to deliver the same amount of bioenergy[84]. In addition to the land spared by highly productive monocultures, expanded use of energy crops within conventional agricultural cropping systems can also improve diversity through integrated agroforestry systems, establishing perennials on fragile parts of the landscape, and using winter energy crops to complement summer annual food crops in temperate climates.

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[82] (Chapter 16)

[83] (Chapter 5)

[84] (Chapter 10)

[p] (Chapter 9)

[q] (Chapter 9)

[r] (Chapter 9)

[s] (Chapter 9)

[t] (Chapter 14)

[u] (Chapter 10)

Today, many regions of the world are under water stress due to population growth or climate change. Climate change may impinge on water resources in uncertain ways and decrease crop yields. Water availability may change geopolitics in ways similar to oil in the last century. Water availability can become a major limiting factor for bioenergy expansion in some regions.

Landscape-level optimization of bioenergy, especially perennial and woody systems, can reduce soil erosion, improve water quality, allow nutrient recycling, and promote carbon sequestration in soils[85].

2.3.6 Indirect Effects

In addition to the direct effects of bioenergy production on prices, trade, land use and emissions there may also be indirect effects. Two important indirect effects are the indirect land use change effect (iLUC) and the rebound effect. iLUC is the change in land use outside a feedstock's production area needed to replace the supply of that commodity and that is induced by changing the use or production of that feedstock[86]. The rebound effect[87] studied in the field of economics, recognizes that substitution of fossil resources by biomass decreases the demand for fossil resources and therefore induces a lower price. A lower price leads to higher fuel consumption in other markets, which partly offsets the initial fossil fuel and GHG savings. In the context of mitigating climate change, model improvements in estimates of iLUC allowed for a downward revision of the initial GHG estimates of 104 g CO_2-equivalent (CO_2e) per megajoule (MJ) of US corn ethanol to values as low as 7 g CO_2e/MJ. For comparison, the emission factor of gasoline is 92 g CO_2e/MJ. Model improvements consisted of factors such as improved data, increased spatial resolution, including pastureland as an option for conversion to bioenergy production, crop yields on existing agricultural land and newly converted land for agricultural and bioenergy crops, treatment of co-products for animal feed, and the modeling of wood products (including by-products and the fraction of carbon that is stored for a longer period). Rebound effects which are proposed to be caused by increased fuel consumption due to a lower induced oil price, are crucial for the renewable energy policies being effective in reducing GHG emissions, yet are presently under-researched and appear to be dependent on policy. The likely range of the change in GHG emissions with the average iLUC effect is -1.2% to 0.4% under the Renewable Fuels Standard, -1.9% to -3.3% under the proposed national Low Carbon Fuel Standard, and -3% to -5.3% under a US$ 60 per-metric-ton carbon tax policy relative to US GHG emissions over the 2007-2030 period[88].

2.3.7 Financing

Estimates of subsidies to fossil fuels are in the range of US$ 500 billion to US$ 1 trillion per year. Global subsidies (for renewables based electricity production and

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[85] (Chapter 18)

[86] (Chapter 17, Chapter 20)

[87] (Chapter 20)

[88] (Chapter 20)

biofuels) had a value of more than US$ 60 billion in 2010 and are anticipated to rise to almost US$ 250 billion in 2035[89]. Recent studies show that US$ 270 billion/yr for innovation on land use, energy and cities, makes it possible to finance a reduction of 50-90% of the GHG emissions needed by 2030 to avoid a 2 ^{o}C increase in global average temperatures[90].

2.3.8 Trade

Wood is the fifth most important product in world trade. The market in wood based products increased from US$ 60 billion to US$ 257 billion in the 20 years up to 2008 and is estimated to be US$ 450 billion by 2020. In 2008, global wood usage amounted to around 4.6 billion cubic meters.

Net global bioenergy trade of wood grew six fold from 56.5 PJ (3.5 Mt) to 300 PJ (18 Mt) between 2000 and 2010. Europe remains the key region for international solid bioenergy trade, accounting for two-thirds of global trade in 2010. The European Union is the main market for wood pellets, of which 81% is currently met by the European pellet industry, however the gap between European production and consumption has grown to more than 8 fold. In comparison with pellets, currently less than 10% of annual trade in woodchip is bioenergy-related[91].

The global trade of liquid biofuels has also increased in the last decade. Fluctuations in trade flows have been heavily influenced by policies and changes in production. For example, facing a blend wall of 10%, the US exported 620 million gallons of corn ethanol in 2013 (mainly to Canada). Ironically, the US imported 242 million gallons of ethanol from Brazil to meet greenhouse gas reduction requirements in the advanced biofuel portion of the revised Renewable Fuel Standard. Sustainability standards also have affected imports of biodiesel from different feedstocks into the EU. It is likely that global trade of biofuels will remain dynamic as economic and policy environments continue to evolve.

2.4 Bioenergy Added Benefits to Social and Environmental Development

2.4.1 Biomass Carbon Capture and Sequestration

The direct CO_2 emissions from biomass combustion broadly correspond to the amount of atmospheric CO_2 captured by photosynthesis through the growth cycle of feedstock production, while ethanol fermentation releases about half the carbon

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[89] (Chapter 20 Figure 20.6)

[90] (http://newclimateeconomy.report)

[91] (Chapter 10, Chapter 20 Figure 20.3)

Box 2.7. Crop yields: biotechnology and cropping intensification as options to increase supply

Projections for 2022 crop production in Brazil show considerable production increases across most of its main agricultural products. Growth in agricultural production is expected to be on productivity gains (yield and cropping intensity) rather than area expansion. Total grain crop production (soybeans, corn, rice, beans, wheat) is expected to increase 21.1% with an area expansion of only 9%. Although most sugarcane production increase is accounted for by expansion of the planted area, yield per hectare has also doubled over the last 50 years. Using conventional breeding to increase the energy content of new sugarcane varieties has been projected to potentially increase Brazil's sugarcane bioenergy yield to 1,228 GJ ha^{-1} yr^{-1} over the next 20 years[v].

On the other side, climate change can alter biomass production for some crops and hinder yield gains. There are new prospects for greatly increasing the yields of energy crops, but they require the use and acceptance of genetic engineering, which has contributed significantly to yield improvement in maize and other crops over the last decade.

Breeding for resource-use efficiency (water-use and nitrogen-use efficiency) and "future climate-resilient" bioenergy crops should be stimulated, including tolerance to drought, water logging and salt accumulation.

Using biotechnology maize production in the USA has achieved impressive yield gains but in other parts of the world maize yields are low. Sugarcane and perennial energy crops are far from theoretical yield potentials. Efforts are under way to use marker-assisted breeding and conventional approaches or the GM route for energy crops biotechnological improvement including perennial grasses and woody plants. These include not only increased yield and adaptation to the environment but also tailor-making biomass chemical composition to different applications including increased saccharification for second-generation biofuels.

captured by photosynthesis as nearly pure CO_2. Recovering this CO_2 from biopower or biorefinery facilities would therefore result in a net removal of atmospheric CO_2, once the direct emissions are sequestered and stored using carbon capture and storage (CCS) technologies. As a consequence, a combination of bioenergy and CCS (called BECCS) generally will result in net negative emissions[92]. Because photosynthesis captures CO_2 at atmospheric concentrations, BECCS could be

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[92] (IPCC 2013)

[v] (Chapter 9, Chapter 10)

valuable for reaching lower concentration levels, and offers one of the few practical strategies to address the potential that global emissions will overshoot beyond target concentrations (e.g. 600 ppm)[93].

The use of BECCS is constrained by the potential for CCS and biomass supply. Capture from combustion exhaust is technically challenging and current approaches are expensive, so power plants fired with biomass and including carbon sequestration do not actually exist today. However, current corn biorefineries already use the wet stream of pure CO_2 by drying, compressing, and delivering through pipelines to commercial applications (carbonated beverages, freeze drying, etc.), and also commercial enhanced oil recovery for facilities in close proximity. This part of the technology is currently being coupled with CCS technologies at a corn ethanol refinery in the USA. This project has completed pilot demonstrations and is permitted to sequester CO_2 emissions to onshore deep saline formations in the Illinois Basin at over 1 $MtCO_2$/yr capacity, with extensive performance testing and monitoring over time.

All bioenergy technologies that emit streams of CO_2 as a product are part of the BECCS family of technologies, with potential to sequester atmospheric CO_2 producing negative emissions, which could become important strategies in climate change mitigation if proven. The larger the scale and the proximity to appropriate geologic storage sites, the more likely the technologies are to be used. Both the U.S. and Brazil have appropriate geologic sites in proximity of current biorefineries[94].

2.4.2 Improvement of Soil Quality

Bioenergy crops that efficiently use nitrogen (N) fertilizers usually have a better carbon footprint than annual food crops. There are several crops employed in biofuel production that present such characteristics. Sugarcane can have dry matter yields above 30 t ha^{-1} with only 30 to 120 kg ha^{-1} of N fertilizers; eucalyptus and other woody plants also have almost similar performance. Miscanthus, depending on when it is harvested, translocates most nutrients from the above ground plant parts to the roots and rhizomes before harvest, thus preventing excessive removal of N from the field and reducing the need for fertilization[95].

The recycling of corn stover residues into the field is required to not only protect against wind and water erosion but also sustain soil organic matter (SOM) because of its effect on aggregation, soil structure, water entry and retention, nutrient cycling, and biological food webs. An average of 5.25 or 7.90 Mg ha^{-1} of corn stover should be left in the field to sustain SOM for continuous maize or maize-soybean rotations. Assuming a 1:1 dry grain to dry stover ratio, these guidelines mean that continuous maize fields yielding 8.5 Mg ha^{-1} (160 bu ac^{-1}) of grain could sustainably provide an average of 3.25 Mg ha^{-1} (1.25 ton ac_{-1}) of stover[96]. It was estimated that soil quality could be maintained if 50% of the stover

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[93] (IPCC 2013)

[94] (Chapter 12), https://sequestration.mit.edu/tools/projects/decatur.html

[95] (Chapter 5, Chapter 11)

[96] (Chapter 14)

were removed[97]. Since 2008, coordinated, multi-location field trials have added 239 site-years of data from 36 replicated field experiments, to help make the general guidelines more site specific. Those studies had grain yields ranging from 5.0 to 12.0 Mg ha^{-1} and showed N, P, and K removal increased by 24, 2.7, and 31 kg ha^{-1}, respectively, with moderate (3.9 Mg ha^{-1}) stover harvest or 47, 5.5, and 62 kg ha^{-1}, respectively, with high (7.2 Mg ha^{-1}) stover harvest. The field studies also quantified removal effects on SOM, microbial communities, trace gases, economics, and other factors[98]. Since the effect on fertility will depend on the absolute amount of stover, the proportion that needs to remain could arguably become progressively smaller as yield rises. However, if we assume a fixed removal of 50%, then by 2030 this would amount to 228 Mt, and at an estimated 380 liters of ethanol that could be produced from the cellulose and hemicellulose in a dry metric ton of biomass, this would provide an additional 86.6 BL of ethanol[99].

Perennials radically reduce rates of erosion and nutrient runoff as compared to conventional tillage, often by over 100-fold, and are widely recognized as leading management strategies to achieve these objectives[100]. Perennial and semi-perennial systems (i.e. crops with multi-year rotations) offer several benefits to soil. In parts of the USA, soil loss could be reduced by 60% if switchgrass was grown for bioenergy instead of corn[101].

Recycling of nutrients can improve soil quality and decrease the need for fertilizers. The iconic example of fertirrigation is the use of vinasse, a by-product of ethanol fermentation, with a high biological oxygen demand (175,000 mg L^{-1}), containing around 3-6 g L^{-1} of organic carbon and 2 g L^{-1} potassium as well as other nutrients. About 10 to 13 L of vinasse are produced for each liter of ethanol, around 300 billion L yr^{-1} from sugarcane in Brazil alone. Vinasse became an important, cost-effective nutrient source, potentially providing 2.45 kg/t in K_2O savings, replacing use of fertilizers derived from fossil sources[102].

2.4.3 Increasing Soil Carbon

Switching of food crops into bioenergy crops can increase soil carbon but the opposite may be true if bioenergy crops substitute forests or peatlands. Different cultures and different managing practices have different payback times. Replacement of tropical peatland forest with oil palm incurs a carbon debt ranging from 54 to 115 Mg CO_2eq ha^{-1} yr^{-1}, varying by site and also by the accounting time frame. In contrast, soil organic carbon (SOC) under oil palm may equal or exceed native forests over time in some locations[103]. Some 150 years of cultivation of the rich cornbelt soils is suggested to have resulted in the loss of about 50% of the carbon in the top 15 cm of soil[104]. Correcting for the carbon removed in the harvest, it was shown that in side-by-side fields of the same maize cultivar under no-till there was a net accumulation of 1.6 t C ha^{-1} yr^{-1} while the tilled field showed a net loss of 0.2 t C ha^{-1} yr^{-1} to the atmosphere[105].

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[97] (Chapter 10)

[98] (Chapter 14)

[99] (Chapter 10)

[100] (Chapter 9)

[101] (Chapter 18)

[102] (Chapter 13)

[103] (Chapter 18)

[104] (Chapter 10)

[105] (Chapter 10)

Box 2.8. Water use in bioenergy processes has been decreasing

In the production of biofuels, water intensity indicators are not sufficient to guide decisions and must be complemented with other metrics and evaluation frameworks. The water intensities (or water footprints) of biofuels reported in the literature vary by orders of magnitude[w]. Though widely adopted, the methodology for such reporting is not standardized, not validated by measurement, and marginally useful for determining ecosystem impact. Some footprints include rainwater inputs, theoretical transpiration losses from plant growth, and in some cases theoretical use of irrigation water. Some include additional water volume as a proxy for water quality impacts. Water use is not consistently allocated when multiple products arise from a particular feedstock. However, the recently completed ISO water footprint standard (ISO 14046) is intended to improve consistency in quantifying water footprints. Nonetheless, it is important to note that over the years, innovation in maize production and processing improved ethanol process water use by a factor of 2. In the nineties, each liter of ethanol used six liters of water in the process. By 2007, only three liters of water were used and by 2012, water use decreased by 10% (2.7 liters of water per liter of ethanol)[x]. Sugarcane cultivation in the Center-South of Brazil does not require irrigation. In case of water deficit during drought conditions it is possible to use residual water from the mills. According to UNICA and the Cane Technology Center (CTC) 93.5 m^3/ha of water can be recycled for agricultural use. Of the estimated 22 m^3 water/ton of sugarcane required for industrial processes less than $2m^3$/ton comes from resources indicating more than 90% of the water used is from reutilization. Investments continue to be made and in less than 3 years the water needed for each ton of sugarcane was reduced by 20%.

Several studies have found that growing perennial grasses in lieu of row crops increases soil carbon stocks at a rate of 1 Mg C ha^{-1} yr^{-1} or more for an extended period of years. Similar outcomes have recently been found for sugarcane when it replaces soy or pasture in Brazil. An increase of 1 ton C/ha in the soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare for wheat and 10 to 20 kg/ha for maize[106]. Deep-rooted perennial bioenergy feedstocks in the tropics could enhance soil carbon storage by 0.5 to 1 metric ton ha^{-1} yr^{-1} on already cleared land[107]. Switchgrass' below ground biomass can be eight times higher than the above ground biomass and it produces 55% more total soil organic carbon than corn/soy bean over two rotations[108].

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[106] (Chapter 9)

[107] (Chapter 16)

[108] (Chapter 4)

[w] (Chapter 18)

[x] (Chapter 10)

2.4.4 Pollution Reduction

The environmental performance of the commercial ethanol industry has improved with time. Most pollution associated to bioenergy is derived from biomass production with phosphorus contained in the fertilizer being the major source.

The conversion process of conventional biofuels has minimized emissions, energy input and water use. Conversion contributed over time to a smaller fraction of the life cycle impacts across the value chain and this trend was mostly associated with power generation.

Corn ethanol in the U.S. has lower ozone layer depletion and particulate matter emissions than gasoline but higher impacts in acidification, eutrophication, photochemical oxidation; and decreased global warming potential (GWP). Sugarcane ethanol in Brazil presents lower impacts than gasoline in terms of GWP, fossil depletion, and ozone layer depletion; higher impacts in acidification, eutrophication, photochemical oxidation, and agricultural land use categories. Human health toxicity values are similar to gasoline.

In terms of tailpipe pollutant emissions, data indicate that automakers can achieve regulatory limits with FFVs, independently of the fuel being used. Present Brazilian emission regulations allow subtracting the unburned ethanol from Non-Methane HydroCarbons (NMHC) to avoid gasohol injection during the cold phase cycle. Upcoming regulations will probably incorporate the Non-Methane Organic Gases (NMOG) concept to limit total volatile organic compounds (VOC) and the potential to form ozone. The use of higher levels of ethanol in FFVs does not seem to imply any significant increase in emissions, with the exception of acetaldehyde and formaldehyde. Even though there is an important increase in these aldehydes, the total air toxic emissions potency, which considers also 1,3 butadiene and benzene and EPA toxicity equivalence factors, is significantly smaller when operating with higher levels of ethanol[109].

Biodiesel may cause a small increase in emissions of NO_x relative to petroleum diesel, by about 2% for B20 in some cases but not always. For more modern engines equipped with diesel particle filters, diesel oxidation catalysts, and NO_x emission control catalysts there is little if any effect of fuel on tailpipe emissions[110].

2.4.5 Social Benefits

Around three billion people in the world rely on solid fuels for cooking, whose consumption produces a number of very negative health impacts[111]. Indoor pollution from inefficient cooking stoves results in the premature mortality of nearly 4 million women and young children every year[112]. In Africa and India more than 10 percent of children under the age of 5 suffer from acute respiratory illness associated with biomass smoke[113].

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[109] (Chapter 12 Box 12.5)

[110] (Chapter 12)

[111] (Chapter 15)

[112] (Chapter 4)

[113] (Chapter 21)

Over 1.2 billion people (nearly 17% of global population) have currently no access to electricity while another 2.8 billion people rely mainly on the use of traditional biomass for energy (cooking and heating). Around three-quarters of the world's population depend directly on agriculture and therefore the links of this sector with poverty reduction possibilities should be considered, such as by making use of agricultural residues for energy that can have positive spinoffs for food preservation, mobility and other energy services. At the same time, there are roughly 2.7 billion people living under a budget of US$ 2.00 per day who are considered "poor" by international agencies. They lack adequate access to infrastructure, which gives rise to the wide dependency on traditional biomass to meet their energy needs. Most live in rural areas in developing countries where the lack of access to electricity and modern fuels is also associated to food insecurity.

There is growing evidence that bioenergy production in poor rural areas can help improve economic growth, job security, market development, food quality and security. The world's gross employment in the biofuel sector was over 3.5 million in biofuel for transport and renewable energy for transport, with an estimated 1.5 million in first generation biofuels[114].

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[114] (Chapter 15)

Box 2.9. iLUC emission estimates have decreased

Since 2008 when first numbers on iLUC were published, improvements on the methodologies have been made. First numbers published were based on the assumption that 1 hectare of land converted to any feedstock for bioenergy production would necessarily needed to be compensated by the conversion of 1 ha of native vegetation, leading to a high carbon debit associated to bioenergy. Factors such as yields improvement, conversion of low productivity pastureland, multi-cropping and double-cropping, intensification, integration and substitution among agricultural markets, production of co-products, use of residues, deforestation reduction in developing countries, were ignored. Recognizing the complexity of agricultural systems, and the unrealistic assumptions made in the beginning, global models and parameters have been improved to provide better estimates for the iLUC effects. Incremental knowledge accumulation has changed the results.

iLUC factors for sugar and starch crops have been estimated by different models, with comparable assumptions and scenarios, and over the years a downward trend in iLUC emissions is observed. Improvements implemented in the models, to allow them to account as much as possible to the complexities of the agricultural systems and markets led to reductions in iLUC factors in the last 7 years. From the initial GHG estimates of 104 g CO_2-equivalent (CO_2e) per megajoule (MJ) of US corn ethanol, with improved models values decreased to as low as 6 g CO_2e/MJ. For comparison, the emission factor of gasoline is 92 g CO_2e/MJ. In the case of sugarcane estimates decreased from 111 to 13.9, almost a ten-fold decrease.

On the oil-bearing crops, the iLUC factors are higher than sugar and starch crops. This is due to:

- Palm oil expansion being until nowadays strongly based on tropical forest or peatlands conversion, although efforts exist to improve yields rather than land conversion.

- The structure of the edible oil markets and several similarities of different oil types (soy, rape, pail oil, sunflower), the demand for edible oil being on the rise, and palm oil being more competitive, any additional demand possibly leading to increased palm production.

section III

Synthesis Chapters

3. Energy Security
4. Food Security
5. Environmental and Climate Security
6. Sustainable Development and Innovation
7. Filling the Gaps - The Much Needed Science

chapter 3

Energy Security

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Highlights

Energy security, particularly in relation to bioenergy as part of an energy portfolio, applies not only to nations within the context of geopolitical security of energy supply, but also for the households and communities that comprise all nations, and for whom accessible, reliable, sustainable, economically viable, and resilient energy is necessary for development and economic health.

Policy decisions are best informed when they consider bioenergy as a valuable option for energy security. When properly planned and managed, bioenergy may have positive synergies with other policy priorities such as water and food security, and can support energy access, economic development, growth and stability, climate security, and other environmental goals.

Bioenergy is expected to be increasingly important to energy security issues due to greater utilization to mitigate climate change. More utilization of cellulosic materials, enabled by technology advancements, ranging from improved cooking stoves to gasification to cellulosic pathways for biofuels, all of which are increasingly commercial today, significantly increases the useful resource base globally and alters the geopolitical landscape due to different national resource endowments.

Energy security and related policy goals can be enhanced through technology advancements and level economic playing fields, for crop production, conversion, and end use.

Sustainable bioenergy can provide flexibility to address multiple energy needs - power, fuels and heat - with locally available, nationally adaptable solutions that adjust to local resource availability, seasonal needs, and diversity priorities. However, bioenergy does have risks associated with weather extremes, economic competitiveness, and crop related disease or pest infestation that must be accounted for.

As international trade expands, bioenergy issues will play an increasingly larger role in the geopolitical dialogue, including the complexities across multiple energy segments and the interconnectivity with other geopolitical issues including food, water, trade, human rights, and conflict.

Sustainable bioenergy is expected to play an increasingly important role for energy access, climate change mitigation, and energy security.

3.1 Introduction

This chapter considers the energy security implications and impacts of bioenergy. We provide an assessment to answer the following questions:

- What are the implications for bioenergy and energy security within the broader policy environment that includes food and water security, development, economic productivity, and multiple foreign policy aspects?
- What are the conditions under which bioenergy contributes positively to energy security?

In addressing these questions, bioenergy's diversity of supply, conversion, and end uses for power, fuel, and heat invites a broader evaluation of energy security than considered in the prior SCOPE report on biofuels (SCOPE 2009). Further, the implications and impacts of bioenergy on energy security are increasingly interconnected with land use, water security, food security, the environment, development, and economic activity.

In many but not all countries, bioenergy and its role in energy security has often focused on a biofuels-centric viewpoint in relation to domestic production directly offsetting imported petroleum products. We take a broader approach here, considering a more comprehensive role across heat, power, and fuel, and from households to nations. Bioenergy currently comprises approximately (10-18%) (IRENA 2014) of human energy use and is an increasingly important issue for energy security, especially in relation to the energy/food/water/environmental security nexus.

Additionally, bioenergy use when properly planned and managed, can enable positive synergies among related systems and policy goals, and can support energy access, economic development, growth and stability, and environmental goals. Bioenergy's role in mitigating climate change is expected to become increasingly important to energy security in the overall context of environmental security. Biofuels are expected to play a more important and bigger role in the world's fuel supply, growing from a few percent today to as large as 30% by mid-century. This significant growth will largely be driven by advanced biofuels conversion technologies that allow utilization of cellulosic materials, hence, significantly increasing the useful resource base globally and simultaneously altering the geopolitical landscape due to different national resource endowments.

3.2 Key Findings

3.2.1 Understanding Energy Security and Bioenergy

Energy in all of its forms is one of the enabling features of human civilization. For millennia people have used energy to satisfy basic needs and extend our capabilities – to stay warm in the cold, to see in the dark, to make and trade goods, to produce food, move water, access resources, and to transport ourselves long distances at high speeds. Bioenergy plays an important part in the energy mix in both the developing and developed parts of the world albeit in different forms. Throughout much of the developing world, basic energy needs are still provided by traditional bioenergy resources, often using inefficient stoves whose smoke contributes to serious respiratory health concerns (Chapter 12, this volume). In developed countries, modern forms of bioenergy are also an important part of the energy mix in such forms as commercial-scale combustion for electricity production, household heating, farm and industrial anaerobic digestion for electricity and heat, and biofuels such as ethanol and biodiesel for transport. In this context, global energy security has two important frameworks within which bioenergy can play a critical role. The first focuses on traditional bioenergy: how can the integrated agricultural, forest, and agroforestry systems that provide the biomass resource improve their productivity and environmental outcomes (see Chapter 13, this volume) and feed cleaner utilization technologies to increase efficiency, expand energy availability, and protect human health (Chapter 12, this volume). The second focuses on modern bioenergy: to what extent can sustainable large-scale feedstock production (Chapters 9 and 13, this volume) provide large quantities of renewable energy to satisfy growing demand for electricity and transportation fuels?

There is a strong correlation between energy consumption and the human development index (HDI), with 80% to 90% HDI achieved at approximately 100 gigajoules (GJ)/person/year (see Figure 3.1). Bioenergy already provides a high percentage of the

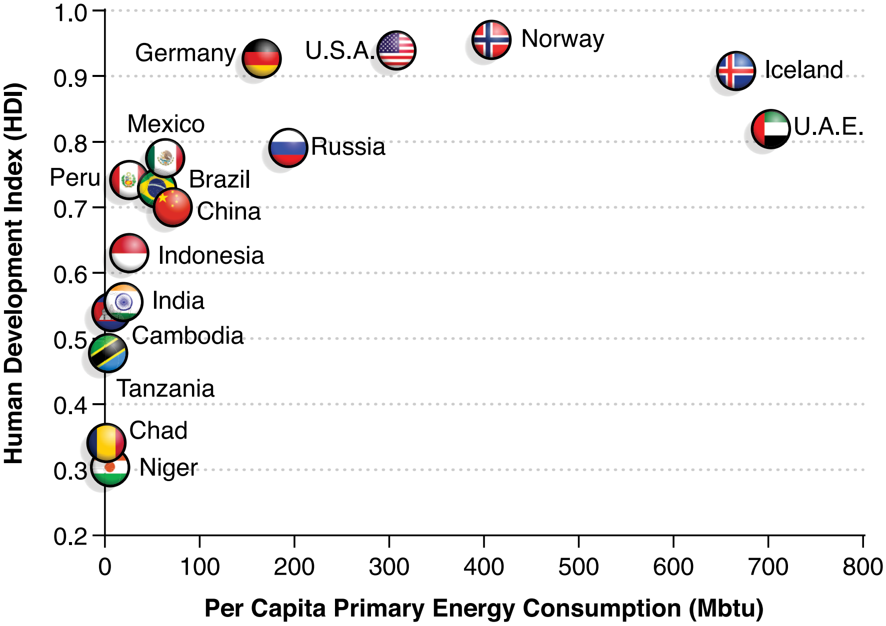

Figure 3.1. Human Development Index versus Per Capita Primary Energy Consumption (EIA 2014; UNDP 2014).

energy for many nations using less than 100 GJ/person/year, while climate stabilization targets require that bioenergy provide roughly 25% of the energy for those nations at the other end of that scale (Chapter 9, this volume).

Meeting these needs for biomass resources must be done in the context of food and climate sustainability, and also in the context of a growing world's population and changing dietary patterns (Popkin 2001).

Framing these issues in the terminology developed for food security, the critical issues for energy security extend into the following crucial areas.

3.2.1.1 Availability and Markets

As with food, water, and other basic human needs, the immediate challenge for those without energy security is not global supply, but local supply and equitable distribution. Importantly, those nations with the greatest need for basic energy security are the same nations that are most dependent on traditional bioenergy, where more efficient use could contribute greatly to closing the energy security gap at a household level. Different challenges apply for industrial bioenergy in developed nations, although a significant resource base exists for those needs as well. In developed nations that have market-driven economies, the largest impediment to large-scale adoption is cost. For bioenergy to be a sustainable component of the energy supply in the developed world, it must be put on a path where it competes with other sources of energy without long-term mandates or incentives. Initial incentives or mandates intended to help bioenergy overcome the development hurdles and higher costs associated with pioneer plants may be required to put modern bioenergy on this long-term economic parity basis. For those nations without large biomass resources, global trade in solid and liquid fuels can play a critical role in adding to the diversity of their energy supply.

The past decade has seen rapid deployment of first generation biofuels, predominantly ethanol, with two major global producers: Brazil from sugarcane and the United States from corn. Although this production has had some impact on global fuel supply and, more dramatically, fuel supply in Brazil and the United States, large-scale global impact is limited primarily due to limitations of producing first generation feedstocks globally. Cellulosic biofuel technologies that have seen initial commercialization in the past few years are predicted to have a much larger global impact with the potential to dramatically change the biofuels availability aspects of energy security. The ability to convert cellulosic feedstock to liquid fuels not only opens up vast new resources, but allows the distribution of renewable chemical energy in a flexible form relevant to all energy needs (cooking, space heat, electricity, and transportation) throughout the developing and developed worlds. Although biofuels can be used to supply all these needs, the predominant use will most likely be for transport fuels since transportation is a high energy intensive application where the cost and thermodynamic losses associated with conversion of biomass to liquid fuels can be justified on a cost basis. Stationary applications that tend to be low energy intensive will most likely use the biomass directly.

Unprocessed biomass is better suited for local use because of its low energy density on a mass and volume basis and in some cases, susceptibility to degradation during storage and transport makes it difficult to transport on a global scale. Although in general, local utilization of biomass resources to supply energy needs is reasonable and can have many positive impacts on global energy security, this will obviously lead to a highly diverse use of bioenergy. Countries with favorable conditions for producing plentiful low-cost biomass will have high degrees of bioenergy utilization, whereas countries that have low biomass availability will have very limited utilization of bioenergy. To broaden bioenergy utilization, in order for bioenergy to reach its full potential and have maximum impact on global energy security, certain forms of bioenergy will need to become global energy commodities.

Commodities must be storable and readily transportable over large distances, ideally by ship, to be suitable for a global commodity model. Both crude oil and primary grains are good examples of commodities that fit this model well. Some forms of biomass such as ethanol or other liquid fuels, as well as stable forms of solid biomass such as pellets or torrified biomass, would also be well suited for global commodities. Although these will most likely be the only forms of bioenergy suitable for trade on global markets, these markets could affect availability and prices of bioenergy for local use.

For example, shale gas from North America is largely stranded on that continent without liquefied natural gas (LNG) export terminals. Yet even though it is used almost exclusively locally for home heating, cooking, and power generation, its availability and low cost have had far reaching effects. Its wide scale adoption for low-cost power generation has significantly displaced coal for power generation, driving down coal prices and leading other regions of the world to switch to coal generation (EIA 2014). Hence, policies and programs intended to encourage increased bioenergy adoption in particular countries or regions need to be developed in the context of global implications.

National and regional policies on foreign trade always play an important role in the international trade of energy commodities. Although many profess that the best model for global commodities is completely open markets without regional or country tariffs or restrictions, these pure global open-market commodity models have some drawbacks for both food and energy security. In the open market model, every food and energy commodity is driven to the lowest cost based on who can supply the market at the lowest price. Over time this tends to concentrate energy and food production in low-cost production areas (i.e., crude oil from the Middle East and primary grains from North America). Political instabilities or weather events such as sustained droughts can cause short-term supply disruptions that can cause wild swings in food and/or energy prices, and thus can cause economic hardships and in extreme cases can be a contributing cause to famine or world-wide recession. Some national or trade organization policies that encourage some level of domestic production of food and energy can act as an effective buffer to ameliorate swings in food and energy commodity prices.

3.2.1.2 Access and Energy Security

As is the case in food security, the biggest impediment to energy security is lack of access. In the developing world, the fundamental challenge to supplying a large percentage of the population that does not have access to the basic energy needs for the desired 100 GJ/person/ year to achieve the 80% HDI threshold is the lack of distribution infrastructure. Numerous studies (Lambert 2014; Costa 2011) have shown that quality of life (Figure 3.1) can be significantly improved with this level of energy production, as well as achieving societal benefits such as an increased education level of the workforce. In the developing world, conventional or evolutionary improvements in traditional bioenergy technologies will supply a significant fraction of these needs. Although it can be effectively argued that some of this advancement will occur organically, careful planning and proper management will accelerate the level of advancement and the extent of this advancement. Hence, proper access to biomass resources as well as efficient, low-polluting conversion technologies will support economic development, growth, and stability while achieving environmental goals for all levels of air quality from the household to the ecosystem level.

This transition is greatly hampered by the lack of suitable infrastructure; hence, addressing infrastructure issues is critical. Developing and deploying the required infrastructure necessary to achieve energy security requires effective planning and policies, as well as stable governments. Infrastructure needs may be the biggest hurdle to energy security in developing nations because infrastructure development is unlikely to occur purely due to natural market factors, and in past cases, the historical data supports this argument (von Hirschhausen 2008). Sustained policies, public investment, and stable governments are necessary for setting the environment necessary for this sustained investment in infrastructure.

In the developed portions of the world that have market-driven economies, the largest impediment to large-scale adoption and hence, access, is cost. For bioenergy to be a sustainable component of energy supply in the developed world, it must be put on a path where it competes economically with other sources of energy without the need for long-term mandates or incentives, although short-term incentives may be required to overcome initial technology deployment hurdles. For those nations without large biomass resources, global trade in biomass solid and liquid fuels can play a critical role in adding to the diversity of their energy supply.

3.2.1.3 Usability and Processing

To maximize the benefit of bioenergy, production and distribution should be synchronized with the intended use. Biomass production and conversion technologies must be developed both in the context of local conditions and time phased on a path to higher sustainability. For example, district heating with combined heat and power (CHP) is highly advantageous relative to stand-alone thermal systems if the electricity comes from 35% efficient coal plants, but the reverse is true when the CHP bioelectricity is substituting for hydroelectricity or other renewables. Policies intended to increase energy, food and environmental security should differentiate alternative bioenergy systems, encouraging some and discouraging others, in light of local contexts.

The degree of processing required and the associated cost of this processing must be commensurate with the intended end use. Biomass used for low intensity applications such as cooking and space heating will need to be low cost and hence, only minimal processing can be accommodated for this intended use. The biggest concern for this use is low- efficiency and environmental pollution. In low-efficiency, poorly designed cook stoves, indoor air pollution can be a significant health concern. Fairly low-cost processing such as drying can significantly reduce indoor air pollution associated with cook stoves (Abeliotis 2013). There are also societal costs associated with low-efficiency uses of bioenergy; for instance, in many low intensity uses, women and children spend inordinate amounts of time gathering and transporting biomass, and this leaves little time for education or other activities that would have far greater impact for improving their HDI. As stated in the previous section, while improvements in infrastructure would greatly help this, improved efficient use would also help in decreasing the amount of biomass required for cooking and space heating.

Higher value forms of bioenergy can accommodate higher degrees of processing. For higher efficiency cooking and space heating, densification such as pelletization can greatly improve the functionality and hence, the conversion efficiency. Densification has also been shown (Dai 2008) to be a useful processing technique to improve the usability of biomass for electricity generation.

At the high end of the technology and value spectrum is biofuels production, because biofuels will have a higher value and energy density compared to other forms of bioenergy, a fair amount of processing can be accommodated. Advanced biofuels conversion technologies that convert lignocellulosic biomass into transportation fuels show great promise to have a significant impact on global energy security since transport is such a large component of global energy use. Current technologies at the initial stages of commercial deployment are focused on ethanol production from lignocellulosic biomass. Many critics of ethanol cite the lack of complete infrastructure compatibility as a significant impediment to large-scale ethanol adoption and argue in favor of approaches that produce hydrocarbon fuels or “drop-in” fuels from biomass. Fuels have a very high energy density, are readily transportable and storable as global energy commodities, and are readily amenable for high value uses such as transportation and high efficiency conversion.

Many researchers and organizations are starting to report early stage promising results on producing hydrocarbon fuels from biomass, but it needs to be cautioned that these are early stage results and considerably more work needs to be done and costs reduced before hydrocarbon fuels from biomass can be commercially deployed (Regalbuto 2009). A strong argument in favor of hydrocarbon biofuels is that the global hydrocarbon fuel production and distribution system is very well developed, second in sophistication and effectiveness to only the food distribution system. Hence, most hydrocarbon biofuels can be readily introduced into this distribution system with no or little adaptation of the system, maximizing their global reach in the near term.

In market economies the biofuel that provides the best value along the various aspects of the value chain will ultimately be the best choice. Ethanol has some advantages as to cost of production whereas hydrocarbon fuels have some advantages as to infrastructure compatibility. Similarly hydrocarbon fuels have some efficiency advantages in current spark ignition engines, whereas research has shown that ethanol or other higher alcohols could have some efficiency advantages in higher efficiency engines being researched (Yang 2010). Compounding on top of this is the world demanding higher efficiency cars both by market choices and government policies and mandates hence it is difficult to forecast the extent to which the world will demand that fuel be compatible with existing infrastructure, and to what extent infrastructure will adjust to supply the fuels being demanded by the transportation industry of the future. Different countries will likely strike this balance differently. In Brazil, the country with the highest fractional use of biofuels, some of each has been observed. Transportation energy storage involving electricity or hydrogen requires infrastructure changes far larger than those required for any liquid biofuel, and yet such changes are widely anticipated and may well occur. If the perceived need and merit of biofuels were to increase say for example by enabling higher efficiency engines, it is likely that greater changes to accommodate them would be considered. Figure 3.2 depicts a process for developing biofuels in an integrated process to enable higher efficiency engines for transport.

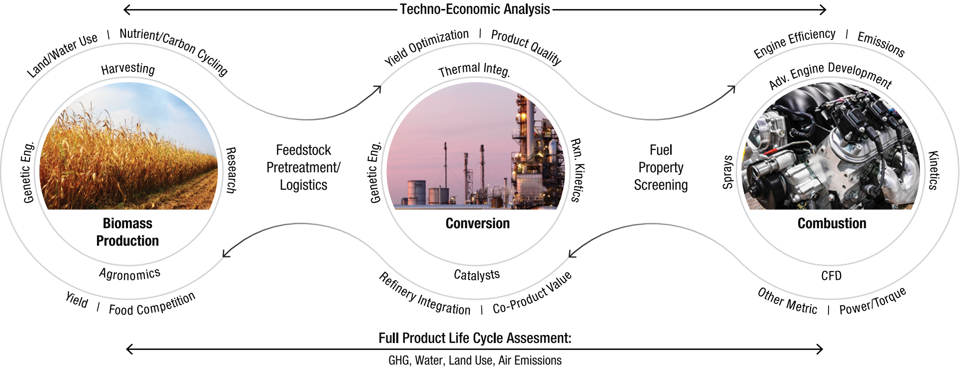

Figure 3.2. Integrated process for developing sustainable biofuels as an enabler for more efficient transport.

3.2.1.4 Stability and Storage

Biomass by its nature is the most easily stored form of renewable energy given that provisions are taken to control biodegradation. This makes it a critical part of a stable renewable energy portfolio. Biomass feedstock production systems also provide a way to increase the resilience of agricultural landscapes and buffer the economic and, in the case of dual-use crops, the supply risks associated with food production.

Biomass storability is dramatically affected by harvest and storage conditions, with poor conditions resulting in significant losses due to spoilage. Storability is often dramatically improved as material progresses through the supply chain (e.g. from raw biomass up to biofuels). Significant losses can occur in unprocessed biomass storage with pelletization or torrefaction significantly improving the stability and hence, storability. Additionally, management strategies such as compacted piles (e.g. of bagasse) and ensiling can render biomass feedstocks quite stable over periods of many months and even years. At the high end of the processing spectrum, liquid and gaseous fuels are very stable and have very long shelf lives.

3.2.2 Interconnectivity with Key Goals and Policies

Energy plays a role in our greatest achievements and most daunting challenges. Accordingly, economic development, energy access, the global economy, local environmental issues, energy and food security, and climate change are at the forefront of national and global concerns, driven by a growing awareness of changes taking place in the natural environment and the critical role energy plays in all economic activities (Bazilian et al. 2011; Gerbens-Leenes et al. 2012; McCornick et al. 2008, Skaggs et al. 2012). Access to modern energy services drives global economic activity and social development. Indeed, energy fuels every aspect of our daily lives; it enables provision of clean water and food, fuels our vehicles, runs our factories, and powers, heats, and cools our homes and businesses. In many developing countries, traditional biomass is still collected by children and women and used in traditional stoves to cook and heat homes, with important consequences for education and health. The production, conversion, and delivery of energy accounts for a very large percentage of global GDP, and energy enables nearly all-commercial activity. In today’s interconnected world, the availability and affordability of energy determines how economies are structured as well as whether and how they grow.

Many national economies and the current global energy economy were built with inexpensive and relatively abundant energy supplies, and without today’s economic, security, and environmental challenges in mind. The current energy system was designed to use the most economically efficient and readily available fuel types with little regard to their environmental or social costs, and yet more than a billion people lack access to modern energy today. Increasing awareness of resource constraints and local and national priorities, including security and food security, and the importance of ecosystem stability and health, suggests that energy security must be considered within a broader policy context (Khan et al. 2009; Olson 2012). Bioenergy’s contribution to energy security is increasingly recognized to be of importance to all economies and beneficial for the transition to a sustainable energy system.

Figure 3.3 depicts the supply chain for bioenergy in context of sustainability parameters.

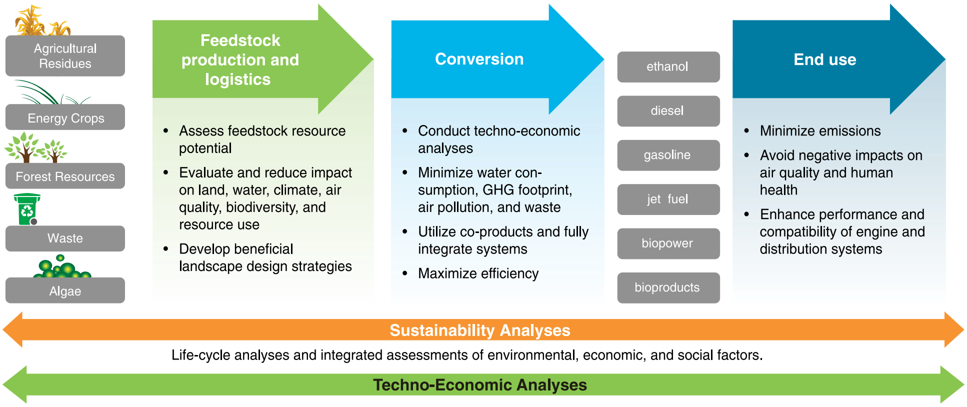

Figure 3.3. Supply chain for biofuels development.

Given what we currently know about the potential risks of energy systems that are overly concentrated on a few sources or infrastructure systems and their impacts on the environment and criticality to development, energy systems are under increased pressure to transform and to better reflect society's interests, but it cannot happen overnight.

The geopolitical, economic, and environmental dynamics of what otherwise appears to be an increasingly challenging future can be reshaped and, in the process, ensure continued economic growth and sustainable development. Such a transition, including bioenergy as well as other renewable and low-environmental impact energy sources (where resources permit), requires that we deploy a new suite of sustainable energy technologies while ensuring that the energy system remains structurally sound and economically viable.

The initial driver for expansion of bioenergy has been energy security. Brazil originally created the ProAlcool Program to minimize balance of trade deficits associated with petroleum imports and to provide alternative demand for sugar and molasses (Chapter 14, this volume). Similarly, the United States implemented federal policies that supported development of corn ethanol to reduce dependency on petroleum imports and to expand demand for corn, thereby reducing surpluses and increasing producer prices (Chapter 20, this volume). Several European countries have implemented biomass technologies to provide heat and power at a significant scale. The driver in this case has been more to reduce fossil fuel consumption. Subsequently, as awareness of the evidence that combustion of fossil fuels is causing climate change has expanded, bioenergy has come to be seen as a mechanism for decreasing the carbon intensity of energy use. Approximately 50 countries now have biofuels mandates predominantly in response to the above concerns. (Chapter 20, this volume).

As noted below, because the use of bioenergy in most market economies currently imposes increased costs relative to fossil fuels at the point of consumption, though not necessarily for the society as a whole, societal support for bioenergy depends on public perception of societal benefits. These may include reduced dependence on energy imports, increased economic activity and employment, and reduced greenhouse gas (GHG) emissions relative to fossil fuels. Evidence of reduced GHG emissions based on life cycle analysis (LCA) has become an important aspect of the public discourse and in some communities, is embodied in legislation concerning policy instruments that support bioenergy use (e.g., the Low Carbon Fuel Standard in California) (Chapter 20, this volume). Similarly, concern about the possible effects of expanded land use for bioenergy production has led to numerous academic studies concerning the impacts of bioenergy production on biodiversity and ecosystem services (Chapter 16, this volume).

The use of bioenergy may involve some tradeoffs. In underdeveloped communities the allocation of some biomass to energy production can provide essential services that cannot be met in any other way. For instance, use of biomass for heat provides home heating and cooking. Conversion of biomass to biogas or biodiesel may allow the production of electricity in communities that otherwise do not have access. This, in turn, can increase education by providing lighting, or by increasing access to telecommunications (i.e., phone, Internet, and TV). Electricity can also enable refrigeration, allowing preservation of food and medicine, and irrigation based on electric pumps. Thus, bioenergy may significantly increase food safety and security. In areas of low population density, the use of biomass for energy may not have any significant downside. However, in densely populated areas, the unregulated use of biomass, other than sources from waste, may have negative consequences. The deforestation of Haiti for charcoal production provides a dramatic example of the worst-case effects of over exploitation of biomass.

In many high income economies, the benefits of bioenergy can include reduced costs of energy, increased price stability because bioenergy is partially decoupled from other sources of energy, economic development and expanded employment in producing regions, reduced GHG emissions, and progress toward the development of energy sustainability. Negative aspects may include competition for biomass with other uses such as food, feed, fiber and structural materials. Such competition may result in increased prices that can benefit producers, but disadvantage consumers. Additionally, for some types of biomass, the diversion to use in production of bioenergy may create expanded demand elsewhere in the global economy, resulting in land use displacement. The demand for land for biomass production may lead to undomesticated land being brought into production. This could have negative impacts on biodiversity, ecosystem services, and GHG emissions. In general, effects on undomesticated public domain lands may be managed through regulation or the use of sustainability certification schemes.

3.2.2.1 The Food and Security Nexus

As depicted in Figure 3.3, bioresources are interlinked with multiple other issues, creating a complex decision making environment. Within these multiple interlinkages, the possible effects of bioenergy on food security deserve special mention. As noted above and in Chapter 4, this volume, in less developed communities, bioenergy can promote economic development, the absence of which is the single largest cause of food insecurity. It may increase food availability by direct effects such as enabling refrigeration and irrigation. Water availability and security are also important within the energy/water/food security nexus (Bazilian et al. 2011). Additionally, in some communities where petroleum is available, local production of biodiesel or other engine fuels may increase the value of local biomass (based on the value of petroleum displaced). The resulting increased local cash flow may help support increased investment in agriculture or infrastructure. An additional potential benefit in developed economies, is the use of food or feed commodities for fuel production may increase food security by creating a source of food or feed that can be redirected from fuels use during shortages. This effect was apparent in the United States during the 2012 drought when many producers discontinued the use of corn for ethanol production, freeing up corn for feed uses. Wright 2011 argued that "governments wishing to protect the food consumption of the most vulnerable could purchase call options on grain from biofuel producers, with appropriate performance guarantees. Specified indicators of food shortages could trigger diversion, and the biofuels supplier would commit to making a corresponding reduction in output (rather than substitute other food grain as feedstock)."

However, there is a widespread public perception that the use of large amounts of grain or other edible feedstocks creates hardship for poor people by increasing food prices. The academic literature of this subject is mixed because of varying assumptions used in the economic models that have been used to estimate cause and effect. A much publicized World Bank report (Mitchel 2008) attributing strong grain price increases to biofuels was subsequently revised downward to a relatively minor effect on food prices (Baffes and Haniotis 2010). General statements regarding food/fuel pricing impacts may be misleading as evidenced in late 2013, when the price of corn in some parts of Brazil was below the cost of transporting the grain to the market (i.e., about US$2/bushel). The main reason for the apparently small effect of grain ethanol production on food prices seems to be due to the fact that the acreage of grain and the productivity per acre have expanded since the run-up in grain ethanol production in proportion to the diversion to ethanol production (Chapter 10, this volume). The price of sugarcane ethanol did not appear to significantly impact the long-term price of sugarcane sugar but was found to increase volatility in sugarcane sugar prices (Serra 2013).

The policy environment is critical to providing a legal and regulatory framework to allow bioresources and other energy (and food) supplies to effectively contribute to local and national goals. As such, a level playing field of fiscal policies, including subsidies and externalities, is important to creating a long-term investment environment for bioenergy and other renewable energies to contribute to the transition to sustainable energy systems.

3.2.2.2 Economics, Markets and Investment

Many studies have indicated the availability of large amounts of biomass that could be used to produce many times more bioenergy than is currently produced worldwide (Chapter 9, this volume). An analysis of 90 recent studies concluded that it is not possible to decide, on the basis of models, exactly how much biomass could be available at this time and that bottom-up empirical studies are needed (Slade et al. 2014). The main factor limiting the use of bioenergy in developed economies appears to be cost. There seems little doubt that if bioenergy was priced comparatively with fossil energy, there would be greatly expanded use. Thus, efforts to expand the use of bioenergy generally follow one of several strategies: [1] mandates that require energy providers to incorporate bioenergy at a set percentage of energy production, [2] mandates that require energy providers to reduce GHG emissions, [3] subsidies that bring down the cost of bioenergy, [4] carbon taxes (or other pricing mechanisms) that increase the cost of fossil fuels or [5] R&D programs to bring the cost of bioenergy to a parity basis with energy from fossil fuels. The choice of instrument seems to depend on political factors such as the degree to which a community agrees that climate change is a threat. In general, economists favor cost parity combined with the use of taxes coupled with wise investment of tax receipts. The second best approach seems to be mandates that reduce GHG emissions (Khan 2009). However, these bioenergy-specific approaches only address one element of a complex policy environment in which, for example, fossil fuels or food production receive significant fiscal support. For example, the main reason for the apparently small effect of grain ethanol production on food prices seems to be that the acreage of grain and the productivity per hectare have both expanded since the run-up in grain ethanol production in proportion to the diversion to ethanol production.

Expansion of bioenergy would require relatively large amounts of investment to support establishment of energy crop acreage, infrastructure, and processing facilities. Because the break-even price of bioenergy based on current conversion technologies is generally similar or higher than that of fossil fuel or other sources of energy, the incentives for investment in bioenergy have historically been low. Technology risk, combined with production/weather risk and relatively low comparable returns on capital create unique challenges for bioenergy investments. In some economies, bioresource investment has proven very successful, particularly where revenue streams offer risk mitigation options and demand side programs set clear production requirements. The petroleum industry invests based on internal rates of return of about 15%, a number that is difficult to obtain with most types of unsubsidized bioenergy. Even though the policy instruments described above may boost returns for bioenergy to an acceptable level, uncertainty about the duration of policy support for bioenergy may preclude investment. In particular, capital investments may be based on approximately 30-year lifetimes. Thus, there is a need for long-term stability of regulatory mechanisms.

Other policies, including those for land use, food, water, environment, and climate, can have a significant effect on bioenergy/food/land use/economics, and vice versa; bio systems offer economic resiliency within an uncertain policy environment.

Key observations relative to bioenergy and energy security include:

- Modern, efficient bioenergy technologies can contribute to energy security while offering the opportunity to improve and enhance our management and stewardship of other key security/development/economic considerations such as water, food, and the environment. Further, prudent management of bioenergy within an energy economy may offer pathways for positive synergies to address multiple policy priorities, including health, education, energy access, economic development, and environmental stewardship. National and local level issues/resource availability (human, physical, financial) must be considered to evaluate bioenergy as part of the energy security portfolio. As with other natural resources, bioenergy is not an unlimited resource and must be managed carefully.
- Efficient production, conversion, and end use are increasingly important areas of focus for improvement of both conventional and new bioenergy technologies, but must be appropriately managed to mitigate risks.
- A level playing field of fiscal policies, including subsidies and externalities, is important to creating a long-term investment environment for sustainable bioenergy to contribute to the transition to sustainable energy systems. Today's policy environment includes not only support mechanisms for bioenergy in some countries, but also many complex policy interactions that inhibit economic attractiveness of bioenergy relative to other energy sources. Other policies, including food, fuel, land use, forestry, and trade policies can have a significant effect on bioenergy/food/land use/economics, and vice versa. Bio systems offer economic resiliency within an uncertain policy environment.
- Economically efficient markets can positively contribute to energy security through commoditization of trade for biomass/bioenergy products. However, many biomass or bioenergy-related markets are strongly affected by domestic or international policies that detract from long-term investment in bioenergy and other alternative energy

3.2.3 Bioenergy Technology Related Energy Security Issues

One likely advantage of bioenergy is that biomass is much more equitably distributed geographically than fossil fuels. However, it is essential that these biomass sources are managed in a sustainable fashion and although relatively plentiful and geographically distributed, biomass for bioenergy is still a limited resource that cannot be harvested beyond a certain threshold. History provides several examples where energy resources were overexploited to the point of some pretty dire consequences. For example, whale oil a major liquid illumination fuel of the 17th through 19th centuries resulted in the extensive killing of whales to the point where the population of large whale species was almost hunted to extinction. Another historical example of overexploitation of biomass resources is for materials. Supplying wood for a rapid construction phase in European cities, in addition to local energy use for mining in the southern part of Norway during the 17th and 18th century, was the reason for cutting down the large oak forests in this part of the world (Torkelsen 2012).

In the same way that all fossil fuels are not created equal (coal, predisposed to heat and electricity production; oil, to transportation and a chemical feedstock (refinery); natural gas to potentially replacing both coal and oil), all biomass is not created equal. Despite the relatively rapid growth in biomass/biofuels trade, there is a very high likelihood that biomass is predisposed to utilization close to its source. Such is the case in the nation whose bioenergy ratio of its total energy mix is the highest, Finland (IEA 2011).

The vast majority of the world's tradable biomass in unprocessed form is forestry derived, and this is the major feedstock in Finland. However, Finland's exports of biomass (pellets) have decreased, partly because of high domestic prices for energy/electricity, thus encouraging more local use, and partly through cheaper competition from external sources (North America, Eastern Europe). Finland also utilizes a full range of technologies to derive bioenergy, from black liquor combustion/gasification through to the integration of CHP facilities to provide the power/heat for local industries and communities. Of its total bioenergy mix, the amount of biomass used for pellet production or external electricity export is minimal. Finland's high percentage of bioenergy production and use has been driven by many factors, but its high technology competence and its former and ongoing dependence on imported Russian oil were significant motivators. Despite its climatic challenges in terms of producing significant amounts of biomass per hectare, Finland has used various technical approaches to maximize its use of bioenergy.

This is in contrast to some other countries, such as Zimbabwe, which has a vastly greater potential to develop biomass than does Finland, but which currently does not have the expertise to maximize biomass production or its utilization. In the case of developing countries, the technical risks range from the sustainable production of biomass while ensuring good local food production to the development of "lower level" technologies such as replacing wood, charcoal, or kerosene stoves with the type of pellet stoves used in Scandinavia.

Whether the biomass is forest or agricultural derived has a significant impact on the logistical challenges that will be encountered, particularly the technology that will be used to harvest, collect, and store the material (as well as processing it). In the case of forestry, much of the equipment is well developed with the biomass frequently "stored on the stump." In the case of agricultural-derived biomass, the harvesting/storage equipment is still evolving with countries such as Denmark pioneering the collection, storage, and processing of wheat straw for its CHB and Inbicon biomass-to-ethanol processes. Other countries such as Brazil are pioneering the storage and use of more friable crops such as sugarcane bagasse in their co-generation facilities located beside modern cane processing facilities.

In electricity generation, the contribution of renewable energy systems is expected to continue to grow from today's annual 19% to 23% by 2035 (EIA 2013). Solar and wind are greatly affected by weather and time of day issues where hydro energy is only available in limited geographical areas. Conversely, the use of biomass in electricity generation introduces flexibility in that it can both be used as baseload and to some degree, peak load, thus making up for the intermittency of the other renewable resources. To take advantage of this flexibility, the necessary investments into the electricity grid must be done such that enough transmission capacity is built so that these plants can be connected to the grid. The flexibility of the biomass-generated electricity makes it highly desirable to introduce into the electrical grid.

Key observations include:

- Biomass may not be a suitable resource for every country, or uniformly used within a country. For those areas with appropriate resource endowments, biomass is a very flexible energy source; it can be used for direct heat, transportation fuel, thermal energy, and electricity generation. Its comparative advantage is limited to certain energy market segments that depend on the geographical region.
- Depending on technology, economics, and multiple other factors, bioresources offer options for local use, enhanced energy access, and economic productivity, and may together contribute economic gains to local, regional, national, and international markets.
- Biomass offers access to energy in developing countries given the appropriate infrastructure and policies.
- As with other natural resources, bioenergy is not an unlimited resource and must be managed carefully. This factor relates to land use, species cultivation, biodiversity, and others.

3.2.4 Geopolitics of Bioenergy and Energy Security

The geopolitics of energy security has received intense evaluation within traditional analysis of foreign policy, with a strong focus on global issues regarding fossil fuels (Levi 2013; Sovacool et al. 2011). The transport fuel sector in many countries strongly depends on imported oil and refined petroleum fuels. Growing concerns regarding geopolitical oil concentrations, increasingly hard-to-reach reserves, restrictions on delivery or access, and high and fluctuating prices promoted initial interest in alternatives, including biofuels. Energy-related issues have been framed within the complexities of foreign policies, including fiscal, military, and political security (Elkind 2010). Further, the relative importance of bioenergy within the geopolitical dialogue is a complex subject that includes future oil and gas supplies and trade, technical power system outages, sabotage and terrorism, geopolitics, weather patterns and extremes, water, and food security. Bioenergy (and other renewable energy resource) projects can assist in reducing the risks of these various energy supply constraints that can have serious political consequences. However, they also carry their own risks of insecurity, variability, and unreliability.

More recently, the two leading countries for biofuels production, Brazil and the United States, have developed policies that reflect the relationship between bioenergy (biofuels) and energy security within the framework of increasing domestic production of liquid transportation fuels to offset import dependence and geopolitical uncertainty (Elkind 2010). However, since the inception of those initial biofuels policies, it is increasingly recognized that bioenergy can play a larger role in the geopolitical dialogue, including addressing the complexities across multiple energy segments and the interconnectivity with other geopolitical issues including food, water, trade, and conflict. For example, energy issues are also related to local energy security and the complexities of local and national politics (Muys et al. 2013). Others have recognized that water may have an increasingly important role in geopolitics, related through food trade, and by inference to bioenergy and energy security (Suweis et al. 2012).

To enhance the security of power generation systems, bioenergy power and cogeneration plants offer fuel diversity, lower GHG emissions, local economic (and perhaps other) benefits, and can be built reasonably close to the demand centers, thus reducing transmission losses, and can at times strengthen the local electricity distribution grid by providing additional and alternative power resources. Security of supply can also be improved by greater diversification of the portfolio mix. Biofuels for power are now shipped globally, (e.g., Canadian and American wood pellets to Europe), which introduces new dynamics into the geopolitical dialogue. In Brazil, as another example, most sugarcane processing facilities are engineered for flexibility to optimize revenue at different times of the day and of the year by varying the outputs of power, heat, ethanol, and sugar. This flexibility is linked to larger national power planning and management related to hydropower production and the interconnectivity of the regional grid. Similarly, biopower is of increasing interest for other Latin American countries to offset some of the geopolitical risk and tensions associated with regional fossil fuel trade. Some Nordic countries use biomass for power and district heating, in a complex interaction with other renewable power sources and regional power markets. Figure 3.4 shows the energy production by source for Finland. If incorporated correctly and in the proper mix this can lead to enhanced local and national economic productivity, as well as reduced GHG emissions. Greater security by using biomass fuels depends on alternative sources of fuels and their reliability, versus the risks involved with securing sufficient supplies of biomass over the long term. Figure 3.5 shows the breakdown of renewable energy sources for IEA member countries.

Key observations include:

- It is increasingly recognized that bioenergy may play a larger role in the geopolitical dialogue, including the complexities across multiple energy segments and the interconnectivity with other geopolitical issues, including food, water, trade, and conflict.
- Bioenergy is expected to be increasingly important to energy security due to greater use to mitigate climate change. There will be increased use of cellulosic materials, enabled by technology advancements ranging from improved cooking stoves to gasification to cellulosic pathways for biofuels, all of which are increasingly

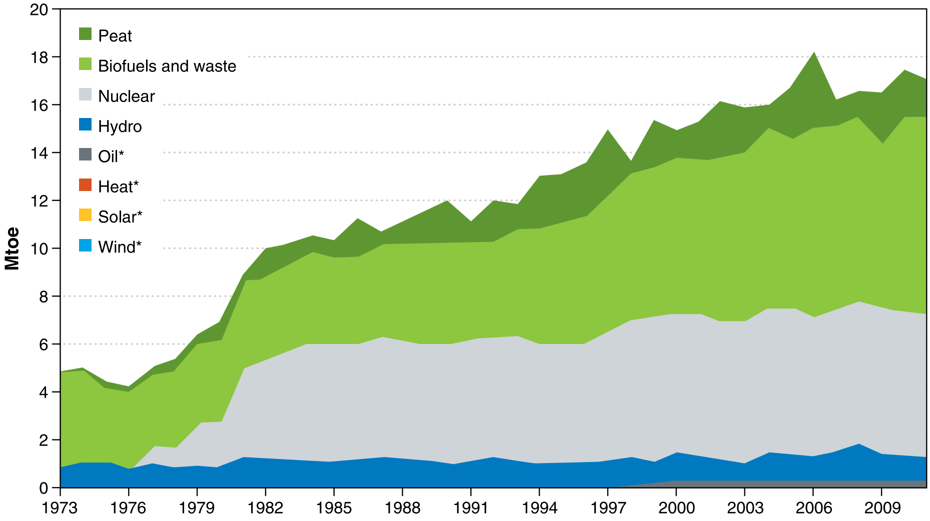

Figure 3.4. Energy production by source in Finland.

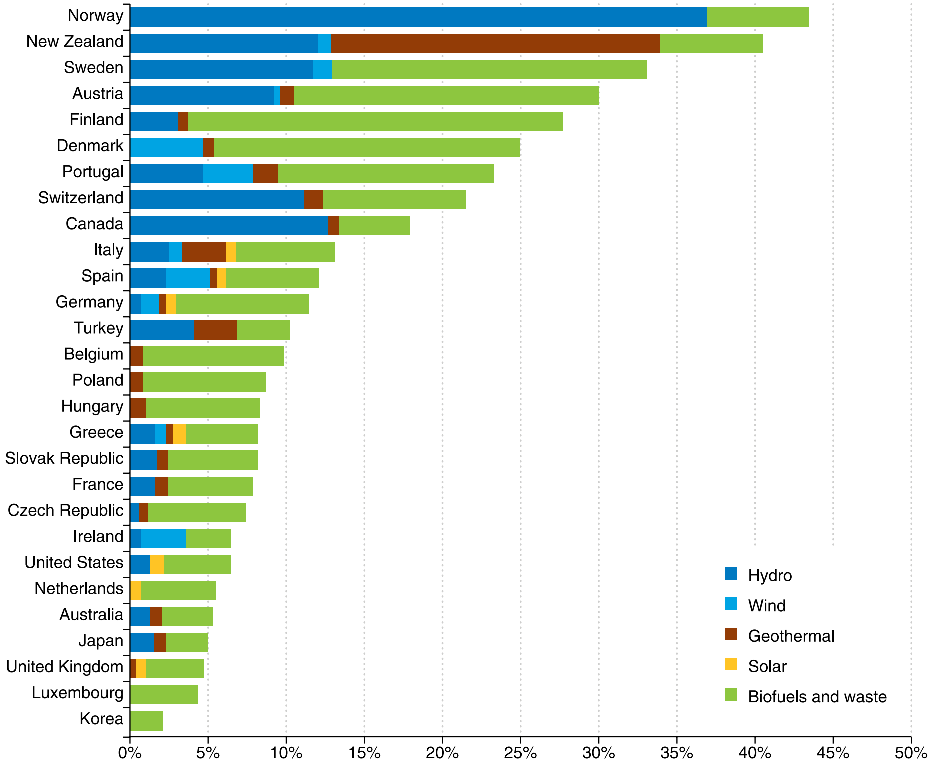

Figure 3.5. Renewable energy as a percentage of TPES in IEA member countries, 2011.

commercial today. This significantly increases the useful resource base globally and alters the geopolitical landscape due to different national resource endowments.

- Energy security and related policy goals can be enhanced through technology advancements and level economic playing fields for crop production, conversion, and end use.

3.2.5 Local Issues

Energy security threats in a dominant bioenergy scenario are manifest at the local level (individual, family, or village) because of the interplay between competing end uses for physically finite, local resources and inputs (land area, water, manpower, standing biomass stock, biodiversity, finance, man-animal allocations) and the type of crop/bioenergy that needs to be or can be raised. Every season, irreversible resource allocation choices are made at this level, and these in turn decide how much of the biomass and bioenergy raised becomes available/accessible locally, which is the focus of this sub-section.

Features of crop and biomass production (agro-climate, genetic resource), agronomic inputs (nutrition, pest control, husbandry), resource allocation (financial and human capital) and local practices (cultural, land, resource and material ownership or sharing patterns, socio-economic, market infrastructure) decide the physical limits to production, shape aspirational profit targets, and allocate realized outputs between market and domestic needs, respectively. Of late, these complex, multi-tiered hierarchical decision processes have begun to place markets before sustenance, and short-term cash availability before sustainability. This then exacerbates and accentuates various socio-cultural manifestations of gender and vulnerability, especially in the Asian region where per capita cultivable land availability is low (0.1–0.2 hectares/capita) and every little bit of biomass (therefore, bioenergy security) needs to be carefully split between aspirational and sustainability needs (Reddy and Nathan 2013).

In other geographic locations of highly endowed local resources and agro-climatic conditions, optimization of local components tends to increase biomass productivity and bioenergy security. However, in less endowed locations, when biomass or bioenergy products become highly marketable, it exacerbates the potential for deprivation (insecurity), such as milk sold for daily cash in Indian villages at the cost of being given to children and therefore needs to be addressed. Towards this end, there is a need to arrive at the concept of which we refer to as “lifeline energy” that involves a locally defined basket of minimum energy services (in our case, through bioenergy/biofuels) that will meet the current and near-future energy security articulation.

3.2.5.1 Lifeline Energy Needs

Biomass has often been and will most likely continue to be the subsistent and most easily accessible fuel and energy source for the unreached population in underdeveloped regions. Field demonstrations of modern bioenergy deployment have indicated that primary biomass resources can provide more than lifeline energy needs (and even reach desirable levels in developed regions) such that access to and use of (lifeline) modern bioenergy not only ensures energy security, but is also a means to development in underdeveloped, biomass-rich regions of the world. There is a strong relationship between the type of end use and the ideal bioenergy technology that could be used.

3.2.5.2 Pollution

Biomass will be converted to its desired form of usable energy or work through various conversion processes such as engines in vehicles, generators, or rudimentary stoves for cooking and heating (Chapter 12, this volume). All forms of end use conversion will have some form of undesirable emissions that impact the local, regional, and world environment. Commonly cited as being particularly problematic are the smoke and hazardous emissions associated with low technology, low efficiency wood stoves and kitchens. These need to be, and can be, addressed through technology, best practices, and control means. In India, solid fuels account for about 63% of the total household energy consumption, with significant contributions to both CO_2 and indoor air hazards (Balachandra 2012).

Traditional methods of bioenergy production and use are generally fraught with drudgery, energy leaks and pollution (Chapters 10 and 12, this volume). Advanced bioenergy routes need to address and overcome these issues to provide energy security and environmental safety. More modernized bioenergy practices can also produce pollution. For example, over-fertilized energy cropping can cause various manifestations of water pollution, and improper combustion techniques can lead to significant and hazardous levels of indoor air pollution.

3.2.5.3 Water Use

Water and biomass/bioenergy production are strongly linked and the influence on energy (and food) security may be examined in three regimes of water availability. In areas of higher water availability (rainfall and/or irrigation), bioenergy crops and food crops are likely to compete if land availability or resources indicated above are limiting. In the absence of such limitations or in well-planned bioenergy-food crop combinations (e.g., multi-tier cropping), they could complement food and energy security. In sub-humid and semi-arid areas (with a 90–150 day crop-growth window), bioenergy derived from crop residues could complement food and energy security, where straw and agro-residue generated bioelectricity provides life-saving irrigation to crops, and the increased gross biomass production provides higher levels of food and energy security simultaneously. In the third category of agro-ecosystems, arid systems, biomass/bioenergy production has not been implemented but may be possible by using water-efficient and drought tolerant plants such as Agave (Figure 3.6) and Opuntia as dedicated energy crops (Sommerville et al. 2010).

Figure 3.6. Agave sisilana growing in East Africa. (Image courtesy of Jeff Cameron).

These are typically local and regional decisions. Water and energy security issues are thus very region-specific. When water supply is adequate for a particular crop, there are few threats; however, as indicated above, in locations of limited water supply, the best decision is what level of bioenergy crop development can be sustainably supported without affecting water availability for food crops. Thus with judicious deployment, food and energy crops are possible without compromising food or energy security.

3.2.5.4 Economics, Jobs and Livelihoods

Bioenergy can have very positive impacts on economic activities and jobs with concentrated impacts at the local level. Increased biomass production tends to increase local jobs, predominantly agro and agro-forestry jobs associated with biomass production. Modern bioenergy options such as biomethane, producer gas, and agro-processing provide a multiplier effect in local jobs and therefore, improve local economics in terms of a higher level of value addition to locally generated biomass products as well as energy carriers (see Figures 12.2, 12.5, and 12.6 in Chapter 12, this volume). Modern bioenergy options such as biofuels or bioelectricity with expensive conversion processes will need to find the optimum between size of the conversion facility and the amount of primary biomass transport required. Biofuels and bioelectricity like any commodity conversion process will be economies of scale dependent. The balance between size of plant and cost of transport of biomass to the plant will be regionally dependent, primarily dependent on biomass production rates and transport options such as rail, road or water transport. Since there will be significant economic activity associated with the conversion plant with the primary jobs and the multiplier effect how this is regionally distributed will be dependent on the size and number of conversion plants.

3.2.5.5 Women and Children, Education and Development

The role of women in bioenergy has been likened to “responsibility without authority” to choose fuel type, technology, and ill effects. They disproportionally bear the brunt of all the current ill effects ranging from the drudgery of biomass collection to indoor air pollution issues. The vulnerability of energy insecurity leads young women to take up fuel-wood gathering at the cost of formal education (Reddy and Nathan 2013). Modern bioenergy such as biomethane, pellet-based stoves, modern wood stoves, and bioelectricity can convert unused crop residues and various biomass and animal wastes to energy for cooking and lighting. This switch involving both a change in bioenergy source and energy use device is expected to increase the useful energy output (see Figure 12.2 in Chapter 12, this volume) and to remove the source of drudgery, deprivation, vulnerability, and loss in health and education.

3.2.5.6 Health Impacts

Traditional biomass burning in smoky kitchens has largely been implicated in large-scale respiratory ailments among adult women in a large part of Asia and Africa (Gumartini 2009). The switch to modern bioenergy options removes drudgery and the time used for gathering fuel, removes exposure to harmful agents in wood smoke, and leads to more time for rest, education or gainful employment. Having removed the need to gather fuel-wood, infants and young children get better maternal attention and therefore, a better means to health. The most direct impact of using solid fuels for cooking is indoor air pollution, which is considered one of the most significant causes of death in the world. Cambodia, with 1,304 deaths per million people in 2004 and India with 954 deaths, occupy the top two positions (Table 24 in Balachandra 2012).

“The human development benefits associated with expanding energy access [in our case bioenergy] are related to better education facilities and opportunities, access to healthcare as well as better health conditions, access to information for knowledge empowerment, gender empowerment through reduced drudgery, productive endeavours, enhanced security and clean working environment. In addition, the enhanced income levels and employment opportunities would significantly reduce the poverty levels thereby enhancing the living standards of the people.”(Balachandra 2012).

3.2.5.7 Co-Benefits and Tradeoffs

Enhanced levels of biomass production and local-level bioenergy generation can in the developing world increase food security and bring with it a large surge in rural and decentralized livelihoods and local employment and can reverse migration to urban areas. Increased employment chances strengthen the bioenergy supply chain manifold (Chapter 11, this volume), its trade and service providers, and enhance and empower local energy entrepreneurship (Chapter 12, this volume). In other regions where there are fewer limitations to biomass and biofuel production, there are tradeoffs between several land use options: processing biomass harvested for food, fuel, fiber, or forage needs of the location, as well as potentially dictated by national policies.

3.2.5.8 Research Needs and Sustainability

Local resource use efficiency (tradeoffs of land, water, human and financial capital, and within the ecosystem) requires more thorough research and analysis to achieve and maintain viability. With an increase in the level of biomass/bioenergy in any given location, apart from tradeoff between input-output options, efficiency benchmarking will emerge. Agricultural crops are already measured for their water use efficiency (grams of CO_2 fixed/liter of water transpired), useful yields (kilograms/hectare and biomass yield/kilogram nutrients added), and, finally, value added/unit investment. These and many more efficiency yardsticks need to be evolved. For example, the tradeoffs between adding a higher fertilizer/water dose for higher yields will become important and needs to be monitored to better establish new sustainability debate metrics.

Key observations include:

- Sustainable, locally based (distributed) bioenergy (and other renewable energy or hybrid) systems can alleviate energy poverty, increase energy access and local and regional energy security, increase food/water/development, and be effectively incorporated into an interconnected energy/economic/agro-eco system. The system will include planning and investments in energy infrastructure that incorporate bio/renewable energy options that will increase local energy security, including biomass collection, storage, and transport infrastructure.
- The policy environment, including related policies on land use, agriculture, forestry, food, energy, and the environment, plays a critical role in enabling (or not) the investment, development, and use of bioenergy at local and national scales.
- Local development and use decisions rely on a complex set of interactions that include not only related resource assessment (land, water, human, and financial capital), but also the implications (positive and negative) of bioenergy within a local economy.

3.3 Conclusions and Recommendations

Energy security, in relation to bioenergy, has evolved, to a comprehensive role for heat, power, and transportation fuels at a range of scales from households to nations. Further, bioenergy can play a significant role in policy decisions if evaluated as a valuable option for increasing energy security. When properly planned and managed, bioenergy may have positive synergies with other policy priorities such as water and food security, as well as supporting energy access, economic development, growth and stability, and environmental goals. As efforts to adapt to and mitigate climate change increase, bioenergy is expected to be increasingly important to energy security issues because of the relatively low carbon intensity of bioenergy compared to fossil fuels. Greater utilization of lignocellulosic materials, enabled by technology advancements ranging from improved cooking stoves for underdeveloped regions to the production of lignocellulosic biofuels, can significantly increase the useful resource base globally and alter the geopolitical landscape due to different national resource endowments.

After a long development period, lignocellulosic biofuels have been commercialized in Europe and the United States using both bioconversion and thermal conversion technologies. If the conversion facilities are able to meet their financial goals, they are expected to stimulate the expansion of lignocellulosic biofuels by reducing risk to investment. Additionally, the first generation of commercial facilities will provide very useful opportunities to improve the technologies and the design of the biofuel production facilities by learning-while-doing. Anticipated improvements will progressively reduce operating and capital costs, thereby improving profitability and attracting additional investment. Because it may take five years or more to design, locate, build, and bring online a biorefinery, it seems likely that a major expansion of lignocellulosic biofuels will not begin before about 2020, but after that time there could be a rapid expansion of capacity in North America, Europe, Brazil and other regions with abundant biomass resources that could resemble the run-up in implementation of corn ethanol facilities in the United States after the year 2000 (Chapter 14, this volume).

Policy and regulatory approaches of bioenergy production, conversion, and use, especially in relation to the energy/food/water security nexus can enable or inhibit positive synergies among related systems and policy goals, and require careful analysis and adaptive approaches that account for changing resource endowments, natural conditions, technology advancements, and geopolitical change.

Finally, the energy security aspects of bioenergy remain important and are likely to increase as climate change is addressed, populations and food demand grow, and traditional fossil fuel sources of energy increase in total cost as well as price volatility.

3.4 The Much Needed Science

Bioenergy can positively contribute to global energy security in the context of food and climate security. In order for the potential of bioenergy to be realized some important science needs to be addressed both as an enabler to needed policy as well as conversion technologies. As discussed in section 3.2 bioenergy technologies need to be developed in the context of "lifeline" needs, which will dramatically differ for the intended application and end use. The limiting factors to increasing the positive impact of bioenergy to global energy security are the availability of sustainable biomass and efficient, low polluting cost effective conversion technologies and the societal factors for increased utilization of bioenergy to improve energy security. Science needs in these areas are as follows:

3.4.1 Availability of Sustainable Biomass

The question of how much biomass is available for bioenergy production in the context of food security has been extensively studied (Vosin et al. 2014; Ajanovic 2011). Regardless of this issue improved land management techniques and practices are required for both food and bioenergy production. Sustainable land management practices vary depending on the amounts and types of food and biomass produced as well as local conditions. Predictive models as well as information dissemination are needed.

Biomass must be produced and delivered to the intended end user to satisfy both aspects of the biomass availability equation. As stated in section 3.2.1 the lack of a viable biomass distribution infrastructure serves as a serious impediment to wide scale bioenergy adoption in developing countries. Studies are needed as to what sustainable infrastructure can be deployed to improve the availability of biomass in developing countries. Policy measures can have significant impact on infrastructure development so these studies should also consider what policy measures are needed and which ones are most likely to be effective in the long term.

In the developed portions of the world the issue is not generally the lack of infrastructure, but usually the suitability of that infrastructure for bioenergy, i.e. transporting ethanol in pipelines designed for gasoline and diesel transport versus dedicated pipelines purposely built for ethanol transport. Studies are needed as to how best synch up the bioenergy forms under development with the existing infrastructure.

3.4.2 Conversion Technologies

A good portion of current bioenergy utilization is traditional bioenergy that tends to be dominated by low efficiency, high polluting conversion technologies. This has a two-tiered detrimental impact; firstly, the low efficiency conversion increases the amount of biomass required which in turn increases the amount of drudgery associated with collecting the biomass. Secondly, the high pollution increases the negative health impacts associated with breathing dirty polluted air. Since pollution and primary conversion efficiency are closely tied, improvements in efficiency will have the added benefit of decreased pollution. Higher efficiency, lower polluting cook stoves and space heating are needed for traditional bioenergy applications as well as the necessary distribution to the users.

Bioelectricity or electricity generation from biomass has the potential to become a significant and beneficial contributor to global energy security.

For developing countries or remote areas without a well-established electrical grid, small low cost biomass gasifers connected to an electrical generator can supply reasonable amounts of electricity to supply refrigeration, lighting and other small electrical loads having a positive impact on food safety, health and other aspects of

HDI. Improvements in conversion efficiency, reliability and ease of operation could greatly improve the utility of these units.

For the developed portions of the world with well established and reliable electrical grids, larger scale base load or peak load biomass combined heat and power gasifiers integrated with efficient electrical generators such as gas turbines can be a cost effective source of electricity. This is very region and country specific dependent on the availability and cost of biomass compared to other fuels typically used for electricity generation such as coal or natural gas.

Biofuels can also be a major contributor to global energy security. As discussed in section 3.2, first generation biofuels technology predominantly ethanol from sugarcane in Brazil and corn in the US have already had a significant impact. However the global impact of these first generation biofuels is limited by the global availability of these feedstocks. Second generation biofuels conversion technologies that use lignocellulosic biomass as feedstock have a significantly improved ability to have a global impact because of the greatly enhanced global availability of these feedstocks. Although these technologies are undergoing initial scale commercial deployment more work is needed to bring down the cost of these conversion technologies.

The predominant biofuel to date has been ethanol. Although ethanol is suitable for gasoline applications it cannot be used in diesel and jet fuel applications. However, diesel and jet fuels are growing rapidly in global use while gasoline demand is relatively stagnant to decreasing in some countries (ExxonMobil 2013). Biofuels that would be suitable for diesel and/or jet fuel applications are desirable to have positive impacts across the transportation sector.

3.4.3 Needed Science for Bioenergy to Achieve Maximum Benefit to Energy Security

Science or research is needed for bioenergy to contribute more to energy security – this includes not only the technological developments, but also how biomass is used, scaled up and deployed at the appropriate level. Accomplishing this in a thoughtful manner includes a thorough understanding of the social, economic and political aspects (social sciences). An important aspect that must be understood in the implications of global trade including the implications of multilateral agreements on energy/climate, etc.

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chapter 4

Bioenergy and Food Security

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Highlights

- There is enough land available for substantial production of bioenergy and food for a growing world population, expansion will be predominantly in Sub Saharan Africa and Latin America
- There is no inherent causal relation between bioenergy production and food insecurity
- Bioenergy can improve food production systems and rural economic development, but requires good governance. Bioenergy can stimulate investments in agricultural production in poor areas and provide a dynamic switch system to produce energy *or* food whenever necessary
- It is our ethical duty to develop and evaluate practices of combined bioenergy and food production in poor areas

Summary

Bioenergy is biomass converted for energy applications in the heat, transport or electricity sectors. It can be obtained from food and feed crops, non-food crops, woody forest based sources and various types of wastes and residues, including the biodegradable fractions of municipal or industrial wastes. An expansion of bioenergy production from agricultural and forestry sources leads to concerns over land use management and governance within a context of growing demands for food, resulting from increasing global population and wealth. Furthermore, some predictions suggest that climate change will negatively impact agricultural yields. So it is important to consider the potential impacts of expanded bioenergy production on food security.

There are up to 1,4 Bha of suitable land available for sustainable rain-fed agriculture without taking forests and urban uses into account (Chapter 9, this volume). This is more than enough to expand the present agricultural area to fulfill growing demands for food production, which is calculated to need an additional 130-219 Mha after taking lower yield increases and possible negative effects of climate change into account. The remaining land should be sufficient to allow bioenergy to make a considerable contribution to global energy needs. The land required for bioenergy and food production does not constitute a zero-sum game: there are various synergies and multiple uses, including the use of residues and wastes. With sufficient investment and

proper management, bioenergy can also be employed to improve an additional area of up to 600 Mha of degraded land and make it productive again.

Thus, land availability per se does not constrain a significant increase in bioenergy production. However, food insecurity still affects nearly one billion people in less developed countries, of which roughly 20-30% live in urban areas and 70-80% in rural areas; for such persons the effects of bioenergy production need to be carefully considered. The key question is therefore not about managing competition for land between energy and food, but rather about finding the most valuable and productive entry points for incorporating bioenergy into human and natural landscapes (Chapter 9, this volume).

Food security is commonly measured across four dimensions: availability, access, utilization and stability. Food prices are the major factor contributing to food insecurity among the urban poor. There is no overall body of evidence showing a strong causal relation between bioenergy production and food price increases although bioenergy expansion can be a minor contributor to higher food prices when multiple pressures coincide. On the other hand, flexibility in bioenergy or food production from the same land or crop can contribute to long-term market and price stability for producers.

With respect to the rural poor, higher food prices can be a benefit where they can sell their surplus. There is also evidence that bioenergy could enhance food availability, access, utilization and stability for the rural poor. Production of bioenergy can potentially provide energy security and boost economic development by improving agricultural management, infrastructure, food preservation, education and market development. Good governance is required to ensure that poor farmers and other rural residents benefit from expanded bioenergy production. The impacts are generally site-specific so it is important to compare governance options and policy measures in specific settings in order to insure that food security is improved.

From recent evidence, including case studies collected in this report, we conclude that bioenergy can be implemented in ways that have neutral or positive impacts on food production and security. Bioenergy can contribute to:

- decreased price volatility, resulting from a diversification of revenue sources from agricultural and forest-based commodities, reducing supply risks and increasing rural income, with associated benefits on farm income and investment;
- agricultural and land use infrastructure development through investments for biomass feedstock and bioenergy systems;
- rural economic development, supported by local energy availability and development of improved value chains, market linkages and infrastructure;
- providing a flexible, market-based system that can adjust the use of biomass for food or energy in times of abundance or scarcity.

The goal is to realize bioenergy expansion that is compatible with improved food security and environmental sustainability. This requires multidisciplinary, applied research across the entire bioenergy chain from resources and feedstocks through conversion, transportation and end-use. Implementation of best practices in bioenergy systems also relies on good governance at local, national and global levels, including capacity-building in developing countries and the design of supportive regulations, certification schemes, investment structures and financing. Transparent communication methods are needed to ensure that trust is built within the diverse communities of agricultural practice and associated stakeholder groups, so as to maximize the benefits from positive synergies between expanded bioenergy and food security around the world.

4.1 Introduction

This chapter describes and analyses the relation with and potential impacts of bioenergy on food security and gives recommendations for policy, research, capacity-building and communication. In reviewing these impacts, we distinguish between global factors (e.g. commodity price shifts, international trade) and localized impacts, whose significance is context-dependent and may also differ in urban vs. rural settings. We draw on relevant elements of Chapters 9-21, this volume and also consider linkages, synergies and conflicts between bioenergy expansion and food security.

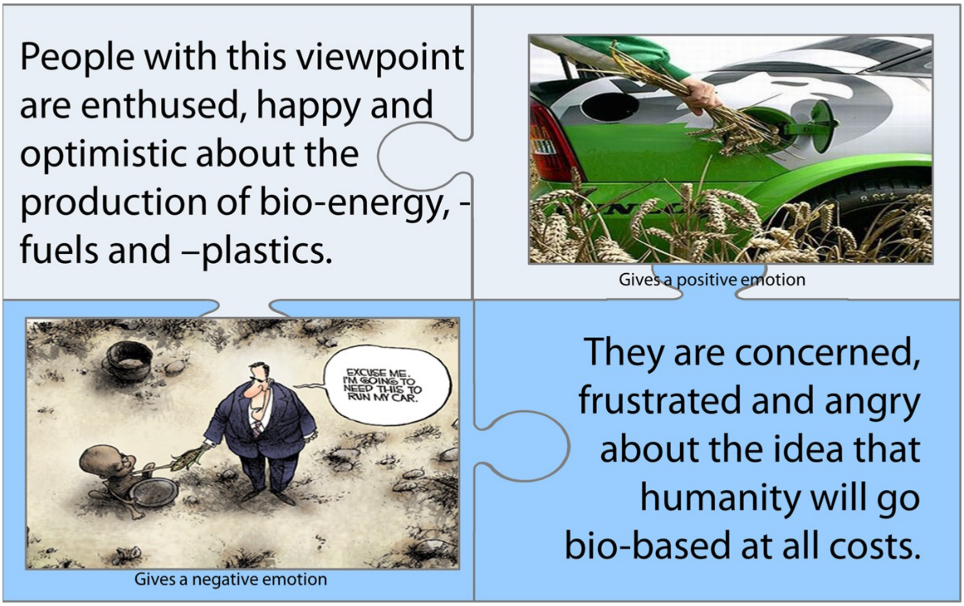
4.1.1 Relevance

Access to affordable and reliable energy is a precondition for improved food security, and independent of its origin, increased energy availability will improve food security (FAO 2008a; FAO 2008b; FAO 2012). Bioenergy that is based on crops, however, has a special relation to food security which - especially in the case of agricultural land dedicated to biofuels production - is perceived as a trade-off between food, feed and fuel and much debated around the world. The debate is characterized by diverse opinions, and includes some ill-informed statements (Landeweerd et al. 2012b, Michaelopoulos et al. 2011). This chapter provides science-based information aimed at improving the decision making process for sustainable bioenergy production. It will, where possible, provide recommendations to avoid negative effects and stimulate positive effects of bioenergy production on food security.

Bioenergy uses biomass to produce electricity, transportation fuels, or heat. Biomass for energy can be obtained from food crops, non-food crops, woody or forest-based sources and various types of wastes or residues, including the biodegradable fraction of municipal or industrial wastes. Crop and forest biomass use leads to concerns over land use management and governance, yet bioenergy production does not lead to a zero sum game of land use: use of agricultural or industrial residues used for energy generally do not increase land use, while some dedicated bioenergy (non-food) crops may be grown on marginal lands where annual food crops cannot grow. Even when current crop land is used, bioenergy production can stimulate rural development and lead to increased food security through income enhancement and general improvements in local infrastructure;

improvement of supply chain logistics and market access and improvement of food safety and health through better access to energy. Positive effects such as increased economic security for rural communities and improved farm and regional capacity for crop production are already demonstrated in the agriculture systems of developed and developing countries (Chapter 15, this volume). In the United States biofuel production from maize brought utilization of underused capacity, and stimulated the development of production capacity in other regions, while in Brazil bioethanol from sugarcane provided an opportunity to expand overall agricultural capacity. In both countries it helped to increase national energy independence (Chapters 10, 14, and 21, this volume; Boxes 4.1 and 4.5). Negative effects can occur for many reasons for example when decisions for biofuel crops were not well accompanied by agricultural adaptation (in case a new crop is not yet domesticated) and/or not followed by effective market infrastructure or governance, such as the premature commercial introduction of Jatropha in some African countries (von Maltitz et al. 2014; see also Box 4.2). In these cases local citizens were left with reduced food supplies, while energy crops did not produce the expected increases in revenues for those affected (Cotula et al. 2008; Gordon-Maclean et al. 2009; German et al. 2011). Also soil quality (including removal of nutrients, biological activity and issues related to water retention) has to be considered, especially when using residues. This has already led to standards and guidelines developed in the US for corn (Chapter 14, this volume) and sugarcane in South Africa (Meyer, 2010). Policy measures such as mandates can be used to create an initial market for bioenergy but should be considered carefully before implementation to ensure compatibility with food security, particularly in terms of avoiding local disruption of food supplies.

However, effective policy necessitates well-informed policy makers and public support for bioenergy promoting measures (Landeweerd, 2012a,b). The food versus fuel debate has greatly influenced decision makers and publics. Real concerns have sometimes been met with inappropriate generalizations and strongly emotive pictures by organizations that have positioned themselves against biofuels or bioenergy development (Rosillo-Calle and Johnson, 2010). This has negatively influenced public support. In a recent qualitative and quantitative study in The Netherlands, 75% of respondents were strongly in favor of sustainable development. However, while they had a positive association with the concept of using bioresources for all sorts of materials, they had a negative association with using biomass for energy and fuels (Van der Veen et al. 2013). Public engagement is shown to increase knowledge and improve development of informed opinions (Stirling 2008, 2012; Fiorino 1990). However, it is difficult to engage people in the complexity of sustainable development, climate change, food security and bioenergy. Investigating the role of emotions it was found that people react differently to different images. Four different emotional viewpoints to a transition to a biobased economy were identified. Figure 4.1 shows the pictures that gave positive and negative emotive reactions of ‘principled optimists’ (Sleenhoff et al. 2014). This may give some clues as to how to improve communication on these issues, but we also need more studies and insights into different cultural and global (ethical) viewpoints to use this to better engage publics.



People with this viewpoint are enthused, happy and optimistic about the production of bio-energy, -fuels and –plastics.

They are concerned, frustrated and angry about the idea that humanity will go bio-based at all costs.

Figure 4.1. Images give different emotional reactions to different people. Emotional reactions of 'principled optimists' to media released pictures (Sleenhoff et al. 2014).

Box 4.1. Sugarcane Ethanol and Brazilian Agricultural Development

Brazil is an example on how a country can increase its bioenergy production while increasing its food security. In fact the expansion of the agricultural production and yields in Brazil were partially derived from a better production environment in the rural sector, related to agronomic practices, availability of services and equipment and adoption of modern technology partially derived from the sugarcane sugar and ethanol sector.

This effect was not in sight when the fuel ethanol production was reinforced in Brazil. The basic driver to implement a large sugarcane ethanol program in Brazil in 1975 was to reduce the high energy dependence and the heavy economic burden resulting from oil imports (80% of domestic consumption). The 1st oil crisis in 1973 saw Brazilian oil imports increase to nearly 50% of all its imports creating a huge structural problem for the economy. Currently, sugarcane provides 17.5% of Brazilian primary energy supply (MME 2013).

The learning process verified through the production of sugarcane ethanol in Brazil notably during the 1975-2008 period (Goldemberg et al. 2008),

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was in great part resulting from the gains obtained in improving sugarcane agriculture. These gains were mainly derived from the introduction of new sugarcane varieties, better agricultural practices (such as vinasse and filter mud recycle), and good management. From 1975 to 2008 sugarcane yield grew from 46.8 to 77.5 tons/ha.year resulting in an ethanol cost decrease from US$ 1.20 to 0.38/liter (Lago et al. 2012).

Until the beginning of the '70s Brazil was fundamentally an exporter of coffee. Due to many factors, including synergies with the sugarcane ethanol program, the country became a large exporter of agricultural commodities, including grains (soybean, corn), meat (beef, poultry, and pork), pulp and paper, and orange juice while maintaining its leadership in coffee exports. Examples of synergies can be the development of more detailed soil maps, improvement of logistics, agricultural machinery, besides more qualified management skills in Brazilian agriculture.

The grain sector (CONAB 2013): in 1977/78 harvested soybean was 9.7 Mt, corn was 14.0 Mt, and total grains was 38.2 Mt; in 2012/13 harvested soybean was 81.5 Mt, corn was 81.0 Mt, and total grains are expected to be 196.6 Mt in 2013/14. Therefore, in the same period of analysis, while soybean production grew 740%, its planted area grew 272%. Corn production grew 478% and the planted area grew 39%. This shows an important gain in productivity (especially resulting from double cropping), and implies that a significant amount of land was saved as a result of productivity gains.

The meat sector (CONAB 2013): the same trend was observed. In 2006, 9.35 Mt of poultry was produced, 10.18 Mt of beef, 2.94 Mt of pork, and 1.05 Mt of fish, with 23.52 Mt of total meat production. In 2013, 13.27 Mt of poultry was produced, 8.92 Mt of beef, 3.55 Mt of pork, and 1.2 Mt of fish, with 26.94 Mt of total meat. In the last decades Brazil became the world's largest exporter of meat (beef, poultry and pork).

All together, according to SECEX/ABAG (2013), the Brazilian agribusiness sector was responsible for nearly US$ 100 billion in 2013 (nearly 40% of overall exports) helping the country to obtain positive surpluses in recent years. According to the Brasilian Institute of Geography and Statistics (IBGE), the total planted area in Brazil is 63,6 Mha (around 7,5 % of total area). The main crops in Brazil are soybean (24,9 Mha) and corn (14,2 Mha). Sugarcane is the third crop occupying a relatively small area in Brazil, around 9.4 million ha or 1.1% of Brazil's total area, divided nearly half for ethanol and half for sugar. It can be stated that Brazil became the largest exporter of sugar in the world mainly because of the existing synergies between the ethanol and sugar productions. The sugarcane sector in Brazil also contributes directly to the production of grains, mainly peanuts and soybean cultivated in the sugarcane reforming areas. (BNDES/CGEE 2008).

4.1.2 What is Food Security?

The Food and Agriculture Organization (FAO) defines food security as a condition that "exists when all people, at all times, have physical and economic *access* to sufficient, safe and *nutritious* food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Distinct components that can be used to analyze and monitor food security have been identified as: availability, access, utilization and stability. Food *in*security is closely related to poverty; fluctuations in international commodity markets, misguided foreign policies or actions; domestic policies undermining food production; poor infrastructure; degraded land; and especially civil conflict and war. In sections 4.2.2 and 4.2.3 we will assess bioenergy development in relation to the four components of food security and consider how positive impacts on food security might be promoted and negative impacts avoided.

4.1.3 Ethical Principles

Independent of the origin of energy, increased energy availability is often a necessary condition for improving food security (FAO, 2008a; FAO, 2008b). If expanded production and provision of bioenergy can help improve food security, and it is within our power and reasonable to do so, then it is prudent and just for nations in a position to help to stimulate such pathways to do so (EGE, 2008, Nuffield Council 2011).

Food is seen as a basic human right[1] and sustainability is considered as a general aim to provide for future generations [Brundlandt, 1987]. Both food security and sustainability have been defined by the European Group on Ethics (EGE 2008) and the Nuffield Council (2011) as ethical goals for which *responsible action is implied*. These goals and actions are based on notions of human dignity and a universal need for justice as conceived by these groups. The latter can be further divided into distributive justice (which guarantees the right to food on an equitable and fair basis); social justice (which protects the most disadvantaged in society); equal opportunities (which guarantee fair trade at national and international levels) and intergenerational justice (which safeguards the interests of future generations). The latest monitoring reports of the millennium and sustainability goals of the United Nations show decreased poverty and increased sustainable practices; however 1 in 8 people (0,9 B people) are still chronically hungry and increased population growth in developing countries (especially Africa) requires further efforts in sustainable energy production. Roughly 20-30 % of people with food insecurity (180-270 M) live in urban areas and are mainly affected by (high) food prices, but 70-80% (630-720 M) of food insecurity problems occur in rural areas where interaction with bioenergy can make a great difference (FAO, 2010; United Nations, 2010; FAO, IFAD and WFP, 2013).

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[1] derived from the International Covenant on Economic, Social and Cultural Rights (ICESCR), recognizing the "right to an adequate standard of living, including adequate food," as well as the "fundamental right to be free from hunger."

Box 4.2. Effects of Jatropha curcus on food security in Africa

Indigenous to central-south America, Jatropha was introduced to Africa a few centuries ago. Very suitable and suitable areas for the plant respectively cover 1.080 Mha and 580 Mha of the continent (Parsons 2005). It is currently widely distributed throughout these areas where rural inhabitants generally make extensive use of it. Because it is unpalatable to livestock, it is predominantly planted in rows around crops, and as wind and soil erosion barriers (Boccanfuso et al. 2013). These 'living fences' enable the time saved seeking suitable wood to make and maintain fences, to be spent tending crops.

Wide ranges of products are made from Jatropha bark, leaves and different parts of the fruit (Oppenshaw 2000; Parsons 2005). Oil from the seeds is used as a diesel substitute or blend in vehicles, pumps and generators; as a kerosene substitute in lamps; for making candles, etc. 'Press-cake'- the by-product from extracting oil from the hulls, and the shells are made into briquettes, used to generate biogas and/or applied as organic manure to cultivated areas. Mkoma and Mabiki (2012) reveal that the press cake is an excellent fertilizer. Money 'saved' from not having to buy, and made from selling Jatropha for bioenergy, household, medicinal and agricultural by-products, improves food security.

Since the new millennium, NGOs and private companies have actively encouraged Africans to plant more Jatropha hedges and to intercrop with it, as a rural development strategy. The strategy involves encouraging communities to form cooperatives to manage their own bioenergy and fertilizer provision. The NGOs variously (a) provide oil extraction machinery, electricity generators, alternators, milling machines and battery chargers, (b) help construct a mini-grid to distribute the electricity to the cooperatives' roads, households and water pumps, (c) distribute seeds/seedlings and (d) train people how to maintain the machines/ infrastructure, manage members to ensure a regular supply of Jatropha seeds, and derive an income from other Jatropha by-products. PAC (2009) and Boccanfuso et al. (2013) examined the Garolo Cooperative in Mali, and Angstreich and Jackson (2007) and Sawe (2013) examined many similar cooperatives in Tanzania facilitated by TaTEDO. They all concluded that Jatropha bioenergy (and by-products) derived, distributed and used in this manner would enhance food security.

Several companies (with or without land holdings) have successfully contracted independent small-scale Jatropha farmers to supply them with seeds, which are variously used to produce oil for blending with diesel and paraffin, fertilizer and briquettes. Research by Mitchell (2008), Gordon-

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Maclean et al. (2009), van Eijck (2009), and Sawe (2013) showed that small-scale Jatropha farmers contracted to sell their seeds to Diligent in Tanzania became more food secure. It must be noted, however, that large-scale markets for seeds are often dependent on government policies for using jatropha oil in the transport sector; if these policies are inconsistent or undeveloped, the market for seeds may disappear and disadvantage small-scale farmers that invested in jatropha (German et al. 2011).

Other companies acquired land for large-scale commercial Jatropha plantations with the intent to produce biodiesel for national and export use. Plantation-style jatropha has proven to be very difficult to make into a commercial crop, which is perhaps not surprising when considering the relatively short period of domestication thus far (van Eijk et al. 2012; von Maltitz et al. 2014). Nevertheless, as of 2008, plantations accounted for 11% of Africa's Jatropha production (Boccanfuso et al. 2013). Plantation-style jatropha in African countries is likely to be more constrained in the future based on such experiences in combination with better project screening and the implementation of certification processes.

4.1.4 What has changed? - Emerging Evidence on Bioenergy and Food Security

In the last five years several developments have brought a new perspective on the relation between bioenergy and food security. In the second half of 2008 and the start of 2009, the vast majority of reports in the literature considered the interaction between food and bioenergy in a negative context (SCOPE 2009). For instance, this previous SCOPE report stated (page 77): "The use of food crop species to produce biofuels will remain problematic as the world struggles to increase food production to better feed an increasing population that currently includes roughly 1 billion who are severely underfed. Special energy crops are not an effective way to avoid competition with food production, because they too require land, water, nutrients, and other inputs and thus compete with food production." Since then, however, substantial new understandings have developed. In particular:

- Although biofuels policies create new sources of demand for agricultural products, this is also true for supply. Production of biofuels from grain crops, therefore, has clear potential to lower price spikes associated to supply shocks (Wright, 2011; Locke et al. 2013), and likely did so in the US during the drought of 2012.
- Africa has potential to meet both its food and fuel needs from biomass, neither of which occurs today. "In particular, biofuel production could help unlock Southern Africa's latent potential and positively increase food production if it brings investment in land, infrastructure, and human resources." (Diaz-Chavez, 2010; GSB, 2010).

- As pointed out by Lynd and Woods: “Consideration of the impact of bioenergy on African food security has tended to focus on land competition and to overlook bioenergy’s marked potential to promote rural economic development. Yet potentially productive land is plentiful in Africa whereas lack of rural development is the most important cause of hunger.” (Chapter 9, this volume; Lynd and Woods 2011).
- A study of 15 small bioenergy initiatives in developing countries found that production of staple foods did not appear to be affected (PAC 2009).
- Estimates of the magnitude of land clearing resulting from indirect land use change (iLUC) have greatly decreased for bioenergy feedstocks grown on cropland, and are likely yet lower for bioenergy grown on converted pastureland. In practice the growth of biofuels has been accompanied by increased food availability worldwide. Whereas the magnitude of estimated iLUC effects was formerly thought to be large enough to negate the GHG emission benefits of an otherwise low-emitting biomass-based fuel supply chain, this is no longer the case. (Chapter 17, this volume).
- Currently, pasture land makes a small contribution to global supplies of dietary protein and calories (Chapter 9, this volume). The intensification potential of pasture land in some locations may be much simpler and offer comparatively greater benefits than cropland (Sheehan et al. in review). Consistent with this, most of the 673 million hectares seen as available for bioenergy production by the World Wildlife Fund (2011) is on land currently being used for low-intensity grazing.
- There is clear potential to grow bioenergy feedstocks on land that is not suited to produce annual food crops (Somerville et al. 2010, see also Chapter 9, this volume).
- Dale et al. (2013) note the importance of integrated landscape approaches to the production of food, feed, fuel and fiber. A landscape perspective allows identification of valuable synergies in water, nutrients and co-products that can improve overall land productivity while also promoting healthier ecosystems.
- A detailed comparison of five global agroeconomic models by Lotze-Campen et al. (2014) found the impact of high demand (108 EJ by 2050) for second generation (lignocellulose-based) feedstocks on global food prices to be modest. For all but one of the models, changes in the amount of cropland are relatively small and currently unmanaged land is by far the largest land category used for traditional bioenergy production.

The results above do not imply that bioenergy cannot or will not have negative impacts on food security. Rather they imply that bioenergy need not necessarily have such negative impacts, and, for many of the studies, that net positive impacts on food security are possible. Consistent with this, several substantial studies (Rosillo-Calle and Johnson 2010; Achterbosch et al. 2013; Hamelinck, 2013) support a nuanced view in which the impact of bioenergy on food security can be positive or negative depending on how it is implemented and the local circumstances, and net benefits to food security can be achieved with strong governance and policy support.

4.1.5 Background and Preconditions

This chapter is based on the premise that there is enough arable land available in principle to feed the expected world population for the foreseeable future (2035-2050) *and* provide for a substantial part of energy through biomass utilization, as developed in Chapter 9, this volume. In principle, since there seems to be enough land available for both food/feed demands as well as bioenergy demand, we could continue to use traditional food crops for bioenergy to some extent. However, good land management is crucial while opportunities to improve conditions of marginal, low productivity lands by adapted (energy) crops should where possible, be considered. In addition, we should optimize integrated biorefinery designs and reduce and use wastes and residues for bioenergy (Chapter 12, this volume), while addressing long term soil quality through recycling of nutrients (Chapter 18, this volume). To compensate for this additional growth in resource use, we should intensify the use of low productivity pasture land and make use of (part of) the available area of pasture, which is estimated to be around 900 Mha, for multipurpose agriculture (Chapter 9, this volume).

Uneven distribution and various comparative advantages in food production require appropriate distribution through trade, good governance and supportive policy measures to avoid food insecurity. Yield increases and appropriate land management are necessary (Chapter 10, this volume). This demands special attention, while also being indicative of opportunities, in developing countries where yields are presently poor. Chapter 20, this volume, on Economics and Policy shows that there is no direct causal relation between food security and bioenergy production. Social development could be stimulated by local bioenergy production (Chapter 15, this volume), leading to the conclusion that the production of bioenergy, where appropriate applications have been chosen and are well managed, can be beneficial for food security.

With proper management, bioenergy expansion can increase local rural development, providing jobs more effectively and/or at lower costs, which increases income and education. For example labor use efficiency can be improved through additional harvests for bioenergy production during the year. Biofuel industry can improve food chains and (local) infrastructure. These are all factors with a positive impact on food access for the poor (Landeweerd et al. 2012b; Moraes 2011). The trade-off here is that with mechanization and loss of economic opportunities the rural population tends to migrate to urban centers. Such a shift could have great consequences, if urban societies do not provide income opportunities, as food security in urban areas is mainly affected by food price. Other measures are required to alleviate food insecurity in urban poor communities where incomes do not grow adequately.

4.2 Key Findings

4.2.1 Food Security, Bioenergy, Land Availability and Biomass Resources

4.2.1.1 Increasing Crop Production versus Increased Demand for Primary Foodstuffs

FAO (1996) defined food security as “all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life”. A first order requirement to have the potential to realize this definition is that the amount of primary food and feedstuffs that is produced equals or exceeds demand. The world’s major crops saw year on year increases in yield per hectare for most of the last half of the 20th Century, leading to surpluses and declines in cost in real terms (FAO 2006b). Although significant proportions of the populations were malnourished, this was not only a problem of production, but also of downstream factors and disposable income. However, the projected rate of increase in global demand (2.4% per year) may now be outstripping these increases in production. The low productivity growth could be induced by the long period of declining real food prices that did not provide an incentive to invest in technological change and led to an underinvestment in public agricultural R&D (Banse et al. 2008). Increasing food prices could reverse this trend. Furthermore, yield gaps around the world and especially in developing countries remain high and allow for catching up and increasing yields especially in developing countries where food security is a problem. The increase in demand is due not only to a rising population, but also to changes in the global average diet driven by urbanization, higher incomes (especially in Asia), and policy choices in some countries (Foley et al. 2011). If this leads to increasing costs of primary foodstuffs in real terms, it will affect economic access for the world’s poorest, and will arguably be a factor in increasing social unrest (Hsiang et al. 2011; Otto et al. 2009).

Maize, rice, wheat, and soybean currently provide nearly two-thirds of global agricultural calories (Rao et al. 2012a,b). A global analysis showed that yields of these crops are increasing at 1.6%, 1.0%, 0.9%, and 1.3% per year, non-compounding, respectively, which is less than the 2.4% per year rate required to double global production by 2050. It has been projected that if historical rates of yield improvement are maintained through 2050, then demand will outstrip production by 30% or just over 1 billion metric tons of these four key primary foodstuffs. Meeting this demand would require recruitment of an additional 130 - 219 Mha, unless we can either improve on historical rates of yield improvement in yield per hectare (Alexandratos and Bruinsma 2012; Ray et al. 2012) or be capable of producing two crops in the same harvesting season. There are positive examples. In Brazil double cropping of soybean and maize has increased significantly in response to improved prices, increasing yields without increasing land use. The demand for land will be less if price induced innovation occurs as real food prices will increase. This has occurred in the Black Sea region in recent years, which has now become a major feed grain, vegetable oil and wheat export region. Yield-gaps might be closed more rapidly due to higher prices or public/private investment in agricultural R&D and when food prices are back on the political agenda. However, the capacity to increase yield, even at historical rates of improvement might be questioned, especially in regions where yield is already high, or where other factors hinder yield improvements. While maize, and also sugarcane yields continue to increase (Chapter 10, this volume), rates of improvement in rice have declined and stalled in wheat (Long and Ort, 2010; Ray et al. 2012). This may be attributed to the fact that the genetic approaches to improving yield potential in these crops can be shown to be reaching their biological limits (Long and Ort, 2010). One option to increase worldwide production is to make more intensive, high input use of extensive areas of arable land in Africa where yields are far from potential in all farming regions. Batidzirai et al. (2006) predicted a seven-fold increase in Mozambique's productivity with moderate use of agricultural technologies, such as fertilizers, pesticides, selected seeds, and large-scale harvesting practices. Bekunda et al. (2009) note how the use of fertilizers, improved seeds and extensive agricultural extension have doubled and even tripled cereal crop yields at local levels in 10 African countries. In addition, bioenergy could help develop better storage and food conservation, avoiding post-harvest losses (Chapter 21, this volume).

There are new prospects for increasing the yields of these crops, but they require the use and acceptance of genetic engineering (Zhu et al. 2010), which as shown in Chapter 10, this volume, have contributed significantly to yield improvement in maize over the last decade. As a first approximation it would appear that diversion of these primary foodstuffs to biofuel would exacerbate price and pressure to clear land. However, the experience of maize ethanol in the USA over the past 10 years should cause a reconsideration (Chapter 10, this volume). Maize in this region, unlike the other primary foodstuffs, has seen a 30% increase in yield per hectare, which was likely (at least in part) supported by this additional market (Box 4.3). Further, in the 2012 drought, additional land planted to corn provided a buffer to shortages and grain was diverted away from ethanol production (Chapter 10, this volume). As discussed in Chapter 10, this volume, this increase has been sufficient to not only offset all the grain diverted into ethanol production, but also allowed an increase in exports and sales to other markets. Other adjustments independent of biofuel use have also contributed to sustaining adequate feed grain supplies. In particular, growth in poultry and pork consumption compared to beef has resulted in less grain being used per kg of meat production. So while this diversion has undoubtedly had some impact on price it also stimulated modifications in US renewable fuel policy. Increased production has also increased residue in high yielding fields, which can be diverted into cellulosic fuel production, which stimulates additional investment in yield improvement.

Box 4.3. Use of maize for ethanol in the US helping food security

Having major food and feed crops produced in diverse regions of the world helps increase food security by buffering the risk of adverse weather and other events on the stability of supply. Increasing the value of major crops leads to temporary increases in price, but also greater investment in technology and infrastructure. In response, depending on demand, prices decline as investments and development increase supply. The decision of the US Congress in 2004 and 2007 to mandate the use of ethanol in transportation fuels in the US increased domestic demand for maize, often produced in large surpluses. Approximately 40% of the US maize crop is now used for this purpose. In turn, this newly significant demand influenced the rise in the price of maize. Other factors influencing price simultaneously were increases in the price of oil relative to maize, and rising demand for soybeans from China produced from the same land (FAO, IFAD and WFP 2013). In response, over the period 2007 to 2013, approximately 4 M ha additional land was planted to maize in the US, diverted from other crops and acres released from land reserves. Maize price rose during this same period. In 2012, an exceptional drought occurred in the primary US maize growing region and average expected yields fell by approximately 30%. Since the US is the major exporter of maize, this was an important event, potentially, for food security. As US domestic demand for maize increased, adjustments were occurring elsewhere. Maize production expanded modestly in areas of the US outside the upper Midwest, to areas less affected by drought. More importantly, maize production and exports increased during this same period from Argentina and Brazil and the Black Sea region, reducing the worldwide effects of the US drought on supply. Additional supplies from these regions, as in the US, were met by increased productivity (double cropping in Brazil, yield increases in the Black Sea region and the US) and some area expansion. Expanded capacity for maize arguably leads to similar improvements in other commodities, and in generally beneficial infrastructure development, for example in grain handling and logistics, and agricultural intensification. This increases stability of the food system against perturbations from local weather events and longer-term climate change, local policy changes or disruptions, access and availability of food, and prosperity in rural areas producing more crops throughout the world. (Tyner 2013; Taheripour et al. 2013). This positive view of crop use for biofuels depends on prudent policies which also encourage other feedstock sources, and reasonable limits on maize use. GHG limits on biofuel emissions arguably act to limit maize use, but limits to mandates do as well. In the US, long-term surplus supplies were absorbed by ethanol production with positive regional and national effects, and productivity increases and shifts in meat consumption patterns from beef towards poultry and pork (both domestically and internationally) have contributed to supply during the ethanol expansion period.

4.2.1.2 Global Change

Three elements of global change affect food crop production and interact with bioenergy namely: climate change (temperature and soil moisture), atmospheric change (rising CO_2 and tropospheric ozone), and land degradation (salinization, desertification, fertility loss). IPCC (2014) asserts that the median of studies indicate that climate change will cause a 0 to -2.5% decline in maize and wheat yields per decade and none in rice and soybean. This appears small in relation to historic rates of yield improvement per decade in these crops. But there are several caveats in relation to a range of extreme events that may on balance become more common, like extreme weather events and adverse altered pest and disease incidence. Tropospheric ozone, which is today some ten times pre-industrial levels, is already estimated to cause yield losses of around 10% in these crops and levels may increase by increasing temperatures and nitrogen oxide emissions, especially in SE Asia. By contrast empirical field scale enrichment of CO_2 to anticipated 2050 levels increased the yield of rice, wheat and soybean (C3 crops) by about 15%, but did not affect maize (C4) yield (Long et al. 2006; Ainsworth et al. 2008). About 607 Mha of farm land worldwide has become so degraded that it is no longer farmed. Not only can degraded and marginal land be used for bioenergy feedstock production, but by doing so, the land can be rehabilitated and improved. Simpson et al. (2009) describe how for example switchgrass improves soil quality and productivity, but grasses in general are restorative in many circumstances, including where salinity is a problem. Chapter 16, this volume, provides an overview of the positive and negative effects of growing crops on degraded land, which concludes that few positive influences on biodiversity and ecosystem services result from biofuels development. Such positive outcomes are of limited spatial and taxonomic scale. Biofuels-mediated improvements might occur when already degraded lands are rehabilitated with non-native feedstocks, but such changes in habitat structure and ecosystem function support few and mostly common species of native flora and fauna. Even the limited evidence of perennial grass crops favoring certain bird species indicates the requirement of special management regimes.

Tufekcioglu et al. (2003 cited in UNEP, 2009) note that switchgrass’ below ground biomass can be eight times higher than the above ground biomass and that it produces 55% more total soil organic carbon than corn/soy bean over two rotations. Hendricks and Bushnell (2008) list several halophytic crops that thrive in soils degraded by salinization. They could be used as bioenergy feedstock while removing the excess salt from the soil by allowing improved water infiltration resulting in salt removal from the root zone (leaching) and rendering it suitable for food crops again. There is a limit, though, since recovery in biomass is not quantitatively significant when lands are seriously salt-affected. A considerable area of land (ca 25 Mha) has also been degraded by industrial and mining activities and is contaminated with heavy metals (Haferburg and Kothe, 2012). Crops such as willow that absorb these pollutants can be grown for bioenergy rendering the soils suitable for food crops or grazing again (FAO/UNEP 2011). In addition to improving the soil/land resource, Lynd and Woods (2011) argue that use of such land for the production of bioenergy from non-food crops can have numerous positive impacts, particularly through introduction of technologies useful for food production, local job creation, enhanced energy self-sufficiency, improved food security and economic status that reduces conflict.

Overall, global change will have negative impacts and the expansion of bioenergy will certainly contribute to the development of new technologies for local and regional adaptation to climate change, potentially opening up other agricultural development pathways.

4.2.1.3 Land and Water Availability

In order to achieve 2050 food and feed consumption projections (above), based on the most recent FAO studies (Alexandratos and Bruinsma, 2012; Conforti, 2011), water and land will not be major constraints at global level. Projections for 2050 indicate a growth of 60 % on agricultural output over the levels of 2005/07, distributed as following: 89 % for oil crops (133 Mton oil equivalent), 76% for meats (197 Mton), 75% for sugar crops (146 Mton sugar equivalent) and 46% for cereals (941 Mton).

As specified in Chapter 9, this volume, according to Alexandratos and Bruinsma (2012) this output increase would require an additional 130 Mha. More aggressive projections on demand indicate a larger additional land requirement: 219 Mha assuming that historical levels of improvement of yield per unit land area continue (Ray et al. 2012). Around 90 % of the 130 million will be met by Latin America and Sub-Sahara Africa, while developed countries will be responsible for the majority of the land decline (estimated as 63 Mha). Out of the 130 Mha increase, FAO (2012) is projecting 19 Mha additional irrigated lands, which is a 6 % increase compared to the 2005/07 level. FAO projections are focused mainly in meeting food and feed demand. A very conservative scenario of diversion of these crops into biofuels was assumed. Therefore, projected land demand in this FAO analysis is driven mainly by food and feed markets.

FAO also estimates that 34% percent of total world surface is “to some extent” prime and good land for rain fed agriculture (4,5 Bha). Of this area, 1,26 Bha is already in crop production and 1,8 Bha is forest, protected areas or urban. This leaves an apparent 1.4 Bha that could be used in principle for crop production. About 26% of this land is Latin America, 32% in Sub-Sahara Africa and most of the remainder in Europe, Oceania, Canada and the USA.

The projected 130 to 219 Mha expansion needed for 2050, therefore, will not face constraints in terms of overal land availability. Water availability does not appear to be a limiting factor at the global level for this needed agricultural expansion, although there are regions that face strong water shortages. One uncertainty is around the water required to support more productive crops in the future. Although, continuation of the historical rates of yield increase is assumed, water use efficiency has remained unchanged, for example if yield is increased 1% per year, so may be water use. On the other hand, improvements in harvest index, agronomy, pest management, land quality and irrigation technology not only correlate with better yields, but also improve efficiency in irrigation water use. However, it may mean that some areas classified as suitable for rainfed agriculture by FAO might in the future require some irrigation to support the improved yield potential.

Irrigated agriculture is expected to expand less than in the past. FAO (2012) projects a net increase of 19 Mha by 2050 from a total of 300 Mha irrigated today 'While the small increases projected for Latin America and Sub-Saharan Africa (<4%) appear sustainable, those for E & N Africa and S. Asia (52% and 40%) do not, based on FAO estimates. Where unsustainable use of irrigation, causing salinization, in poor communities is driven by the need to generate a livelihood, bioenergy crops that do not require irrigation or that can tolerate salinity (see Chapter 10, this volume for examples) could provide more sustainable livelihoods in these particular locations.

In general, at global level, land is not a constraint but availability is concentrated in two main regions.

4.2.2 Interplay between Bioenergy and Food Security

4.2.2.1 Analysis of Food Security in the Bioenergy Context

How can bioenergy be produced within the context of increasing food security? The food crisis of 2007-08 led to the re-emergence of the old food-versus-fuel debate, raising concerns about biofuels competing with food security (Sagar and Kartha, 2007). Biofuel and bioenergy use can increase pressure on the global demand for biomass unless a commensurate supply response is initiated. A clear distinction was noted, however, between highly productive crops and applications, particularly sugarcane ethanol in Brazil, vs. the relatively inefficient production of biodiesel from soy and rapeseed (Rosillo-Calle and Johnson, 2010). Some empirical studies suggest that biofuels contributed to 10-15% of food prices increases. This is in direct contrast to previous studies (Mitchell, 2008; World Bank President, Robert Zoellick, NPR, 2008; Rosegrant et al. 2006) which had stated a much higher impact on food prices arising from the conventional biofuel programs of Brazil, USA, EU and others, e.g. up to 75% of the 2008 increase in food prices. However, analysis on observed data has not identified an impact at these levels. Figure 4.2 projects the estimated price impacts based on different scenarios for 2020 and 2030.

Recent econometric evidence by Baffles and Dennis (2013) found that oil prices were the main driver of the higher food prices. Van Ittersum (2011) suggests that agricultural output will need to triple between 2010 and 2050, if global agricultural biomass were to deliver 10 per cent of global energy use by 2050. More fundamental objections to increased demand for biomass for energy are voiced by Krausmann et al. (2013) who state that with a 250 EJ/y bioenergy scenario, by 2050 HANPP[2] would increase from 27-29% to 44% and they caution against a further increase. Higher *food prices* are in general considered as negative for food security in poor urban regions and therefore bioenergy and especially biofuels from food crops has become unpopular, particularly where government policy apparently

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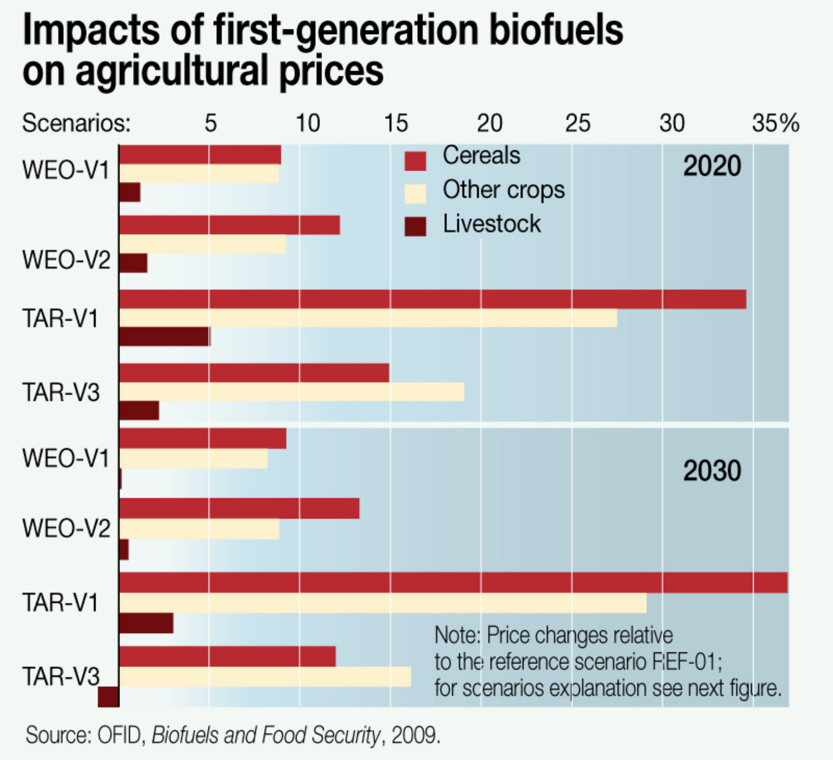
[2] Human appropriation of net primary productivity



Note: Price changes relative to the reference scenario REF-01; for scenarios explanation see next figure.

Source: OFID, *Biofuels and Food Security*, 2009.

Figure 4.2. Impacts of conventional biofuel production on agricultural prices in different scenarios (UNEP GRID Arendal 2011).

directly stimulates markets. However, the analysis is not so simple, for example higher food prices might also lead to higher farm income in poor rural areas, with subsequent investments in the agricultural system leading to higher food security over the long run (Achterbosch, et al. 2013). Direct and indirect or more dynamic effects might have different impacts on food security over various time-scales. The FAO has divided the analysis and monitoring of food security into four categories (FAO 2006b):

1. *Availability* of sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid). Available land and food production play an important role.
2. *Access* by individuals to adequate resources for acquiring appropriate foods for a nutritious diet. Here, land, income, infrastructure, conflicts and consumer prices play an important role.
3. *Utilization:* Utilization of food through adequate diet, clean water, sanitation and health care to reach a state of nutritional well-being where all physiological needs

are met. Storage, infrastructure, income and local consumer food prices play an important role.

4. *Stability:* To be food secure, a population, household or individual must have access to adequate food at all times. Macro-economic conditions play an important role in stability.

4.2.2.2 Availability

The production of biomass for bioenergy affects the goal of availability dimension of food security in several ways. A direct effect is through land use: if agricultural land is used for the production of biomass for bioenergy, it is no longer available for food production, and thus in principle, it negatively affects food production. While (global) land availability has been shown to not be a constraint, local availability may become an issue. Double cropping, reduction in fallow periods, and complimentary crop-shifting within cropping systems help counteract or eliminate these effects. This has occurred in some regions in soy, maize and sugarcane production. The availability question is more complex than the food versus fuel debate suggests. For example, in Brazilian tropical agriculture, second crops are becoming more and more important. Very large areas are grown with soybean followed by corn in the same year. Both crops can be used either for food or biofuel, but the amount of land is the same as if it was only one crop for only one use. Rising prices, in turn, may lead certain producers to grow more food, until a new equilibrium is found. The dynamic effects are initiated by the higher farm prices and increased income that facilities investments in irrigation, better varieties, fertilizer, education and increased efficiency. All these investments increase food production and food availability. The increased availability of high quality energy sources also has a positive effect on agricultural production, especially in areas where there is energy poverty. The expansion of agro-industries can offer a low-cost energy feedstock in the form of wastes or residues, together with enhanced agricultural system performance, thereby addressing both energy access and food security (see Chapter 21, this volume). Another important way to obtain synergies is through implementing integrated food-energy systems, which offer valuable climate benefits alongside their economic benefits (Bogdanski, 2012).

4.2.2.3 Access

Access refers to the relationship between food prices and disposable income, but also to access to land and other natural resources for subsistence or smaller-scale producers, where resources are used to generate income, provide energy services or food. Prices play a role in that food may be available, but too expensive for poor households to purchase in sufficient quantities. Any additional income generated by bioenergy production raises the purchasing power of the household, and also results in a lower share of food costs in household expenditures. Where bioenergy production is organized at small-scale and/or household-level, the access benefits could accrue directly. However, where bioenergy is led by large companies, such as sugarcane in Brazil, the costs and benefits will differ, depending on the degree of mechanization and the extent to which displacement of small farmers occurs. To some extent these shifts are a basic feature of industrializing societies and are not closely related to bioenergy *per se*.

The impact on food access for farmers and land owners will be negatively affected by the higher food prices and positively by their higher income. Bioenergy will have a negative effect on food access for consumers that do not increase their income from bioenergy production if they do not share in increased prosperity. These effects are clearly different for the urban poor and the rural poor (that are farmers). Carefully designed and implemented policy measures are needed to avoid the adverse effects of food price shocks. In addition to feedstock diversification and safety nets for the most vulnerable, a certain level of flexibility will thus be needed in bioenergy policies to respond to food supply disruptions or price shocks. The need for such policies is not restricted only to the case of bioenergy production from land.

4.2.2.4 Utilization

Utilization refers to what kind of food people consume; quality and diversity is an important nutritional concern. This also relates to prices and income, but other factors, such as health care, access to clean water, education, knowledge about nutrition etc., are important as well. There is a weak link between bioenergy and utilization. An important health issue might be the ‘switching’ from the use of traditional low quality fuels and inefficient and unhealthy cooking and heating devices which lead to indoor pollution at rates that result in the mortality of nearly 4 million women and young children prematurely every year (Bruce et al. 2006; Conway 2012; Chapter 15, this volume). Modern small-scale bioenergy technologies such as advanced/efficient cook stoves, biogas for cooking and village electrification, biomass gasifiers and bagasse based co-generation systems for decentralized power generation, and energy for (clean) water pumping, can provide energy for rural communities with energy services that also promote rural development (IEA 2013; Woods 2006; Chapter 15, this volume). Such improved systems could increase food safety (by avoiding microtoxins and aflotoxins through better prepared and stored food)(PAC 2009). Another perspective that is valuable for utilization is that of landscape ecology, in which integrated management methods can improve diversity and resilience (Dale et al. 2013).

4.2.2.5 Stability and Resilience

Stability refers to the fact that “a population, household or individual must have access to adequate food at all times. They should not risk losing access to food as a consequence of sudden shocks from weather or social factors or chronic economic and social conditions.” (FAO 2006a). An improvement in the *functioning of markets* leads to more stability (Achterbosch et al. 2013). Policy corrections can help to restore the imbalance in supply and demand when crops are used for biofuels, such as illustrated in Thailand for palm oil (Box 4.4). Markets are closely related to prices and income as well. They determine food and biofuel prices, and consequently household incomes. It is important to understand how markets can contribute to a stable household income, allowing a stable access to food and good quality nutrition. Three ways in which households can achieve this have been identified: inclusion into value chains, opportunities of small to medium enterprises (SMEs) and local value adding. In general, producing biomass and fuels for the energy market in addition to the food market diversifies revenue sources for the agricultural sector and from a portfolio and risk point of view this might reduce risk and increase income. Whenever the food market is weak (low prices) for farmers they can sell more to the energy market. Producing energy locally might also increase energy self-sufficiency, which might increase resilience when energy markets get tight. This occurred in the developed market of the United States, where commodity use for bioenergy helped to significantly increase rural incomes. Assato and Moraes (2011) also noted that jobs generated by the expansion of the sugarcane industry in Brazil and related sectors have played a key role in reducing rural migration. (Chapter 15, this volume). Similarly, Satolo and Bacchi (2013) assessed the effects of the sugarcane sector expansion over municipal per capita GDP, noting that the GDP for one municipality and that of its satellite neighbors grew from 24% in 2000 to 55% in 2010. (Chapter 15, this volume). A simplified relation of food prices to bioenergy is illustrated in Figure 4.3.

Biofuel developments may contribute to an overall improvement in *macroeconomic performance* and living standards because biofuels production may generate growth (i.e., multiplier or spill-over effects) to the rest of the economy. This might benefit both the urban and rural poor. Improving the investment climate is crucial: achieving these growth linkages

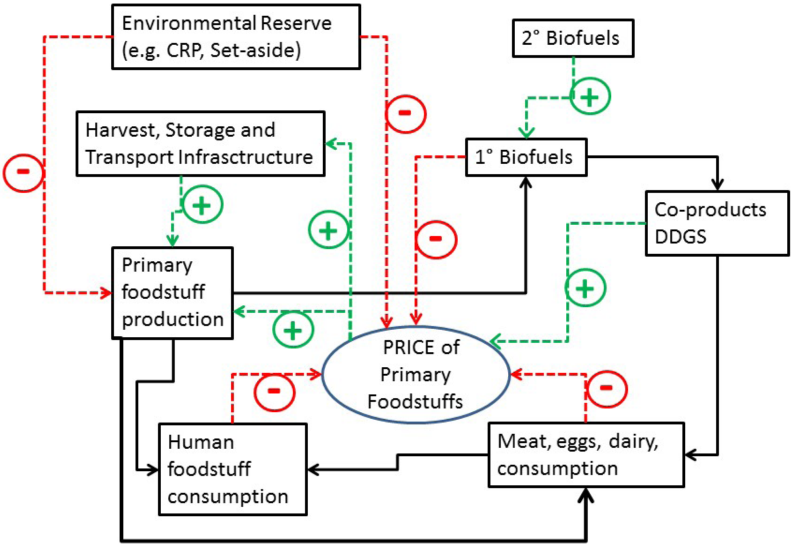


Figure 4.3. Simplified relation of food prices to bioenergy. Black lines show flow of material. Green + dotted lines show an effect that promotes production and investment, and decreases price through increased supply. Red - lines show factors that depress production or increase price, by decreasing amounts available for human consumption.

requires strict control and governance of the proposed biomass investment; only then can the stability dimension of food security be addressed (Achterbosch et al. 2013). It is important to ensure that the investment strengthens the rural economy and that the local population benefits from additional economic activity, value retention and employment. Four issues can facilitate this. First, investments in biomass production for bioenergy may have spill-over effects that benefit food production. Second, enabling government policies need to be in place to ensure biomass production for bioenergy benefit rural communities. Third, farmers' organizations may play an important role in this, ensuring equity and good extension. Finally, land tenure rules need to be in place to ensure that rural communities continue to have access to land for their livelihoods or are adequately compensated for their land.

Box 4.4. Food and energy competition for crude palm oil in Thailand[3]

Thailand has increased the share of alternative and renewable energy from 0.5% of final energy in 2005 to 11% in 2013 (www.dede.go.th); the ten-year National Alternative Energy Development Plan (AEDP 2012-2021) now aims to increase that share to 25% by 2021 (DEDE 2012). Targets of 9 and 7.2 million liters per day have been established for ethanol and biodiesel, respectively. Competition between food and energy arose for crude palm oil (CPO); its use for B5 blends resulted in a price increase of over 30% in 2011. There were shortages of cooking oil, its price rose by over 50% and household purchase was rationed. Corrective measures were applied to restore the balance between domestic and transport demand, including international trade with Malaysia, flexibility in the blending ratio and maintaining buffer stocks. There has also been some concern about the effects of the oil palm expansion on the indigenous rice cultivation, and only a small project has been done to evaluate such effects and determine how they can be mitigated. An agricultural zoning policy has also been launched to address productivity issues and ecological impacts related to palm oil and other crops.

4.2.3 Causal Linkages: Bioenergy, Rural Agricultural Development and Food Security

Bioenergy development need not become a zero sum game for land use that results in either energy or food. Poverty and hunger predominantly result from inadequate supplies of food and from a lack of income. The majority of the rural poor depend on farming and grazing, many poor use a large portion of their income for food. Increased income among

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[3] Information provided by Aparat Mahakhant, Thailand Institute of Scientific and Technological Research (TISTR), 35 Mu 3, Khlong 5, Khlong Luang, Pathum Thani 12120,Thailand. E-mail: aparat@tistr.or.th

rural poor reduces food insecurity, as does increased food production. Where farming is possible, bioenergy production can stimulate rural development broadly and result in increased food security by improving rural incomes. Agricultural industries support larger numbers of jobs than many other types per unit of investment capital, and development in the agricultural sector is especially productive of jobs and income growth in the poorest regions and countries (Cervantes-Godoy and Dewbre 2010).

Rural development initiates a process of sustainable intensification of land use in which the production potential of the landscape is more closely approached, and new, previously unanticipated or constrained agricultural enterprises evolve. Increasing capacity for food production has characterized the agriculture of developed nations, and is reflected in more recent case studies (Brazilian case study and others, see Chapter 14, this volume). Potential positive and negative effects from locally optimal biomass energy projects are identified in their relation to causes of food insecurity in Table 4.1.

Poorly conceived or developed bioenergy projects may have adverse effects on rural populations and landscapes as well. Bioenergy is not necessarily universally prudent. The most obvious concerns are exploitive, unsustainable land use and/or the creation of extractive businesses aimed primarily at exports, which may offer few advantages for rural populations other than additional cash income. Metrics and indicators of food security are not necessarily the same as the underlying causes of food insecurity. Thurow and Kilman (2009) identify the following key causes: poverty; local food production being undermined by cheaper subsidized imports; poorly developed infrastructure (physical, institutional, and human); degraded land; conflict and instability; and loss of access to land (Figure 4.4). Commentary on each of these causative factors is presented in Table 4.1.

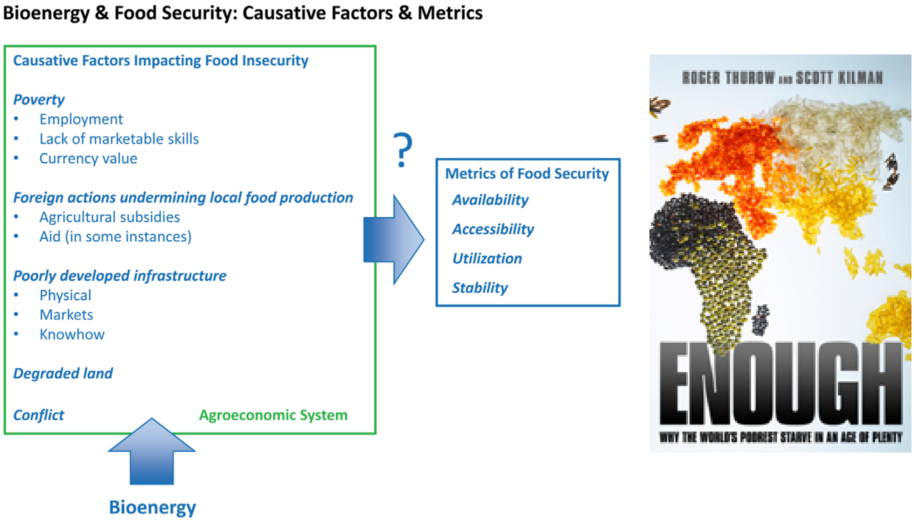

Figure 4.4. Causative factors impacting food insecurity (Thurow and Kilman 2009).

Table 4.1. Potential impacts of bioenergy expansion to food security dimensions.

Causes of Food Insecurity			**Value maximization strategies**
	Positive	**Negative**	
Poverty			
Lack of employment and income	Substantial job creation, stimulation of rural development and market economy	Labor force could be drawn away from food production at critical times. Bioenergy development can be done without local employment benefits	Emphasize local employment, products using local materials and methods of distributing benefits
Lack of saleable products	New markets for producers	Lost opportunities (see loss of land access)	Local equity in bioenergy systems as well as feedstock production
Lack of marketable skills, underdeveloped human capital	Opportunities to learn improved agricultural skills and other forms of human development	Labor becomes indentured (in the case of large or medium-scale estates)	Education, extension
Low currency value (higher priced imported goods)	Improved buying power if energy imports are meaningfully reduced	Bioenergy (fuels) produced by foreign companies for export only	Some caution should be taken with foreign investment that is intended only for foreign markets (land grabbing effects), however, there is a time dimension: if the country has no blending policy or technical infrastructure then it should be perfectly ok to export and then use the new agro-industrial capacity to start up national policies for domestic use
High food prices	Increased resilience --> less price volatility	If good land is scarce, devoting land to bioenergy reduces food supply and increases prices (positive for producers), negative for consumers)	Agricultural development and sustainable intensification Use land of little agricultural value for energy production For those countries that have fossil fuel subsidies, make revenue-neutral shift to food subsidies for the poor

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Causes of Food Insecurity			Value maximization strategies
	Positive	Negative	
Loss of Access to Land	Employment income mitigates need to grow food	Bioenergy concentrates good land in a few hands, rural poor shifted to marginal lands Displaced persons have their livelihood affected	Land tenure for rural poor must be recognized Land registry systems to avoid inequitable transfers of land Promote economic development in rural areas
Local food and feed production undermined by cheaper, subsidized imports	Energy production and agricultural development are less disadvantaged by subsidized imports compared to food	Improved storage opportunities by energy access further reduces incentive to locally produce food	Subsidized food production from exporting countries should be eliminated
Poorly developed infrastructure (physical, institutional, and human)	Bioenergy can be a major catalyst for development of agricultural infrastructure and formalization of the economy	Diversion of resources to bioenergy from other needed infrastructure development	Maximize local benefits - e.g. electrification, food processing, district heating and cooling
Degraded or marginal land	Perennials have potential to enhance fertility and improve soil structure and reclaim salt-affected soils New income opportunities from previously unused land	Soil and other resource exploitation and further degradation	Use perennial feedstocks Sustainable crop and crop-livestock systems Incentives for using degraded lands, with attached socio-economic conditions (to avoid displacing farmers without compensation)
Conflict and instability	Added income, markets, development, trade and stability reduce causes of conflict	Exploitive bioenergy deployment could exacerbate causes of conflict	See above

The presence of both positive and negative impacts of bioenergy on each of the causative factors listed in Table 4.1 is consistent with the emergence of a nuanced understanding of bioenergy and food production as presented in Section 4.1.4.

4.2.4 Governance

4.2.4.1 Introduction

Governance refers to the collection of laws, policies, mechanisms and regulations that are used to steer social, economic and political systems. The actors involved in governing include legislatures and other public entities but also private companies and social groups. Economic governance functions through price systems established through different markets but also through various types of contracting, business or corporate rules, centrally planned production and other modes of organization (Williamson 1985). Good governance is critical for the management of agricultural systems and associated inputs (soils, water, nutrients, etc.) and is therefore required to ensure food security. The governance of forestry resources affects the availability of wood and other biomass for energy and thus impacts food security, indirectly in many cases, but nevertheless significant. There are a variety of institutional arrangements for effective governance of “common” resources where each individual has both rights and responsibilities in using the resource base (Ostrom 1990). Governance for bioenergy systems has ethical implications in terms of how such rights and responsibilities are assigned and are carried out in practice (Gamborg et al. 2012).

The socio-economic interconnections among the rural poor in developing countries—where food insecurity is especially problematic—result in complex linkages between bioenergy and food security. Both the efficiency and effectiveness of governance systems must be addressed. Effectiveness is about the extent to which such systems achieve their stated goals, whereas efficiency is about improving the means of achieving those goals, i.e. the time and resources that are expended. A lack of appropriate governance systems for the management of land, water and other resources can lead to exploitation of precisely those groups that modern bioenergy is purported to help (Dauvergne and Neville 2010). Consequently, building institutions for improved social, economic and political governance is an important element within the process of implementing modern bioenergy systems in a given community or region, as well as at the national level where key resource governance decisions are made.

The governance issues that arise at the interface between food security and modern bioenergy systems have just started to emerge since rather few least developed countries have had large-scale bioenergy programs. In some cases the governance issues will be similar to those in the agriculture or forestry sector, although there are additional dynamics involved as energy policy issues enter the equation. Some evidence suggests that the addition of bioenergy options can in some cases force a greater level of accountability on the part of investors and resource owners compared to typical experience in the agriculture and forestry sectors (German et al. 2011). The additional scrutiny when international investors are involved and the development of international commodity markets rather than domestic markets appears to be a factor. Similarly, investment in modern bioenergy by multinational corporations--which tends to be viewed suspiciously by the non-profit sector due to potential or presumed distributional implications—can positively influence weak social and political governance structures through the empowering effects of strong economic governance in contracting and related institutional mechanisms (Purkus et al. 2012).

Community participation has been found to increase the likelihood of persistence and long-term socio-economic sustainability in bioenergy projects in forestry. This includes Community Based Forest Management, while for agriculture it may call for some type of agricultural cooperative that manages some of the physical and financial aspects of implementation. The cooperative must achieve a certain level of trust in the community and thus socio-economic and political governance are strongly linked at the local level. Where there are traditional land tenure systems, additional effort in institutional capacity is required in order to create the channels of distribution along the bioenergy supply chain.

The existence of extension programs has proven to be important for rural transformations away from subsistence agriculture, and these extensions can usefully incorporate bioenergy add-ons, such as the use of residues for production of biogas or for small-scale gasifiers (Chapter 15, this volume). The approach used by the FAO in some countries in establishing Agricultural Business Centers (ABCs) can complement extensions by adding a business model through the creation of some basic technical capacity such as small rice mills or grinding, drying and extraction (FAO/WHO 2013). These models serve to mobilize community-level action to improve harvesting efficiency and create a surplus. Rural development is thereby stimulated not only through the physical infrastructure but also from the informal governance mechanisms for coordination of supply and demand that is created at the local level.

At the national level, governance for the agriculture and forestry sectors—as well as more general financial and infrastructure governance—can have significant implications for the linkages between bioenergy and food security. Conservation efforts in the forestry sector are sometimes designed without recognition of the resource needs of neighboring communities. Combining conservation efforts with income-generating activities through woody biomass can reduce the extension of slash and burn agriculture and facilitate “land sharing” rather than “land sparing” although the choice between the two strategies (or even some mixture) is context-specific and depends on land tenure and related issues (Phalan et al. 2011; Edwards et al. 2014). On the agricultural side, the provision of subsidized fertilizers and other inputs has been practiced in some least developed countries (LDCs) but faces a number of implementation problems (Chirwa and Edwards 2013). Alternatives that address both agricultural and energy productivity could be considered instead, such as supporting the use of agricultural residues for energy production, which creates useful synergies in the value chain (Ackom et al. 2013).

4.2.4.2 Implementation, Scale and Resource Ownership in Relation to Food Security

The importance of a reliable feedstock in bioenergy systems means that the manner in which the supply chain is implemented has a significant effect on its economic viability and furthermore it also has distributional effects depending on the ownership of resources, property rights and governance systems. The scale and ownership of resources in bioenergy, agricultural and forestry management systems has some intrinsic relation to food security from the perspective of economic dependencies and risks. Table 4.2 provides a characterization based on the distinction between large and small-scale property rights and/or ownership of land, and can be applied regardless of whether bioenergy is the main product or a secondary product.

Professionally managed large-scale options may carry lower economic risks but may yield fewer benefits for the community; some benefits can be maintained if production is organized in favor of smallholders. One can distinguish three types (and two sub-types) of ownership relations between suppliers and purchasers of biomass:

- Scheme 1: One company or operating entity receives and processes biomass grown on large-scale plantations owned by the company or operating entity (vertical integration of agricultural/forestry and industrial sides of bioenergy production).
- Scheme 2: A partnership is established between a company or entity and smallholders; normally this constitutes some type of contract farming in which land is purchased (or inherited) or leased (Bijman 2008). This scheme should be distinguished by two types, based on large-scale vs. small-scale production or company size.
- Scheme 3: The community-based small farmers are organized into a decentralized scheme whereby biomass feedstock is used in smaller-scale production, often coupled to local small-scale conversion options such as generators for off-grid power.

Schemes 1 and 2.1 have potentially large scale impacts with likely more will and capacity to comply with sustainability standards and regulations especially transnational. This scheme is also more related to export and national markets. Schemes 2.2 and 3 have potentially smaller-scale impacts if mainly and local markets are involved.

It should also be noted that as agricultural and bioenergy markets develop and mature and demand for both food and energy increases, there will tend to be migration to Schemes 1 and 2 and away from 3, although this will differ somewhat depending on the underlying scale economics of the particular feedstock or crop and application.

Small-scale schemes can often have significant potential to promote rural development, especially when using locally produced feedstock, through proximity to energy production, job creation, income diversification, and increased local capital accumulation (PAC 2009). Coordination at the national level can support rural development initiatives, such

Table 4.2. Implications of alternative bioenergy schemes for food security/poverty reduction.

Ownership schemes		**Potential impacts on food security and/or poverty reduction**	
		Positive	**Negative**
Scheme 1: Processor by themselves/large-scale plantations		More jobs in rural areas, but duration and scale depends on degree of mechanization Cash injection into local economy	Difficult working conditions for rural workers The processor does not promote distribution of the generated income. For example, land prices may increase but only the operator is benefited Displacement of more vulnerable groups (e.g. smallholders, indigenous groups)
Scheme 2: Company – smallholder partnership (contract farming**)**	Scheme 2.1. Large company	More secure income due to better access to markets Reduced risk of smallholders' loss of land Support to smallholders regarding input supply and market outlets	Emphasis on bioenergy production might affect food production Smallholders' overdependence on company for inputs and market outlets
	Scheme 2.2. Small company	More secure income through better access to markets Reduced risk of smallholders' loss of land Closer support to small-scale farmers regarding input supply and market outlets	Emphasis on bioenergy feedstock production at the expense of food crop production Smallholders' overdependence on company for inputs and market outlets Reduced efficiency in the system due to no economies of scale
Scheme 3: Smallholders/ communities by themselves – small-scale decentralized schemes		Greater energy autonomy and availability at local level Better processing potential for agricultural products and other local products Health improvement if from traditional fuelwood to cleaner cooking energy Enhancement of education level due to enhanced lighting	Unfair competition for land for food and bioenergy production (but likely to be limited)

Source: adapted from FAO/UNEP 2011

as the case with Thailand's ethanol program in which cassava from small farmers serves as a feedstock in addition to molasses/sugarcane (Chapter 14, this volume). Some of these schemes are not mutually exclusive. In fact, in the case of sugarcane and some other crops, it is common in many African countries that a company operates a large estate but also has agreements with smallholders accounting for perhaps 20% of total production. The company provides technical support and equipment, and the farmers agree to provide a certain quantity and quality of feedstock. Reliance on smallholders saves administration costs for the company, improves the flexibility of feedstock supply through diversification and also maintains good public relations with the community through socio-economic benefits and infrastructure (Johnson et al. 2007).

It is worth bearing in mind that smallholders can be key partners and investors (through labor and resources) in bioenergy development even when technical and financial conditions require large-scale processing. The relation between investment and resource ownership can also be assessed on the basis of the risks and rewards to different actors and how they vary as the institutional arrangements change (Vermeulen and Cotula 2010). The effects of small vs. large-scale schemes nevertheless tend to be quite different; large-scale schemes tend to be less connected to the community needs as they are focused on international or regional markets, creating concrete economic benefits but entailing social and environmental risks. When community members are engaged in the whole bioenergy chain (i.e. growing the feedstock, establishing conversion systems, choosing final markets and products) there are better opportunities to internalize socio-economic impacts. With good governance systems, the costs and benefits are more likely to be fairly distributed, even when large firms are involved. Some communities may nevertheless prefer the higher certainty and tangible cash benefits of working through a larger entity or company, and this choice should be left up to the community when it comes to specific investments or projects. In summary, the impacts of bioenergy production do indeed differ across scales, while the costs and benefits of those impacts and the resulting risks will be borne by different groups depending on land tenure and resource governance systems.

4.3 Conclusions

- On a global scale enough food and energy are currently produced, so that hunger and malnutrition are primarily problems of access and/or distribution along with the income levels of the poor
- There is enough land available to produce the required food demand for the foreseeable future and to produce a considerable fraction of energy demand through bioenergy
- Some care must be taken to avoid reliance on staple food crops and to avoid excessive reliance on productive agricultural lands for bioenergy by promoting the use of degraded lands, expanding co-products, practicing integrated land use

management, and promoting advanced biofuels that use many types of biomass as feedstock

- Bioenergy can improve food safety; food production systems and reduce or re-use wastes
- Bioenergy can improve supply chain / infrastructure for food products
- Bioenergy can stimulate investments in agricultural production improving yields and create long term stability
- Bioenergy infrastructure can provide a dynamic and flexible production system, in which farmers and suppliers can switch between energy, food and other bio-based products as needed
- Bioenergy can provide better access to foods as Bioenergy provides jobs, which increases food security by higher income, education and improved infrastructure
- In order to achieve these identified benefits, good governance and supporting policies are crucial, both at local scales as well as at national and global levels

Reliable energy access is generally a precondition for improved food security, and independent of the origin of the energy, increased energy availability will help to reduce poverty and improve food security (Chapter 21, this volume). If bioenergy can help improve food security, it makes sense prudentially for all parties to support bioenergy development.

Food security depends on access to food, which is impacted by poverty, conflict and availability. For rural areas, biomass utilization for bioenergy can negatively impact availability, but positively impact economy (jobs, increased income, investment and improved infrastructure) and food quality (better preservation and preparation options through availability of energy). For urban communities, availability is not so much an issue, but higher food prices due to more competition of feedstocks, could negatively influence access and increase food insecurity. So far, the effect of bioenergy production to food prices however has been shown to be relatively small. Therefore, there is no clear causal relation between bioenergy/biofuels and food insecurity; it can be neutral or impact positively or negatively and needs good management systems and governance to support (economic) development, poverty reduction and food security.

From the recent evidence collected in this report we can conclude that bioenergy can be implemented in ways that have neutral or positive impacts on food production and security. If done right, production of bioenergy contributes to:

- decreased price volatility of grain crops, resulting from a diversification of revenue sources from agricultural produce, reducing risks and increasing income;
- agricultural infrastructure development by investments for biomass production for bioenergy;

- rural economic development, supported by local energy availability and development of chains, market structure and infrastructure;
- providing a flexible switch system (use of biomass for food or energy) in times of abundance and of scarcity.

The question then can be asked, is there enough land available to sustainably produce food, feed and biomass for energy for a growing population? As specified in Chapter 9, this volume, it is concluded that there is ***enough land available*** for substantial bioenergy production and increased food demand, considering impacts of global change affecting crop production, yield increase predictions, and preservation for urban areas, forestry and protected land.

Three elements of global change that affect food crop production and interact with bioenergy are taken into account: 1) climate change may cause a small decline in yields by temperature changes and extreme events; 2) changes in atmosphere, the tropospheric ozone may reduce yields but rising CO_2 may increase yields (effects will be mixed); and 3) land degradation, where bioenergy production can help to recover land for food production that became degraded. Overall we conclude that there is an increased yield potential at higher latitudes but reduced yields and food production in semi-arid tropics. Also the projected rate of increase in global demand for food and feedstuffs of around 2.4% per year was assessed against the yield improvements in main food crops (maize, rice, wheat, and soybean). Projections suggest that due to anticipated low rates in yield improvements demand will outstrip production by 30% over the coming 35 years, requiring an additional 130 - 219 Mha of agricultural land. Even if pessimistic projections are true, this should not be a problem as land availability for rain-fed agriculture is estimated to be 1,4 Bha (excluding land already in use for agriculture, forests and protected land). This land is strongly concentrated in Latin America and Sub-Sahara Africa (almost half of the available 1,4 Bha), and presently used predominantly for low intensity grazing. Developed countries also have land available but the agricultural area is expected to remain stable. In addition there is about 607 Mha of farmland available that has become degraded. Not only can degraded and marginal land be used for bioenergy feedstock production, but in doing so, the land can be rehabilitated and improved, providing a positive impact on soil quality, productivity and again on food security. In conclusion, at a global level, land is not a constraint but availability is expected to be concentrated in two main regions.

In considering the impacts of bioenergy to food security we found many positive examples of local benefits from bioenergy production. However, it is important to be aware of negative impacts, and to know how much these affect food security and how they can be avoided. For example, land grabbing as detailed by Cotula et al. (2008) (acquisition of large tracts of arable land by foreign countries or multinational corporations for export markets) may offer no food security benefits and could even exacerbate food insecurity. The data we investigated, however, show that only 0,5% of land deals in recent years were related to bioenergy production (Hamelinck 2013). We emphasize that good governance is an important factor to ensure that positive impacts of bioenergy are achieved. In terms of implementation, policy measures and investment in research, piloting and business development will be required, but attention must also be given to technical support for farmers, land tenure schemes and development of cooperatives. In countries with weak political structures, (foreign) investment can promote agro-industrial development, which in turn, could enhance food security; financial and environmental scrutiny is increased when international investors are involved, while at the same time local entrepreneurs are empowered through market discipline. More examples on how local, national and global policy measures and infrastructural measures impact food security should become more widely communicated to both increase our learning on the benefits of implementing bioenergy as well as to ensure that wrongly based assumptions do not negatively impact public (political) opinion.

In defining strategic policies and investment schemes it is important to realize that bioenergy is inextricably connected with ethical questions, particularly the responsibility to manage risks of food insecurity and climate change in ways that take into account persons who are underrepresented because they are poor or unable to look after themselves. This includes looking after future generations, implying that we have an ethical obligation to try to prevent the damaging effects of climate change. In the case of food insecurity, some NGOs have opposed the production of bioenergy using arguments based on (global) land availability and (expected increased) food prices. We have shown that these arguments based on global land availability are *not founded* by the fact that there is enough land available and also by the fact that 60-70% of people with food insecurity live in rural areas, where energy poverty is also common. Here bioenergy can increase food security as increased food prices would increase income for farmers and that together with increased energy security rural economies will be boosted.

Much research has been done in the last 5 years to investigate the assumptions behind assessments on bioenergy and food security. We now have much better insight in the availability of land and the development of food prices. As land availability is not expected to be an issue and food prices are not expected to be too much impacted by bioenergy production, we have the duty to consider ways in which bioenergy production can improve food security. Although the impact of bioenergy on food security must always be taken into account, it need not create obstacles to introducing bioenergy where its impact on food security is neutral or positive. Moreover, the status quo of areas with food insecurity that also lack energy access is not acceptable, since such conditions often involve a cycle of negative environmental impacts with little or no economic return, such as the traditional, unhealthy practices of the use of wood or dung for cooking. The responsibility to look after the food-insecure poor is the responsibility of society at large, and not solely the responsibility of the agricultural or food-producing sector, the latter being the case when there is an overemphasis on keeping food prices low. It is prudent to help those affected to acquire the means to solve their food and income problems through their own agency, which is the basic idea behind stimulating development that benefits rural communities. Bioenergy has a clear potential to achieve this goal and should be considered as a viable option for policy measures and investment schemes.

4.4 Recommendations for Research, Capacity Building, Communication and Policy Making

Research recommendations:

- We need critical empirical studies that will identify the key success factors and generate the general and specifically context related conditions for positive impacts of bioenergy on food security.
- Research is needed to clarify the impact of bioenergy production on rural food security and urban food security and account and monitor to create insight in positive and adverse, transient effects of bioenergy developments. This also requires the development of improved governance, and monitoring of sustainability and social benefit indicators, likely based in part on (spatially) explicit information systems. This information must be available and usable for local populations and decision makers.
- We need a robust research and extension system focused on constant improvement in farming practices, including the impacts of different scales of operation. Research on effective management of land with a focus on yields and sustainable practices should inform agriculture worldwide and include the development of markets for agricultural products.
- We need to continue to try to understand and predict the food security impacts of specific regulations, policy measures and institutional arrangements (such as cooperatives for small-scale production) in relation to bioenergy and agricultural systems.
- Financial and knowledge investment in sustainable agriculture for biomass production for food and energy is crucial to increase food security. This requires insight in best practice models of investment in both innovation and finances (such as the role public private partnerships can play to achieve both economic and social benefits). The support or creation of adequately funded agricultural research and extension systems capable of supporting sustainable agricultural intensification in each locale is essential.
- The estimates on land availability for food, feed and energy production vary and are uncertain due to uncertain predictions about local and regional consequences of climate change generally, and effects on yields particularly. Ground truthing of

satellite imagery and government land use data is crucial, particularly in poor regions to improve data on actual land use patterns. Such data will support factual assessment by regulatory bodies of consequences and opportunities for complimentary developments of further bioenergy and food production.

- Retrospective analysis of "what would have happened without bioenergy?", particularly with respect to food security, agricultural development, and social benefits in Brazil and the US would enable a better understanding of the impacts of bioenergy on food security.

Capacity building recommendations:

- Activities and funds should be organized to ensure capacity building on the use of good practices in (mixed) bioenergy production and food security achievement through education and communication, with a focus to local and regional actors. The support or creation of adequately funded agricultural research and extension systems capable of supporting sustainable agricultural intensification in each locale is essential.
- Agri-business development training in rural areas through entrepreneurial extensions (in addition to agricultural extensions) can help farmers to access markets for food and energy crops or products, as well as for improving supply chains and distribution channels.
- Governments should facilitate investments in skills and other manpower development needs for (local) bioenergy production (including on technology, governance, management and effect on food security).
- Training in business skills and community-based participatory processes would help to better prepare rural residents for foreign investors, so that they can maximize the benefits for food security as well as energy provision. This has to be done after business starts to develop with due attention for local conditions as they suggest appropriate solutions.

Communication recommendations:

- The global food versus fuel debate is dominated by misinformation, causing policy makers to hesitate implementing policies to stimulate bioenergy production when it could benefit food security. Communication and engagement between stakeholders should be improved and scientists should be involved to ensure better informed debate and better informed policies to increase the mutual learning process. This requires research on effective methods of communication, taking into account the role of trust, normative viewpoints and cultural practices.
- Scientific data, defining best practices (technology, sustainability and social and economic impact), should become available in understandable formats for local and regional actors, including farmers and companies producing bioenergy. This can be developed through national and regional research and extension programs.

- Assembled data, such as in this report, should become readily available for policymaking and governance. Efforts should be made to engage key policy makers in discussing the conclusions presented and recommendations in workshops and/or conferences to optimize the delivery of the main conclusions and ensure a proper perception of the data.
- Investment should be made into better communication between stakeholders in the novel chains of multi-scale agriculture, producing bioenergy and food. In countries like the US, this is the role of cooperative extension programs though other models are possible. They need to collaborate to improve social welfare, food security, and other elements of sustainability.
- Many development programs for improved agriculture presently do not consider the integration of bioenergy production. Meetings between bioenergy experts and aid supporters (such as the FAO, Oxfam, etc.) should be organized to inform these programs on positive impacts of bioenergy and how this could be realized.

Policy recommendations:

- Promising novel developments in bioenergy production that improve food security need to be rewarded and stimulated through policy measures that encourage and reward local entrepreneurial developments. Governments should stimulate bioenergy innovation by supporting research and pilot-scale developments, based on well-considered indicators that are meaningful for specific local contexts.
- Local and national governments should identify and solve conflicting regulation (e.g. across policies in agriculture, forestry, energy, transport and environment) for those innovations in bioenergy that promise a positive impact on food security.
- To create a level playing field and reward innovation and capture all possible GHG savings, biomass energy projects should be judged on their ability to reduce GHG's, while also satisfying other community needs (sustainability and food security). California's Low Carbon Fuel Standard is a possible model for such a program.
- There is a need for governments and international agencies to support objective trials, evaluating social benefits, economics and food security to poor communities in such areas to inform farmers and international communities on the options and viability of utilization of these lands.
- Improving the investment climate is crucial and needs strict control and governance to improve the stability dimension of food security. Low yields and high initial input costs may put off potential investors in bioenergy feedstock production on degraded and marginal lands. Therefore we need low interest start up loans, tax relief and discounts on the transport and distribution of the produce. The policies need to ensure that biomass production for bioenergy benefits rural communities. Farmer organizations may play an important role in this. In addition land tenure rules need to be in place to ensure that rural communities continue to have access to land for their livelihoods.

4.5 The Much Needed Science

Integrative approaches addressing bioenergy and food security are essential. If there is a consensus about the importance of alternatives to fossil fuels and the necessary increase in food security from the local to the global scale, efforts must be made to conciliate these two demands. These efforts should be science based and hence require further scientific research in the following fields.

4.5.1 Farming practice and management in relation to food security

Integrating bioenergy production in food production systems in ways that increase food security requires knowledge of key success factors. Empirical studies are needed that will identify these and that will generate the general and specific context related conditions for positive impacts of integral systems. This necessitates multidisciplinary studies in which agronomics, economics and management studies, bioprocess engineering and social studies provide input to fully understand the value chains in specific regions. Studies will have to identify improved yields, and better water and nutrient management while generating insight on the required scale of operations for bioenergy production, which will increase sustainability of agriculture in general. This also includes studies into the use of degraded pasture lands that have been recognized as an available option for bioenergy production. Thus, research on the potential of pasture intensification, including particular strategies to maximize sustainability benefits should be carried out. Currently lands that were previously used for food and/or cash crop production and are currently abandoned and those that are only marginally suitable or unsuitable for food and/or cash crop production should also be evaluated for the same purpose. International collaboration with developing countries can address agricultural research and food security directly by drawing on common experiences, such as the case with Brazil and Mozambique (Box 4.5).

4.5.2 Food security indicators and monitoring

Bioenergy is only one of the many aspects that can affect food security. Validated monitor systems of food security need to be developed that can be used to assess the possible impact of bioenergy. This requires insight in the relative effects of all factors including local infrastructure (transport, grid availability, water availability, industry infrastructure, etc.), employment levels, availability of education, economic opportunities, market structures, etc. Data need to be assembled and interpreted and linked to specific contexts. In addition to quantitative data this also requires the evaluation and incorporation of qualitative factors. Novel methods for cheap and easy monitoring need to be developed on the basis of insights of relative impacts, which could be incorporated in sustainability schemes. This will provide steering

Box 4.5. Parallels – Bridging cooperation in both ways

Understanding the arrangements established between the historically produced biophysical and human factors allows the identification of regional patterns and processes, an essential knowledge for the management of natural resources and agriculture. The Brazil-Mozambique cooperation, which is based on the parallelism among geographical situations and prospects for development, falls within this context of latitudes, culture, and agriculture (Batistella and Bolfe 2010).

The cooperation between the Brazilian Agricultural Research Corporation (EMBRAPA) and the Agricultural Research Institute of Mozambique (IIAM) includes land management systems, soil surveys, land-use and land-cover mapping, agroecological zoning, environmental impact assessments, productive process improvements, agricultural intensification and land degradation monitoring, among others.

There are several development opportunities for the Mozambican agriculture and bioenergy production based on the knowledge generated in Brazil. The Brazilian experience in the cerrado area is an important experience for the development of tropical agriculture, now enriched with the need to minimize environmental impacts. More than just exporting technologies, there is the will to learn how to build together a virtuous future integrating mutual experiences and common goals, i.e. interdisciplinary actions for development and cooperation, based on the promotion of agricultural intensification, implementation of good practices, and on cautious indications for the expansion of the agricultural frontier. The ties that unite Brazil and the African continent surpass historic links, cultural heritage, behaviors, and traditions. They strengthen themselves in actions that promote social and economic integration, especially for agricultural and regional development.

knowledge for policy incentives and investment requirements and will increase our understanding of differences between specific rural and specific urban food insecurity and how bioenergy can impact these. Again this will necessitate the collaboration of different disciplines, including e.g. social sciences, socio-economic modeling, and market studies.

4.5.3 Governance including regulations, local and global policies and certification

Governance has been identified as a key factor to achieve positive effects of bioenergy production on food security. However, our knowledge on how local, regional and global measures, regulations and certification schemes impact rural practices and food security is very limited. There is an immediate need for empirical studies that evaluate these effects on a local scale and translate that knowledge to better governance practices. This includes specific knowledge on institutional arrangements (including for example cooperations) and how local or regional communities are likely to embrace these. For the latter we also need to understand community values on technology utilization and governance structures. The interplay between local, regional, national and global schemes needs to be evaluated for different situations, so we increase our understanding of conflicting systems and adverse impacts. Input is required from science policy, international relations studies, market studies and management studies, with understanding of impacts in agriculture for bioenergy, feed and food production.

4.5.4 Finance and investment models

In addition to governance we also require insight in financing models for improved sustainable agriculture. Investment in bioenergy production could be made in many ways, and has likely different impacts in different local situations. Understanding the key relations for specific schemes to specific contexts is crucial. Data on best practices should increase our insight on improved schemes for financing as well as on how this should be governed or organized. Knowledge on requirements for small and large-scale bioenergy production from bioprocess design should be combined with knowledge on innovation management and financial management.

4.5.5 Communication and mutual learning

Integration of disciplinary knowledge highly depends on ability of mutual learning and effective communication. In deploying bioenergy for improved food security we deal with many stakeholders and experts who have not collaborated before. This requires communication which provides the validated scientific facts and which is trusted by all parties. Trust is a precondition for learning and can be improved by transparency and mutual engagement (to listen and respond). Novel ways of communication need to be designed that take these factors into account and can increase the learning curve. In addition, communication of factual data on how bioenergy can improve food security to public(s) in general should be designed in such a way that it takes the negative and wrong assumptions away and decrease the negative impact of public opinion to policy and decision makers. This requires input from communication sciences and ethics.

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chapter 5

Environmental and Climate Security

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Highlights

- Bioenergy is critical for environmental security and climate change mitigation. Global warming levels greater than 2°C will lead to significant adverse impacts on biodiversity, natural ecosystems, water supply, food production and health. Any potential impacts of bioenergy should be viewed in this context.
- In general, environmental security deals with local to regional issues, while climate security deals with global issues. Geophysical distribution of land and climate around the globe is not homogeneous. The impact in local activities such as biofuels production will be singular, demanding specific engagements of governments and regulatory constraints.
- The expansion of biofuels production across less profitable (degraded, abandoned or marginal) lands may have positive impacts on biodiversity and biofuel and food production. Land Use Change (LUC) can result in the loss of biodiversity, wildlife habitat and the alteration of ecosystem structure and delivery of ecosystem services but these effects can be minimized through appropriate choice of bioenergy crop and management practices. Biodiversity losses caused by Indirect Land Use Change (iLUC,) due to the displacement of existing agricultural activities to pristine areas beyond the biofuels croplands are of less importance than previously reported.
- Environmental impacts need to be considered at appropriate scales, across the whole feedstock production and bioenergy processing chain and across landscapes, catchment basins, functioning ecosystems and where migratory species are affected, dispersion areas.
- Environmental impact assessment frameworks have evolved, integrating individual metrics such as water, soil, and biodiversity into a systematic view. However, the requirements to conduct and implement such assessments still present formidable technical and sociopolitical challenges.
- Conservation of priority biodiversity is paramount; effects of biofuels on biodiversity and ecosystem services are site and context specific; and management practices in biofuels production should minimize threats. Of critical importance is the conserving of primary tropical forests, and strengthening the representation of ecosystems in effectively managed protected areas across the globe. Appropriate management systems can reduce negative impacts on new croplands and enhance biodiversity in previously degraded lands.

- Water use in bioenergy production systems is highly variable and the impacts are site-specific. Wherever possible, full water budget analysis, rather than a reliance on water use efficiency metrics, should be conducted. Poorly managed bioenergy production may decrease water abundance and quality. However, locally optimized feedstocks, improved wastewater management, proper agronomic practices, and landscape-level planning can minimize these impacts and may, in some case, improve the status of water resources.
- Mining nutrients from the soil with inadequate or insufficient fertilization, removing excessive amounts of plant material or improper disposing of residues may reduce soil fertility, cause loss of organic matter and predispose soil to erosion. However, properly managed bioenergy crops can help to maintain soil quality and even result in carbon accumulation, thus mitigating CO_2 emission.
- Governance policies are needed that are especially designed to avoid the implications of unsustainable exploitation of natural forests for biofuels, which frequently lead to "exporting" deforestation to other regions in the same country or to other countries as well as encouraging illegal logging and illegal trade in wood and non-wood forest products.
- Sustainable biofuel production must be part of sustainable forest management and sustainable agriculture (food security) where both are needed as integral components of land use with clear understanding of the uniquely complex set of environmental, economic and social issues involved.

Summary

Bioenergy has a key role to play in the stabilization of global climate change. In this chapter we assess the potential environmental and climate security opportunities and risks associated with bioenergy expansion and examine the main guidelines, regulations, incentives and policies that will help promote it in an environmentally and climate-friendly way.

Current projections are that climate change will be more severe than originally predicted. Warming at a level greater than $2^{O}C$ could have significant adverse impacts on biodiversity, natural ecosystems, water supply and food production. Stabilization of global warming to less than $2^{O}C$ has thus become an imperative. Challenges also need to be faced with respect to the environmental consequences of intensive agriculture for food production, and of urban expansion, such as building on prime soils, increased soil erosion, loss of soil organic carbon, excess nutrient run-off, increased pollution and loss of biodiversity. Bioenergy is recognized by many as being critical to combating many climatic and environmental problems (e.g. energy supply, soil remediation, nutrient run-off). There is now strong scientific consensus that achieving a low carbon energy future is more likely with bioenergy than without it. However, it has also been posited that bioenergy expansion may result in unacceptable negative impacts, such as substantial greenhouse gas (GHG) emissions, biodiversity losses, land degradation and water scarcity, primarily through land use change (LUC). Here, we examine these issues and demonstrate that through awareness, careful management and appropriate integrated policies, we can produce sufficient bioenergy sustainably to fulfill its anticipated role in mitigation of climate change, whilst encouraging positive benefits and minimizing negative impacts on natural resources.

In general, environmental security is determined at local- and regional-scales and climate security is at a global scale. Assessment of environmental impacts should be carried out at appropriate scales (farm, landscape, region, country, global) that recognize that impacts may operate at the ecosystem (e.g. forests, grassland, arable, coastal) level. It will be important to develop integrated and complementary management systems, in which the interdependencies of forestry and agriculture policies, as well as systems for producing food crops, meat and dairy, and bioenergy feedstocks should be recognized and harmonized. Increasing agricultural productivity and reducing food waste are essential to reduce the overall needs for expansion of lands (Chapters 4 and 13, this volume).

The more recent studies of indirect Land Use Change (iLUC), arising from displacement of existing agricultural activities to non-cultivated areas beyond the biofuels, report lower effect than earlier studies. Estimates for new land brought into cultivation due to production of bioenergy feedstocks on cropland have been reduced by an order of magnitude for corn ethanol, and by 3-fold for sugarcane ethanol. Similarly, new evidence indicates that postulated biodiversity losses caused by iLUC are far smaller than previously reported. Thus, recent results indicate that the land use sectors are capable of accommodating a significant part of the modeled bioenergy expansion without claiming new land. However, it should be noted that iLUC studies investigate modest bioenergy scenarios compared to prospective biomass demand in the 2050 time frame; about 2.5 EJ of biofuels was produced in 2013, compared with the prospective biomass demand of some hundreds of EJ per year.

Clearly, the expansion of bioenergy (and food crops) to meet human needs will likely have major implications for land use. However, whilst LUC involving previously non-cultivated land for bioenergy production can have negative impacts on ecosystem services, this does not mean it has to. Use of previously cultivated but abandoned lands and of marginal lands deemed less suitable or profitable for food production, may have positive effects. This will be helped by improvements in feedstock selection and agricultural practice to compensate for the poorer quality of such lands. Pressure on land use can be further reduced by including wastes and crop residues as sources of biomass, although a proportion of crop residues should be left to maintain carbon and nutrient levels in soils.

Effects on biodiversity and ecosystem services are both site and context-specific. Many possible impacts are valid concerns for arable food crops, however, many bioenergy plants, particularly grasses and woody plants have specific attributes that can be advantageous if used properly. These include their longer growing seasons, perenniality and associated stability of habitat, and their reduced need for fertilization and cultivation. Management practices for bioenergy crop production should exploit positive attributes of these cropping systems and minimize threats to biodiversity and ecosystem services. Effective management of water and nutrients can be achieved through a systems approach that recognizes the spatial heterogeneity of landscapes, ecosystems and species, and landscape level processes dependent on catchment connectivity, fluxes in water-yield and nutrient cycling (Figure 5.1). Bioenergy cropping can either cause soil degradation or help maintain or improve soil quality and can even cause carbon accumulation, thus mitigating CO_2 emission. Negative impacts can be minimized by careful crop selection for soil type and climate.

To manage environmental impacts, new bioenergy croplands should be selected and developed following both Strategic Environmental Assessments (at a regional scale) and Environmental Impact Assessments (at local/site scale) as these provide baselines for monitoring positive and negative impacts and guide adaptive management strategies. Sustainable bioenergy production should be based on, and support, good governance,

Figure 5.1. A future multifunctional landscape for both environmental and energy security. Strategic spatial integration of bioenergy crops on poorer land with food cropping on arable land can provide energy and alleviate environmental problems associated with arable land use. Perennial bioenergy crops can provide natural refugia for biodiversity, regulate flooding and provide filters to remove excess nutrient run-off into waterways. Arable crop and urban food wastes can be converted to various energy forms by anaerobic digestion, together with animal slurries, whilst waste water can be applied to biomass crops such as willow. Note; for ease of illustration, elements are simplified and not drawn to scale or directly connected.(Source; L.Castle, Rothamsted Research, UK).

strong institutions, market based voluntary certification, and access to information about appropriate management strategies that support sustainable resource use and benefit biodiversity. Scale and cost of the bioenergy end product should be part of this equation. To ensure compliance with sustainable forest management, and sustainable agriculture, national and regional integrated forestry, agriculture and bioenergy governance policies will be required. These will need to address the full valuation of forest goods and services and opportunity costs of forestland and cropland conversion, whilst recognizing law enforcement and institutional capacities and safeguarding local user rights and land tenure arrangements.

5.1 Introduction

This cross-cutting chapter examines the potential environmental and climate security opportunities and risks associated with bioenergy expansion and the main guidelines, regulations, incentives and policies that will help promote bioenergy in an environmentally and climate-friendly way.

5.1.1 Security is Important

Bioenergy production exploits the natural opportunity offered by plants to remove carbon dioxide (CO_2) from the atmosphere and convert it into dry matter (biomass) that can be used as substitute for fossil fuel-based energy. Plants are also the principal source of carbon in soils. Bioenergy implementation can cause gains or losses of carbon in soils and vegetation. The outcome depends on the character of the bioenergy system and on local conditions, not the least prevailing land use. The use of biomass for energy in combination with carbon capture and storage can deliver net removal of atmospheric carbon along with energy provision. Thus, the contribution of bioenergy to climate change mitigation can vary widely depending on the character of the bioenergy system and the implementation strategy.

Climate change is arguably the biggest environmental and developmental challenge facing humanity. The latest IPCC (Intergovernmental Panel on Climate Change) Report (IPCC 2013) has concluded that “warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia...[and that]...continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system”. The world has warmed by nearly 1^{O}C compared to pre-industrial revolution stage. IPCC Working Group II (IPCC 2014a) has concluded that any warming level greater than 2^{O}C will lead to significant adverse impacts on biodiversity, natural ecosystems, water supply, food production, health etc. In fact, there is scientific evidence that climate change is already affecting natural ecosystems and food production. The Copenhagen Accord, taken note of by delegates at the Fifteenth Session of the Conference of the Parties (COP 15), expresses a strong political will to urgently combat climate change and prevent dangerous anthropogenic interference with the climate system. The Accord recognizes the scientific view that the increase in global temperature should be kept below 2°C and that deep cuts in global emissions are required. Many scenario studies and assessments, including IPCC (2011), GEA (2012) and the forthcoming IPCC (2014 b, c), the IEA (2014), Greenpeace, and the World Wildlife Fund, have all highlighted the role for bioenergy in meeting greenhouse gas (GHG) stabilization targets judged compatible with a $2^{O}C$ target. These observations are indicative of strong scientific consensus that achieving a low carbon energy future is more likely with bioenergy than without it. Sustainable bioenergy production has thus become both urgent and imperative.

Many bioenergy production systems are based on farming practices that have fewer impacts than intensive agricultural food production. As with all technologies, however, not all bioenergy routes will be appropriate in all circumstances. Unfortunately, the negative image of those systems that fail to meet all expectations are in grave danger of impeding the beneficial bioenergy production systems that are urgently needed. To achieve full sustainability goals, the expansion of bioenergy production has to be progressed within a framework of the broader ecosystem functions associated with land use. This chapter focuses on key issues in environmental and climate security, whilst land availability, bioenergy energy supply, impacts on food production and sustainable development are covered by Chapters 3, 4 and 6, in this volume.

5.1.2 Key Opportunities and Challenges

The low carbon energy scenarios cited above suggest a strong growth in the use of biomass for energy, equating it in places to exploitation by humans of photosynthesis of comparable scale to that for agriculture or forestry today. For instance, the SRREN review of 164 long-term energy scenarios predicted bioenergy deployment levels in year 2050 ranging from 75 to 150 EJ per year (for ~440–600 ppm CO_2eq concentration targets) and from 115 to 190 EJ per year (for less than ~440 ppm CO_2eq concentration targets). As a comparison, the energy content in the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) was estimated at about 60 EJ per year in IPCC (2011). See also Chapters 3, 4 and 9, this volume, for further information.

The expansion of bioenergy offers considerable opportunities for the agriculture and forestry sectors, which can find new markets for their products and also make economic use of biomass flows earlier considered to be waste. However, bioenergy growth has prompted much concern about possible negative impacts such as biodiversity losses, land degradation and water scarcity. Sustainability concerns further include direct and indirect social and economic aspects, including land-use conflicts, human rights violations and food-security impacts. The view that bioenergy represents an attractive alternative to fossil fuels has also been challenged based on the notion that bioenergy expansion may cause substantial GHG emissions associated with land use change (LUC) (SCOPE 2009; IPCC 2011).

While bioenergy can be developed in ways that have negative impacts, there is strong scientific evidence that bioenergy can also be deployed in ways that offer substantial benefits including, but not limited to, mitigation of climate change. In support of this, we note that there is a great deal of land that is suitable for growing bioenergy crops exclusive of current and anticipated cropland, forest, protected land, expansion of the built environment, and land reservation for protection of native vegetation and biodiversity (Chapter 9, this volume). Much of this land is classified as pasture land, although not all of it has livestock on it, for which the contribution to global food production is quite small (Chapter 9, this volume). Integration of bioenergy production into existing land uses can in many ways improve the productive use of land and water, and can provide environmental benefits in addition to the GHG savings (Chapters 16-18, this volume). Bioenergy demand also opens new opportunities for climate change adaptation. For example, cultivation of hardy and drought tolerant plants as bioenergy feedstocks presents an opportunity to diversify land use and reduce vulnerability to failures in production from major food crops that are more dependent on intensive agricultural inputs. Furthermore, in some countries bioenergy expansion could be driven by the need to create energy access, mitigate fuel poverty and to promote self-reliance and/or rural development. Governments also promote bioenergy to improve energy security, especially to reduce dependency on oil and fossil gas. Thus, bioenergy deserves attention for many more reasons than just the need to meet renewable energy obligations.

Governance of bioenergy development is imperative in order to promote benefits and avoid, or at least mitigate, negative effects. In the sections that follow, the potential environmental and climate security threats and opportunities associated with bioenergy expansion are assessed and policies and measures that address these threats and opportunities are suggested. It is made evident that although there are trade-offs in some situations, there is also clear potential for win-win approaches that should be followed. Implementation of the recommendations would require the development and enforcement of guidelines, regulations, incentives and policies that promote environment and climate-friendly bioenergy. It should be noted that whilst many of the issues raised here apply to bioenergy in general, the current momentum in the area of liquid biofuel production has attracted somewhat more attention, and this emphasis is reflected here.

5.2 Key Aspects

5.2.1 Climate Change

The availability and distribution of natural resources is of growing concern in the context of human population expansion (Rockström et al. 2009). Environmental and climate security both refer to concerns about the impact of human activities on environment and climate, and conversely about how changes in climate and other environmental factors influence the human society. Both environmental and climate security deals with issues at multiple scales. The climate change issue is global by nature, but both mitigation and adaptation strategies are formulated on local, regional and global scale. Environmental impacts are commonly experienced on local to regional level, but are caused by the way society exploit resources and shape production processes to meet the demand for goods and services, which increasingly follows a global uniform pattern.

Resource depletion and environmental degradation threatens the functional integrity of the biosphere and can lead to economic losses as well as social and political instability and conflict. Society faces the challenge to address the underlying causes, including unsustainable land use practices, while mitigating and adapting to climate changes that are increasingly being recognized (Jordan et al. 2013). The frequency and intensity of climate extremes (floods, drought, hurricanes, tornados, etc.) have important social, economic, and environmental consequences. There is scientific consensus that the slow, but monotonic increase in global average temperatures can adversely affect the distribution ranges of both natural and cultivated/domesticated species. Changes in rainfall patterns and temperature are critical to agricultural productivity, whether for bioenergy or food. These are also important at the regional level, because some areas are warming much faster than the average (IPCC 2013) and/or are experiencing different environmental challenges. For example, some regions, such as Southern Latin America, experienced a 30% increase in precipitation over the last 50 years, while others, such as Southern Australia, experienced important precipitation reduction.

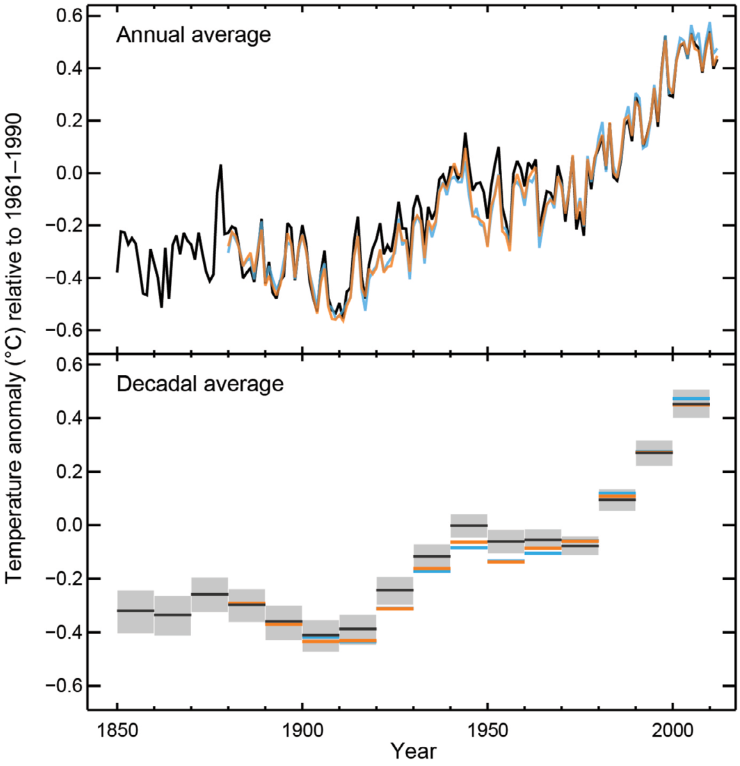
Figure 5.2 illustrates how temperature has varied in the last 110 years. As a consequence, the impact in local activities will demand specific engagements of governments as well as specific regulatory constraints. Global climate change brings instability and difficulties in long-term planning for food and energy production - a relatively new issue that is being addressed in this volume.

5.2.2 Land Use Change (LUC)

Land use change (LUC) associated with bioenergy production is a central factor in this, and many chapters in this Volume, due to it being a common denominator in food, energy and environmental sustainability. In Section 5.2.3 we consider LUC within the context of major ecosystems most likely to be affected by bioenergy expansion (agricultural, forest and grassland landscapes, coastal areas and marginal or degraded land), whilst here we discuss LUC in generic terms.

Bioenergy production and its potential are dependent on human activity. Regional demographic demand is affected by local infrastructure and socio-economical context and the long-term sustainability of bioenergy options will be dictated by factors like local climate and soil-water availability (Chapters 10, and 12). Direct LUC (dLUC) refers to the changes in land use that occur where bioenergy feedstock production becomes established, such as the “change from food or fiber production (including crop rotation patterns, conversion of pasture land, and changes in forest management) or the conversion of natural ecosystems”. Indirect LUC (iLUC)

(a) Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012



(b) Observed change in surface temperature 1901–2012

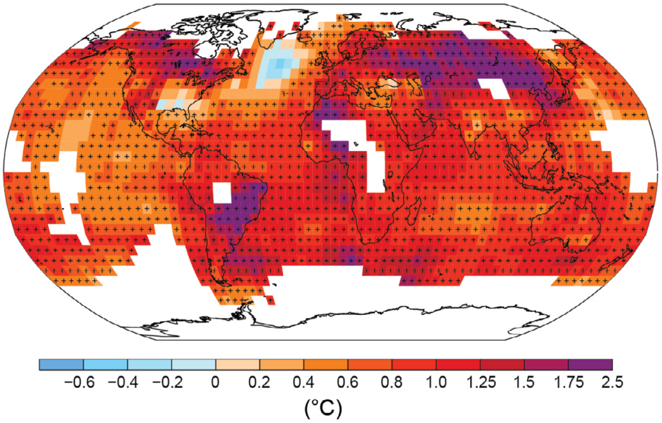


Figure 5.2. Temperature variations over 110 years period. a) Three global land and ocean annual mean temperature series are shown on continuous and decadal averages. b) Overall warming trends are apparent. For regional trends only one data set is shown. Source: IPCC 2013.

“refers to the changes in land use that take place elsewhere as a consequence of the shift to produce bioenergy feedstock. For example, displaced food producers may re-establish their operations elsewhere by converting natural ecosystems to agriculture land, or due to macro- economic factors, the agriculture area may expand to compensate for the losses in food/fiber production caused by the shift to produce bioenergy feedstock. A wide definition of iLUC can include changes in crop rotation patterns and/or intensification on land used for food or feed production” (Berndes et al. 2011) (see also Searchinger et al. 2008; Kloverpris et al. 2008; Hertel et al. 2010; Delucchi 2010; Berndes et al. 2013).

Land use and LUC are inevitable consequences of the continuous changes in the human society. LUC is associated with many human activities inextricably linked with agriculture. Given this, it is expected that effects on local biodiversity and other environmental consequences will occur. However, the effects do not have to be negative. Land use under sustainable bioenergy cropping could be a steady and significant part of the cost-effective portfolio of climate change mitigation strategies (Rose et al. 2012). LUC associated with bioenergy projects can result in both positive and negative effects on environment and resource quality. For example it is widely recognized that converting land planted in row crops to perennial grasses can be accompanied by significant benefits in terms of biodiversity, habitat, and increased soil carbon and fertility. Environmental consequences of converting pasture land to bioenergy crops, or more intensive pasture (which could make room for energy crops), could be positive or negative, depending on how this conversion is managed. Similarly, there are sustainable forest management practices that can provide net benefits to both habitat and livelihoods, while there are others that are abhorrent from an environmental stand point. Worst-case scenarios such as clearing rain forests or draining peat land to make land available for bioenergy are important to avoid. The challenging posit is how to improve the awareness of governments and society that it is possible to avoid or mitigate negative effects whilst taking advantage of the positive benefits of bioenergy crops to address environmental problems.

While GHG emissions can be appropriately treated as a global impact, the climatic consequences of rising atmospheric GHG concentrations are experienced on global, regional and local scales. Thus, as other environmental impacts, climate change needs to be considered within the local context. The risks and resiliency of individual regional niches to the impact of land cover change, biomass removal, and climate vary greatly and continue to change.

Improved data collection and processing and modeling capability now allow high resolution assessment of local impacts. Environmental impact assessment frameworks have evolved, integrating individual metrics such as water, soil, and biodiversity into a systematic view (Chapter 12, this volume). However, the requirements to conduct and implement such assessments (Table 5.1) still present technical and socio-political challenges.

Table 5.1. Regional impact assessments.

Requirements to conducting regional impact assessments
Fairly detailed regional baseline
Adequate understanding of mechanistic linkages in regional environmental processes
Reconciliation of overlapping boundaries for different ecosystem service components in region
Characterization of complex interactions between bioenergy production systems and other regional activities including other human and non-human use
Models sufficiently reticulated to forecast changes in the above
Technical expertise and computing infrastructure
Requirements to implementing knowledge gained from regional impact assessments
Consensus for desired outcomes (e.g. minimizing 'damages', restoration/improvement criteria and goals, etc.) appropriate to region
Political will and consistent guidance through regulatory requirements
Regional stakeholder participation
Reconciliation of disparate and overlapping political governance and ecosystem/watershed boundaries
Translation of goals and assessment outcomes into reliably measurable and enforceable regulated metrics

5.2.3 Ecosystem Change

The increase in area used for bioenergy feedstock cultivation may come from a variety of land uses, principally agricultural (food) and pasture production, natural ecosystems (forests), marginal lands and coastal areas (FAO 2010; Cai et al. 2011; Chapter 9, this volume).

5.2.3.1 Agricultural, Forest and Grassland Landscapes

Agricultural, forest and grassland landscapes have long provided humans with food, fiber and energy as well as a range of other ecosystem goods and services. LUC, especially forest conversion to agricultural land, has been and still is the primary driver of global deforestation and forest degradation in many countries, currently especially in the tropics, in addition to mining, urban development and other anthropogenic changes.

One of the most important environmental concerns is deforestation and land clearing. Forests around the world face pressures from many human activities including agriculture (for both row crops and animal grazing), urban expansion, mining, and land tenure disputes. The forestry-agriculture nexus is clearly demonstrated through the competition for food, fiber and fuel production and consumption. In many parts of the world these three systems, plus others, have been traditionally practiced simultaneously, with minimal coordination among individual regulatory policies. Pasturelands have the potential to provide large amounts of land for bioenergy expansion (Cai et al. 2011; Horta Nogueira and Capaz 2013), with less impact than that of forests. However, the relatively recent surge, particularly in biofuel feedstock production and consumption, has introduced some imbalances in land use systems, especially in the tropics (FAO 2013). In order to adequately protect forest resources and other natural landscapes, all LUC drivers and trade-offs ought to be well understood. In addition, the land-sparing potential of highly productive systems needs full consideration. Crop and pasture intensification, although usually associated with increased use of fertilizer and other agrochemicals, can significantly increase biomass production, thus sparing land for other uses, including forest preservation (Lapola et al. 2014; Martha Jr et al. 2012; Snyder et al. 2009; Chapter 9, this volume).

Direct LUC is relatively straightforward to estimate for feedstocks such as soy in Argentina and oil palm in Indonesia and Malaysia but iLUC is more difficult to estimate and the cause of much debate and concern (see Sections 5.2.3.1 and 5.2.3.3). There have been particular concerns that rapid expansion of oil palm may have resulted in many of the consequences outlined above. However, so far, bioethanol is being produced mostly without clearing forests. Corn for ethanol in the USA is grown mainly in the cornbelt and only 0.6% of the sugarcane expansion in Brazil in recent years (2000 to 2010) occurred in forests (Adami et al. 2012). Whilst there might be isolated instances of unsustainable practices (Lapola et al. 2014), the importance of iLUC has been over estimated (Langeveld et al. 2013; Finkbeiner 2013) but further research is needed to address methodological challenges and help avoid premature conclusions (Pacheco et al. 2012). Trade-offs, including those related to poverty, equity and the environmental integrity must also be evaluated when choosing a bioenergy system.

One of the relatively recent initiatives that can potentially integrate policies governing landscape management systems is REDD+1. It is believed that REDD+ strategies can reduce deforestation, improve global carbon balance and enhance land use efficiency by steering agricultural expansion for biofuel production to already degraded lands that have low potential for regeneration of carbon-rich forests and directing agricultural extension for food production to priority landscapes and to those with minimal potential conflicts within the REDD+ strategies (Kissinger 2011).

5.2.3.2 Coastal Areas

Coastal areas and the open ocean are suffering strong changes due to environmental and climate change, and protection of marine ecosystems becomes even more important when bioenergy crops and production facilities are located in coastal regions. Ocean acidification is a serious issue that could have critically important consequences. Never in the last 300 million years has the rate of acidification been so high. In the last

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[1] REDD+ is “Reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries”. http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf

150 years, acidity in oceans increased by 30%. The main cause is emissions from fossil fuel burning, especially the release of CO_2. The oceans are an important CO_2 sink, absorbing 26% of the CO_2 emissions, but due to accelerated acidification and rising sea surface temperatures, this capacity may be reduced (Le Quéréet al. 2010; McKinley et al. 2011; Schuster and Watson 2007). The effects of such acidification on ocean biodiversity are large. It is predicted that in a few decades the increased acidity of oceans could affect severely all marine organisms. Coral reefs will be threatened as well, due to the importance of calcareous compounds in their structure.

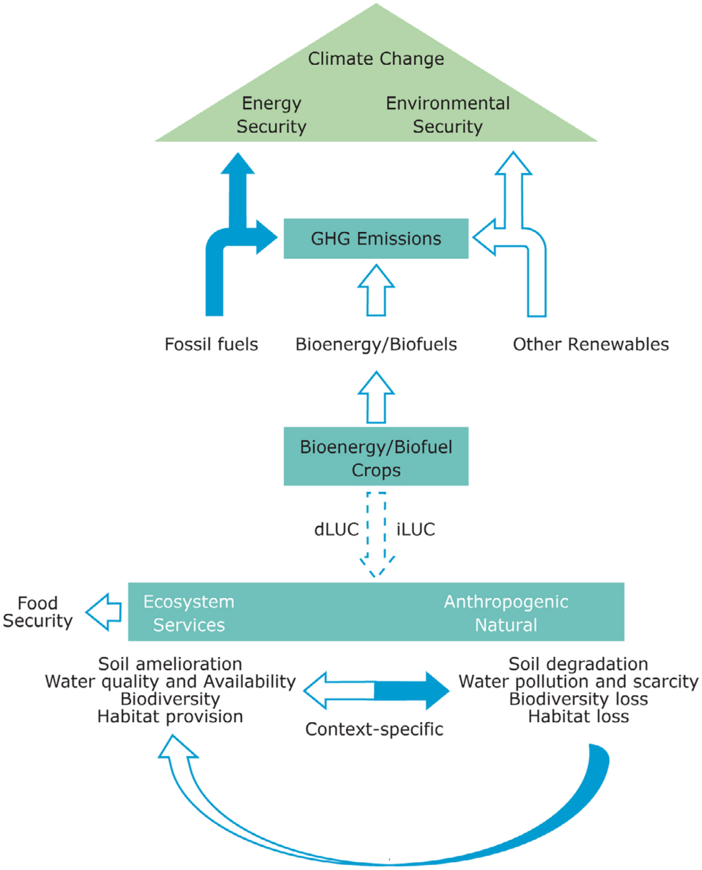
Because of run-off from continental areas, coastal zones are under pressure. Run-offs from small catchments to large rivers usually carry pollutants and agricultural residues. Worldwide, there are now more than 500 'dead zones' covering 250,000 km^2 (UNDP 2013). Insecticides and fertilizers are important agents in these changes. The increase in the level of nutrients, such as nitrogen and phosphorus, is causing important impacts at coastal ecosystems (Canfield et al. 2010; Liu et al. 2012) and to the human populations that depend on them.

Most of these factors can be readily controlled through appropriate location of bioenergy crops and associated conversion activities. Some bioenergy crops, for example short rotation coppice willow, can be used as natural filters to help prevent run-off, whilst others, for example some energy grasses, have been selected to cope with the more extreme environments found in coastal areas that make food production impractical. The rooting of these crops can help in the fight against coastal erosion and the land cover can help provide habitats for coastal fauna. Adequate agricultural practices are also important to prevent or decrease the amount of nutrients that go into surface and groundwaters (Fixen 2009; Neary and Koestner 2012; Snyder et al. 2009).

5.2.3.3 Marginal and Degraded Lands

To reduce competition with food production and because of economic factors, expansion of biofuels crops is often foreseen on non-cultivated land, previously un-managed ecosystems, or marginal/degraded lands (Plieninger and Gaertner 2011), and less profitable arable crop lands that have recently gone out of production (idle land) (Gelfland et al. 2013; Chapter 9, this volume). More than a billion acres of idle land may be available for bioenergy production (Cai et al. 2011; Chapter 3, this volume). LUC can result in the direct loss of biodiversity due to the loss of wildlife habitat and deep alteration of ecosystem structure (Koh et al. 2011) but impacts will depend on the ecosystem being replaced and the bioenergy cropping system introduced (Chapter 16, this volume). iLUC effects, although formerly very controversial (Zilberman et al. 2011) are now seen to have far less impact than previously thought (Kim and Dale 2011: Langeveld et al. 2013; Finkbeiner 2013). The use of marginal or degraded lands for biofuel crops can be associated with the general impacts of agricultural intensification (Prins et al. 2011), including an increase in the use of agrochemicals with consequential effects on the biota and the physical environment (e.g., Meche et al. 2009; Schiesari and Grillitsch 2011; Verdade et al. 2012). However, these can be minimized, and even remediated, by careful choice of bioenergy crops (see

Section 5.4). Similarly, degraded lands are usually associated with soil and water limitations that require the selection of plant species adapted to such circumstances (Li et al. 2010). Whilst expansion of biofuels production over less profitable lands can affect food security (Chapter 4, this volume), it may also have positive environmental effects in comparison with expansion of annual agricultural crops (Milder et al. 2008). Harmonizing forestry and agriculture policies is key to achieving sustainable bioenergy production by ensuring integration of bioenergy crops into existing landscapes in ways that enhance benefits and avoid bad practices (Figure 5.3).



- Protecting natural ecosystems and promoting biodiversity in antropogenic landscapes through policies and governance
- Promoting higher land use productivity of food and bioenergy crops
- Promoting bioenergy crops with positive environmentalimpacts
- Integrating bioenergy, food production and landscape planning
- Balancing crop residue removal / return and soil management
- Promoting integrated sustainable production (planting perennial crops to manage nutrient run-off, increase habitat diversification, and stabilise soil

Figure 5.3. Schematic of the energy security environmental security nexus. White arrows indicate positive impacts and blue arrows negative impacts.

Key Messages

- Harmonizing forestry and agriculture policies is fundamental for the sustainable production and supply of bioenergy through integration into cropland and forestland, and land currently classified as pasture, in ways that do not compromise food production or other ecosystems services. These should include policies for marginal land and coastal areas where bioenergy expansion might also be expected.
- Rational and state-of-the-art agricultural practices can also lead to increased biomass productivity for bioenergy and spare land and sensitive ecosystems.
- Pasturelands are more abundant than croplands and have the potential to provide large amounts of land for bioenergy expansion; both crop and pasture intensification can significantly increase biomass production, thus sparing land for other uses
- In drawing up national and regional integrated forestry, agriculture and bioenergy policies it is imperative to address the underlying drivers of land conversion and unsustainable use of resources. Issues for such multi-sector policies include full valuation of forest goods and services, opportunity costs of forestland conversion and alternative cropping systems, governance and law enforcement, institutional capacities, safeguarding local user rights and land tenure arrangements.
- Enabling conditions for effective land use policies include, *inter alia*, integrated land use mapping and planning, as well as eliminating perverse subsidies or regulatory barriers. There is also an urgent need to increase the coordination of objectives and planning within governments, as well as between governments and concerned international institutions, NGO’s and the private sector.
- Incorporating initiatives such as REDD+ programs and Green Economy into national development strategies would constitute another venue to strengthen cross-sector forestry and agriculture policies and aligning implementation pertaining to bioenergy.

5.3 Environmental Security

Understanding of the potential environmental implications of bioenergy production is a prerequisite to maximizing positive benefits, whilst ensuring that negative impacts are minimized. In this Section we demonstrate that provided there is awareness of the key issues, bioenergy production can be expanded without compromising ecosystems services. Although environmental issues need to be considered in relation to whole feedstock chains, in principle they revolve around both feedstock production and bioenergy production (Rowe et al. 2013). More emphasis is given to feedstock production here. For impacts associated with conversion see Chapter 12, this volume.

The environmental effects of industrial plants will depend upon the technologies used for feedstock processing, energy conversion and waste handling (Chapter 18, this volume), and on whether the infrastructure needed (buildings, transport, etc.) already exists. The environmental implications of feedstock production will depend on whether there is use of existing resources (e.g. forests, crops and residues), expansion of land under forests, or crops that are already widely grown (e.g. sugarcane, maize, oil palm, eucalypt), or whether there is planting of crops that have not previously been grown extensively (e.g. perennial energy grasses, fast growing trees, Jatropha) (Chapters 10 and 11, this volume).

As discussed in Section 5.2.3, whilst the initial change will occur in a specific location (e.g. a plantation or field, or use of a site for an industrial plant), environmental effects need to be considered at appropriate scales (Chapter 12, this volume). Water, for example should be considered with respect to whole catchments (see Section 5.3.2) whilst biodiversity needs to be considered in the clear understanding that spatial ranges for foraging, dispersal and reproduction will be species-dependent and potentially far-ranging (see Section 5.3.1 and Chapter 16, this volume).

Technology options for sustainable bioenergy will differ depending on context. This includes both choice of feedstock chain and scale of adoption. Smaller scale adoption (such as for domestic heat) will normally result in much lower and even negligible impacts compared with large-scale adoption (such as for industrial power). Even at the large scale, negative impacts can be minimized if conversion of extensive and continuous land areas to bioenergy cropping is avoided and more dispersed introduction encouraged, resulting in diversified landscapes. Such landscapes would have multifunctional uses that are more in keeping with the existing ecosystem (Section 5.2.3).

To minimize negative impacts, cropping systems should be used that are known to be suitably adapted through breeding and appropriately scaled field trials in multiple environments. Use of bioenergy crops that have not been previously subjected to appropriate breeding and field testing should be discouraged, as this can lead to substantive failures that set the industry back and result in lost confidence in both the industrial and agricultural sectors (Section 5.3.3). Mismatch of crop with environment can lead to unwanted environmental consequences (e.g. invasion, excessive water use) or complete crop failure as plants succumb to local environmental stresses for which they lack tolerance. Sufficient research and development time should be supported to allow breeding and field trials of those bioenergy crops recently identified as potentially important (Chapter 10, this volume), so that informed decisions can be made about optimal siting, infrastructure needs, and economic considerations.

5.3.1 Biodiversity Related Impacts

Although any form of LUC is considered as a potential threat to biodiversity, the extremely rapid growth and the anticipated upward trajectory of the biofuels industry and consequent biodiversity losses is particularly relevant in Southeast Asia, Africa and Amazon region in South America. This, in turn, was considered to negatively impact on ecosystem services and contribute to an increase rather than decrease in GHGs and global warming. However, these concerns are not supported by recent research. Life cycle analyses of key biofuels feedstocks indicate that they significantly reduce GHGs; that biofuel production in Brazil does not threaten Amazonian rain forests; forests (Horta Nogueira and Capaz 2013); that current and proposed feedstock species do not pose risks of invasiveness; and that ecosystem services can be maintained if appropriate agricultural practices are implemented. Biofuels can contribute to the avoidance of the greatest threat to biodiversity – climate change.

This positive trend in research results should not be taken to mean that bioenergy does not pose any risks for the environment. Three general principles for sustainable biofuels production systems can be recognized (Chapter 16, this volume):

1. *Conservation of priority biodiversity is paramount*. Recent meta-analyses on global trends in species extinction rates point to three key issues of importance to the biofuels industry. First, when it comes to maintaining tropical biodiversity, there is no substitute for primary forests (Gibson et al. 2011). Second, the rapid disruption of tropical forests probably imperils global biodiversity more than any other phenomenon (Laurence et al. 2012). Third, protected areas are the cornerstone of conservation efforts and now cover nearly 13% of the world's land surface, but globally, half the important sites for biodiversity protection remain unprotected (Butchard et al. 2010). Thus, the development of the biofuels industry must take into account the critical vulnerability of tropical ecosystems for the maintenance of the world's diversity of life.
2. *Effects of bioenergy on biodiversity and ecosystem services are site and context specific*. Biodiversity resources are unevenly distributed across the globe. As a consequence, any consideration of the impacts of bioenergy on biodiversity is likely to be biome-, site- and context-specific. Similarly, the agricultural potentials, socio-economic context, technical and scientific capacities and political trajectories of countries vary significantly around the globe. Feedstock selection and bioenergy production guidelines need to be location specific. Existing global and regional information systems makes possible the identification of key biodiversity sites of concern to guide decisions on land use planning.
3. *Management practices in bioenergy production should minimize threats to biodiversity and ecosystem services*. Good practice guidelines, standards and certification systems, technology transfer and capacity development programs are available for sharing between biofuels producer and user countries. These should optimize bioenergy productivity while minimizing threats to natural capital. The breeding, testing and use of selected feedstocks for environmentally safe, economically profitable and socially acceptable use in degraded lands and areas of marginal agricultural productivity should enjoy priority instead of the expansion of biofuels production over non-cultivated lands.

Advances towards more sustainable bioenergy production systems will benefit from a systems perspective, recognizing the spatial heterogeneity of landscapes, ecosystems and species, the temporal dynamics of seasonality in animal breeding and migration behavior, and landscape level processes dependent on catchment connectivity, fluxes in water-yield and nutrient cycling. Agricultural practices that incorporate mosaics of natural habitats, pastoral lands, croplands and forestry plantations will optimize the maintenance of biodiversity and ecosystem processes while ensuring sustainable production, resilience to uncertain future changes, and preservation of cultural values in the living landscape (Herrero et al. 2010; Vilela et al. 2011). Mixed systems also bring economic advantages because short cycle crops or livestock are regular source of income. The maintenance of corridors of riverine and wetland ecosystems, forest patches and woodlands should be included in integrated land use planning and zonation based on explicit, recent, spatial information systems of the appropriate scale and policy relevance. Both biophysical and socio-economic data should be incorporated into such information systems, which will need trans-disciplinary approaches to design, collect and use in biofuels production systems.

The adoption of more sustainable agricultural practices entails defining goals for sustainability within the particular context, developing easily measured indicators of sustainability and monitoring them over time, moving toward integrated agricultural systems, and offering incentives or imposing regulations to affect behavior of land owners. Good governance, strong institutions, market based voluntary certification, and access to information about appropriate management strategies and tactics all support sustainable resource use and management that can benefit biodiversity (Verdade et al. 2014b).

5.3.2 Water Supply and Quality Impacts

5.3.2.1 Impacts on Water Resource Abundance

Agriculture is a major user of water and expansion of agriculture can affect water availability for other uses (see Chapter 18, this volume). Additionally, there are specific concerns relating to many bioenergy crops, which are fast growing with a capacity for high biomass yields, and consequently potential “high water users”. They can also have deeper root systems and longer growing seasons than arable crops, raising concerns over impacts on water recharge. However, the estimates for water use in bioenergy production are highly variable. Processing of biomass to biofuel typically requires one to six liters of water per liter of fuel (Chapter 12, this volume). The water requirements for biomass production vary significantly by crop, cultivation practice and location, and estimates of the water requirements due to methodology differences. Several hundred to several thousand liters of water per liter biofuel can be consumed in natural evapotranspiration of rain-fed crops and is included as water loss in many estimates, rather than an ecosystem service. Competition for water will occur in water-limited areas and it is in such areas of production that bioenergy feedstocks need to be carefully managed. Climate change also needs to be taken into consideration as this may change the distribution of water availability in both space and time.

Most crop models indicate that the available water content of the soil is one of the most critical factors limiting yield, alongside day length and temperature. The soil available water content depends on both soil type and climate. Sandy soils have limited water-holding capacity (both water and nutrients drain away), whilst clay soils may hold too much water resulting in limited oxygen for root growth. To avoid excessive run-off, use of soil maps is essential (see also Section 5.3.3).

The evaluation of bioenergy systems with respect to reference systems is not well developed. The reliance on water footprints obscures complete impact analysis, discounting local effects. The use of water use efficiency (WUE) concept, which refers to the use of water in relation to biomass or bioenergy produced, can be misleading and is not as informative as the total water budget, which considers water used throughout the season. Important considerations with respect to different cropping systems, in addition to WUE, include canopy architecture, length of growing season, canopy duration, rainfall interception by the canopy, rooting depth and litter/residue coverage. Thus, a perennial with high WUE may start using water earlier than annual crops and continue using water for longer. Moreover, if the plant retains leaves after senescence, long into the winter, there will be a degree of rainfall interception by the leaves.

Through good cooperation with breeders and proper landscape-level planning, optimal crops can be selected for different environmental conditions so that negative water impacts are minimized, particularly where water availability is of concern. For example, plants such as short rotation coppice (SRC) willows can be used to mitigate against water-related environmental problems, such as flooding, excess nutrient run-off, and wastewater treatment (Mirck et al. 2005). Growing SRC willow in this way is attractive to farmers as the added value that the phytoremediation confers on the energy produced has the potential to improve the economic sustainability of the crop (Rosenqvist and Dawson 2005). Such environmental applications have become increasingly important to meet the requirements for improved organic waste handling and for operational tools aimed at water protection, such as the water framework directive of the EU. As climate change will result in exacerbation of many environmental issues continued crop breeding of plants adapted to water-limited and water-excess environments is essential.

In seasonally water-limited areas, it is impossible to rule out the unsustainable use for water in any agricultural or silvicultural endeavor under current policy regimes in most nations. Although there is no inherent need for bioenergy feedstocks to use irrigation, the growth of bioenergy feedstocks is an economic activity that occurs in the context of agricultural and silvicultural production, and, in some areas, managed production of plant materials for a variety of uses includes irrigation. Sometimes, supplementary irrigation in rain fed areas can significantly increase biomass yield (Gava et al. 2011) with little additional water use. Unfortunately, irrigation can involve the unsustainable use of water resources. Since this can present ethical problems related to water security, water withdrawals (both quantity and timing) should be carefully considered in context of watershed needs, vulnerability, and resiliency. Use of drought-tolerant plants, plants adapted to regional seasonal water constraints, and proper management of water transfers and groundwater recharge can mitigate water stress impacts.

Water requirements for biofuel processing continue to improve. Water use per ton of feedstock has decreased dramatically for both corn and sugarcane ethanol (Januzzi et al. 2012). However, water demand by new or expanded facilities can still be problematic in water stressed regions. Technological improvements in water recovery and recycling have progressed to the point that some facilities are able to use municipal wastewater and some have achieved closed loop recycle.

To determine whether growing and processing bioenergy feedstocks impacts on water availability for other uses requires a complete understanding of the water balance at the watershed and/or basin level. This means a full understanding of the land cover-soil-atmosphere feedbacks on the hydrologic cycle in the context of all human uses and ecosystem functions (Chapter 18, this volume). Determining “competition” requires a common understanding of “acceptable limits” to change in the hydrologic system components and requires agreement on metrics, methodology, and ethical values, including social, economic, and environmental sustainability criteria.

5.3.2.2 Impacts on Water Quality

As mentioned above, some bioenergy crops have a unique advantage of being able to take up excess nutrients and even pollutants such as heavy metals. However, the expansion of bioenergy production provides both an opportunity to improve water quality and the potential to decrease it. The effects will depend entirely on management choices including the fit of the feedstock to the local watershed and the methods used to establish, maintain, and harvest such feedstocks. The negative effects of agriculture (tilling, the use of pesticides and herbicides, and overuse of synthetic fertilizers) and industrial processing (discharge of chemicals) on surface and ground water are well documented (Liu et al. 2012; MacDonald et al. 2011; Sutton et al. 2013). However, there are improved wastewater management, agronomic practices, and novel bioenergy feedstocks that can diminish or eliminate many of these impacts (Fixen 2009; IFA 2009; Neary and Koestner 2012; Snyder et al. 2009). When combined at the landscape level, these new practices can increase water quality in some watersheds.

Nutrient runoff and erosion remain concerns for sustainable bioenergy production. While there has been some progress in management practices for both corn and sugarcane ethanol production systems, some watersheds continue to see high nutrient loads, including no-till and green harvest for sugarcane. The use of riparian buffer strips to capture nutrients from field run-off has increased and offers an opportunity for next-generation perennial crops and woody biomass to improve water quality. Perennial systems are already being deployed to control runoff and erosion (see Box 5.1 and Chapter 18, this volume).

Bioenergy conversion processes have non-negligible impacts on water quality; however, these impacts are similar to activities such as electricity and beverage alcohol production. Stillage from biofuel production represents both a problem and an opportunity. Several companies have developed processes that treat and recycle water from stillage within the facility (Mutton et al. 2010). Nutrients can be recovered directly, as is the common case of vinasse fertirrigation in Brazil, (Magalhães et al. 2012), or following treatment by anaerobic digestion or emerging technologies such as hydrothermal liquefaction. While biogas recovery from stillage is becoming more common in refineries in the U.S., nutrient recovery from the process has not been fully embraced.

Bioenergy can offer substantial solutions to remediation of wastewater and waste products from other activities. Generation of biogas from food waste, animal manure, and municipal wastewater not only addresses discharge of organic material into surface waters and reduces landfill, it can displace fossil methane use contributing to substantial GHG reductions. New data on the use of saline-tolerant lignocellulosic feedstocks that can remediate some wastewater streams provides strong evidence for substantial new landscape level optimization opportunities.

5.3.2.3 Selecting Watershed Appropriate Bioenergy Systems

The best approach to avoiding unwanted effects on watersheds is to appropriately match feedstocks and conversion systems to individual watershed requirements. Matching growing season to patterns of soil moisture availability, selecting for appropriate water use efficiency and tolerance to flooding and drought can alleviate stress in watersheds while improving productive capacity.

Climate change presents a special challenge and highlights the needs for a wide suite of resilient bioenergy feedstocks and appropriately adaptable conversion solutions. Government policy has an important role in incentivizing integrated sustainable solutions that fully consider effects on water resources. Policy regulating water withdrawal and water quality continues to evolve in both forest management and agricultural contexts in many countries; however, it is still considered largely insufficient for long-term sustainability goals. While bioenergy offers an opportunity to re-examine water policy, the dialogue should not be restricted to bioenergy only.

5.3.3 Soil Quality and Nutrient Cycling Impacts

The preservation of the soil chemical, physical and biological characteristics associated with soil quality is essential for long term productivity for different purposes, including food and bioenergy (Chapter 18, this volume). The exploitation of soils beyond their ecosystem capacity may jeopardize soil quality. Erosion, nutrient impoverishment, soil compaction, and reduction of microbiological activity or biodiversity may cause land degradation and compromise important soil resources. Agriculture and biomass production for bioenergy can be the cause of downgrading soils but also can help to protect or recuperate soil quality.

Soil erosion is a major source of land degradation. Over cultivation and excessive export of plant material can have detrimental effects on soil quality (Zuazo and Pleguezuelo 2008), especially in marginal lands and high sloping areas. However, plant cover and roots are important means of controlling or reducing soil erosion (Zuazo and Pleguezuelo 2008) and cultivation of grasses or perennial crops for bioenergy is a way of helping to preserve soils (Anderson-Teixeira et al. 2013; Khanal et al. 2013) and can be part of a sustainable land use system (Dimitriou et al. 2011).

Despite the well-known benefits of forest and perennial plant cover to soil preservation, the intense mechanical operations associated with plant and harvesting usually cause soil compaction and disrupt soil aggregation and structure (Bottinelli et al. 2014; Goutal et al. 2012; Goutal et al. 2013), which increases the risks of erosion, negatively affects plant rooting and water retention and infiltration. Therefore, proper management of forest resources for bioenergy is necessary for sustainable production (Bellassen and Luyssaert 2014; Egnel and Björheden 2013 Holub et al. 2013; Kleibl et al. 2014).

In any cropping system, mining nutrients from the soil with inadequate or insufficient fertilization, removing excessive amounts of plant material or improper disposing of residues may reduce soil fertility, cause loss of organic matter and predispose soil to erosion (Lal 2009). However, properly managed bioenergy crops, particularly perennial systems which recycle the majority of their nutrients and do not require annual cultivation of the soil, can help to maintain soil quality and lead to carbon accumulation, thus both improving soil quality and mitigating CO_2 emissions (Anderson-Teixeira et al. 2013; Figueiredo and La Scala Jr. 2011; Segnini et al. 2013).

Excessive use of nutrients may cause environmental problems if they contaminate ground water and surface water bodies. In addition, the manufacture and use of nitrogenous (N) fertilizers are important components of the GHG and energy balances of agriculture (Boddey et al. 2008; Lisboa et al. 2011). Those bioenergy crops that efficiently use N fertilizers usually have a better carbon footprint. There are several crops employed in biofuel production that present such characteristics. For example, sugarcane can have dry matter yields above 30 tha^{-1} with only 30 to 120 kgha^{-1} of N fertilizers (Cantarella and Rossetto 2012); eucalyptus and other woody plants also have almost similar performance. Miscanthus, depending on when it is harvested, translocates most nutrients from the above-ground plant parts to the roots and rhizomes before harvest, thus preventing excessive removal of N from the field and reducing the need for fertilization (Chapter 11 and 18, this volume).

However, for some agricultural systems, especially for annual plants, crop intensification may be an option to enhance biomass production (Snyder et al. 2009). Although this usually means more agrochemical inputs, the overall effect may be positive in the sense that high plant yields allow for the optimization of other resources such as soil, water and solar energy. In addition, high yields may mean less land demand, thus helping to preserve other land uses, including natural ecosystems. The adoption of best management practices is important in crop intensification because it tends to minimize risks of excessive or inadequate use of inputs (Mead and Smith 2012; Snyder et al. 2009).

The high biomass production of some crop systems dedicated to bioenergy can also increase soil organic matter, which improves soil quality and may also mitigate CO_2 emission. Usually, the replacement of row crops with perennial plants or the cultivation of degraded land with crops for bioenergy enhances soil carbon content. Several studies have demonstrated that sugarcane harvested without burning causes a significant increase in soil carbon (Bordonal et al. 2012; Galdos et al. 2010; Pinheiro et al. 2010; Thorburn et al. 2012). On the other hand, corn stover, wheat straw and sugarcane trash, among others, are increasingly important feedstocks for bioenergy and the industry wants to collect as much as possible. However, excessive removal of plant material from the field may jeopardize long-term soil quality, causing economic and environmental losses. The amounts of plant residues that have to be preserved are site-specific (Cantarella et al. 2013; Gollany et al. 2011; Hassuani et al. 2005; Karlen et al. 2011; Leal et al. 2013; Tarkalson et al. 2011) and regional data are important to guide farming practices.

Bioenergy crops offer good opportunities for nutrient recycling, thus improving the overall sustainability of the system. Biofuels such as ethanol and biodiesel are composed of carbon (C), oxygen (O), and hydrogen (H). Therefore, the mineral nutrients contained in the biomass feedstock are not exported with the fuel and theoretically may be recycled back to the fields. Typically, sugarcane mills in Brazil return residues such as ash, filter cake and vinasse of the ethanol production to the field in various ways, which allows reduced fertilizer application. The vertical integration of the sugarcane industry in Brazil, in which large areas of field crops belong to the mill, makes the distribution of the residues easier because of shorter distances, rights of access of pipelines and trucks, etc. (Magalhães et al. 2012). But residues are bulky materials with low nutrient concentrations and unit value. Industries with other scales, structures and feedstock supply systems may not share these favorable conditions and may require different solutions (Mutton et al. 2010).

Some residues such as vinasse, a by-product of ethanol production, deserve attention. Large amounts of vinasse are produced in the ethanol industry (10 to 13 L/L ethanol, in the case of sugarcane). If dumped in water bodies it will cause environmental problems because of its high biological oxygen demand. Excessive application to the soil also has detrimental effects. However, when adequately returned to soil, vinasse acts as a source of readily mineralizable organic carbon and nutrients, reducing the need for fertilizers.

The bulky nature of residues imposes limits to recycling. In Brazil, it is usually economically feasible to apply fresh vinasse up to 25 to 30 km from the processing plant, through trucks, pipelines and other means. However, the increasing size of mills and continuous application of vinasse in soils close to the plant make it necessary to carry the residue longer distances. Concentrating vinasse by removing water and biodigestion are devised options. The latter generates biogas, an extra source of energy. However, reducing costs for these solutions is a challenge. Vinasse from second generation biofuels will have other properties, such as lower nutrient levels, and may need different solutions. Proper legislation is important in order to stimulate the adequate utilization of residues (Box 5.1).

Box 5.1. Sugarcane vinasse disposal in Brazil (Mutton et al. 2010)

In the past vinasse was considered a nuisance in the ethanol industry and many times it was just dumped in rivers at a time when environmental concerns were less important. Successive rules and regulations changed behaviors and perceptions and today vinasse is seen as a valuable source of nutrients to be recycled:

1978: Directive 323 (Ministry of Internal Affairs): vinasse disposal in water bodies is forbidden. Project for vinasse treatment and use is required.

1980: Directive 158 (Ministry of Internal Affairs): Extend directive 323 to encompass other residual waters and distillery effluents.

1984: Resolution 002 (Conama): stricter projects to control pollution from effluents of ethanol distilleries.

1986: Resolution 001 (Conama): turn mandatory the projects of Environmental Impact Assessment and Environmental Impact Report for approval of new distilleries or expansion of existing ones.

1988: Establish that liquid, solid or gaseous residues from agriculture and other sources shall be disposed of in a way that will not pollute underground water. Additional regulation in 1991 (Decree 32,995).

1991: Law 7.641: industrial effluents of organic origin used for irrigation or fertigation must have evidenced biodegradability in soil and be free of organo-metallic compounds.

2005: Technical Norm P4.231 (Cetesb, São Paulo State): further control of vinasse use in agricultural soils. Establishes detailed rules for the rate of vinasse application based on vinasse and soil composition so that exchangeable K in the 0-0.8 m soil layer does not exceed 5% of the cation exchange capacity or that the K load is compatible with amounts extracted by sugarcane.

Before the technical Norm P4.231 was applied, “sacrifice areas” where overdose of vinasse was applied were common. In some soils, plants could undergo salt stress because of excess K and other nutrients, a problem that is prevented by present legislation.

Plant species and varieties have limitations as far as the soils and climates for which they were bred or selected. Insufficiently tested crops may present poor results and jeopardize bioenergy promoting programs. Some crops were promoted for bioenergy production before they were at a stage where they could be widely cultivated without risk. For instance, Jatropha (*Jatropha curcas*), which is a perennial crop used to produce oil, has been promoted as a drought tolerant oil crop capable of growing in marginal, low fertility soils and yet capable of yielding high amounts of seed and oil. Jatropha has been little studied but its cultivation has been stimulated in many regions. In 2008 an estimated 900 thousand hectares of Jatropha was cultivated worldwide, most of it in Asia (Kant and Wu 2011). Reports of failure to meet expectations are common. In India the Government incentivized small farmers to plant Jatropha but after a short time, most farmers discontinued cultivations because of unsatisfactory results (Openshaw 2000; Kant and Wu 2011; Kumar et al. 2012). Similar unfavorable results were reported in Asia and Africa (Kant and Wu 2011; Mudonderi 2012). In Australia, Jatropha has been declared a noxious weed, because of its propensity to produce masses of seed that can quickly establish new plants in low rainfall areas. Thus, Jatropha, as is the case for many other species, may have potential to become a bioenergy crop but much agronomic work is still necessary before it can be widely recommended.

Key Messages:

- Bioenery production can have either positive or negative impacts on biodiversity, dependent on scale, practice and site conditions.
- Water impact assessment at all levels of the bioenergy value chain should be transparent, with broad stakeholder engagement and included in sustainable certification schemes, using metrics which are consistent with other agricultural and silvicultural activities.
- The use of water footprints and the reliance on WUE, or productive water use, in lieu of proper ecosystem impact analysis should be avoided. Such metrics, while convenient and intuitive, can be highly misleading and irrelevant to achieving sustainable production and environmental security.
- Wherever possible, full water budget analysis should be conducted for the bioenergy system and an appropriate reference state (e.g., other crop, native ecosystem). Water impact assessments for bioenergy must account for changes at the watershed and basin level due to other human activities, climate change, and evolving ecosystem needs.
- The use of irrigation for bioenergy must be subject to a high level of scrutiny. Irrigation of energy crops may need to be avoided, even in instances where it represents the most productive use of available water in terms of output or income per unit water, if there is a risk for serious impacts on local livelihoods and food security. However, there may be some conditions under which irrigation can be compatible with sustaining ecosystem services. Caution, periodic evaluation, and appropriate water pricing and allocation systems can help avoid unwanted effects in water-stressed regions.
- The high nitrogen use efficiency of many bioenergy crops means that they have a better carbon footprint than arable crops. Once perennial cropping systems are established the ground is not cultivated annually and both soil quality and soil carbon stocks can be increased.

- Bioenergy crops also may offer good opportunities for nutrient recycling and strategic planting can help alleviate environmental problems associated with intensive agriculture, such as nutrient run off.

5.4 Climate Security

In this section bioenergy technologies and bioenergy mitigation options, and their potential in climate stabilization are discussed. Modern bioenergy is a highly versatile energy in solid, liquid, and gaseous form for a range of applications including cooking, heating, and transport. It can also be used for electricity generation. Bioenergy can bring about sustainable development by providing energy for many services, promoting particularly rural development, self-reliance, energy security, and finally mitigating climate change. Bioenergy is receiving increasing attention as an opportunity for addressing climate change, as indicated by recent major reports: IPCC – SRREN of 2011 (IPCC 2011), Global Energy Assessment of 2012 (GEA 2012) and the latest IPCC – Assessment Report 5 of 2014 (IPCC 2014a). According to IPCC (2014a), bioenergy deployment offers significant potential for climate change mitigation but it depends on i) Technology used; ii) Land category used and carbon stock on land (Forest land, grassland, cropland or marginal land), iii) Scale of production and iv) Feedstock used and source of feedstock.

Bioenergy conversion technologies: A large number of bioenergy conversion technologies are available to transform biomass into heat, power, liquid and gaseous fuels for application in residential, industrial, transport and power generation. Detailed coverage of the bioenergy conversion technologies is provided in Chum et al. (2011), GEA (2012) and Smith et al. (2014). Some of the recent large scale applications include; increased use of biomass – hybrid fuel systems, direct bio - power generation, combined heat and power, biofuels from multiple sources along with small scale applications of bioenergy technologies such as improved cook stoves, biogas and decentralized biomass power systems in rural areas. Technologies to produce cellulosic, Fisher – Tropsch, algae based and other advanced biofuels are in development and may become available for commercial use in future. Bio- methane from biogas or landfill gas can also be used in natural gas vehicles. BECCS (Bioenergy and Carbon Capture and Storage) is one of the important new opportunities which is capable of not only being a carbon neutral technology but also potentially lead to net removal of CO_2 from the atmosphere. BECCS offers potential for large-scale net negative GHG emissions, but the technology is still in development phase and many technical challenges remain.

Net GHG mitigation benefit from bioenergy technologies: The net GHG or mitigation potential of different bio-energy crops and technologies is highly contentious (Chapter 17, this volume). The IPCC- SRREN report (Chum et al. 2011) provides the end-use lifecycle GHG emissions for corn, oil crops, crop residues, sugarcane, palm oil and grasses, etc. Chum et al. (2011) concluded that the direct CO_2 emissions per GJ (excluding Land Use Change) are lower for most bioenergy technologies compared to electricity from coal and oil. Life-cycle GHG emissions for biogas and biomass are lower than fossil fuel options for electricity and heat generation. Similarly, direct CO_2 emissions for sugarcane, sugar beet, corn and wheat and lignocelluloses for ethanol production are lower compared to gasoline (Horta Nogueira and Capaz 2013; Walter et al. 2014; Wicke et al. 2012).

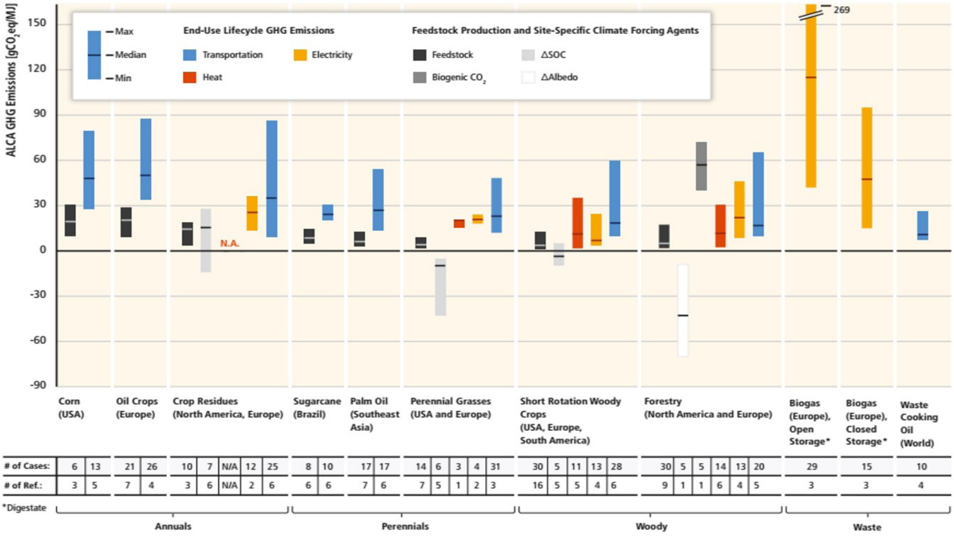


Figure 5.4. Direct CO_2eq (GWP100) emissions from the process chain or land-use disturbances of major bioenergy product systems, not including impacts from LUC (Smith et al. 2014).

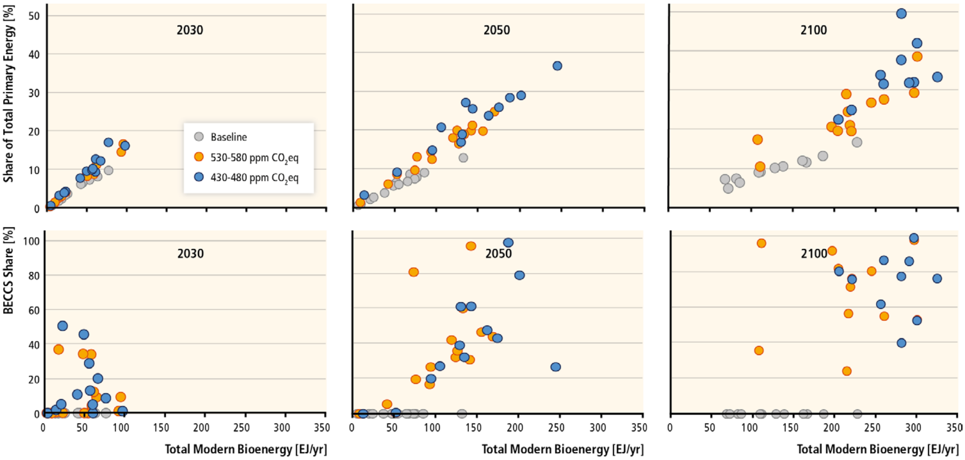


Figure 5.5. Annual global modern biomass primary energy supply and bioenergy share of total primary energy supply (top panels) and BECCS share of modern bioenergy (bottom panels) in baseline, 550 ppm and 450 ppm CO2eq scenarios in 2030, 2050, and 2100. Source: Rose et al. (2014). Notes: All scenarios shown assume idealized implementation. Results for 15 models shown (3 models project to only 2050). Also, some models do not include BECCS technologies and some no more than biopower options.

The IPCC – 2014 report (Smith et al. 2014) presents a comprehensive assessment of a range of lifecycle global direct climate impacts (in g CO_2 equivalents per MJ, after characterization with GWP (time horizon=100 years) attributed to major global bioenergy products reported in the peer-reviewed literature. Results are broadly comparable to those by Chum et al. (2011), who reported negative emissions, resulting from crediting emission reduction due to substitution effects. The results presented in Figure 5.4 do not allocate credits to feedstocks to avoid double accounting.

The assessment shows diverse values depending on the methods and the conditions used in the studies, site-specific effects, and management techniques. It can be observed that fuels from sugarcane, perennial grasses, crop residues, and waste cooking oil provide higher net GHG benefits than other fuels (LUC emissions can still be relevant). Another important result is that albedo effects and site-specific CO_2 fluxes are highly variable for different forest systems and environmental conditions and determine the total climate forcing of bioenergy from forestry. Thus, for the majority of bioenergy crops involving no LUC from high carbon density lands, net GHG benefits are likely.

Bioenergy and mitigation potential: Diverse global estimates of the potential of bioenergy are available. Chum et al. 2011 estimated a technical potential of 300 -500 EJ by 2020 and 2050, respectively and a deployment potential of 100 – 300 EJ globally by 2050. The Global Energy Assessment provides a potential estimate of 160-270 EJ/year (GEA 2012). However, Smith et al. (2014), suggest a technical bioenergy potential of about 100 EJ possibly going up to 300 EJ.

Rose et al. (2014) project increasing deployment of, and dependence on, bioenergy especially with high climate change mitigation goals. Share of bioenergy in total regional electricity and liquid fuels is projected to be up to 35% and 75%, respectively, by 2050. The availability of BECCS is critical for large-scale deployment of bioenergy. Share of modern bioenergy under Baseline, 430-580 ppm CO_2 eq and 530-580 ppm CO_2 eq is presented in Figure 5.5. The share of modern bioenergy is projected to increase even under Baseline scenario by 2050 and 2100. Under stringent mitigation scenarios, the share of modern bioenergy could be in the range of 20-30 % by 2050 and going up to 30-50% by 2100 of Total Primary Energy for majority of model projections. In scenarios that include BECCS technologies, BECCS is deployed in greater magnitude and even earlier in time and potentially representing 100% of bioenergy in 2050 (Figure 5.5). Rose et al. (2014) further project that bulk of biomass supply for bioenergy and bioenergy consumption will occur in developing and transitional economies. Thus developing countries will play a critical role in promoting bioenergy technologies in the coming decades.

According to the IPCC (2014b), BECCS is critical to scenarios for the stabilization of global warming at <2°C; however, the potential and costs of BECCS are highly uncertain with some integrated assessment models being more optimistic than bottom-up studies.

Apart from large-scale commercial and high technology-based modern bioenergy applications, Smith et al. (2014) also highlight the importance of bioenergy for rural applications and for creating access to modern energy services for the poor. Improved cookstoves, biogas, and decentralized small-scale biomass power could not only improve the quality of life, livelihoods and health of 2.7 billion rural inhabitants, but also reduce GHG emissions.

There are several barriers to large-scale deployment of bioenergy for mitigating climate change. These include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. Sustainability and livelihood concerns might constrain the large-scale deployment of bioenergy production systems. The potential of bioenergy could be adversely impacted by climate change itself. The IPCC (2011) concluded that "the future technical potential of bioenergy can be influenced by climate change through impacts on biomass production such as altered soil conditions, precipitation, crop productivity and other factors. The overall impact of mean temperature change of >2^0 C on the technical potential of bioenergy is expected to be relatively small on a global scale. However, considerable regional differences could be expected." Porter et al. (2014) also conclude that if climate change detrimentally impacts crop yields, the bioenergy potential may decline and costs may rise because more land will be required for food production. Further, biofuel production could also be adversely impacted by climate change, constraining shift to low carbon fuels (de Lucena et al. 2009).

According to IPCC (2014a) achieving high bioenergy deployment levels for mitigating climate change would require, "extensive use of agricultural residues and second-generation biofuels to mitigate adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with CCS to produce low net GHG-emitting transportation fuels and/or electricity". Land demand for bioenergy, which is one of the major concerns and a barrier, depends on: (1) the share of bioenergy derived from wastes and residues; (2) the extent to which bioenergy production can be integrated with food and fiber production, and conservation to minimize land use competition; (3) the extent to which bioenergy can be grown on areas with little current production; and (4) the quantity of dedicated energy crops and their yields. The GEA (2012) concludes that extensive use of agricultural residues and second-generation bioenergy is necessary to mitigate adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with CCS to make low net GHG-emitting transportation fuels and or electricity.

The IPCC AR-5 approved 'Summary for Policy Makers' (IPCC 2014c) states the following on bioenergy in the context of climate security: "Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land use competition effects of specific bioenergy pathways remains unresolved. Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e.g., sugarcane, Miscanthus, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. As mentioned above, in some regions, specific bioenergy options, could reduce GHG emissions and improve livelihoods and health in the context of sustainable development".

Key Messages:

- Bioenergy is critical for climate security and energy security. Bioenergy, particularly BECCS is critical for mitigation of climate change, especially for low climate stabilization scenarios (at <2^{O}C increase in global temperatures).
- The IPCC's Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC 2011) suggested a sustainable bioenergy potential to be between 100-300 EJ by 2050. The GEA (2012) projects a potential of 80-140 EJ by 2050. The IPCC (2014b) suggested a conservative technical potential of 100 EJ and possibly going up to 300 EJ.
- The share of bioenergy in the global primary energy supply will continue to increase even under Baseline scenario, thus it is necessary to ensure that bioenergy is produced sustainably with no or minimal adverse environmental and socio - economic impacts.
- The negative implications of land deployment for bioenergy can be avoided or minimized by: i) production and utilization of co-products, ii) increasing the share of bioenergy derived from forest, plantation, and crop wastes and residues, iii) integrating bioenergy production with crop production systems and in landscape planning, iv) increasing crop land productivity especially in developing countries, freeing up crop land for bioenergy crops, and v) deploying marginal or degraded lands.
- Achieving high level of deployment of bioenergy requires extensive use of agricultural residues and second-generation biofuels to mitigate the adverse impacts and land use and food production, and co-processing of biomass with coal and biogas with CCS to produce low net GHG emitting transportation fuels and/or electricity.
- Modern bioenergy deployment for meeting rural energy needs (cooking, lighting and mechanical applications) not only creates energy access for rural communities and promotes quality of life, but also reduces GHG emissions, with no or minimal environmental impacts.

5.5 Governance and Policy Guidelines

This Section considers governance perspectives relating to sustainable bioenergy development and pays particular attention to the agriculture-forestry nexus where national and regional integration is required.

5.5.1 Underlying Causes of Deforestation

General underlying drivers of forestland conversion and unsustainable use of forest resources include undervaluation of forest goods and services, poor governance, institutional failures such as inadequate law enforcement, low financial returns on forest use compared to other uses, lack of local user rights and inadequate land tenure arrangements as well as other disincentives to sustainable forest and agricultural resource use. From another governance perspective, there are also negative social impacts of uncontrolled agricultural expansion into forests. Medium- and large-scale forest plantations may stimulate land concentration, which may displace local people and threaten their livelihoods (Pacheco et al. 2012). Furthermore, the evolving, and often growing, global markets for forest products, including feedstock, and the relocation of processing capacity create increased local deforestation in producing countries, *i.e.*, consuming countries are increasing their imports and thus “exporting deforestation” as production of raw material shifts mostly to Africa and South America.

To ensure bioenergy is only developed in sustainable ways, it is important to recognize the general drivers of forestland conversion and put into place governance policies that are designed to avoid unsustainable exploitation of natural forests for biofuels. The linkages between agriculture and mitigating GHG emissions, forestry and bioenergy need to be considered from different yet interdependent governance angles: (a) agriculture and forestry are major sources of GHG emissions, (b) horizontal expansion of agriculture is mostly at the expense of clearing forests, although other alternatives for increasing agriculture production in the tropics exist (Martha Jr. et al. 2012; Pereira et al. 2012); (c) competition among food, fodder, fiber and fuel production often occurs on the same landscape, and (d) socio-economic factors, especially those related to land tenure and rights of indigenous peoples.

The need for a global response to the challenges of climate change, deforestation, biodiversity and food security has already been recognized in international commitments and conventions. The Brazilian Forest Code is a good example of conservative law applied to agricultural landscapes since early last century. Although it lost part of its contents for political pressures recently, it still assures that agricultural landscapes have the mission to keep part - varying according to the biome - of the native vegetation. Although there is no intergovernmental governance mechanism to deal with bioenergy or biofuels policies, several existing treaties and initiatives that touch upon issues related to forests, food security, energy, environment and trade are relevant to bioenergy. In building an international consensus on sustainable forest management and food security-compliant biofuels, the experiences of the existing conventions such as UNFCCC, CBD and CCD as well as the Sustainable Development Goals may prove useful.

5.5.2 Guidelines for Social and Environmental Factors – Biodiversity, Water

The existing environmental impacts caused by LUC can be mitigated by local restrictions in which limits for the expansion of biofuel crops over previously uncultivated ecosystems are established by the producing and/or the importing country. The mitigation of the usual agricultural impacts of biofuel expansions over marginal or annual crops should be based on the maintenance of connectivity among remnants of native vegetation at the landscape level and on the use of wildlife friendly agricultural practices. All these approaches are complementary in terms of public policy (Soderberg and Eckberg 2013) and national and international market (Palmujoki 2009). However, in order to be effective such strategies should include long-term monitoring programs of such environmental impacts (either positive or negative) including water, soil and biodiversity (Verdade et al. 2014a).

Key Messages:

- Climate change-forestry-agriculture-bioenergy nexus are best discussed at intra- and inter-governmental levels in order to develop and implement appropriate governance policies. Sustainable biofuel production must be part of sustainable forest management and sustainable agriculture (food security) where both are needed as integral components of land use with clear understanding of the uniquely complex set of environmental, economic and social issues involved.
- Identifying which eco-regions and countries have the greatest opportunity to use which raw material as a source for bioenergy along with analyzing the full potential and merits of each biofuel source is highly recommended as an environmental and livelihood issue. For example, the new opportunities associated with bioenergy developments may avail a potential to incorporate smallholders of both forest and agriculture communities into bioenergy production schemes, thereby improving their livelihoods.
- In drawing national and regional integrated forestry, agriculture and bioenergy governance policies it is imperative to address the full valuation of forest goods and services, opportunity costs of forestland conversion and alternative cropping systems law enforcement, institutional capacities, safeguarding local user rights and land tenure arrangements.
- Governance policies for investments related to expansion in bioenergy feedstock production through forest conversion should be clear regarding enforcement and compliance of social safeguards and environmental regulations.

5.6 Conclusions

Bioenergy has a key role to play in environmental and climate security. As for any new development, environmental consequences associated with LUC are inevitable but LUC associated with bioenergy can be positive. Many initial concerns regarding rapid expansion of particularly biofuels for example on biodiversity, and of iLUC, have not been substantiated by recent research, indicating these issues are of much less importance than indicated in the previous SCOPE Report (SCOPE 2009). However, this should not be taken to mean that there are no risks associated with bioenergy development. Governments worldwide can influence the deployment of sustainable bioenergy through the use of appropriate assessment practices, governance and policies. Assessment of environmental impacts should recognize the different attributes (both positive and negative) of different bioenergy cropping systems, particularly with regard to the use of arable (food) crops compared with more favorable perennial bioenergy crops, and must be carried out at appropriate scales (farm, landscape, region, country, global) that recognize that impacts may operate at the ecosystem (e.g.,forests, grassland, arable, coastal) level. New bioenergy croplands should be selected and developed following both Strategic Environmental Assessments (at a regional scale) and Environmental Impact Assessments (at a local and site scale) as these provide baselines for monitoring positive and negative impacts and guide adaptive management strategies. Sustainable bioenergy production should be based on, and support, good governance, strong institutions, best available scientific information, marke based voluntary certification, and access to information about appropriate management strategies that support sustainable resource use and benefit biodiversity. Through these approaches bioenergy can realize its potential for mitigation of the unprecedented environmental and climatic change that challenge the future of humankind.

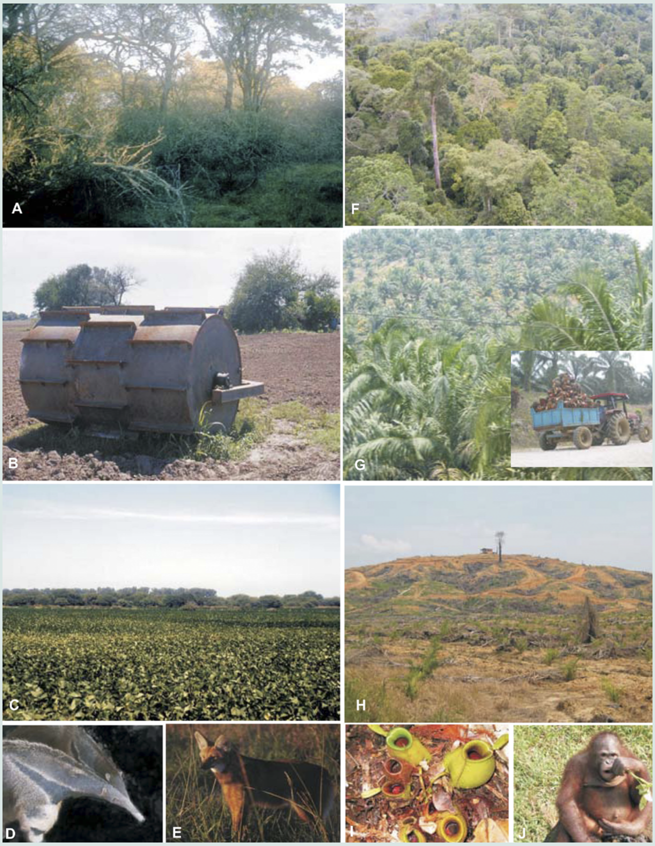
5.7 Recommendations

1. Within the context of climate change and its potentially devastating consequences, policy-makers and governments around the world now share the responsibility to encourage sustainable bioenergy development.
2. Local and global issues should be distinguished when considering the positive and negative impacts of bioenergy systems. New bioenergy croplands should be selected following both Strategic Environmental Assessments (at regional scale) and Environmental Impact Assessments (at local and site scale) and should recognize the spatial heterogeneity of landscapes, ecosystems and species, and landscape level processes dependent on catchment connectivity, fluxes in water-yield and nutrient cycling.
3. There is a clear need for increased coordination of objectives and planning procedures within governments, as well as between governments and concerned

international institutions, NGO's and the private sector. It is particularly important to recognize the interdependencies of forestry and agriculture policies with a view to harmonizing them for the sustainable production and supply of bioenergy.

4. Actions should respond with appropriate land use planning, environmental governance, law enforcement, and strengthening of institutional capacities and the safeguard of local user rights and land tenure arrangements. Incorporation of initiatives such as REDD+ programs and Green Economy into national development strategies will help to strengthen cross-sector forestry and agriculture policies and aligning implementation pertaining to bioenergy.
5. The negative implications of land deployment for bioenergy should be avoided or minimized by i) promoting bioenergy crops with positive attributes with respect to water use, soil impacts and biodiversity; ii) increasing the share of bioenergy derived from wastes and residues; iii) integrating bioenergy production with crop production systems and in landscape planning iv) increasing crop land productivity especially in developing countries, freeing up crop land for bioenergy crops, and v) deploying marginal or degraded lands. Breeding of crops that can maintain productivity on poorer land not suited that is more marginal should also be encouraged. See also Box 5.2.
6. In drawing national and regional integrated forestry, agriculture and bioenergy governance policies, it is imperative to address the full valuation of forest goods and services, opportunity costs of forestland and cropland conversion and alternative cropping systems, law enforcement, institutional capacities, safeguarding local user rights and land tenure arrangements. Governance policies for public and private investments related to expansion in bioenergy feedstock production through natural forests and farmland conversion should be clear regarding enforcement and compliance of social safeguards and environmental regulations.

Box 5.2 A. Lessons Learnt: Bioenergy done wrong

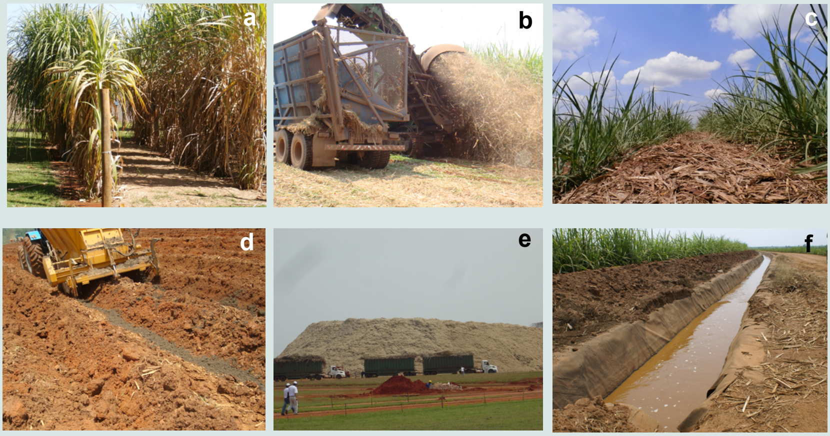


In Argentina and Bolivia, the Chaco thorn forest (A) is being felled at a rate considered among the highest in the world (B), to give way to soybean cultivation (C). In Borneo, the Dypterocarp forest, one of the species-richest in the world (F), is being replaced by oil palm plantations (G). These changes are irreversible for all practical purposes (H). Many animal and plant populations have been dramatically reduced by changing land use patterns, to the point that they could be considered functionally extinct, such as giant anteater in the Chaco plains (D), the maned wolf (E), several species of pitcher plants (I) and and the orangutan (J) in the Bornean rainforest.

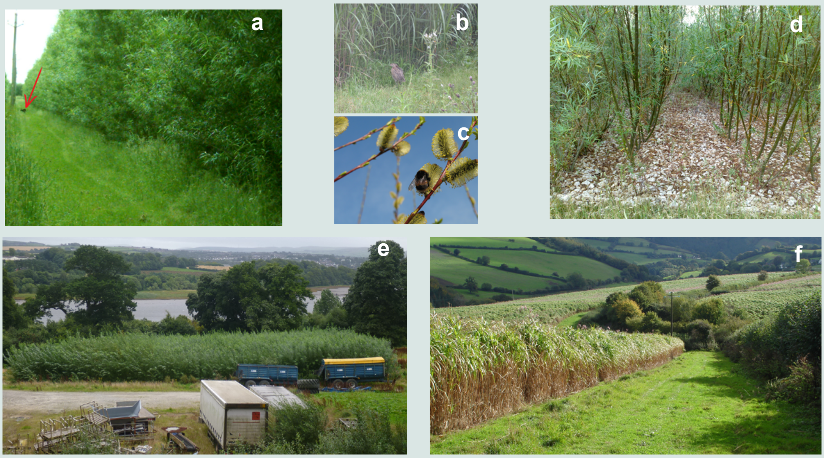
Photos by Sandra Díaz, except (A and C), courtesy by Marcelo R. Zak.

From Citation: Díaz S, Fargione J, Chapin FS III, Tilman D (2006) Biodiversity Loss Threatens Human Well-Being. PLoS Biol 4(8): e277. doi:10.1371/journal.pbio.0040277

Box 5.2 B. Bioenergy done right



Bioenergy done right Sugarcane: (a) Breeding plants with superior traits; (b) Harvesting without burning; (c) Keeping plant residues to protect the soil and recycle nutrients; (d) Recycling industrial residues (vinasse and filter cake) in the field; (e) Bagasse: by product to produce bioelectricity or 2G ethanol; (f) Fertirrigation using vinasse.



Bioenergy done right - Miscanthus and SRC willow: (a-c) Attracting biodiversity: (a) deer (arrow) in willow ride; (b) birdlife on Miscanthus border; (c) bee using early willow pollen source; and (d-f) using marginal land: (d) willow on stony, dryland site; (e) willow alongside river as a riparian filter; (f) Miscanthus in grassland-dominated area.

5.8 The Much Needed Science

- Improved methodologies for the estimating, quantifying, and verifying of LUC;
- Methods for identifying win-win situations as well as trade-offs, e.g. land-sparing pasture intensification with bioenergy crops grown so that overall soil carbon storage and fertility are increased;
- Increased trials of bioenergy crops in environments where bioenergy expansion is anticipated, to provide much needed data on crop performance in target environments before wide spread expansion;
- Breeding of resource-use efficient and “future climate-resilient” bioenergy crops;
- Continued development of integrated, resource-efficient biomass conversion pathways;
- Long-term studies of perennial bioenergy crops and short-rotation forests in relation to ecosystem services, biodiversity, water quality and availability and soil carbon;
- Policy development to encourage sustainable bioenergy development and landscape-level planning.

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chapter 6

Sustainable Development and Innovation

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Highlights

- Sustainable bioenergy has an important role to play in the future energy mix that provides access to modern energy services for all.
- Sustainable bioenergy can increase the share of renewables in view of using the variety of locally available energy sources and needs to mitigate climate change.
- Integrated assessments of bioenergy systems are essential.
- Monitoring of bioenergy systems needs to be improved.
- The public perception can impede or accelerate realization of sustainability objectives via bioenergy.
- Institutional and policy frameworks as well as capacity building are critical for sustainable bioenergy.

Summary

Bioenergy can play an important role in facilitating the attainment of sustainable development but this requires innovation and enlightened public policies that effectively respond to economic, social and environmental considerations. To promote beneficial and efficient use of natural resources via bioenergy deployment, this chapter emphasizes the need for integrated analysis and assessment of production chains, under a landscape approach to natural resources management (land, water, biodiversity) encompassing enhanced and sustained productivity (bioenergy, food, feed, feedstocks, timber), environmental services (hydrology, biodiversity, carbon) and economic value. Key needs for advancing sustainable development using bioenergy include: a) improved data gathering and analysis to support the development of appropriate public policies and governance systems in bioenergy R&D and operations, b) enhanced monitoring and evaluation of the economic, social, and ecological costs and benefits of bioenergy systems, c) enhanced institutional and human resource capacity in both public and private sectors for improved governance, knowledge generation and extension services in bioenergy systems; d) the development and promotion of innovative financing schemes for business models, especially to enable communities to benefit from small scale bioenergy projects; and e) innovative communication tools to foster enhanced participation by bioenergy stakeholders and civil society in developing integrated and state of the art bioenergy investments and operations.

Examples of Innovative and Integrated Bioenergy Systems

In order to achieve sustainable development goals, modern, efficient and well designed bioenergy systems can facilitate an effective transition towards sustainable and renewable energy systems. This is most productively approached by local natural resource management that closely matches the supply opportunities with local demands operating at an integrated landscape scale.

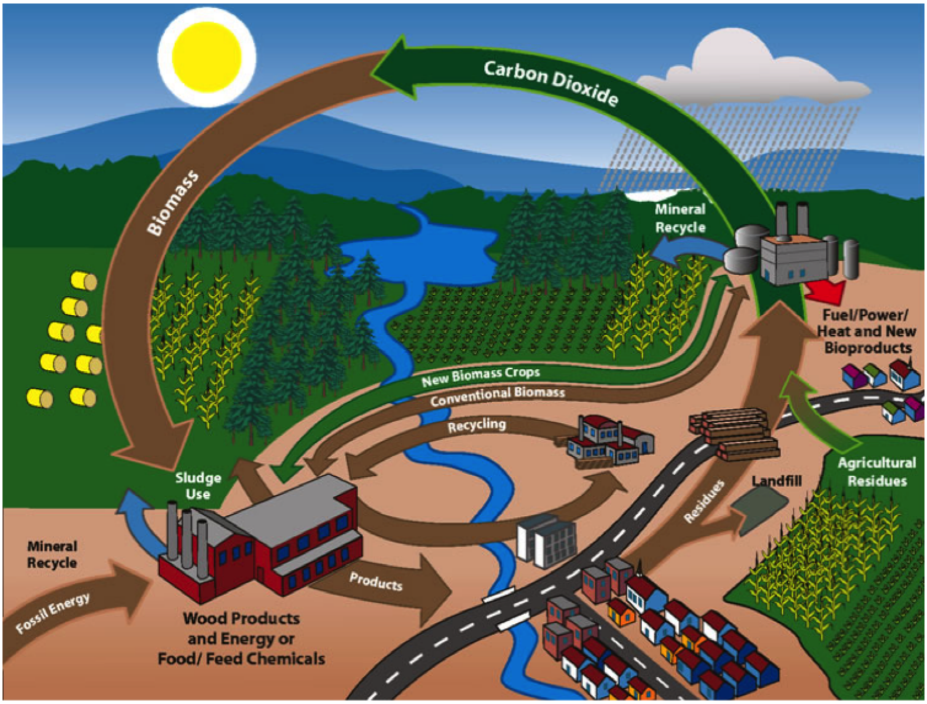

Figure 6.1. illustrates a large bioenergy system showing many of the key material and energy flows, as incorporated into the Biomass Site Assessment Tool (BioSAT 2014). The US Forest Service and University of Tennessee in the United States developed BioSAT, with the goal of assessing the potential for bioenergy from biomass produced from planted forests and biomass residues. This tool includes a natural resource geo-referenced database, physical (soil, slope, hydrology, biomass) and economic data, which are used to objectively identify suitable sites for woody and agricultural residue biomass collection and processing centers (biorefineries). Using tools such as this, it is possible to achieve integrated production of food and multiple energy products while simultaneously optimizing societal demand and local landscape potential and constraints.

6.1 Introduction

Sustainable and equitable development involves meeting the needs (including basic needs for food, energy, clothing, shelter, decent jobs) of human society within the sustainable carrying capacity of natural systems (Box 6.1).

Box 6.1. Sustainable Development definition

Sustainable Development has been defined in many ways, but the most frequently quoted definition is from *Our Common Future* (WCED 1987), also known as the Brundtland Report: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". All definitions require systems thinking – connecting space and time. The concept of sustainable development has in the past most often been broken out into three constituent domains: environmental sustainability, economic sustainability and social sustainability. A fourth domain often added is that of institutions and good governance.

Sustainable energy is a key enabler for sustainable development. As pointed out in different studies using various integrated economic, social, environmental models (WWF 2012; Greenpeace 2008, GEA 2012; IEA 2013) bioenergy has important roles to play in the future sustainable energy mix. Presently, bioenergy accounts for about 10% of the global primary energy mix, with most of it being inefficient and harmful use of traditional biomass for home cooking and heating. The actual energy mix and potential for sustainable bioenergy development, however, will depend on the conditions and needs of particular countries and regions. The scale of deployment of bioenergy and the realization of benefits therefrom will be maximized by innovation in science, technology, business models, and policies that enable them, as well as continuous improvement and extension services based on learning from experience involving all these aspects.

It is important to recognize the potential role of bioenergy in the framework of Sustainable Development Goals (SDGs), established in 2012 at the United Nations Rio+20 summit in Brazil, integrated into the follow-up to the Millennium Development Goals (MDGs) after their 2015 deadline and introducing explicitly as the Goal 4: improve universal, affordable access to clean energy that minimizes local pollution and health impacts and mitigates global warming (Griggs et al. 2013). Reinforcing this nexus of energy and sustainable development, as well as proposing an active commitment of the national governments, connected to SDGs, the UN Secretary-General's Sustainable Energy for All initiative (SE4All) put forward a global platform "to ensure universal access to modern energy services, to double the global rate of improvement in energy efficiency, and to double the share of renewable energy in the global energy system (all by 2030)" (UN 2014). These targets are relevant for all countries, but depending on the national conditions different priorities and emphasis can be adopted to implement actions towards the desirable development of the energy sector, necessarily interacting with other national strategies and policies (Nilsson et al. 2013). Under such integrating concept, bioenergy is a prime example of how energy interlinks with other areas, including water, ecosystems, health, food security, education and livelihoods, and can harness multiple benefits, if properly planned and managed. This desirable development of sustainable and modern bioenergy can be promoted from small-scale local use in stand-alone applications or mini-grids as well as large-scale production and commoditization of bioenergy, through automotive biofuels and bioelectricity. On the other hand, modern bioenergy can replace predatory and inefficient bioenergy systems.

To live up to its potential to contribute to sustainable development, bioenergy deployment needs to be planned and implemented well. A number of environmental and social risks have been highlighted in chapters 9 to 21, this volume, and appropriate environmental and social safeguards need to be put into place and effectively implemented. Yet, beyond risk mitigation, bioenergy can generate substantial sustainable development benefits and concretely contribute to many of the following policy objectives:

Diversity and security of energy supplies: Many nations have the ability to produce their own bioenergy from agriculture, forestry and urban wastes. Produced locally, bioenergy can reduce the need for imported fossil fuels – often a serious drain on a community or developing country's finances. By diversifying energy sources, bioenergy can also increase a country or region's energy security.

Equitable energy access: Currently more than 1.4 billion people have no access to electricity and the access of an additional 1 billion is unreliable. Bioenergy can help provide access to energy for energy-deprived and off-grid communities, thereby contributing to the goal of universal access to modern energy services by 2030. Modern bioenergy technology can improve living conditions for 2.4 billion people relying on biomass and traditional fuels for cooking and heating.

Rural development: With 75% of the world's poor depending on agriculture for their livelihoods, producing bioenergy locally can harness the growth of the agricultural sector for broader rural development. Availability of bioelectricity or biodiesel allows productive services such as irrigation, food and medicine preservation, communication, and lighting for students. Transitioning from traditional biomass use to modern bioenergy can reduce the time needed to collect water and firewood, which means that many women and children have more time to study or to dedicate to income generating activities. Care is needed not to compromise local food production and water access systems.

Employment: Agriculture is labor-intensive, and job opportunities can be found throughout the bioenergy value chain. With increasing scale and sophistication, the bioenergy value chain can be the driver of industrial development and create a more skilled labor force over time.

Health benefits: When modern bioenergy replaces the traditional inefficient combustion of biomass, indoor pollution is reduced along with subsequent health impacts. The health of women and children who spend time around cooking fires, is disproportionately impacted by inefficient biomass cooking systems.

Food security: Bioenergy can increase food security when investment and technology improve the overall agricultural productivity and food availability. While higher food prices can reduce food accessibility, bioenergy can improve family incomes and hence improve the ability to purchase food. New infrastructure built to support a developing bioenergy sector, can improve access to markets in various industry sectors, thereby increasing overall accessibility. Stability as well as food utilization can be improved through increased access to locally produced bioenergy that, for instance, enables crop drying, cooking and purification of drinking water.

Greenhouse gas emission reduction: Bioenergy that replaces fossil fuels or traditional use of biomass for energy can reduce GHG emissions as well as carbon black emissions, a short-lived climate pollutant. However, the potential to live up to this promise depends on the GHG balance during production and conversion of bioenergy across the feedstock supply chain to energy production and use.

Climate change adaptation: Although directly dependent on rainfall regime and climate conditions and thus potentially affected by climate change, bioenergy production involving improved and adapted germplasm can result in enhanced resilience to climate change. In some cases, increased atmospheric CO_2 concentrations could result in increased productivity of bioenergy feedstock via a CO_2 fertilization effect. Alongside adaptation of agriculture at the landscape level, bioenergy crops may increase system resilience.

Biodiversity and land cover: In order to reduce impacts on biodiversity, bioenergy systems should not be promoted in forested and environmentally sensitive areas, and adequate measures must always be taken to preserve the natural landscape as much as possible, for instance adopting biological controls of pests (instead of pesticides), creating and/or preserving wildlife corridors and maintaining riparian forests. Beneficial effects for biodiversity can be expected when abandoned, formerly intensively used farmland or moderately degraded land is used and rehabilitated via a systemic approach.

Deforestation: Sustainable bioenergy production avoids deforestation, by replacing natural forest firewood, a key source of deforestation today. In some contexts, forest management and afforestation should be promoted to increase the availability of woody biomass. The REDD (United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) (UN 2013) guidelines must be considered.

Although bioenergy is not in all cases the best-suited option to achieve any one sustainable development objective, it has the capacity to deliver benefits with respect to several sustainable development objectives simultaneously. Furthermore, modern bioenergy systems are able to utilize a large variety of feedstocks including feedstocks and agricultural residues from a variety of agroclimatic regions. In addition, flexibility of bioenergy systems is derived from feedstocks processed through different conversion routes, serving different end uses, and being produced at different scales, and catering for local and export markets. Thus, while inherently complex, involving several actors and interests, properly designed and well implemented bioenergy systems are able to serve diverse objectives, covering social, environmental and economic aims.

In this chapter the innovation perspective is discussed initially, as an essential element of sustainable bioenergy schemes, focusing more closely on liquid biofuels production chains, exploring new methodologies required to assess and follow-up bioenergy programs and systems, and commenting, under this innovation standpoint, the relevant nexus food security and bioenergy. In the following sections, the need for improved data gathering and analysis, capacity building and new financing schemes is presented, as well as the crucial role of consultation and communication in this context.

6.2 Bioenergy Systems: the Innovation Perspective

Bioenergy production is being practiced in different regions and is contributing not only to energy diversity but also to a significant part of the energy needs, locally or globally, while concurrently addressing pressing environmental concerns and promoting development goals. In attempting to reap all these cross-cutting benefits, the bioenergy sector has become complex because of the variety of feedstocks and producing conditions used, which make it difficult to share learning experiences and scale up and out such systems. More recently, however, there are a range of emerging and proven bioenergy production systems from which replication and adaptation experiences are starting to be derived.

The underlying requirements for bioenergy development involve the identification of a reliable supply of suitable feedstock for various locations and agroecozones. In addition, there is a need for sustainable feedstock supply chains and properly designed conversion systems (conventional and emerging) at appropriate scales, while sustainably managing the natural resource endowments (land, soil, water, waste, etc.). The whole chain requires optimization in terms of agricultural and industrial productivity, logistics management, optimum resource use, and integrated management to meet with the main socio-economic and environmental aspects as far as practically possible. All products, by-products and waste products should be valued in the production chain under a multi-functional landscape approach that involves food, feed, fiber and energy production in balance with the environment, ecosystems services, and social development. It is interesting to observe that innovation acts independently in the elements of biofuel value chain, but improves the overall production system, as depicted in Figure 6.2.

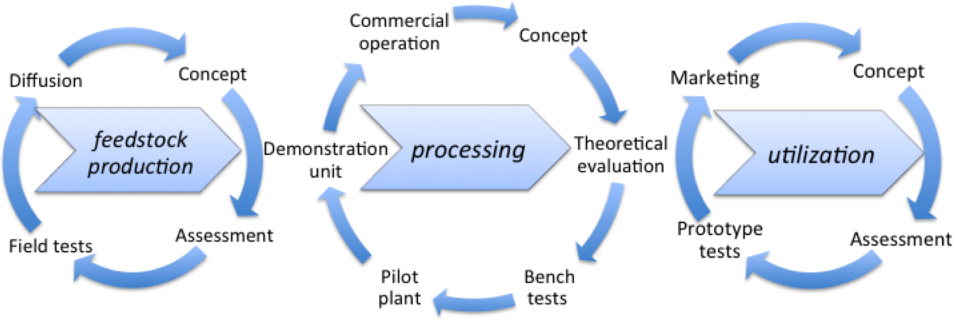

Figure 6.2. Innovation cycles in biofuel value chain.

In each element of this chain innovation can play a decisive role, and some areas are more promising, as depicted in Table 6.1, but there are three main areas where bioenergy and development can intersect: 1) Industrial-scale production of biofuels from agricultural land, 2) Village-scale production and utilization of bioenergy (e.g. methane digesters, biofuel-powered cooking stoves) from any plant feedstock on any kind of land, and 3) Industrial-scale use of forest products. In this chapter, we will focus on the first area to explore the perspectives of sustainable development and innovation. In fact, the production of ethanol from sugarcane and corn (maize) provides significant and tested examples of mature industries for the concurrent production of food (sugar/starch and feed products), energy (bioelectricity and bioethanol) and multiple co-products (chemicals and allied products).

Table 6.1. Areas and topics of more interest for innovation in bioenergy.

Innovation applied to feedstock production	**Innovation applied to processing**	**Innovation applied to utilization**
Forestry Agricultural land Urban residues Particular issues of Developing Countries (scale, appropriated technology)	Transport fuels Heat and cooking fuels Industrial and village models Biorefinery, other products (e.g. aviation biofuels)	Combined heat and power Innovative uses of biofuels (e.g. ethanol in Diesel engines) Developing Countries context (e.g. cooking stoves, niche biofuels production and use)

To foster innovation in bioenergy is more than just promoting R&D in agriculture and conversion technology. Significant improvement can be done also in logistics, management, environmental impacts mitigation and byproducts development, among other areas. In any case, a significant effort is required in terms of planning, sourcing, human resources preparation, co-operation with more advanced centers, etc. The results of innovative bioenergy systems will strongly depend on the suitability of a given technology in a given context and human resources. Skilled and motivated professionals are absolutely essential for effective stage-skipping and leapfrogging processes (Lee and Mathews, 2013).

6.2.1 Innovation and Biofuels

Today, significant amounts of biofuels are produced for direct use as automotive fuel or blended with conventional fossil fuels in several countries, as presented in Chapter 8, this volume. The use of ethanol as a transportation fuel is currently concentrated in the USA (Box 6.2) and Brazil (Box 6.3), but blends of 10-20% ethanol in gasoline have proven feasible in many countries and the automotive technology has expanded the conditions for using ethanol. The flex-fuel engine technology no longer requires dedicated cars that only run on alcohol and compression-ignited engines have been shown to run well on 95% ethanol (E95), as demonstrated in a thousand busses abroad (Scania 2007). Looking toward the future, the prospect of fueling agricultural machinery and trucks with locally-produced ethanol could be highly advantageous for developing countries, for many of which fuel for light duty vehicles is not the highest priority energy need.

6.2.2 Innovative Tools and Methodology Issues

Adequate policies are generally required to reduce business risks by providing clear strategic long-term demand targets and insertion in the country´s energy mix, price structure and incentives, infrastructure development and expansion. At the same time, policies must aim at avoiding the negative impacts on the landscape and local community and take into consideration the existing and future environmental protection regulations and land use planning. All these requirements demand new analytic tools and methodologies (Box 6.4).

To consider bioenergy development integrated with other aims, such as agricultural development, environmental protection, and energy planning, the whole landscape including agriculture, forestry, livestock, recreation and infrastructure components need to be included in the analysis to optimize synergies. A key aspect of the landscape approach is the possibility to conserve and harness ecosystem services (biodiversity, hydrology, carbon sequestration) that are essential for long-term sustainability of feedstock production. The production model should be evaluated, involving the way the feedstock is produced (small grower, outgrower or extensive crop), scale, technology (mechanization and automation levels) and land tenure, interactions among growers, processing plant and local community in terms of services exchanged, infrastructure and labor use. Given the complexity of a multisector approach at a landscape scale, it is essential to have a good system of monitoring and evaluation with respect to targets, incentives, pricing policy, impacts on resources, public acceptance, etc.).

Box 6.2. Ethanol from corn: impact on rural development and sustainability

Corn ethanol in the United States has several interesting characteristics that have contributed to improving rural activities. For example: 1) local policies and fiscal incentives in support of corn ethanol resulted in attractive ethanol prices and not only provided a more secure income for rural communities, but also encouraged innovation and investment into farm infra-structure; 2) R&D boosted maize yields by 30% per hectare over the past decade, cancelling out the grain that is diverted from food and feed systems into ethanol production, while increasing sales to domestic and international markets; 3) statistical evidence shows that the introduction of GM[1] traits accounts for 1/3 of this increase in yield because of the technical innovation; 4) nitrogen pollution remains a problem, but improved agronomy and genetics have resulted in a 30% decrease in the amount of nitrogen used per metric ton of grain produced; 5) stover production increased 30%, improving the potential resource for lignocellulosic biofuels, with lower impacts on soil carbon because more stover could be returned to the soil; 6) increased productivity and no-till cropping has resulted in corn ethanol systems changing from net loss of soil carbon to a gain under maize; 7) in the dominant ethanol from corn dry milling process responsible for 90% of the production mills, in 10 years, innovation in maize production and processing improved ethanol GHG benefits versus fossil fuels by 35%, reduced the fossil energy use by 30%, and process water use by a factor of 2 (Chum et al. 2013); 8) systems approaches to improve agricultural lands and reduce non-point pollution emissions to watersheds, remediate nitrogen run off, and increase overall ecosystems' health (Gopalakrishnan et al. 2011; Gopalakrishnan et al. 2009) are being tested that could release significant amount of land to even more efficient lignocellulosic feedstock production. In fact advanced technologies to produce ethanol from lignocellulosic materials have recently been commercialized and are expected to create new opportunities to utilize currently underutilized biomass.

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[1] All GM development should comply with the Biosafety Protocol, in the framework of the Cartagena Protocol on Biosafety (CBD, 2000), that seeks to protect biological diversity from the potential risks posed by genetically modified organisms resulting from modern biotechnology.

Box 6.3. Sugarcane ethanol: innovation in a mature agroindustry

Many sugarcane producing countries can become cost-competitive ethanol producers, due to the lower cost of cane compared to other ethanol feedstocks and the fact that two-thirds of ethanol production cost is from feedstocks. Sugarcane is widely recognized as an efficient alternative among first generation biofuel feedstocks, because of its high productivity, high yield per hectare, potential for expansion, a very positive energy balance, its potential for producing surplus electricity, and the avoided lifecycle GHG emissions (Leal et al. 2013). Sugar factories are being transformed into "bio-refineries" with multiple energy and non-energy products, which can be extended further in the future by second generation biofuels technology based on cane fibers.

Experience with the global sugarcane industry (involving more than 100 countries) provides a wealth of lessons that could, with appropriate adaptation, be applied to other biomass crops in terms of breeding and agronomy, supply chains, industry operations and optimization, co-product utilization, optimum resource use, and market development, as well as the institutional and regulatory framework required to foster innovation in bioenergy. Innovations in terms of product development, technologies, policies and strategies undertaken over the past decades with respect to large scale commercial bioethanol production (e.g. the Brazil case, Chapter 8, this volume), electricity production (e.g. the Mauritius case, Chapter 14, this volume) and alternative products utilization at smaller scales, have paved the way towards sustainable production which deserves to be seriously considered to be undertaken in most cane producing countries.

The process of sugar manufacture from cane is mature and fairly standardized worldwide, with limited opportunities for improvements in efficiency and productivity. However, as widely demonstrated, sugarcane can sustain a far more diverse and multifunctional role beyond sugar production. The flexibility of sugarcane as a feedstock is derived from its significant biomass potential and product portfolio, especially bioethanol from molasses/juice and electricity from bagasse, all of which can improve profitability and competitiveness. For example, although distillery effluents have a high polluting potential, they can be recycled to cane fields thereby replacing part of the chemical fertilizer requirement. Improvement in using solid residues has increased substantially the electricity production in sugar mills. Modern bagasse cogeneration plants operating at high pressure of 82-87 bars can export 130-140 kWh of electricity per metric ton of cane processed, which can be increased through further system optimization and improvement in energy efficiency (Seabra and Macedo, 2011). The use of cane agricultural residues (equivalent in volume to bagasse generated in factories but usually left in fields) can double the electricity production potential. In order to facilitate carbon and nutrient cycling in sugarcane systems, however, only part of these residues are collected and used to generate electricity.

Box 6.4. Agroecological zoning: a tool for landscape approach

One tool to help address cumulative impacts on a landscape level is agroecological zoning for the different bioenergy feedstocks. Brazil has extensive experience, as illustrated in Figure 6.3 for sugarcane in Brazil (MAPA 2009). Macedo, Nassar et al. in Chapter 17, this volume discuss this aspect. In addition, complementarity of energy resources, even spatially separated, can provide valuable seasonal resilience to a country´s energy mix as in the case of the seasonal low hydropower production in Northern Brazil which is compensated by the bagasse-based electricity production (Seabra et al. 2011).

Figure 6.3. Agroecological zoning for sugarcane in Brazil (MAPA 2009).

The assessment of the maximum practical biomass energy potential through agricultural productivity and industrial efficiency improvements provide innovation opportunities. For example, first generation energy production technologies are mature while second generation technologies are being demonstrated, applied, optimized and deployed in a range of small to commercial scales. Continued support for research and development, capacity building, innovation attempts and absorption is urgently needed for continuous innovation and improvements to the current state of the art bioenergy process. However, the limits of optimum resource use and efficiency improvement need to be recognized in forecasting analysis and policy and strategy development.

To be able to have a clear view of future potential improvements it is important to make an assessment of the full potential of the selected feedstock in terms of limits for yield gains and trait improvements (metric tons/ha of dry biomass and sugar/starch/oil content). This process should take into consideration the yield gaps compared to other locations, the theoretical potential of the crop, possibility to introduce irrigation and other agriculture management practices (no tillage, precision agriculture, GMO varieties, low impact mechanization, nutrient use and application techniques).

On the processing side, it is important to evaluate the overall conversion efficiency of the primary energy content of the biomass in the field as a crop to the total useful energy of main product and co-products. Such information provides opportunities for integrating and optimizing the different steps involved in the combined agro-industrial processes for desired improvements. One important point to consider is that if the feedstock in question is not part of the traditional agriculture of the region, or if crop diversification and integration is planned, the anticipated potential is unlikely to be achieved due to the inherent conservative nature of farmers and the resistance to accept new or different practices and crops.

6.2.3 Bioenergy and Food Security: an Innovative Approach

Food and bioenergy production can coexist positively. Some approaches to develop synergies between both products are:

- integrating bioenergy production into existing activities and land use in ways that do not displace food production and in some cases improve the food production (forest products, buffer strips, perennial rotations, resilience, agricultural development);
- producing bioenergy in land that makes a small contribution to food production, which includes the huge quantity of global pasture land;
- using excess agricultural capacity to bring additional value and resilience into agricultural economies and the human communities that depend on them.

To access the effective impacts of bioenergy on the food availability and prices it is very important to visualize and deploy techniques for the joint or integrated production of food with bioenergy. Many examples involving use of agricultural residues as feedstock in bioenergy processes, as well as corn, wheat, soybeans and rapeseed meal production as co-products of the ethanol and biodiesel production already exist and must be harnessed more systematically. For example, (a) corn-soybean rotation on the same land in alternate years, (b) the sugar/ethanol integrated production where the full use of the sugars in the cane juice is made and no molasses need to be produced, (c) peanuts and soybean rotated with sugarcane in the area that is going to be renewed with new cane planting, (d) the use of cane irrigation system to provide water for food crop production, (e) greenhouse food production using utilities from the cane processing plant. It is also worth evaluating the fungibility effect of biomass, which can be generally used as food, feed and feedstock for bioenergy, ultimately providing resilience and greater food security in cases of droughts or other severe weather events, for example.

Globally, pasture and grazing land occupied an area estimated as 3,500 Mha (million hectares) in 2000, which is more than two times the global agricultural land (FAOSTAT 2013) and there is an interesting potential for integrating bioenergy feedstock and food production. In Brazil, where pasture occupies around 200 Mha and cattle is raised in a low density system (about one live unit per hectare) a small improvement in cattle stocking rates can liberate a few million hectares for agriculture and biofuels; the federal government program called Low Carbon Agriculture (ABC in Portuguese) has provisions for soft loans sufficient to release 4 Mha of current pasture to other land uses in agriculture (BNDES 2012).

The use of agricultural residues (straw) for soil protection, nutrient recycling and soil carbon increase and the use of factory wastes (vinasse, filter mud and boiler ashes) as fertilizers, displacing some of the chemical fertilizer use is a traditional practice in the sugarcane sector (Costa et al. 2013). Especially, vinasse could be used for the production of liquid fertilizer through concentration and blending with other nutrients for direct application in the field, when soil conditions permit, or after anaerobic digestion. The residues from the sugarcane production and processing (bagasse and straw) and the ethanol itself can be used to replace traditional cooking fuels (e.g. collected firewood, and dung or charcoal) in the forms of pellets, briquettes and alcohol or gels, used efficiently in modern cooking stoves. More information about this is available in Chapter 14, this volume.

6.3 Need for Increased Capacity in Data Gathering and Analysis

Bioenergy has been in the spotlight for some time, some claiming the virtues of bioenergy for energy supply and climate change mitigation, and others pointing to environmental and social impacts. Bioenergy's future greatly depends on verifying these claims through scientific assessment, analysis, objective evidence and feedback loops into decision-making processes that are integrated and complex. This approach will allow taking corrective actions to maximize benefits and minimize risks. Chapters 9 to 21, this volume, identify multiple areas where clear gaps exist in data and analysis of bioenergy potentials, and many call for the systems-level data gathering and synthesis approach that we similarly advocate here from an innovation perspective.

In Chapter 9, this volume, Woods et al. point to some critical data and knowledge gaps such as (a) a lack of data and models, and coordination, (b) competing demands for food, feed and fiber; agricultural and forestry management practices; (c) marginal lands; (d) water availability and use; (e) ecosystem protection; (f) climate change; (g) choice of energy crops; (h) economic market development; and (i) costs associated with biomass production. According to the authors, “the inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize.” They further identify key uncertainties associated with assessment of bioenergy potential, such as population growth and demand for land-based products, climate change impacts, and the extent of land degradation, water scarcity, and nature conservation requirements. They recommend that major policy efforts, such as land use zoning, will need to occur despite the uncertainties and shortcomings of zoning. A similar perspective also emerged from a recent analysis of 90 published studies on the potential for bioenergy production in which estimates varied by several orders of magnitude (Slade et al. 2014). The authors concluded that it was necessary to pursue ground-up empirical studies to obtain reliable estimates of bioenergy potential for purposes of policy formulation.

Macedo, Nassar et al. in Chapter 17, this volume, highlight success stories in agro-ecological zoning, but note that new governance systems (also an innovation) must be put in place to deal with increased complexity of land use regulation, as well as to engage stakeholders properly. Richard and El-Lakany in Chapter 13, this volume, advocate for government strategies that encourage multi-functional landscapes, integrated landscape design, and landscapes that are resilient to climate change. For this to occur, bioenergy stakeholders must facilitate innovation in complex environmental assessment and analysis, as well as communication.

Such a landscape approach could hardly be achieved through sustainability certification (Chapter 19, this volume). As the authors caution: “...if standards are to be the most credible measurement of environmental, social and economic performance, they must translate their paper aspirations into frameworks that: (1) assess baseline conditions; (2) collect data and measurements; and, (3) analyze those results to the baseline at the appropriate landscape level”. From their collective experience in sustainability policy and certification, they contend that such capabilities are only in their infancy and still must be reconciled with emerging environmental and social principles negotiated in certification standards.

The examples elaborated in Chapter 14, this volume, demonstrate that integrated assessment is being attempted in some cases, such as the development of the LEAF tool in the U.S. that measures impacts on water, soils and climate from corn stover removal. Assessment outcomes, however, cannot remain static; instead, public and private sustainability policies must take information acquired and use that information to adjust mandates if necessary. Alongside the technical complexity, there are the multiple policy objectives related to bioenergy deployment: socio-economic and environmental benefits, which depend on the context. As identified by Diaz-Chavez et al. in Chapter 15, this volume, relevant drivers for developing countries include poverty alleviation, job creation, access to food and health care, energy access, maintenance of land rights, and protecting women and other vulnerable groups from exploitation.

In chapters 3 to 6, this volume, the fundamental need to approach bioenergy policy development from a systems perspective to overcome “siloed” or segregated approaches was clearly identified. For example, some media focus has fanned pushback to biofuels' mandates because of their possible conflict with food security, although the actual impact of bioenergy production is not clearly assessed and in some cases improves food production and access. It goes beyond what biofuels policy can legislate separately or biofuels research alone can solve, while recognizing the need for safeguards in bioenergy development as well as for approaches that deliver on both food and energy security. It should be acknowledged that biofuels policies have already spurred innovative assessments of impacts beyond the capabilities of other sectors similarly affecting land use. Still, the bioenergy field has yet to pull together multiple data points and analytical tools that would give society a more informed perspective on the *systemic* impacts bioenergy can have on the environment and society. In this context, the Bioenergy Decision Support Tool is a relevant reference, which offers support for both the strategy and the investment decision-making processes, under the concept of identification and mitigation of risks and a longer-term perspective of sustainable use of resources, key elements to maximize the potential benefits from bioenergy (UN Energy 2010).

Moving forward, innovations must occur across the spectrum to generate data where it is missing, and build meta-analyses with the capability of applying multi-criteria analysis to harness and integrate multiple, diverse data sets and analytical tools at the proper spatial and longitudinal scales. Further, equally dynamic policies must be in place both to incentivize additional data collection and building complex analytics, as well as on the receiving end to properly put these to use. Currently, no such policy regime successfully achieves this goal. As the authors of Chapter 19, this volume, note, for example, the U.S. Renewable Fuel Standard triennial assessment about its environmental effects clearly acknowledges that assessment of environmental baselines in many cases does not exist. Furthermore, the Standard creates no channel to incorporate what is being learned about biofuels' sustainability back into the Standard. Similarly, while the EU has received reports back from member states on the results of sustainability certification, the EU summary of the results is quite conclusory and it is not transparent as to what type of data and analysis regimes are applied, nor the baselines to which continuous improvement is being used. Based on the data and analytical gaps identified above, it is unlikely that such a summary can be achieved at this time, even though the chapters of this volume clearly expect this type of environmental analysis to occur. As the complexity of data and analytical tools increase, which must occur in order to gauge systems-level achievements, those responsible for incorporating outcomes into policy must ensure transparency and build capacity for all stakeholders to participate meaningfully in complex decisions.

Certification regimes can play a leading role in identifying missing data and analytical tools. Many principles of sustainability certification theoretically require that biorefineries and farmers conduct assessments of baseline conditions, and where practices do not maintain or improve those conditions, they should adjust management practices accordingly. Even in the US, with advanced technological capabilities and policies, this type of assessment is extremely difficult. If a farmer were directed not to contribute to water pollution in a sustainability certification, that farmer would have to know first what waters fall under the prescription. Within the farmer's control are waters that physically are present on or under the property; however, multiple landowners upstream can affect water quality conditions. With the exception of the Chesapeake Bay, which has been led by US EPA, many states have not completed studies of water quality conditions of receiving waters, nor have they mapped agricultural contributions to nutrient pollution that could guide more targeted producer-by-producer goals. Standards would be confronted, then, with having to impose blindly practice-based requirements that prevent water pollution (e.g., no-till, reduced fertilizer use), without knowing the exact contribution of that farmer to baseline conditions. Chesapeake Bay modeling of water quality conditions and agricultural contributions to nutrient pollution has been a decades-long process, and is being challenged in federal court by farm groups as not based on accurate field-level data (ironically, however, agriculture has lobbied successfully not to be required to report such data), and too uncertain to base nutrient prescriptions on. The same models are being applied in other watersheds such as the Mississippi, to develop state non-point source pollution policy. Ideally, for certification to most accurately and economically apply a water quality principle to an individual producer, tools such as LEAF, which incorporate tools such as RUSLE2 (which gauges soil loss), would also tie into water quality models being developed for nutrient-stressed watersheds. Further, data on economic profitability at the micro-grid level could be incorporated into such models to identify those ecologically sensitive lands where perennial biomass cropping would make more sense economically and environmentally over corn production. At this time, no such capability exists.

Even if water, soil, climate and economic analytical tools could be tied together, the issue for certification regimes, too, is to construct an interface between the information required from the farmer for certification and these models. That is, the most convenient way to conduct assessments for certification is for the farmer to enter information through a web-based interface. This interface must 'communicate with' analytical tools by providing the necessary information in a format that software applications can use. Farmers must understand how to use the interface, why such information is needed, and how the information is analyzed to reach conclusions about the sustainability of the operation. This is onerous for farmers, and arguably only gauges one economic actor's effects on the system. Current thinking is that that these types of analytics would likely be more useful, from the perspective of gauging systems-level sustainability, at the biorefinery level. Biorefineries have greater economic capacity to take in information from the farmers they purchase biomass from and apply "shed" level analytics to that data, whether watershed, biodiversity shed, or socio-economic shed. Gauging biomass' overall effect within a watershed or species habitat is much more valuable information to a policymaker concerned about advancing sustainability than individual, field-by-field certifications. Biorefineries, too, typically are the economic actors responsible for sustainability accounting in bioenergy policies.

Closing this section on data needs, it is worth stressing that although bioenergy is inherently complex and site-specific solutions should be evaluated, several analytic tools and cases studies are already available to support decisions and put forward plans to implement sound bioenergy programs.

6.4 Capacity Building and Sustainable Bioenergy

Proper institutional framework and skilled human resources are essential for promoting sustainable bioenergy, at several levels. At the level of governmental agencies, trained personnel is required to plan, design, implement, follow-up and oversee national and regional bioenergy programs, defining consistent objectives, establishing budgets and financing schemes, indicators and assessment activities. At operational level, professionals are needed to design, build, commission and start-up, operate, maintain and assess bioenergy systems.

Thus, training programs, at different levels should be developed, and some should consider international and horizontal co-operation. Some countries have relatively mature bioenergy programs and can help train and mentor teams. In order to provide support to farmers, considering the adoption of new cultures for feedstock production, as well as the introduction of new practices and technologies, it will be critical to strengthen the extension services, and to scale out and scale up the application of innovative ideas.

There is also an urgent need to train personnel for developing Research & Development activities in the field of bioenergy, including for planning, designing and assessing programs and projects. Regional and international co-operation and the financial support of multilateral agencies can be relevant, although the national perspective on bioenergy priorities, domestic demands and resources should be kept. It is also important to observe that time and resources are needed to prepare and train skilled personnel and it thus requires long-term and stable programs. At a more general level, it is advisable to consider introducing curricula that cover bioenergy concepts, potentials, perspectives and constraints to inform students and future professionals on the fundaments and applications. This aspect is discussed below, in the context of promoting public awareness and participation in the process of implementation and evaluation of bioenergy programs.

Sustainable bioenergy programs will benefit from appropriate and nationally relevant institutional, legal, and regulatory frameworks, involving governmental, private agencies, and other institutions able to develop and execute policies in bioenergy. Some important characteristics include:

- Bioenergy necessarily involves multi-sectorial or multi-ministerial management, co-operation and coordination, to harmonize the perspectives of agriculture, energy, social affairs, the environment, and industry, among other agencies and institutions. To implement this approach requires sometimes a learning phase, but the results are rewarding, as observed in the application of UN Energy in the Decision Support Tool for Sustainable Bioenergy in some African countries (UN Energy 2010).
- An essential corollary of a good institutional framework is a comprehensive legal framework that provides the necessary governance and enforcement conditions

to propose and develop bioenergy programs. A good indicator of the level of government commitment to promote and support bioenergy is the existence of clear legislation, defining responsibilities, setting general and specific objectives and defining elements of control.

- Although stable and foreseeable legislation is important to reduce the risk perception about bioenergy and to stimulate actors to develop bioenergy projects, it is also important to maintain a level of flexibility to adjust targets and programs according to local conditions. In this regard, permanent follow-up and monitoring of results are good resources to guide the Administration facing changing contexts and perspectives.

The relevance of capacity building cannot be overlooked. In all the cases where a bioenergy program developed successfully, it is relatively easy to find the existence of trained people, with good institutions and proper legislation in place, as well as with enough and updated information available. Studies evaluating different situations, from Europe (McCormick and Kaberger 2007) to India (Ravindranath and Balachandra 2009), confirm that the lack of know-how and weak institutional capacity are barriers obstructing the expansion of bioenergy. Recognizing this demand, the Global Bioenergy Partnership launched the Working Group on Capacity Building for Sustainable Bioenergy in 2011 (GBEP 2011a).

6.5 Need for Flexible Financial Models

While promoting sustainable bioenergy projects in developing countries demands usually relatively modest investment compared to conventional energy systems, the majority of bioenergy systems in developed economies require massive capital requirements, not only for the development phase but also for their implementation and operation. As a reference, to absorb the average growth in transportation fuels (currently 2 billion tons worldwide), which seems coupled to economic growth (1.5% annually or 30 million tons), one needs to annually mobilize 120 million tons of extra biomass, with scales comparable to rebuilding the world's largest port (Shanghai) every 5 years.

When implemented in 150 kton/year production facilities (typical scale of today's 1st generation liquid biofuel plants), this translates into an estimated annual increase in capital requirement of 50 billion dollars for the approximately 200 plants that cost USD 250 million each. To meet the RFS2 targets by 2022, USDA estimated that USD 168 billion would be required to finance about 500 biorefineries (USDA 2010). Clearly this level of investment requires cumulative development, testing and implementation times of 20 years or more, given the average rate of innovation in process industries as shown in Figure 6.4. Change in conventional logistic systems to accommodate this increase in biomass transport and use (road, train, ship/port) will require comparable huge investment and lead times. For example, a change in agro/forestry system depends on the sort of biomass equivalent to annually replanting grains, 5-7 cycles of sugarcane, and 10-20 years for forestry and (palm) plantation replantings), at somewhat more modest investment, but still needing relatively large amount of capital.

Capitalizing the bioenergy sector is now a major priority and a massive opportunity for private and public investors (agro-banks, pension funds and other institutional investors, insurance companies, national development banks, and private equity funds. There is still a high level of risk for investors because:

- there are – with the exception of conventional agro-food/fuel processors such as sugarcane and corn ethanol – no clear mature and demonstrated winning technologies yet and there may be a need for multiple energy products;
- no guarantee of biomass supply since – again with the exception of conventional commodity agro/forestry products for food and paper industry – there are no established biomass markets with clear specifications and pricing mechanisms. An exception is the APX/ENDEX (Amsterdam Power Exchange) wood pellet trading, based on a weekly updated traders index.
- few companies are vertically integrated in bioenergy (or biorenewables) technology portfolio and biomass value chain yet, whereas many, if not most, traditional (fossil) fuels and power companies have a well integrated well-to-wheel or power-to-plug model. This implies that most (commercial) bioenergy developments, especially for 2nd generation biomass utilization, require forms of open innovation such as ranging from public-private partnerships (BE-Basic, CLIB2021, EBI) to joint ventures (Shell-Cosan, DSM-POET, DuPont-Genencor etc.). The open-innovation format has substantial financial benefits due to sharing risk, capabilities and costs.
- most bioenergy industries suffer from the relatively low added value of energy products, which is augmented by the inherently low mass yield of energy densified products (energy carriers) from biomass. This is obviously related to the relatively high state of oxidation of biomass: 23% (lignin) to 53 % (cellulosics) of the dry biomass is oxygen atoms, with an average of 40-43% of whole biomass.

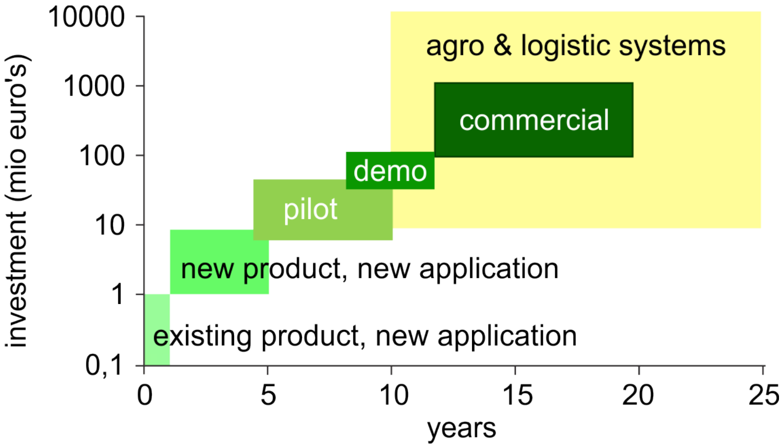

Figure 6.4. Time and investment scale estimates (van der Wielen and van Breugel 2013).

- whereas the fossil energy world has been successful to add value to nearly all of its feedstock, the biorenewables industry is still struggling to implement the full biorefinery model, including higher added value product portfolio with biochemical and biobased materials.
- hence, co-products are generally beneficial for closing the gap between revenues and production costs (and prevent emissions), but unfortunately most current co-products such as power/heat from CHP-installations, and biogas from wastewater treatment have relatively low added values. Further technology and market development for full biomass utilization is urgent. This financial situation affects the competitiveness of bioenergy systems negatively, and renewables based electricity production and biofuels are heavily subsidized at a global level. Global subsidies had a value of more than $ 60 billion in 2010 and –without additional measures - are expected to raise to almost $ 250 billion in 2035, of which roughly 25% for liquid biofuels and 25% for power (co-firing) (IEA 2013). In many countries, governments strive to reduce subsidies or phase them out.

Considering the different categories of risks, in Table 6.2 some mitigation strategies are suggested, to accelerat implementation of innovative biofuels projects (Koonin and Gopstein 2011). It is worth to observe that the technology risk should be the first to mitigate, since robust and well tested bioenergy paths are possibly the most important feature of really feasible bioenergy projects.

Table 6.2. Risk mitigation strategies to develop bioenergy projects.

Risk	Mitigation Strategy
Technology	Validation of R&D at pilot and demonstration scales
Construction	Engineering, procurement and construction performance guarantees at demonstration scale
Operations	Validate operations performance at pilot and demo scales
Finance	Competitive awards, loan guarantees, IPOs, debt finance
Feedstock supply	Develop harvest and logistics operation at pioneer scale
Product off-take	Advocate long-term purchase agreements

Source: Koonin and Gopstein (2011)

The development of bioenergy (or more generalized biorenewable) production systems will likely follow two parallel pathways:

1. **large-scale:** continue the trend of ever larger scale biorefineries such as those for sugarcane in Brazil and elsewhere, corn (USA and France), wood pellets (Canada, USA, Baltic) or palm oil (Malaysia, Indonesia, Colombia, elsewhere) serving national and export markets, or;

2. **distributed manufacturing:** based on smallholder models ranging from individual farmers to small and medium sized producers with mostly regional markets. In addition, rapid development in internet technologies also allow small businesses to have global costumers, although transportation costs rapidly increase with distance (up to 10% for sugarcane based production, and up to 40-50% for more difficult terrains) (Palmeros-Parada et al. 2014, Pantaleo and Shah 2013).

With respect to financial aspects and especially financial innovation (innovation in financing models), we need to distinguish between the development stage (Research, Development and Demonstration, R&D&D), the demonstration (1st) plant and the nth plant (mature technology and supply/value chain), for each of those pathways, as indicated in Table 6.3. Government support is required for bioenergy particularly at the development stage: R&D expenses in biofuels in 2012 was about \$1.7 billion (\$1.2 billion from governments), much of it going on next-generation technologies like cellulosic ethanol, Fischer-Tropsch biodiesel and algal oil from a total USD 4.8 billion governments RD&D and total \$9.6 billion on all renewables (BNEF 2013).

Table 6.3. Financing models for promoting bioenergy.

Financial models	Large scale	Distributed manufacturing
Development stage (R&D&D)	National science and technology foundations and internal private resources Public private partnerships, and publicly (co)subsidized pilot facilities	National science and technology foundations and internal private resources Co-operatives such as in dairy, sugarcane, potato, beet, grains and other commodity (including co-operative agro-banks) Public private partnerships Venture capital including business angels
1st Plant	Loans and guarantees by national development banks, regional development funds and other government linked financials, joint ventures and public-private partnerships (often also Joint Ventures), excise tax credits and feed-in tariffs	Loans and guarantees by regional development banks and regular financing agents Various (regional) governmental including fiscal holidays / exemptions Crowd or cloud funding Micro-credits
nth Plant	Senior debt (secured (priority) loans mostly on company assets) from financials, investment funds, institutional and other equity investors governmental/fiscal stimuli such as excise tax credits and feed-in tariffs	Regular (regional) financing agents with various loans/debt structures, usually too small for investment funds and institutional and other equity investors

In the case of small-scale projects, at farm level and bioenergy programs in developing countries, innovative finance and insurance schemes must be considered, in order to reduce risk and improve attractiveness in context of lower resources available. In these cases, to connect projects and programs with extension services and operational support is advisable, since it requires more attention to reinforce entrepreneurship and local capacity, particularly in the design and deployment of bioenergy systems, as already mentioned.

6.6 Relevance of Consultation and Communication

Due to various strong relationships with other sectors, which create conditions for multiple benefits and impacts, bioenergy requires a clear strategy of stakeholder involvement aiming to build and support the development of sustainable bioenergy programs. The different voices of those who may benefit and those who may run risks need to be heard, and engagement in the identification of pathways that balance impacts needs to be ensured. Thus, proper consultation and communication strategies are crucial aspects to take into account. We categorized them below as follows: public participation overview, stakeholder engagement, public participation and bioenergy; and public perception and communicating good practices.

6.6.1 Public Participation - An Overview

The term participation is often used interchangeably with involvement, consultation, and engagement. Public participation is used as a general term to cover the range of approaches involving members of the public. Guidelines on public participation and stakeholder involvement are provided by various organizations including the International Association of Public Participation (IAP2), the International Association of Impact Assessment (IAIA), the ISEAL Alliance, which is the global membership association for sustainability standards, the Roundtable for Sustainable Biomaterials (RSB), the United Nations Environment Programme (UNEP) and the Global Bioenergy Partnership (GBEP).

The ladder of participation introduced by Arnstein (1969) was one of the first attempts to articulate the range of approaches explaining how much power was given to the public from the lowest side (manipulation) to the highest side (citizen control). Public participation therefore needs to be considered at the highest level including citizens in the decision-making process. This public participation has been used systematically in environmental management tools including Environmental and Social Impact assessments and Strategic Environmental assessments.

For the last 20 years, public participation has been a key issue in environmental assessment and decision-making processes. In Principle 10 of the Rio Declaration, Earth Summit (UNCED 1992), public participation was considered a main issue for sustainable development and this was reaffirmed at the World Summit on Sustainable Development (WSSD 2002). A further key driver for public participation in environmental decision-making has been the Convention on Access to Information, Public Participation in Decision making and Access to justice in environmental matters (UNECE 1998) known as the Aarhus convention.

6.6.2 Key Principles of Stakeholder Engagement

The basic rationale underlying public participation is the public's 'right' to be informed and consulted, and to express its opinion on matters that affect them (Sheate 2011). Out of distrust on governments and experts, the public has been demanding to have a more influencing role in the decision-making process. As a process, public participation should lead to better decisions being made and can lead to improved relations between developers and local people. Early stage dialogue may contribute to provide clarifications and reduce misunderstandings. Table 6.4 summarizes the principles for good practice on stakeholder engagement presented by UNEP (2012).

Table 6.4. Principles for stakeholder engagement.

Principle	**Process**
Integrated	The process should be able to integrate the contributions of very different groups of stakeholders from government to international organizations to local communities. This principle ensures inclusive and fair representation
Adaptive	The process should be flexible and also engage a range of stakeholders through different methods
Transparent	The process should have clear, easily identified requirements. It should ensure that there is public access to information. Limitations and difficulties should be acknowledged and the reasons why particular decisions were taken should follow a trail that is accountable
Credible	The stakeholder engagement process is the only way in which affected stakeholders may have an influence on the decision-making process. It is important that the process be conducted by professionals to ensure faith in the process and those facilitating it
Rigorous	The process should apply "best practices", using methodologies and techniques appropriate to the scale and phase of the stakeholder engagement process, specifically when it comes to stakeholder consultation and record-keeping
Practical	The process should result in information and outputs which assist with problem solving and are acceptable to and implementable by proponents
Purposive	The process should aid in decision-making by taking into account the concerns of all stakeholders

Source: UNEP (2012)

According to the UN Commission on Human Rights principle “Free prior and informed consent (FPIC) (Tamang 2005), is the principle that a community has the right to give or withhold its consent to proposed projects that may affect the lands they customarily own, occupy or otherwise use”. Such principle is even considered “a key principle in international law and jurisprudence related to indigenous peoples” (Forest People 2013).

The Forest People Organisation (2013) considers FPIC necessary to ensure a level playing field between communities and the government or companies and it helps to reduce risks in investments. FPIC also implies careful and participatory impact assessments, project design and benefit-sharing agreements. FPIC has been widely accepted in the ‘corporate social responsibility’ policies of private companies working in sectors such as dam building, extractive industries, forestry, plantations, conservation, bio-prospecting and environmental impact assessment.

6.6.3 Stakeholder Participation in the Bioenergy Sector

Bioenergy initiatives have been implemented under different business models in developed and developing countries, reinforcing in all cases the need for properly considering the public’s participation, identifying and engaging stakeholders in the project conception and implementation, mainly due to land use and food security concerns. This participation has been recommended by good practice guidelines, including the Roundtable for Sustainable Development, the United Nations Environment Programme and some research projects such as the EU COMPETE project and the Global-Bio-Pact project.

Mapping stakeholders for bioenergy initiatives should include national level policy and institutions as well as stakeholders at the productive level including NGOs, farmers, other civil organizations and the industry sector (including also farmers with different forms of participation (e.g. outgrowers). A simple tool could be to use a quadrate to represent them and identify the links between these different bodies and stakeholders (Diaz-Chavez et al. 2010), as shown in Figure 6.5. Several sustainability standards for bioenergy crops have included in their criteria issues related to FPIC such as the Roundtable for Sustainable Palm Oil, the Roundtable for Sustainable Biomaterials, and BONSUCRO. Figure 6.6 depicts the Credibility Principles of the ISEAL Alliance.

Some developing countries have engaged local communities in a participatory approach. An example is the Task Force on Biofuels in Tanzania, which involved different stakeholders. The Ministry of Energy in Tanzania started in collaboration with the Swedish Development Agency (SIDA) the consultation with different villages as part of the Strategic Environmental Assessment for the biofuels policy.

The private sector has also complied with this participatory process as demonstrated in the certification of biofuels initiatives by the Roundtable on Sustainable Biomaterials (RSB).

Figure 6.5. Mapping stakeholders for bioenergy initiatives (Diaz-Chavez et al. 2010).

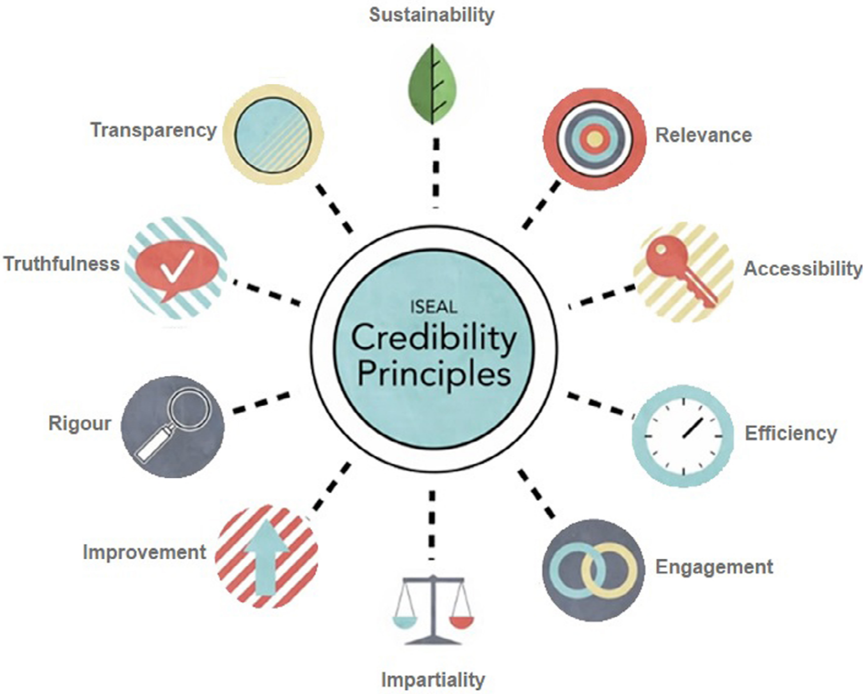

Figure 6.6. Example of the Credibility Principles (ISEAL 2013).

6.6.4 Public Perception and Communicating Good Practices

The analysis of public perception (PP) should be a prerequisite for future development of the Bioenergy initiatives since PP determines the public acceptance, and thus the demand of biofuels/bioproducts as well as the possibility to develop their supply (Fallot et al. 2011).

It is important to recognize that there are significant differences in the way experts and the public perceive risks associated with environmental and social issues. Decision makers legitimately consider the public's opinions when making decisions but it is their duty to inform the public timely and clearly about benefits and possible drawbacks associated to bioenergy projects. Although public perception is recognized as an important determinant of success of renewable energy programs, there are few studies analyzing its real impact and how those perceptions are formed. Fallot et al. (2011) reported this lack of analysis to assess the relationship between public's acceptance of biofuels and the sector's development (Rohracher 2010; Devine-Wright, 2010).

There is a difference between perception and belief. Perception is the result of current experiences and information and adapt over time while beliefs are formed based on past experiences (Bleda and Shackley 2008). Public perception also depends on cultural aspects, history and economy of the producing countries, objectives of importing countries, environmental and social targets, as well as on the positive or negative impacts on individuals and communities (Fallot et al. 2011). Public perception of Bioenergy (particularly biofuels) is often tackled in a rather informal way ("people say …"). A proper methodology for assessing public perception comprises statistically sound methods including representative samples (Fallot et al. 2011).

Analyzing public perception will help the government and private sector to better understand how to orient policies and initiatives. This should also be the result on how to communicate the findings, proposals and benefits of bioenergy projects including employment generation and jobs quality; energy security; food security; positive impacts on climate change mitigation and adaptation.

Communication with the media and opponents of bioenergy should also be promoted. Six case studies analyzed on public perception within the Global-Bio-Pact EU funded project demonstrated that the public gets most of the information on bioenergy initiatives through the media (mainly newspapers, TV, radio and internet) (Global-Bio-Pact 2010). Cultural aspects were one of the key issues addressed in countries where NGOS have dominated the media, people were more informed about the negative issues rather than the positive aspects of biofuels demonstrating the need to find better forms of communicating with stakeholders including the media. Different methods for engaging with stakeholders and the public have been developed that contribute for better communication. In Table 6.5 are presented some alternatives for promoting stakeholder engagement, public participation and forms of communication that can be employed.

Table 6.5. Tools and forms of communication for stakeholder engagement.

Tools for stakeholder engagement and public participation	Forms of communication
Stakeholder mapping	Visual aids (posters, leaflets, photos, diagrams)
Participatory rural appraisal	Software images including GIS
Stakeholder forum groups	Focus groups
Participatory ecological land use management	Experts and general public meetings
	Stakeholders dialogue meetings
	Media communication reports

Source: UNEP 2012

6.7 Final Remarks

Making bioenergy an integral part of sustainable development requires a systems approach and integration on different levels: assessment, policies and strategies, and business models. Political leadership, providing long-term, consistent policy legal, and institutional frameworks are necessary to leverage the necessary investment in innovation and scale up of the existing good practice examples.

Bioenergy cannot be looked at in isolation, but as part of a wider energy system in the context of wider resource use for different end uses. At the heart of any decision making process is integrated resource assessment, particularly: integrated water management and land use planning. Methodologies have been developed for both and are ready for implementation. Furthermore, projected energy, food and materials needs should be accounted for as part of the assessment.

Policies need to be long-term, providing investors' security, and consistent with policies for climate, rural and industrial development, and energy and food security. Targets and mandates as well as feed-in tariffs for bio-electricity have proven useful tools spurring market development – if derived based on integrated assessments, taking into consideration the different pressure points, and flanked by sustainability standards on the project level.

Monitoring and verification of policies' effectiveness is important. Capacities for data collection and analysis need to be strengthened. The Global Bioenergy Partnership (Box 6.5) has developed 24 indicators agreed upon by a wide network of governments and intergovernmental organizations, which can provide useful guidance for such a monitoring process (GBEP 2011b). Analysis of progress towards or away from previously set national objectives allows for effective corrective action. Sustainability standards, developed in multi-stakeholder processes, which reflect the social, economic and environmental pillars are a tool that can be used to improve project level planning and management.

A number of examples exist, where innovation has given rise to new business models. The use of co- or by-products is one, where different business opportunities have been combined. Similarly, for integrated food-energy systems, which cater for different end uses by making the most of resource inputs. It is also interesting to consider that new technologies for biomass processing aiming at energy products are posed to produce high value chemicals, which can justify the implementation of demonstration plants.

Innovation and scale up of sustainable, modern bioenergy can contribute simultaneously towards the achievement of the three objectives of the Sustainable Energy for All initiative: universal access to modern energy services; doubling the share of renewable in the global energy mix, and doubling the rate of energy efficiency improvements globally by 2030. To achieve the renewable objective, the share of traditional biomass needs to be decreased dramatically and modern bioenergy can be a key stepping stone in this transition. Local production in remote, energy poor areas improves access. Both a transition from inefficient firewood and dung use to modern bioenergy, as well as use of co-/and by-products, residues and waste, and technology advances allowing the use of highly efficient feedstocks, contributes to the efficiency objective. This last aspect is essential: innovation could lead to much better feedstocks and much better processes, essential to feasibility of bioenergy systems.

6.8 Recommendations

1. To promote cross-sector data and information gathering, for informing innovative design and continuous monitoring of bioenergy systems.
2. To promote integrated assessment of social, economic, environmental aspects of bioenergy systems, adopting a landscape approach of natural resources management (land, water, etc.) to enhance productivity (bioenergy, food, feed, feedstocks, timber), environmental services (hydrology, biodiversity, carbon) and economic value, as a key reference framework informing innovation.
3. To promote innovative bioenergy technologies, considering the whole production chain: feedstock production, conversion and final use, in different scales and contexts.
4. Policies need to consider short- and long-term costs and benefits to avoid negative social and environmental impacts, while offering safe investment conditions.
5. To develop financing schemes and business models, especially to enable communities to benefit from small-scale bioenergy projects.
6. To enhance institutional frameworks and capacity building for improved governance, human resources, knowledge generation, innovation and extension in bioenergy systems.

Box 6.5. The Global Bioenergy Partnership (a summary from GBEP 2014)

The Global Bioenergy Partnership (GBEP) was launched in May 2006, resulting from a consultation process among developing and developed countries, international agencies and the private sector interested in bioenergy. GBEP aims to organize, coordinate and implement targeted international research, development, demonstration and commercial activities related to production, delivery, conversion and use of biomass for energy, with a focus on developing countries. GBEP and its Partners comprise 23 countries (Argentina, Brazil, Canada, China, Colombia, Fiji Islands, France, Germany, Ghana, Italy, Japan, Mauritania, Mexico, Netherlands, Paraguay, Russian Federation, Spain, Sudan, Sweden, Switzerland, Tanzania, United Kingdom, United States of America) and 14 international organizations and institutions, such as the Economic Community of West African States, European Commission, Food and Agriculture Organization of the United Nations, Inter-American Development Bank, International Energy Agency, International Renewable Energy Agency, United Nations Conference on Trade and Development (UNCTAD), United Nations Department of Economic and Social Affairs, United Nations Development Programme, United Nations Environment Programme, United Nations Industrial Development Organization and United Nations Foundation. A further 27 countries and 12 International Organizations and institutions are participating as Observers.

GBEP provides also a forum to develop effective policy frameworks to suggest rules and tools to promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation and foster R&D and commercial bioenergy activities. GBEP's main functions are to:

1. promote global high-level policy dialogue on bioenergy and facilitate international cooperation;
2. support national and regional bioenergy policy-making and market development;
3. favor the transformation of biomass use towards more efficient and sustainable practices;
4. foster exchange of information, skills and technologies through bilateral and multilateral collaboration;
5. facilitate bioenergy integration into energy markets by tackling specific barriers in the supply chain;
6. act as a cross-cutting initiative, working in synergy with other relevant activities, avoiding duplications.

6.9 The Much Needed Science

1. Develop integrated assessment of social, environmental, economic aspects of bioenergy systems, adopting landscape approach of natural resources management.
2. Develop conceptually and implement bioenergy systems models proper to integrated analysis of impacts, risks and benefits, in a broad sense.
3. Develop bioenergy technologies considering the "new" opportunities of feedstock supply (such as urban residues, agricultural residues) and innovative processes, aiming at different markets (domestic, national, local).

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chapter 7

The Much Needed Science: Filling the Gaps for Sustainable Bioenergy Expansion

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SCOPE Bioenergy & Sustainability is a collective effort with contributions from 137 researchers from 82 institutions in 24 countries. The volume is the outcome of a Rapid Assessment Process that included a meeting at UNESCO, Paris, in December 2013 where 50 experts discussed bioenergy sustainability crosscutting aspects. For additional details refer to the synthesis volume that includes background commissioned chapters to provide context, issues, latest developments and the much-needed science regarding bioenergy expansion.

Integration of Sciences for Bioenergy to Achieve its Maximum Benefits

SCOPE Bioenergy & Sustainability reports on recent technological advances, scientific developments and challenges for bioenergy expansion across its whole lifeline considering land use, feedstocks, conversion technologies and impacts. It covers all products of bioenergy production and describes added benefits to energy security, food security, environmental and climate security, sustainable development and innovation. It also aims to define the next research steps, the much-needed science where gaps of knowledge exist.

There are several challenges that need to be addressed in bioenergy so that it achieves its maximum benefits. They should preferably be assessed in an integrated manner. Factors that limit the positive impact of bioenergy to global energy security are (1) the availability of sustainable biomass, (2) non-polluting, energy positive, and cost-effective conversion technologies, and (3) the societal aspects[1]. Factors supporting increased utilization of bioenergy as a pathway towards improved food security should also be considered, since bioenergy is only one of many aspects that can affect food security. Good methods for monitoring food security need to be developed. Methods for identifying win-win situations as well as trade-offs for integrated Food-Energy systems are required[2]. Conversion technologies that use biomass carbons with great efficiency such as in the production of ethanol from starch and sugar or fatty acid methyl ester (FAME) biodiesel exist today, but for other applications many pathways are still developmental or too expensive[3].

In addition to research and data collection, assessment frameworks are required to support the integration of bioenergy systems into existing agriculture and forestry practices. Such strategy needs broad stakeholder involvement in order to capture synergies and strike a balance between social, economic and environmental objectives.

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[1] (Chapter 3)

[2] (Chapter 5)

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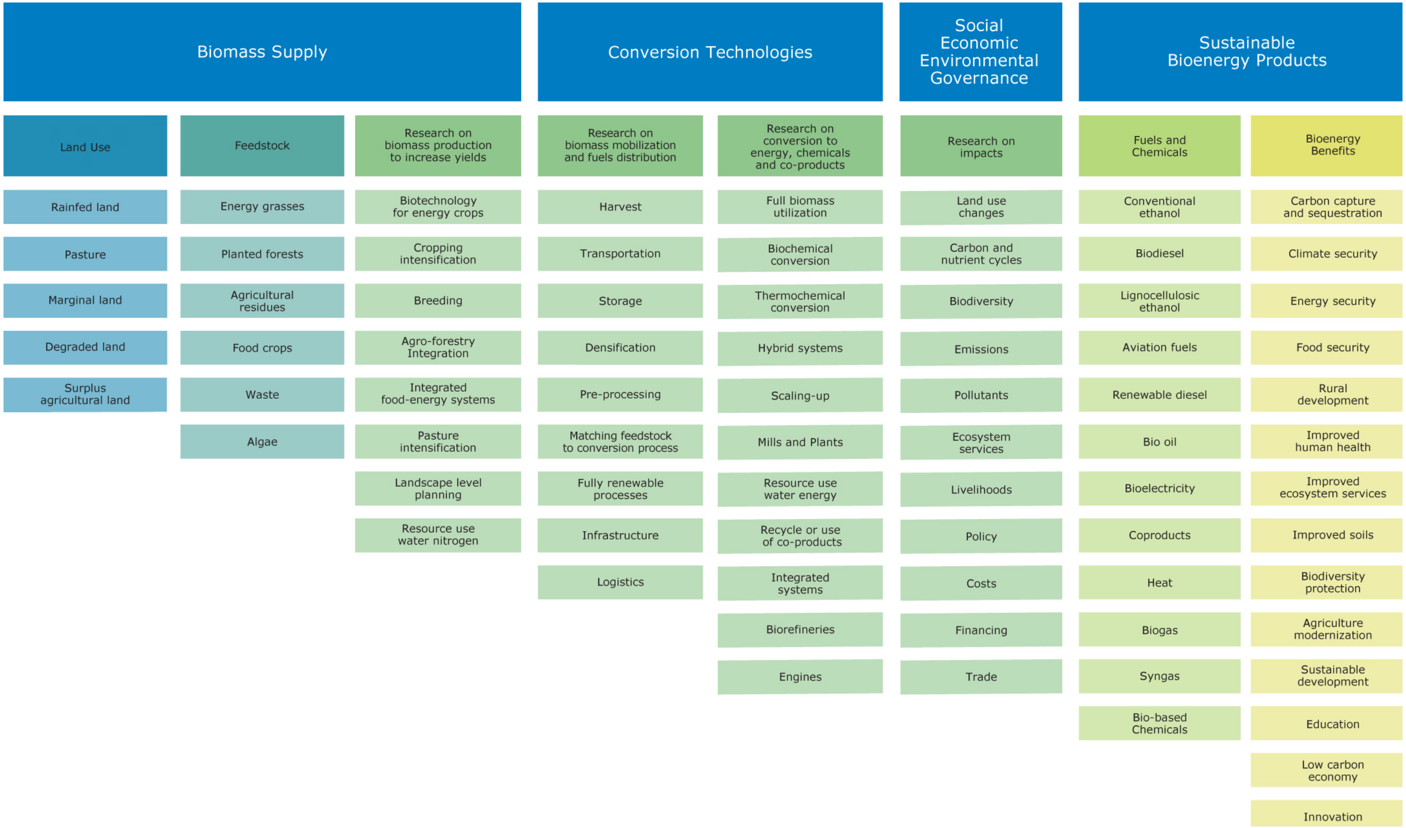

Biomass Supply			Conversion Technologies		Social Economic Environmental Governance	Sustainable Bioenergy Products	
Land Use	Feedstock	Research on biomass production to increase yields	Research on biomass mobilization and fuels distribution	Research on conversion to energy, chemicals and co-products	Research on impacts	Fuels and Chemicals	Bioenergy Benefits
Rainfed land	Energy grasses	Biotechnology for energy crops	Harvest	Full biomass utilization	Land use changes	Conventional ethanol	Carbon capture and sequestration
Pasture	Planted forests	Cropping intensification	Transportation	Biochemical conversion	Carbon and nutrient cycles	Biodiesel	Climate security
Marginal land	Agricultural residues	Breeding	Storage	Thermochemical conversion	Biodiversity	Lignocellulosic ethanol	Energy security
Degraded land	Food crops	Agro-forestry Integration	Densification	Hybrid systems	Emissions	Aviation fuels	Food security
Surplus agricultural land	Waste	Integrated food-energy systems	Pre-processing	Scaling-up	Pollutants	Renewable diesel	Rural development
	Algae	Pasture intensification	Matching feedstock to conversion process	Mills and Plants	Ecosystem services	Bio oil	Improved human health
		Landscape level planning	Fully renewable processes	Resource use water energy	Livelihoods	Bioelectricity	Improved ecosystem services
		Resource use water nitrogen	Infrastructure	Recycle or use of co-products	Policy	Coproducts	Improved soils
			Logistics	Integrated systems	Costs	Heat	Biodiversity protection
				Biorefineries	Financing	Biogas	Agriculture modernization
				Engines	Trade	Syngas	Sustainable development
						Bio-based Chemicals	Education
							Low carbon economy
							Innovation

Figure 7.1. Research landscape on bioenergy and sustainability. The central four green boxes indicate research themes that should be addressed, preferably in an integrated effort, for maximum benefits of bioenergy to be attained considering its complete lifeline. Research opportunities exist that range from local and regional to global efforts of bioenergy expansion in both developed and developing countries for an increasing number of products.

The development and use of relevant indicators is one critical part of this work[4].

There is need for social science research into the preconditions, processes, and governance required so that emerging bioenergy models grow and thrive. Dissemination tools need to be developed. Challenges are often not technical, but relate to educational resources, social and cultural norms, private and public financing, infrastructure, markets, policy and governance[5]. Governance has been identified as a key factor for bioenergy to achieve its positive effects on food security and climate change[6].

In addition to governance we also require insight in financing models for improved, more sustainable agricultural systems. New finance and investment models are needed. Data on best practices should increase our insight on improved schemes for financing as well as on the way this should be governed or organized[7]. Economic models should be enhanced to better quantify the indirect land use and rebound effects of the bioeconomy, understand better the impact of bioenergy on the various dimensions of food security, and to improve the modeling of technological change[8].

Communication and mutual learning will be very important in the transition to a more sustainable global energy matrix. Novel ways of communication, especially on how to involve the public, need to be designed. Communication of factual data on how bioenergy can improve food security to public(s) in general should be designed in such a way that it takes the negative and wrong assumptions away and decreases the negative impact of public opinion on policy and decision makers. This requires input from communication sciences and ethics. At a higher level, we need knowledge on institutional arrangements, the interplay between local, regional, national and global schemes, international relations, market and management studies, with understanding of impacts in agriculture for bioenergy, feed and food production[9]. We need to build capacity directed at the diverse networks that support biomass, bioenergy, and biofuels implementation to facilitate governance, research, public understanding of the different options and their impacts, and improve awareness of environment, safety and health implications across supply chains. Bioenergy production schemes could profit from international cooperation to adequately be deployed, while still accounting for diverse economic and agricultural circumstances of different countries, including infrastructure for current local fuel distribution and use, vehicle and jet plane manufacturing facilities and use, cultural practices, regulations and their enforcement, and a number of other factors.

7.1 Policy

Evidence is needed on the effectiveness of policies with regard to the various sustainability dimensions (people, profit, planet and governance)[10]. Studies should also address what policy measures are needed at local and global scales and which ones are most likely to be effective in the long-term. Research is needed to understand the influence of regional

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[4] (Chapter 18)

[5] (Chapter 13)

[6] (Chapter 4, Chapter 5)

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[10] (Chapter 20)

sociopolitical landscapes, technology readiness, economic resilience, infrastructure capacity, and maturation of environmental awareness among stakeholders on both the scope and timing of effective policies. With increasing globalization, research must be undertaken to bring knowledge on the implications of global bioenergy trade including the implications of multilateral agreements on energy and climate[11]. Holding emerging bioenergy to higher standards than the current agriculture and forestry ones may inhibit, not aid, emerging and more sustainable opportunities[12] and studies on policy are needed to define a comprehensive beneficial policy framework. Knowledge and theory are needed to craft policies that enable transitions to sustainability within a context of minimizing uncertainty and maximizing positive social outcomes for current and future generations.

7.2 Sustainable Biomass Supply

Understanding the potential uses of degraded land, pasture lands, lands that were previously used for food and/or cash crop production and are currently abandoned land, and those that are only marginally suitable or unsuitable for food and/or cash crop production requires new comprehensive, integrated, and where possible, landscape-level research approaches[13]. It is not currently possible to clearly distinguish among these categories of land[14]. Understanding intersections between biophysical, agronomic, and economic constraints, along with environmental impacts of change in the various possible uses of these lands, are key knowledge gaps.

Increased trials of bioenergy crops in environments where bioenergy expansion is anticipated are needed to provide data on crop performance in target environments before their wider expansion[15].

The decision making process could benefit from modeling approaches in the identification of optimal locations for energy crops[16]. The availability of yield models and empirical verification could help define available areas for bioenergy crops cultivation, including subsequent efficient crop handling[17]. These will require the development of applied research and extension capacity. A robust research and extension system focused on constant improvement in farming practices, including the impacts of different scales of operation, is an essential feature of an agriculturally based bioenergy economy. Research on effective land management with a focus on yields and sustainable practices should inform agriculture worldwide and include the development of markets for agricultural products[18]. Such models should also take into account regional social benefits; this requires insight in social benefit accumulation of introductions of bioenergy production systems.

Studies will have to identify improved yields, in parallel with better water and nutrient management while generating insight on the required scale of operations[19]. Long-term studies on use of ash and biochar as fertilizers and soil amendments should be supported[20].

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We need a robust research and extension system focused on constant improvement in farming practices, including the impacts of different scales of operation. Research on effective management of land and water with a focus on yields and sustainable practices should inform agriculture worldwide and include the development of markets for agricultural products[21].

We need integrated assessments of social, environmental, economic aspects of bioenergy systems for a sustainable supply of biomass, adopting a landscape approach of natural resources management[22]. This approach requires multidisciplinary studies in which agronomy, economics, management, bioprocess engineering and social studies come together to provide input to fully understand the value chains in specific regions[23].

The mechanisms and magnitude of the productivity of diverse, agro-forestry integrated systems relative to uniform monocultures remain contested and need further studies. Fundamental research on ecological principles, possibilities of cropping intensification, along with systems research on specific mixtures and integration strategies in different socio-ecological contexts, is needed to quantify the costs, advantages, and trade-offs of integration. These studies should be done with a common set of metrics, so that valid comparison to other studies in other regions is possible, and eventually so that a meta-analysis of the results can be made[24]. Impacts of agroforestry residues on the soil resources, pest populations and disease dynamics must be better understood[25].

7.3 Feedstocks

Climate change can alter biomass production for some crops and hinder recent yield gains. Breeding for resource-use efficiency (water-use and nitrogen-use efficiency) and “future climate-resilient” bioenergy crops should be stimulated, including tolerance to drought, temperature extremes, water-logging and salt accumulation[26].

Using biotechnology, maize production in the USA has achieved impressive yield gains but in other parts of the world, maize yields are low. Sugarcane and perennial energy crops are far from theoretical yield potentials. Using either marker-assisted breeding and conventional approaches or the GM route, energy crops biotechnological development is desired[27]. Long-term studies of perennial bioenergy crops and short-rotation forests in relation to ecosystem services, including biodiversity, water quality and availability, and soil carbon are needed[28]. More extensive trials with a range of agronomies for emerging perennial crops to test the assumption that these will be high yielding and sustainable on marginal land and other areas unsuitable to competitive food crop production are also needed[29].

The appropriate fraction of biomass residues that should be left in fields for preserving

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the agronomic benefits should be investigated for specific crops to provide opportunities for collecting part of it for bioenergy production. The nutrients obtained in the form of ash or sludge in processing plants should be investigated for their potential reuse or recycling to fields as good sustainable practices[30].

There is also need for research into barriers to adoption of new and emerging crops by farmers[31].

7.4 Logistics

The internal or captive use of renewable energy in biorefineries should be investigated and promoted in biomass supply chains to make the overall biomass to bioenergy system sustainable[32].

Alternative modes of biomass harvesting, transportation and storage should also be developed to improve soil quality, energy balances and adequacy of the biomass delivered to processing facilities. This should include evaluation of factory-scale in relation to biomass transport. Supportive technology and mechanization improvements are needed. Appropriate biomass densification techniques and equipment that can handle multiple types of biomass should be developed and deployed for field operations to improve transportation and storage for upfront processing. Other techniques such as pelletisation should be deployed while emerging ones like torrefaction should be investigated with respect to its technical performance and economics. Low cost in-field biomass drying options should be investigated in an attempt to reduce any equipment and energy-intensive upfront processing in bioenergy processing plants; on the other hand moisture tolerant conversion technologies should be developed[33].

In developed countries studies are needed as to how best synch up the bioenergy forms under development with the existing infrastructure. Studies are needed as to which sustainable infrastructure can be deployed to improve the availability of biomass in developing countries[34]. In all regions, research to understand how electricity from biomass can integrate in the future renewable energy supply is needed. Electricity from biomass can serve in either a baseload or firming capacity (through biogas), thus providing crucial support to intermittent sources of electricity such as wind and solar, which can allow greater system-wide efficiencies. Understanding trade-offs in distributed versus centralized electricity and the role of biomass is also an emerging gap. Research in system-wide leveraging of heat[35] and electricity at bioprocessing centers for additional industrial activities or community level energy access and security should be supported.

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7.5 Technologies

Long-term goals are to improve efficiency, decrease environmental impact, and enhance the economic viability of advanced biofuel processes.

Technologies need to be developed in the context of “lifeline” needs and address the integrated system - from biomass production and conversion to end use of all products - for the specific sites where these technologies will be applied. These dramatically differ depending on the intended application and end use[36]. Knowledge on requirements for small and large-scale bioenergy production from bioprocess design should be combined with knowledge on innovation and financial management[37].

There is need for investment in advanced biosciences research-genomics, molecular biology, and genetics - for major platforms - sugar, syngas, methane and other bioproducts for fuels, including hydrogen, and chemicals[38]. Careful consideration is needed to define how best biomass is used, converted, scaled up and deployed to an appropriate level and in understanding the potential value of every single stream of organic matter - a no waste philosophy[39]. The complete use of feedstocks must be sought to convert all primary energy content of the material to useful products[40].

Continued innovation in use of waste materials and in water and nutrient reuse and recycling in bioenergy systems is needed to fulfill the potential contribution of biomass to sustainable energy production[41].

Most processing technologies for first generation 1G biofuels are fully mature, but there is room for improvement, especially in the energy balance[42]. Higher efficiency technologies are needed for traditional bioenergy applications and continued development of integrated, resource-efficient biomass conversion pathways[43]. For instance, multi-fuel processing (e.g., co-combustion or co-firing of several biomass types in a single furnace) in flexible plants should be investigated based on the physico-chemical properties of biomass collected, handled and sent to processing plants[44].

Lignocellulosics are going commercial. Although cellulosic ethanol is undergoing initial scale commercial deployment, more work is needed to bring down the cost of the new conversion methods[45]. Improvements in microorganisms and enzymes are needed, especially for pentose fermentation, and in added value co-products (such as the use of lignin for energy and its fractions as source of value added co-products)[46].

Advanced biofuels still require many technical and financial advances. Biofuels that would be suitable for jet fuel applications are highly desirable[47] and in need of pilot and demonstration scale plants. Catalysts are needed with increased robustness and

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longevity and cost reduction in clean up. Flexible biorefinery systems need designing and engineering efforts[48].

To be able to use the “new” opportunities of feedstock supply (such as urban residues, agricultural residues)[49] there is need of advances in metagenomics. Vegetable oil production needs feedstock flexible processes[50].

7.6 Exploring Social and Environmental Benefits

Among the renewable energy options, bioenergy is the system with more wide spread benefits. To better explore and enhance benefits associated with agriculture and rural development, such as improved energy and food security as well as opportunities to develop a whole new industry based on biomass, it is essential to develop monitoring and evaluation systems[51], or use existing ones, to evaluate the progress towards sustainability on social and environmental issues[52]. There is need to improve datasets regarding good cases where projects clearly demonstrate the link between the reduction of energy poverty and greater energy access, through the improvement of livelihoods, and based on more effective and efficient use of biomass for energy. Because bioenergy impacts tend to be site-specific, not only more case studies are needed but also integrative approaches that can draw lessons from those case studies and from improved indicators and methodologies for tracking and monitoring progress[53].

Data collection should be carried out according to carefully selected indicators used to measure the evolution of different aspects of environmental or socio-economic contexts. This will entail a larger effort that needs to involve producers, local governments and international organizations[54]. We need improved methodologies for estimating, quantifying, and verifying land use changes (LUC)[55]. Long-term research is needed on soil nutrient and carbon cycles under perennial crop and forest systems, and on how land use changes affect water and soils[56]. Improved methods should be developed to leverage remote sensing capabilities for monitoring land use and soil and water status[57].

Understanding the dynamics of land use change, both direct and indirect, is very important for the assessment of several key impacts of biofuels. There is no consensus on the methodology to be used and there is a critical shortage of reliable, reasonably disaggregated data in time and space[58]. Research should aim to develop methods and generate data for a higher level of scientific consensus on the indirect land use change (iLUC) evaluation, and on the treatment of net emissions for co-products, by-products

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and N_2O emissions data in bioenergy systems[59]. Further development of greenhouse gas life-cycle assessment (GHG LCA) methodologies is needed to quantify the influence of timing of emissions and removals, albedo change, and short-lived climate forcing agents. New data will be required in order to apply these methods[60].

The next step in standards development must be the critical pursuit of the technical, scientific, and educational capacity to assess baseline conditions and tailor implementation solutions that provide measureable outcomes both at the sub-field, field, and landscape levels. These capacity needs are particularly pressing in the area of biodiversity, water quality, carbon accounting, and socio-economic conditions within broader communities. At least from a certification perspective, it is questionable whether additional research dollars should be spent in the pursuit of more indirect effects modeling. Instead, investments should be made in building capacities in public governance parallel to those for certification[61].

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section IV

Background Chapters

8. Perspectives on Bioenergy
9. Land and Bioenergy
10. Feedstocks for Biofuels and Bioenergy
11. Feedstock Supply Chains
12. Conversion Technologies for Biofuels and Their Use
13. Agriculture and Forestry Integration
14. Case Studies
15. Social Considerations
16. Biofuel Impacts on Biodiversity and Ecosystem Services
17. Greenhouse Gas Emissions from Bioenergy
18. Soils and Water
19. Sustainability Certification
20. Bioenergy Economics and Policies
21. Biomass Resources, Energy Access and Poverty Reduction

chapter 8

Perspectives on Bioenergy

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Highlights

- Holistic studies of the energy sector show that bioenergy is an essential component of GHG reduction technologies
- The development of biofuel industries in Brazil and the USA illustrate that biofuels can make significant contribution to the transportation sector
- Commercialization of cellulosic biofuels has begun
- Biogas is underutilized in most regions and could expand strongly in the future
- Biodiesel from plant oils has limited potential but new routes are opening up for conversion of sugar to diesel and jet fuel
- Restricting bioenergy and minimizing prices are not likely to increase food security
- The use of marginal land for production of cellulosic biofuels will reduce the use of food crops for biofuels and concerns about land use change

Summary

Our understanding of the challenges and opportunities associated with bioenergy production has strongly expanded since a previous SCOPE report on biofuels in 2009. Concerns about escalating food prices and negative environmental effects associated with indirect land use change have significantly abated; the promise of lignocellulosic fuels has begun to be realized with the startup of the first generation of commercial lignocellulosic biofuels biorefineries; bioenergy production has continued to expand under the implementation of more stringent sustainability criteria; and there has been technical progress on many fronts. The motivations for reducing greenhouse gas (GHG) emissions have become more compelling, as summarized in the recent IPCC reports, and holistic analyses of the options for GHG reduction have confirmed that bioenergy has an essential role to play in accomplishing such reductions.

8.1 Introduction

Biomass was the first energy resource used by mankind, the unique source of fuel for millennia. Even today, biomass accounts for nearly 10% of world total primary energy supply (IEA 2012c) and is the largest contribution to renewable energy – 52.2% of renewable energy is provided by biomass. Roughly 60% of biomass is used for primary energy production (residential heating and cooking via combustion), largely in non-OECD countries. This form of inefficient use has considerable negative impacts on human health (smoke pollution) and the environment (deforestation) (Chapter 16, this volume). This volume focuses primarily on technologies that move away from this form of bioenergy, which requires not only attention to technology but to social and economic factors including energy access and social equity.

The modern concept of bioenergy, based on advanced and efficient conversion processes, is largely motivated by energy security and sustainability concerns (Chapters 3 and 5, this volume). Worldwide bioenergy contributes 310 TWh of electricity (2% of world electricity generation in 2011), 8 EJ of industrial heat, and 110 billion liters of liquid biofuel (2.3% of transportation energy) (IEA 2012c). Bioenergy is expected to be an important contributor to reducing greenhouse gas (GHG) emissions required to address climate change, as well as meeting the increase in energy demand expected in the coming years (IPCC 2014). However, one of the main challenges in envisioning and implementing optimal paths for bioenergy deployment is the large diversity of feedstocks, processes and products that must be considered. In some cases, there are options that are compatible with both environmental benefits and economic feasibility, in other cases, bioenergy production scenarios need more assessment to avoid undesirable impacts. In this volume, several alternatives are put forward and discussed, recognizing that bioenergy can supply transport fuels and electricity, in different contexts and scales.

The developed economies of the world provide a vast array of goods and services that depend upon the consumption of large amounts of inexpensive energy. Less developed societies aspire to have similar goods and services, so energy demand is expected to continue to expand into the foreseeable future. According to the World Energy Council, the world fleet of 800 million LDV (Light Duty Vehicles) in 2010 is expected to reach the range of 1.7 to 2.1 billion cars in 2050 (WEO 2011). The International Energy Agency (IEA) predicts that world energy use will increase by more than a third between 2010 and 2035 (IEA 2012b). At present, approximately 87% of energy demand is satisfied by energy produced through consumption of fossil fuels. Although the IEA predicts that this share will fall to 75%, the total consumption of fossil fuels will continue to rise, adding another 6 Gt of carbon to the atmosphere by 2035. In view of the fact that current rates of carbon emissions are causing climate change, the prospect of increased emissions far into the future is disheartening.

Climate change is unwelcome for many reasons that are well documented in the recent

IPCC reports (IPCC 2014b) and many other thoughtful commentaries. However, in the context of this volume, perhaps the most important impacts of climate change are those that are expected to impact agriculture and natural ecosystems, including marine environments. The most fundamental implication is that in many regions of the world, agricultural production will decrease because of heat-induced damage or drought resulting from changes in rainfall patterns. Reduced agricultural productivity combined with increasing population may be expected to cause conversion of natural ecosystems to agriculture. Similarly, the altered temperature, ocean acidification and changing rainfall will also disrupt many ecosystems. Thus, it is imperative that we explore all possible means of reducing carbon emissions if we hope to preserve some vestige of the natural ecosystems that remain today and avert the social disruptions that may attend regional agricultural failures. A recent study of all options for reducing GHG emissions in California concluded that, even with massive commitment to efficiency and other sources of renewable energy, the use of bioenergy and biofuels, in particular, is essential (Box 8.1).

The utility and impact of liquid biofuels was the subject of a previous SCOPE study in 2009 (SCOPE 2009). Since that time there has been rapid progress on many aspects of bioenergy, including biofuels, which are described in chapters 9-21 of this volume. The implications of these advances in a forward-looking global context were discussed by many of the authors and other experts during a week-long meeting in Paris in December 2013. The conclusions from those discussions were captured in four crosscutting chapters (chapters 3-6, this volume) entitled Energy Security, Food Security, Environmental and Climate Security and Sustainable Development and Innovation. Thus, the crosscutting chapters represent a consensus view of the field of bioenergy that may be particularly helpful to policymakers and regulators who must confront the often confusing barrage of academic discourse in this field.

In this brief perspective, we have endeavored to highlight a few rapidly evolving topics, mainly focusing on liquid biofuels, where we have formed opinions, based on our experiences in two of the major regions of biofuel development, that are less nuanced than is possible in a consensus document.

8.2 The Upward Trajectory of Biofuels

The fossil fuel industry has, for more than a century, provided an abundant and relatively inexpensive source of liquid, solid and gaseous fuels and chemicals and, based on current estimates of reserves, can continue to do so for centuries (BP 2013). More fossil fuel remains in the earth than the total amount used in human history. Thus, in order to envision the future trajectory of biofuels, it seems worthwhile to reflect briefly on the progress made in several regions of the world in partially displacing liquid fossil fuels with biofuels. The feasibility of the use of biofuels in Diesel and Otto engines was recognized early last century in the automotive industry, but discoveries of abundant, cheap oil made biofuels uncompetitive and their contribution marginal.

Box 8.1. Bioenergy is essential

There are many conceivable ways to reduce carbon emissions. Thus, critics of bioenergy argue that biofuels and other forms of bioenergy are not necessary. The fallacy of this argument was recently exposed in a major study conducted by the California Council on Science and Technology (CCST) on behalf of the Government of California. In brief, in 2005, the governor of California issued an executive order that established a state mandate to reduce California's carbon emissions to 1990 levels by the year 2020 and by another 80% below 1990 levels in 2050 (Schwarzenegger 2005). The CCST was charged with evaluating the technical possibilities of meeting those goals. Approximately forty scientists representing all sectors of the energy system collaborated for more than two years on an analysis of how much energy demand could be reduced through efficiency and how much energy could be produced and distributed within the state by all known or pending low-carbon technologies. This analysis resulted in the conclusion that even though California is well-suited to production of solar, wind, wave and geothermal energy and even with efficiency measures, it was impossible to reach the GHG reduction goals without significant inclusion of bioenergy, particularly for liquid biofuels (Long et al. 2011). Furthermore, it was concluded that it would be necessary for the state to import large amounts of biofuels from other regions, such as Brazil, in order to satisfy the demand for low-carbon fuels for the heavy duty fleet and aviation (Youngs and Somerville 2013).

The necessity of biofuels was surprising to many participants in the study who previously held the opinion that vehicle electrification and solar or wind-based electricity generation could sufficiently decarbonize transportation. Indeed, the CCST study was based on the unrealistic assumption that a large percentage of the light-duty fleet, buses and rail in California would be electrified and fuelled by such means. However, there is no known or pending storage technology that would allow electrification of the aviation or heavy duty ground transportation fleets. Furthermore, because of inescapable use of natural gas for electrical grid load following, it was necessary to propose the phasing out of all fossil-based transportation fuels in order to reach the goal of reaching the goals of AB-32. Thus, as previously noted (Pacala and Socolow 2004), biofuels are an essential part of the suite of approaches needed to minimize climate change. Indeed, the main conclusion of the CCST study was that we need to use all known and pending low-carbon technologies in order to have any chance at a significant reduction in energy-based carbon emissions. A similar conclusion was reached in a large multidisciplinary study of America's energy future by the U.S. National Academy of Sciences (US NRC 2009).

The sudden rise of the price of petroleum during the oil crisis of the 1970s changed that. Particularly hit were the developing countries that depended heavily on oil imports. For some, the oil import bill reached 50% of all their export earnings. As a consequence, large sugar-producing countries, such as Brazil, started aggressive programs for producing ethanol from sugarcane as a replacement for gasoline (Box 8.2). Environmental considerations didn't play an important role in such decisions at that time.

Box 8.2. A Short History of Brazilian Ethanol

The production of sugar from sugarcane juice results in a byproduct called molasses that has long been used for alcoholic beverage production, among other things. Thus, in some sugarcane-producing countries there is a long tradition of ethanol production. In 1931, the Brazilian government implemented a compulsory blend of at least 5% anhydrous ethanol in gasoline, aimed at reducing the impact of total dependence on imported petroleum and absorbing the excess production of the sugar industry. The ethanol content in Brazilian gasoline varied over successive decades as indicated in Figure 8.1. Thus, for more than eighty years, all Brazilian cars have been using blends of ethanol and gasoline.

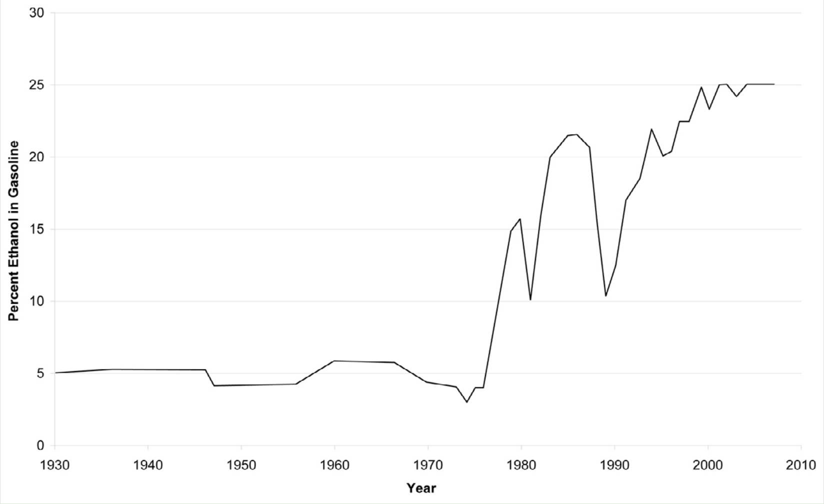

Figure 8.1. Evolution of ethanol content in Brazilian gasoline from 5% in 1930 to 25% in 1998.

In 1975, in response to the impacts of the oil shocks during the 1970s, the Brazilian government initiated the National Alcohol Program (Proálcool) which fostered the expansion of ethanol use as a replacement for gasoline, initially

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increasing the ethanol blending up to 25% in gasoline (E25) and also introducing pure hydrated ethanol (E100) for use in dedicated vehicles (reviewed in Nogueira 2008). The combination of incentives adopted by Proálcool at that time included the following measures: a) minimum levels of anhydrous ethanol in gasoline were established; b) lower consumer prices for hydrated ethanol than for gasoline were guaranteed (fuel prices were determined by the government at that time); c) competitive prices for ethanol producers were guaranteed, even when international prices for sugar were more advantageous than for ethanol; d) financing under favorable conditions for mills to increase their production capacity was offered; e) taxes on new cars were reduced and annual registration fees for vehicles capable of running on hydrated ethanol were reduced; f) the compulsory sale of hydrated ethanol at gas stations was mandated; and g) the creation of ethanol reserves to ensure supply throughout the year were mandated (Nogueira 2008). Given this favorable policy framework, the production of ethanol expanded significantly (Figure 8.1). This, in turn, stimulated the breeding and diffusion of better varieties of sugarcane, adoption of more efficient agroindustrial practices, such as vinasse use as fertilizer and improved cogeneration schemes. Additionally, the automotive industry improved significantly the pure ethanol motors, eliminating some problems initially observed with material compatibility and cold start, reaching performance similar to the gasoline motors. Almost all sales of new cars in this period were of models for hydrous ethanol use.

Around 1985, due to the decline in oil prices and strengthening of international sugar prices, that positive situation faltered. In 1986, the government revised the ethanol policies, thereby reducing the average financial returns to the sugarcane industry and stimulating the allocation of sugarcane to produce sugar for export, rather than for ethanol production. This led to a temporary end to expansion of the Proálcool initiative. The mechanisms for creating ethanol reserves failed, and policy changes that included reduced levels of ethanol in gasoline, ethanol imports, and the use of gasoline-methanol blends were implemented. The consumers grew wary of pure ethanol as fuel and moved towards gasoline cars, progressively reducing ethanol demand. Thus, the use of ethanol was gradually restricted to anhydrous ethanol blended with gasoline.

By the beginning of the 1990s, because of decades of strict government control, agricultural and industrial production was under the control of the sugar mills, there was limited utilization of byproducts, and the competitiveness of the Brazilian sugarcane industry was largely driven by low salaries and efficiencies of scale (CGEE 2007). Between 1991 and 1999, the Brazilian government initiated administrative reforms that included a shift

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towards free-market pricing in the sugar and ethanol sectors, progressive removal of subsidies, and a reduction of the government's role in setting ethanol prices. Additionally, a new set of rules was implemented to organize the relationships between sugarcane producers, ethanol producers, and fuel distributors. The only feature of the original framework of legal and tax measures that remained, and was maintained until recently, was the differential tax on hydrated ethanol and gasoline, which was intended to maintain approximate parity of consumer choice between hydrated ethanol and gasoline. In this context, ethanol is freely traded between producers and distributors. Sugarcane is also traded freely, but its price is mainly determined according to a contractual voluntary model jointly coordinated by the sugarcane planters and ethanol and sugar producers.

The institutional restructuring of the ethanol industry continued with the creation in 1997 of two important institutions: the National Energy Policy Council (CNPE), and the National Oil Agency (ANP), later renamed the National Oil, Natural Gas and Biofuels Agency. The CNPE is responsible for establishing directives for specific programs for biofuels use. The ANP oversees the regulation, contracting, and inspection of biofuel-related economic activities and implements national biofuel policies, with an emphasis on ensuring supply throughout the country and protecting consumer interests with regard to product price, quality and supply.

In 2003, flex-fuel cars were launched and were well accepted by consumers. Flex-fuel cars offer owners the options of using gasoline (with 20–25% anhydrous ethanol), hydrated ethanol, or any blend of the two. Thus, the consumption of hydrated ethanol in the domestic market made a comeback, creating new opportunities for the expansion of the sugarcane industry in Brazil, as well as the possibility of meeting the demand of the international market for ethanol for use in gasoline blends.

During the period 2003–2008, the Brazilian sugarcane industry expanded rapidly, new and more efficient mills were commissioned, and a consolidation process was initiated, at the same time that positive indicators for the industry's environmental sustainability were demonstrated (Macedo 2005). Flex-fuel cars currently represent approximately 90% of sales of new cars, and pure ethanol can be used nowadays by 12.7 million Brazilian vehicles (mostly cars with flex-fuel engines), which represent approximately 47% of the national fleet of light road vehicles (ANFAVEA 2013).

However, since 2008 the Brazilian ethanol agroindustry has been facing hard times, essentially due to the increasing lack of competitiveness in relation to

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» gasoline. Officially motivated by inflation control, the Brazilian government (which controls Petrobras, the main oil products supplier) has held the gasoline price at the refinery gate (ex-taxes) at approximately 70 US$/barrel for the last 5 years, significantly below the international parity prices formerly adopted. Besides, although taxes have historically represented more than 40% of the final price of gasoline, the Federal government also has been gradually reducing taxes on this fuel and in June 2012, the main Federal tax on gasoline was set to zero. Thus, the current gasoline price (Nov 2014) at Brazilian gas stations is significantly below the value that would be expected if taxes were applied. Thus, as the Brazilian fleet is predominantly flex-fuel, ethanol demand has decreased as this biofuel has been substituted by gasoline, and ethanol production in 2010 was 30% less than in 2008. This situation has brought heavy economic losses to Petrobras, to the Brazilian trade balance and to the Treasury, highlighting the relevance of proper public policies to foster bioenergy.

At present, the word “biofuel” generally means ethanol from sugar or starch (e.g. corn or sugarcane), or biodiesel (fatty acid methyl esters) made from oils (e.g. soy, palm, rapeseed). Worldwide, consumption of ethanol is roughly three times that of biodiesel (Table 8.1). Brazil and the USA produce about 88% of the fuel ethanol used in the world and consume much of what they produce. Ethanol use elsewhere in the world is comparatively anemic, with China being the third largest producer and user of fuel ethanol. In some cases the low level of production may be related to the fact that few other regions have the land, climate, and experience required to scale-up production of highly productive starch or sugar crops to the extent possible in the USA and Brazil. However, just as most countries are not self-sufficient in petroleum, it is unrealistic to assume that all regions will produce their own biofuels. Thus, for instance, Germany and the UK import about half of the ethanol used whereas other countries such as France use approximately the same amount as they produce.

Brazil currently substitutes about a quarter of gasoline demand with ethanol as a result of a somewhat tumultuous eighty year development program (Box 8.2) and is a significant net exporter of ethanol (Table 8.1). The long-term commitment to ethanol by Brazil led to the development of flex-fuel vehicles that can operate using variable blends of ethanol and gasoline. The international auto manufacturers responded, which could facilitate the expansion of ethanol use around the world. Ethanol production in Brazil is projected to triple by 2040 because Brazil benefits in net international trade by exporting petroleum rather than using it domestically (US EIA 2013). The development of the ethanol industry in Brazil is due, in part, to the availability of large amounts of land that is suitable for sugarcane production. However, even under such favorable conditions, the development of the ethanol industry has required persistent

Table 8.1. Biofuel production and consumption in 2011 (thousands of barrels per day).

	Ethanol		Biodiesel	
	production	**consumption**	**production**	**consumption**
North America	938.9	883.4	65.9	62.9
United States	908.6	841.1	63.1	57.8
Central & South America	415.9	350.1	103.2	72.8
Brazil	392.0	332.4	46.1	45.0
Europe	72.8	104.3	177.7	239.5
France	17.4	16.0	34.0	40.5
Germany	13.3	26.5	52.0	47.4
United Kingdom	5.0	11.2	4.0	16.0
Africa	0.6	1.3	0.2	0.1
Asia & Oceania	64.8	66.0	53.4	36.4
China	39.0	38.0	7.8	7.0
India	6.0	6.0	2.0	2.0
Indonesia	0.1	0.0	20.0	5.0
Japan	1.0	2.0	0.3	0.3
Korea, South	0.0	0.2	6.3	6.3
Thailand	8.9	7.0	10.2	10.2
World	1493.5	1405.6	403.7	414.2

Data: U.S. Energy Information Administration

policy support. Thus, it seems likely that, for the foreseeable future, the development of biofuels industries in other regions with advantageous growing conditions will also depend on implementation of supportive policies.

Similarly, the development of corn ethanol in the USA resulted from supportive policies, though the motivations were different (Box 8.3). The rapid phasing out in 2005 of a gasoline octane-booster called methyl *tert*-butyl ether (MTBE) for environmental reasons created a demand for a high octane additive that could be satisfied by ethanol. During that same period, corn prices were depressed to a level where crop subsidies were necessary to keep farmers profitable. In order to stimulate demand, and to address persistent concern about dependency on foreign petroleum, the US government instituted a subsidy for corn ethanol and implemented an annually expanding mandate for blending of ethanol into the gasoline supply.

In 2013, consumption of ethanol in the US may have begun to plateau because of a perceived "blend wall". The blend wall refers to the fact that until 2011, the US Environmental Protection Agency (EPA) authorized the blending of ethanol in gasoline up to 10% of total volume to produce "E10" for most vehicles (US DOE 2013). In 2012, the US EPA raised the blending limit to 15% for cars manufactured after 2001. However, the belief that auto manufacturers would void warranties and resistance from large gasoline distribution franchises to allow station owners to sell E15 has caused delayed implementation of the new fuel blend. Adoption of flex-fuel vehicles in the US has been extremely slow. Although there are approximately 10 million flex-fuel vehicles in the USA (US EIA 2011), this only represents about 5% of the light-duty fleet, effectively limiting expansion of the ethanol fuel market. Similarly, there are few flex-fuel vehicles in other developed or developing countries other than Brazil; however there may be potential for additional ethanol consumption in previously untapped markets including some EU countries, and countries in Latin America, Asia and Africa. Some studies indicate that about 21 million hectares of sugarcane (less the current area of soy in Brazil) would be enough to implement 5% ethanol blending in the global gasoline demand in 2025 (Cerqueira Leite et al. 2009).

Box 8.3. Corn Ethanol in the USA

As noted in a previous account of the history of corn ethanol (Youngs 2012), from which modified excerpts are reproduced here for convenience, interest in biofuels began with mass production of personal automobiles. Henry Ford was a proponent of both ethanol and biodiesel but the low cost of petroleum derivatives allowed fossil fuels to dominate the transportation fuel market. When price volatility and embargoes in the 1970s created fuel shortages, the U.S. began subsidizing production of corn ethanol for blending with gasoline.

"The first push for corn ethanol was short-lived, fading quickly with falling oil prices during the economic boom of the 1980s and political changes in many oil producing countries. Interest rebounded in the 1990s – blending of ethanol had the added benefit of anti-knock properties and could replace tetraethyl lead as a combustion facilitator, reducing smog formation. The Clean Air Act Amendments of 1990 required reformulated gasoline to contain at least 2% oxygen by weight. The Winter Oxyfuel Program (1992) required 2.7% oxygen in cold months for cities with elevated carbon monoxide with ethanol as the common oxygenate. The Year-Round Reformulated Gasoline Program (1995) required 2% oxygen. MTBE (methyl-tert-butyl ether) and ethanol were the cheapest oxygenates and both were widely used. Ethanol was popular in the farming states of the Midwest, while MTBE was used elsewhere in the country. At its peak use, MTBE represented 87% of reformulated gasoline oxygenate. However, environmental impact studies in

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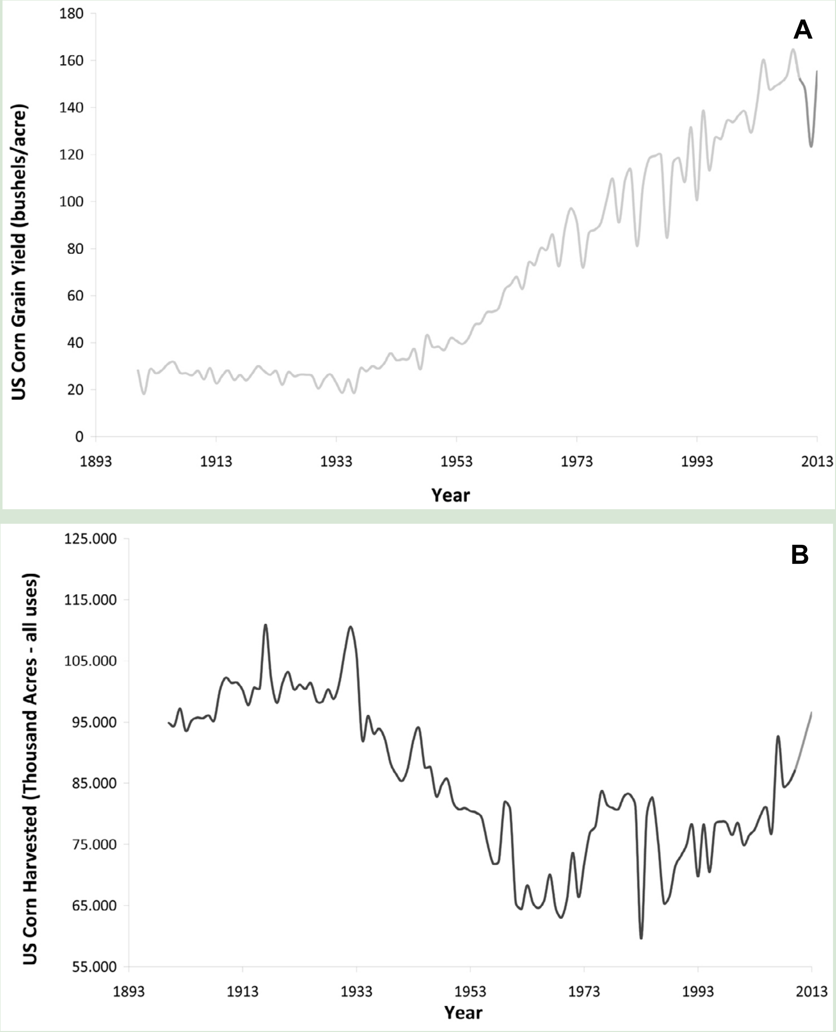
» the mid to late 1990s showed MTBE was not only toxic, it moved easily into water systems exacerbating contamination events (Squillace et al. 1997). California, the largest user of MTBE at the time, was the first state to ban the compound in 2003. With other states following suit. With ethanol as the only economically viable replacement, a new corn ethanol boom began. The Energy Policy Act of 2005 established the first renewable fuel standard, mandating volumetric requirements for biofuel use.”

The use of corn ethanol in the U.S. has been a continuing source of controversy. On one hand, by increasing demand for corn, the industry has had a positive economic impact on rural farm communities, contributed to investments in yield improvements and reduced dependency on imported petroleum. On the other hand, critics note that intensive production of corn requires inputs of fertilizer and agrichemicals that cause pollution, soil loss and negative impacts on biodiversity. The animal products industry (i.e., meat, milk, eggs) experiences increased costs for feed grain, and many people question the morality of converting corn to fuel when there are hungry people. “Industry critics have alarmed the public by stating that as much as 40% of the corn acreage is used for ethanol, implying that farmers are shifting from food to fuel production (hence the “food versus fuel” debate). While it is true that a large acreage is being used for corn ethanol, the actual production of corn for food and feed (domestic and exported) has not been reduced. The U.S. produced 13.2 billion bushels of corn in 2009, a new record - up from 9.5 billion bushels in 2001 (Figure 8.2). Feed corn and residual use has fluctuated between 5 and 6 billion bushels per year from 1992 to 2009 and exports have remained steady at around 2 billion bushels per year (Figure 8.2). In 2009, 42.5% of corn was used for feed, 32.1% for ethanol, 15.7% for exports, 3.5% for high-fructose corn syrup, and 6.2% went to other uses (starch, sweeteners, cereal, beverage alcohol and seed) (NCGA 2011).

As a result of improved productivity and some redistribution of acreage out of subsidized set-aside land and soybeans, the U.S. expanded corn production to meet the ethanol blending market. The yield per acre has risen with a fairly constant trend, increasing 1.6 bushels per acre per year. Whereas an acre of U.S. farmland produced an average 138.2 bushels in 2001, the average yield was 152.8 bushels per acre in 2010. The number of corn acres also increased from roughly 75 million in 2001 (a low point in the trend) to 88 million acres in 2012 (a return to the acreage used for corn production in 1933) (USDA NASS, 2014). Total farmed acres in the U.S. have remained flat at around 240 million acres for the eight major crops (corn, sorghum, barley, oats, wheat, rice, cotton, and soy) (FAOSTAT 2009). »

Increased corn production was not without impacts. The ethanol boom of the mid-2000s coincided with rising oil prices, which negatively impacted all agricultural production, including corn, causing food prices to rise. Petroleum prices affect the cost of activities on the farm (planting, field maintenance, and harvesting) as well as fertilizer prices and, of course, transportation from farms to feedlots, food processors, and consumers. Conditions incited speculation in commodity markets including general agricultural markets and corn ethanol. The outcome was a substantial rise in food prices, which many blamed directly on the corn ethanol mandate. However, John Baffes and Tasso Haniotis at



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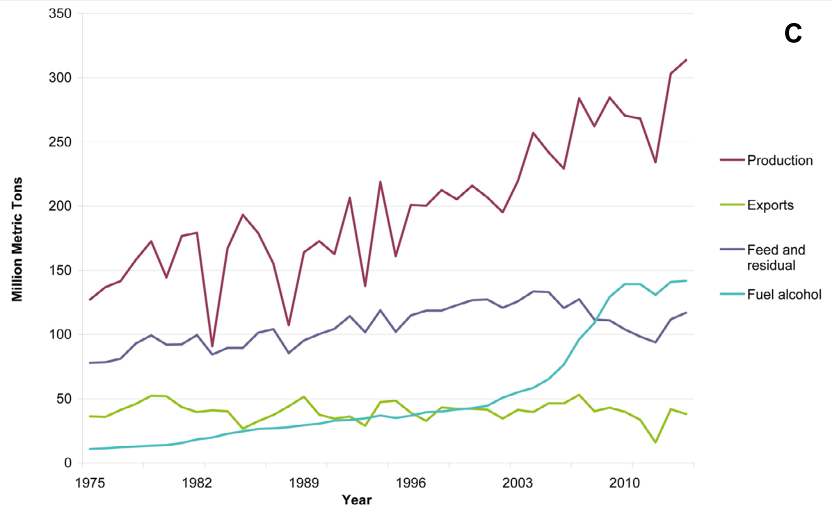

Figure 8.2. Corn grain yield (A), harvested corn acres (B) and uses (C). USDA National Agricultural Service 2014.

The World Bank Development Prospect Group stated "*We conclude that a stronger link between energy and non-energy commodity prices is likely to have been the dominant influence on developments in commodity, and especially food, markets… We also conclude that the effect of biofuels on food prices has not been as large as originally thought, but that the use of commodities by investment funds may have been partly responsible for the 2007/08 spike*" (Baffes and Haniotis, 2010). While the actual contribution of corn ethanol versus oil prices and market speculation are difficult to sort out, the clear potential for a negative impact of food-based biofuels was sobering."

Demand for ethanol is also limited by the fact that the diesel and jet fleets, which comprise about 60% of the European market and about 30% of the US market, cannot directly utilize ethanol. The demand for bio-based, low-carbon diesel and jet fuel to satisfy mandates has led to the use of various sources of lipids to produce fatty acid esters (i.e., biodiesel) or hydrogenated alkanes (renewable or green diesel). Because the technology for conversion of fats and oils to biodiesel is very simple (Chapter 12, this volume), it is possible to produce biodiesel at any scale down to single users or small cooperatives (Pienaar and Brent 2012; Skarlis et al. 2012). The use of waste cooking oils for biodiesel is an environmentally attractive option, although it is limited in scale.

Lifecycle analyses of biodiesel from palm or soy indicate a GHG reduction of about 70% (Nogueira, 2011) (see also Chapter 17, this volume). The net energy return is about 3.5 GJ output per GJ of energy input, which is substantially better than the 1.2

GJ per GJ estimated for corn ethanol but much worse than the roughly 6 or 9 GJ per GJ for lignocellulosic or sugarcane ethanol, respectively. While, biodiesel from oil seeds is also potentially suitable for local production in developing economies, we believe it is unlikely to expand and may present a less than ideal use of land compared with other options on an industrial scale in developed economies. For example, in Brazil, soy yields about 700 liters per hectare of oil and in Europe, rapeseed yields about 1100 liters per hectare.

By contrast, oil production from palm is highly productive, yielding about 4700 liters per hectare. Because its geographical range is limited, it may be that palm biodiesel will expand significantly in those regions, such as in degraded cropland or pasture, where it can be established without major GHG deficits or ecosystem destruction. For example, according to studies by EMBRAPA, there are about 30 million hectares suitable for planting oil palm in Brazil (4% of national area) (Yui and Yeh 2013). In this zoning, the eco-physiological requirements of the palm and environmental constraints were taken into account, including soil, climate, and topography, and areas protected by legal or other regulatory restrictions were excluded. Palm plantations also produce as much as ten metric tons per hectare per year of palm fronds that may be useful for conversion to lignocellulosic fuels and may further improve the lifecycle impacts. The challenge associated with expanded use of palm will be in identifying land that can support the growth of palm but which does not lead to the loss of native ecosystems or the release of large amounts of carbon during land conversion (see Chapters 9 and 17, this volume, for discussions on land use and land use change emissions).

Based on measurements of the productivity of C4 perennial grasses, such as switchgrass, Miscanthus and Arundo (Chapter 10, this volume), a recent study by the European Environment Agency (EEA 2013) concluded that it would be possible to produce much larger amounts of lignocellulosic biomass on the land used for soy or rapeseed production than the total seed yield of those crops. In 2008, total plant lipid production worldwide would have been equivalent to only about 36 billion gallons (136 billion liters) of biodiesel, about 20% of global diesel consumption. As commercial development of lignocellulosic fuels matures, we envision that biodiesel production from oilseeds may be displaced by perennial grass species because the total yield of fuel per unit of land could be more than four-fold greater. However, it should be noted that oil production from soybean is a byproduct of protein (soymeal) production, thus the demand for soy and the associated availability of its oil and derived fuel co-products are largely driven by the demand for animal feed at present.

8.3 Low-Carbon Heat and Power

Besides liquid biofuels, modern bioenergy includes also bioelectricity, which is increasingly competitive in some places around the world and has high relevance for mitigating GHG emissions. With GHG reductions of 55 to 98% for most systems (Chapter 17, this volume), the EU has included biomass power alongside other renewables in all of its “20-20-20” carbon mitigation scenarios (Tasios 2013). Globally, biomass power capacity is currently about 60 GW (IRENA 2012) and is projected to grow to 270 GW by 2050 (BNEF 2011).

Using efficient steam power systems, generally in cogeneration schemes, wood represents an important share of total primary energy supply in some industrialized countries (e.g. Finland (28%), Latvia (28%), Sweden (27%), Denmark (19%)) (AEBIOM 2013). In 2010, wood accounted for 44% of electricity from biomass (IRENA 2012). Waste biomass accounts for nearly one-third of biomass electricity capacity. Energy recovery from wastewater and municipal organic waste have increased with changes to policy regarding water quality and landfill in the US and EU (Chapter 12, this volume). The use of agricultural residues and energy grasses for heat and power is also growing. Sugarcane bagasse is largely used for power generation in countries such as Brazil, Guatemala and Mauritius, where electricity sold to the grid represents a significant income in sugar mills, with good potential for expansion (Chapter 14, this volume). The introduction of advanced thermal cycles can increase the current efficiency and almost double the amount of electricity produced (IEA 2007).

Public acceptance of biomass power is mixed. In many respects biomass power is seen to compete directly with other renewables; however, biomass can also provide a flexible option for balancing supply and demand for intermittent renewables such as wind and solar. Biomass can function as a source of constant or baseload power or, when converted to biogas or syngas, it can operate in fast-ramping turbines to accommodate demand peaks, effectively substituting for natural gas. Finally, as highlighted by the IPCC, combining biomass electricity with carbon capture and storage (CCS), although logistically and economically challenging, is one of the few options for carbon negative energy production with substantial climate stabilization potential (IPCC 2014).

8.4 The Unrealized Potential of Biogas

In many regions of the world biogas may be the best option for producing energy from biomass. Biogas is a methane-rich gas produced by the degradation of organic materials by microorganisms (Chapter 12, this volume). Biogas can be produced from carbonaceous feedstocks via anaerobic digestion by methanogenic bacteria primarily, or, less commonly, by catalytic gasification (also called “bio-synthetic natural gas,” or bioSNG, to distinguish it from synthetic natural gas produced by the gasification of coal). The former is well suited to high-moisture feedstocks such as waste streams or green harvest, while the latter is more effective for feedstocks with low moisture contents (below about 15% by mass).

Biogas is well suited for both developed and developing economies because the capital investment is small, the facilities can be from single-family units to industrial scale and the technology is mature. The two main sources for biogas production are organic wastes, such as manure or landfill organics, and harvested biomass, such as dried or ensiled grasses. In Asia, where biogas facilities are abundant, the feedstock is usually based on waste. By contrast, in 2012, Germany had more land area devoted to dedicated energy crops for biogas, primarily corn silage and grasses, digested with or without manure, than for production or biodiesel or ethanol (IEA Bioenergy 2013) (Chapter 14, this volume).

Biogas, which is generally about half methane and half carbon dioxide, with small contributions from other gases such as H_2S and NH_3, can be used in a number of ways. Post-digestion treatment depends upon the selected end use. With minimal post-treatment, namely some drying and desulphurization, biogas can be combusted to provide local heat or, with more extensive desulphurization, heat and power for use on-site. Alternatively, biogas can be used in fuel cells or can be upgraded to methane, which can be compressed for used in modified vehicles. Worldwide, there were about 17 million natural gas vehicles that could use upgraded biogas, including 1.7 million in Brazil, 1.5 million each in India and China, and 2.2 million in Argentina.

The IEA's scenarios prior to 2012 did not assign any market share to natural gas vehicles, suggesting that they thought it unlikely for such vehicles to make a significant contribution in the future. However, the low price of newly available fossil natural gas has prompted an expansion of natural gas-powered heavy-duty vehicles and the associated fuelling infrastructure in some regions, which could ultimately create the conditions for utilization of biogas in transportation. In 2012, the IEA projected a possible six-fold increase in use of natural gas in transportation by 2035 (IEA 2012a).

8.5 Cellulosic Biofuels Have Arrived

Science and technology play a crucial role in developing sustainable biofuels. In the Brazilian experience, several obstacles successively emerged against ethanol market development and were overcome essentially by aggregating knowledge and innovation. Thus, questions regarding the feasibility of using high ethanol blends or pure ethanol in engines (drivability, cold starting, compatibility of metallic and polymeric engine materials with the oxygenated fuel, etc.), the conformity to the environmental legislation and the ample debate on sustainability (energy balance, water use, soil conservation, biodiversity, economic and social impact, etc.) were tackled and solved with the relevant contribution of scientific and academic communities, allowing a remarkable improvement in the whole production process of ethanol. In recent decades, Brazilian ethanol productivity has grown at a rate of 4% per hectare per year (Goldemberg and Guardabassi 2010). As a direct consequence of this continuous upgrading, in 2010, the conventional ethanol from sugarcane was designated by the Environmental Protection Agency as an "advanced biofuel", meeting a minimum lifecycle greenhouse gas reduction of 50% over fossil fuel. This advancement is permanent and new frontiers for biofuels production are under exploration.

In 2013, the first biorefineries capable of converting lignocellulose to liquid fuels began commercial production. Mossi & Ghisolfi Group opened the word's first commercial lignocellulosic ethanol plant in Crescentino, Italy. The Beta Renewables subsidiary will produce 13 million gallons (50 million liters) of lignocellulosic ethanol annually from agricultural residues and the grass *Arundo donax*. A second facility based on the same design began operation in 2014 in Northeastern Brazil, with others planned for the US, Colombia, and China. Additionally, the startup company, KiOR, and the chemical company Ineos began commercial production of cellulosic fuels in the US. Ineos is using a combined thermal gasification and biological fermentation to produce ethanol from wood and municipal wastes in Florida. The KiOR plant has the capacity to produce 50 million liters per year of hydrocarbon fuel by thermal decomposition of pine at a facility in the southern US. The "bio-oil" produced by KiOR needs upgrading in a petroleum refinery before use. Thus, unlike ethanol, which essentially bypasses the need for petroleum refineries, KiOR's technology substantiates the large existing refinery complex and can lead to production of diesel and jet fuels.

And so, the long-awaited jump from pilot-scale experiments to small-scale commercial production has been taken. Several additional commercial-scale facilities have recently started-up in the USA (Chapter 12, this volume). It is noteworthy that several conversion technologies reached the market in the same time frame. Presumably, the first generation of commercial facilities will provide significant opportunities to learn how to improve biomass conversion processes, reducing risk to subsequent capital investments.

8.6 Diesel and Jet-fuel from Sugars

Worldwide, advanced biofuel capacity increased by 30% in 2012 with over 100 plants and 4.5 billion liters in capacity (IEA 2012c). Parallel with the development of lignocellulosic fuels, a number of companies have demonstration units producing "drop in" fuels of various types. For example, Gevo and Butamax are attempting to produce isobutanol, Amyris is working on isoprenoid based fuels, and Renewable Energy Group Inc is producing alkanes and long chain alcohols, all by fermentation. The conceptual attraction of drop-in fuels is that they can be blended into gasoline in higher quantities than ethanol or can be blended into diesel or jet fuel. However, all of the companies that use fermentation routes appear to have experienced technical difficulties in producing commercial quantities of fuels at acceptable costs. Thus, it is unclear which, if any, drop-in fuels will reach commercial success. Similarly, diesel and jet fuels produced from algae can be considered a special case of drop-in fuels if the algae are grown on sugars, as is done by Solazyme. Several detailed techno-economic analyses have concluded that production of algal fuels under photosynthetic conditions is unlikely to reach economic feasibility for the foreseeable future (Davis et al. 2012).

The dark horse of biofuels is the possibility of converting ethanol to gasoline, diesel and jet fuel through catalytic conversions. Various types of dehydration and condensation reactions, such as the Guerbet reaction, are known to operate at high efficiencies. The reason that such conversions are not currently done industrially may be due to the fact that there is currently no premium for the energy content of a liquid fuel. In the US, for example, consumers pay as much for ethanol as gasoline on a volumetric basis, even though ethanol has lower energy content. Thus, there is no financial incentive to convert ethanol to gasoline and the price differentials for diesel and jet fuel are not currently high enough to cover the cost of conversion. However, if a carbon tax or mandate were to increase the value of low-carbon hydrocarbon fuels and if fuels were priced on energy content, the landscape in biofuels might be expected to shift decisively toward ethanol as a synthon and increased demand would follow.

8.7 Biofuels Done Right

One of the challenges associated with the public discourse on biofuels is that there are many different ways of producing a liquid fuel from biomass (Chapter 12, this volume). Some pathways, such as producing palm-based biodiesel by converting tropical peat land to plantations, appear to result in more carbon emissions than would result from burning fossil fuels. Others, such as sustainable mechanical production of ethanol from sugarcane without burning, can lead to large reductions in carbon emissions compared to the use of fossil fuels. Thus, a central task of the academic community involved in biofuels research, including the contributors to this volume, is to provide understanding to allow good decision-making.

The most important tool for deciding among various routes to biofuels is life cycle analysis (LCA) discussed in Chapter 17, this volume. The underlying concept is that by careful accounting of the energy inputs and outputs and the associated environmental impacts such as greenhouse gas (GHG) emissions, it is possible to determine whether a biofuel is preferable to a fossil fuel. Although we endorse the LCA concept, the actual use can be fraught with issues because: 1) there are no generally accepted criteria to establish the time frame in which effects on emissions from land conversion are estimated. Selection of different time frames can change the sign of an LCA; 2) the inclusion of hypothetical indirect effects such as indirect land use change (Chapter 17, this volume), predicted by untestable and highly aggregated economic models, is problematic because such concepts do not allow validation of results and cannot attribute predicted effects to specific actors; 3) many of the processes being modeled do not exist at industrial scale (e.g. lignocellulosic conversions) and are prone to the effects of convenient assumptions; 4) there is disagreement on how different types of water use should be accounted for (Chapter 18, this volume); and 5) the ability to adequately peer review results is compromised by the non-transparency and interdisciplinary nature of the modeling and data sources. Because the very clear and quantitative measure of performance provided by LCA can be hugely affected by assumptions and implementation in all these areas, it is possible to use LCA to advance ideological positions. There are ISO standards for LCA and some curated life-cycle inventory databases exist; however, there are many studies published that do not adhere to these standards.

Since the SCOPE report in 2009 (SCOPE 2009), there has been significant progress in the use of LCA in government biofuel policies. The use of LCA in policy and the continued evolution of standardized models used by government agencies are important steps toward ensuring rational use of natural resources and actual progress toward reduction of carbon emissions associated with transportation fuels. It is to be hoped that the roughly 50 countries that currently have biofuels mandates will incorporate similar legislation (Figure 8.3). It should be noted that Brazil, which has the largest mandate for the use of biofuels, does not require an LCA analysis because of widespread acceptance of the fact that sugarcane ethanol has a very low GHG footprint compared to fossil fuels. In view of the CCST study (Long et al. 2011; Youngs and Somerville, 2013), which found that it would be necessary to replace all transportation fuels with biofuels in order to achieve substantial GHG reductions, the current blending mandates and targets seem very modest.

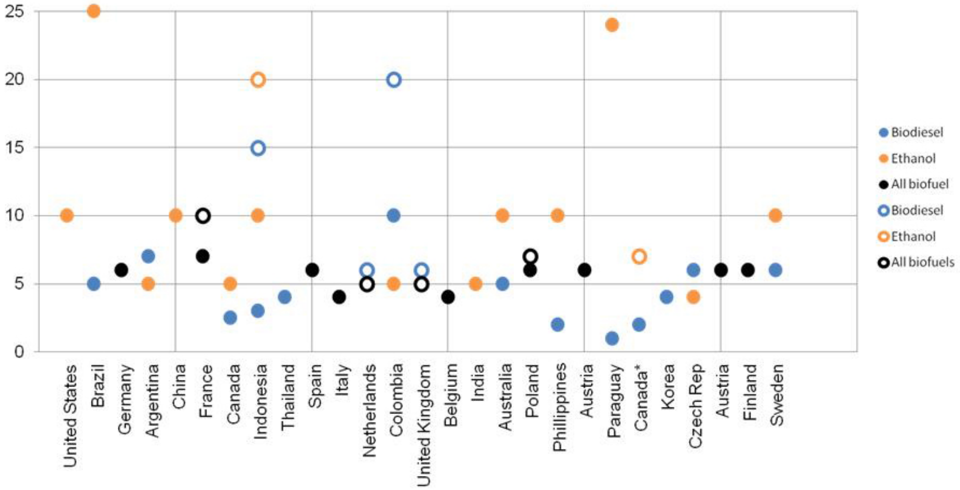

Figure 8.3. Blending mandates and targets in key countries. From (IEA 2012c).

8.8 Abundant Idle Land for Bioenergy Production

Perhaps the most controversial aspect of biofuels concerns the issue of land use (Chapter 9, this volume). The first question, in this respect, is whether there is any idle land. Several authors have investigated this question by using historical records and global satellite imaging to estimate the amount of land that has been farmed in the past but is not currently farmed (Cai et al. 2010; Campbell et al. 2008). These analyses concluded that approximately 1.5 billion acres of such land is available worldwide. This land can be considered to have lost most of its ecosystem services when it was originally converted to agriculture. The conversion from a natural ecosystem to agriculture would also have released GHGs. Thus, allocating this land to production of biofuels should not interfere with food production and the environmental costs were paid previously. Although it seems certain that this land is of poor quality (i.e., “marginal land”), there is a lot of it. In some cases the idle land appears to be too dry for conventional crop production. However, we speculate that it may be suitable for production of water-efficient species such as Agaves that can have up to ten times the water use efficiency of C3 species such as wheat or rice and are very drought tolerant (Somerville et al. 2010). Some Agaves have high sugar content and low lignin and should be well suited for production of first or second generation biofuels (Chapter 10, this volume).

Brazil appears to have large amounts of land that could be converted to sugarcane production with little or no impact on food production or ecosystem services. There are approximately 200 million hectares of cattle in Brazil, most of which are raised at very low stocking density in the Cerrado region (Chapter 9, this volume). Native Cerrado soils and rainfall support relatively low productivity ecosystems. However, liming and fertilizer treatment can result in conversion of Cerrado pastures into highly productive sugarcane production. Thus, a key to long-term expansion of Brazilian sugarcane production is to understand how to intensify cattle production. The Brazilian government has passed Agroecological zoning legislation (Chapter 19, this volume) that will allow expansion of sugarcane from approximately 9 million hectares in 2012 to more than 64 million hectares (EMBRAPA 2009). By some estimates, this could produce enough ethanol to supply approximately 10% of global transportation fuels while still maintaining current sugar production trends, if the bagasse is also used to make lignocellulosic ethanol (Cerqueira et al. 2009; Somerville et al. 2010). The factors limiting this expansion seem to be access to capital, depressed ethanol prices in Brazil due to gasoline price controls, infrastructure limitations, and trade barriers or tariffs. A commitment by one or more of the major economies to an increased ethanol blending mandate (Figure 8.3) could create the conditions for rapid expansion of sugarcane ethanol production in Brazil.

Another large amount of underutilized land can be found in Africa. The World Bank has estimated that as much as 600 million hectares of land suitable for agriculture is available in the Guinea savannah region of Africa (Morris et al. 2009). In this case there would be some impacts on ecosystem services that would need to be evaluated but the GHG impacts may be relatively small if sugarcane or perennial grasses could be grown for biofuels on some of the land. As noted in the World Bank report (Morris et al. 2009) there are many logistical and societal issues standing in the way of the eventual use of this land in addition to concerns about ecosystem conversion. It is to be hoped that the leadership shown by Brazil in the development and implementation of the Forest Code laws may provide useful guidance about how some of this land can be brought into use. (See also Chapters 6, 15, 16, 19, and 21, this volume for discussions on certification, biodiversity, social considerations and sustainable development).

Estimates of biomass availability for production of lignocellulosic biofuels in the USA have indicated that more than one billion tons of biomass could be available annually (Perlack et al. 2005). That amount of biomass could provide for production of liquid fuels that would substitute on an energy basis for approximately half of US liquid fuel consumption of about 200 billion gallons (760 billion liters). Additionally, the USA has about 750 million acres (303 million hectares) of woodland and forest, much of which is privately held, that was not included in the capacity survey. The declining use of wood for paper may allow the use of some wood for biofuel production in the USA and elsewhere. One factor limiting the use of this billion-plus tons of biomass supply is the commercialization of an efficient lignocellulose to fuel conversion technology (Chapter 12, this volume). It seems likely that this limitation will be removed during the next decade as the first commercial lignocellulosic fuel plants implement process improvements. Public acceptance of some biomass feedstocks may also limit some opportunities. Improved understanding of socio-economic and environmental impacts will heavily influence the development of some resources.

Thus, without attempting a comprehensive survey of how much biomass could be available worldwide it is apparent that there is significant potential to expand biofuel production several-fold over current levels of about 100 billion liters. The exact amount that might eventually be produced will depend on evolution of the conversion technology, local sensibilities, national policies regarding carbon emissions and a wide variety of other factors. The key conclusion for the purposes of this study is that significant expansion of biofuel production is possible but will require appropriate financial incentives (Chapter 20, this volume), innovation and some tradeoffs.

8.9 Bioenergy Risks and Tradeoffs

The attractive thing about petroleum is that once a field is located and mapped, it is usually a reliable source of inexpensive hydrocarbons for a long time. By contrast, biofuels are messy. Rainfall can be unpredictable, pests and pathogens are relentless, large amounts of labor are required, policy supports are unreliable and the technology requires continuous attention. Even worse, the situation is changing in troubling ways. The world population is predicted to increase by another two or three billion people in the next forty years and they will need food and fiber, among other things (UN 2013). Thus, competition for arable land will intensify. Logically, the use of land for food will trump the use for production of fuel, reduction of carbon emissions, and presumably preservation of ecosystems. Some thoughtful people think these facts imply that the use of biofuels necessitates a choice between feeding and clothing the poor and supporting the energy-intensive lifestyles of the developed world. Some contend that switching to lignocellulosic fuels could remove the direct conversion of food to fuel but others think this tradeoff could be illusory because some of the land used to produce biomass might support food production (see Chapters 3, 4, 9, 10, 13, and 21, this volume for discussions on land availability, alternative feedstocks for marginal land, integrated land use, energy access and food security).

Some critics of biofuels assert that, through the simplistic law of supply and demand, if we stop production of biofuels, the price of grain and other foods will decline and the poor will be more readily able to obtain affordable food. Indeed, before the advent of corn ethanol, grain was sold below the cost of production because governments subsidized production to ensure a stable supply. However, those subsidies for grain producers also suppressed food production in many regions of the world because it was less expensive to import subsidized or free grain than to produce it locally. Also, if demand for grain is reduced, farmers will once again reduce acreage to match the demand by those who can afford to pay. Thus, it is not clear that reducing demand for biofuels will make food more affordable in the long run. One solution to this important issue is not to depend upon subsidy-based agriculture but to subsidize the poor to purchase food at the prevailing price. Such a policy would encourage local production and would ensure food availability for the poor while also facilitating rational choices about the value of land and the commodities and services that can be obtained therefrom. Obviously, incentivizing food production through pricing in areas of the world with high agricultural potential while ensuring food security for areas of low agricultural potential is complicated by many factors (Herrmann 2009). It is worth noting that the use of food commodities for biofuel production can *increase* food security if thoughtfully managed. The basic idea is that, during a crop-failure-induced food shortage, food that was grown for biofuel production can be redirected towards food uses. Indeed, the biofuel mandates in the USA have a provision that relaxes the mandate under situations of “severe harm”, which can include food or feed shortages (US Congress 2007). (See Chapters 3, 4, 20, and 21, this volume for discussions on economics, policy, poverty reduction, energy access and food security issues).

The other big risk to expanded production of biofuels is climate change – the motivation for making biofuels in the first place. Changes in rainfall patterns and other effects of climate change may alter the productivity of lands used for food or biofuel production. Thus, understanding the effects of climate change should be an important theme in agricultural research, as noted in a recent report to the US President (PCAST 2012). Additionally, the positive effects of biofuel-mediated reduction of carbon emissions on global ecosystems need to be estimated so that we can have an understanding of tradeoffs with potential negative effects associated with land use change, water use, or other factors. In other words, the important question is whether or not it makes sense to convert some low diversity land to biofuel production if it helps save high diversity ecosystems such as barrier reefs from climate change-induced disruption. (See Chapters 5, 9, 10, 16, and 18, this volume, for discussions on land availability, feedstocks, climate and environmental security and impacts on water, soil and biodiversity).

The energy company BP predicts that biofuel use will expand to approximately 5% of world transport fuels by 2030 (BP 2013). The US Energy Information Administration estimates biofuels at only 2.2% of world consumption of liquid fuels by 2030 (US EIA 2013). The interesting discrepancy in predictions illustrates the large degree of uncertainty about future trends in energy production and consumption. The future of biofuels is particularly cloudy because of the importance of government policy in sustaining demand. Unpredictable types of events that could enhance demand for biofuels include the implementation of carbon taxes or expanded mandates. The dire predictions of the IPCC suggest that we may expect slow progress toward lower carbon fuels but the rate of change cannot be known in advance. The development of cost-effective drop-in fuels produced from lignocellulose, starch, or sugar would probably also expand demand by allowing expanded use in diesel and aviation fleets, and in overcoming limitations associated with the "blend wall" in the USA or the shortage of flex-fuel vehicles in most regions. However, because of the relatively long time required to build biorefining capacity it seems unlikely that drop-in fuels will be a significant component of the biofuel mix before 2020 or beyond. In the long run, the development of new biofuel feedstocks that are suited to the very large amount of arid land of low conservation value might also expand production of biofuels to regions outside the USA and Brazil while also reducing land costs and concerns about negative environmental or social effects of some types of biofuels. Presumably, the productive use of such lands might generate policy support from local governments because of regional economic benefits. Conversely, demand could be reduced by policy concerns arising from food shortages which may be anticipated because of the intersections of climate-change induced crop failures, expanding population, and prosperity-induced increases in meat consumption.

Although the future of biofuels is unknowable, it is clear that the inherent opportunity will not be realized unless the scientific community continues a broad-based investigation of both technical innovations and the social, economic and environmental consequences of possible future scenarios. Hopefully this study will help define some of the goals for sustainable development.

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chapter 9

Land and Bioenergy

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Highlights

Projected land demands for bioenergy fall well within conservative estimates of current and future land availability (240 to 905 Mha). Estimates for the amount of modern bioenergy needed to meaningfully mitigate climate change range from 80 to 200 EJ in the 2050 timeframe. At the upper end of this range, we estimate that about 200 million hectares would be required. This may be compared to most estimates for the amount of land available for bioenergy, which exceed 500 million hectares. Long before the world reaches any significant fraction of 200 Mha devoted to modern bioenergy, we will have opportunity to be guided by experience rather than projection. The real danger is not that once the bioenergy genie is out of the bottle that ruinous land use change will ensue. The recent application of the brakes to bioenergy expansion worldwide provides ample evidence that the growth of bioenergy can be curtailed. Rather, the real danger is that bioenergy development will proceed so slowly that a key strategy for climate change mitigation will be taken off the table.

- Historic estimates of land demand have significantly overestimated direct and indirect land use impacts from bioenergy, particularly conventional biofuels. Timing and rates of change are however important;
- Modern bioenergy is likely to increase reforestation drivers as opposed to increase deforestation rates;
- Ignoring the importance of the integrational benefits of bioenergy with the global food production systems is dangerous and an inappropriate use of the ‘precautionary principle’. Most analyses of bioenergy development are carried out independently of the development of the food production system;
- In particular, we highlight the potential and the need for increased cropping intensity (including double cropping) and for pasture intensification to simultaneously increase food and bioenergy provision whilst increasing soil fertility and improving ecosystem services. More research is urgently needed to understand the full potential for these novel approaches to land management;
- In practice, extensive interaction and integration already occurs between the food and bioenergy provisioning systems, will continue and likely expand, and presents new opportunities to optimize benefits.

Summary

In this chapter we address the questions of whether and how enough biomass could be produced to make a material contribution to global energy supply on a scale and timeline that is consistent with prominent low carbon energy scenarios. We assess whether bioenergy provision necessarily conflicts with priority ecosystem services including food security for the world's poor and vulnerable populations.

In order to evaluate the potential land demand for bioenergy, we developed a set of three illustrative scenarios using specified growth rates for each bioenergy sub-sector. In these illustrative scenarios, bioenergy (traditional and modern) increases from 62 EJ/yr in 2010 to 100, 150 and 200 EJ/yr in 2050. Traditional bioenergy grows slowly, increasing by between 0.75% and 1% per year, from 40 EJ/yr in 2010 to 50 or 60 EJ/yr in 2050, continuing as the dominant form of bioenergy until at least 2020. Across the three scenarios, total land demand is estimated to increase by between 52 and 200 Mha which can be compared with a range of potential land availability estimates from the literature of between 240 million hectares to over 1 billion hectares.

Biomass feedstocks arise from combinations of residues and wastes, energy cropping and increased efficiency in supply chains for energy, food and materials. In addition, biomass has the unique capability of providing solid, liquid and gaseous forms of modern energy carriers that can be transformed into analogues to existing fuels. Because photosynthesis fixes carbon dioxide from the atmosphere, biomass supply chains can be configured to store at least some of the fixed carbon in forms or ways that it will not be re-emitted to the atmosphere for considerable periods of time, so-called negative emissions pathways. These attributes provide opportunities for bioenergy policies to promote long-term and sustainable options for the supply of energy for the foreseeable future.

9.1 Introduction

Bioenergy[1] features strongly in most global energy provision scenarios of the Intergovernmental Panel on Climate Change (IPCC 2014), Global Energy Assessment (GEA), International Energy Agency (IEA) – as well as environmentally-motivated NGOs – e.g. World Wildlife Fund for Nature (WWF), Greenpeace. Bioenergy provides nearly 200 EJ by 2100 across all recent IPCC scenarios with somewhat higher biomass utilization in low-carbon compared to high-carbon scenarios. Most biomass is derived from terrestrial photosynthesis with its associated use of natural resources (water, soil, carbon dioxide and sunlight). Projections of land required to meet demands for food, fiber and bioenergy are uncertain, complex and controversial given the emotive issues of food security, and the provisioning of cultural, spiritual and ecosystem services that are central to the human well-being.

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[1] Provision of energy for heat, mobility, light and power in all its forms

Most low-carbon energy scenarios take a “non-biomass renewables first” approach, wherein other renewables (e.g., wind, solar, etc.) are used to provide energy services for which they are suitable. But some energy services are difficult to meet with non-biomass renewables. These services include transportation over long distances (aviation, long-haul trucking, ocean transport), heat for industrial processing, and dispatchable power, heat and electricity needed to complement the variable supply characteristics of other forms of renewable energy.

As shown in Figure 9.1, scenarios developed by five organizations (IPCC, IEA, GEA, WWF and Greenpeace) average 138 EJ by 2050 with a low of 80 EJ[2]and a high of 180 EJ. These absolute amounts of biomass-derived energy correspond to a range of 14 percent to over 40 percent of primary energy supply. In some scenarios developed for these studies, biomass is the single largest primary energy source supporting humanity in 2050.

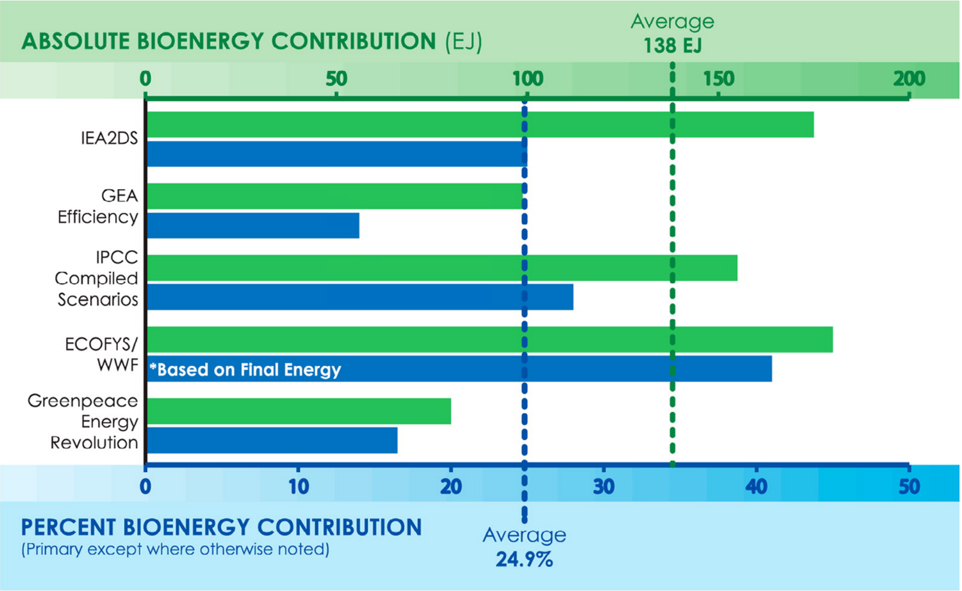

Figure 9.1. Bioenergy contribution in 2050: Comparison of five low-carbon energy scenarios (Dale et al. 2014).

Whilst most of the scenarios in these studies focus exclusively on terrestrial rather than aquatic forms of biomass provision for energy they acknowledge that aquatic systems may provide as yet unknown but potentially significant quantities of bioenergy in the future. Novel production and conversion technologies and adaptation strategies will be required over the next four decades in response to the effects of climate change on agriculture and forestry.

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[2] The lowest estimate reflects 70 EJ of traditional biomass use and a minimum of 10 EJ of “modern” bioenergy.

9.2 Key Findings

9.2.1 Global Land Availability and Projected Demand for Food, Fiber and Infrastructure

At the global level, the world's 13 Gha of land is categorized by the FAO into forest, pasture and crop ('arable and permanent crops') land (Table 9.1). Estimates of current and future land use and associated vegetation cover are, however, uncertain, as highlighted by Lambin and Meyfroidt (2011), and Fritz et al. (2011). The interactions among food, fiber and livestock supply systems involve multiple uses, feedbacks and rotations across categories which further complicate the assessment of current and future land demand. However, significant areas of land suitable for rainfed agriculture are currently un- or under-used offering the potential to reconcile future demands for food (including livestock), biodiversity protection, amenity and bioenergy. This potential is evaluated further in this section.

9.2.1.1 Land Demand

Most projections of global land demand reflect increasing pressures to provide services to the world's growing population. These services include provisioning services such as food, clean water, and energy, and regulating services such as biodiversity, air quality, hydrological, etc.

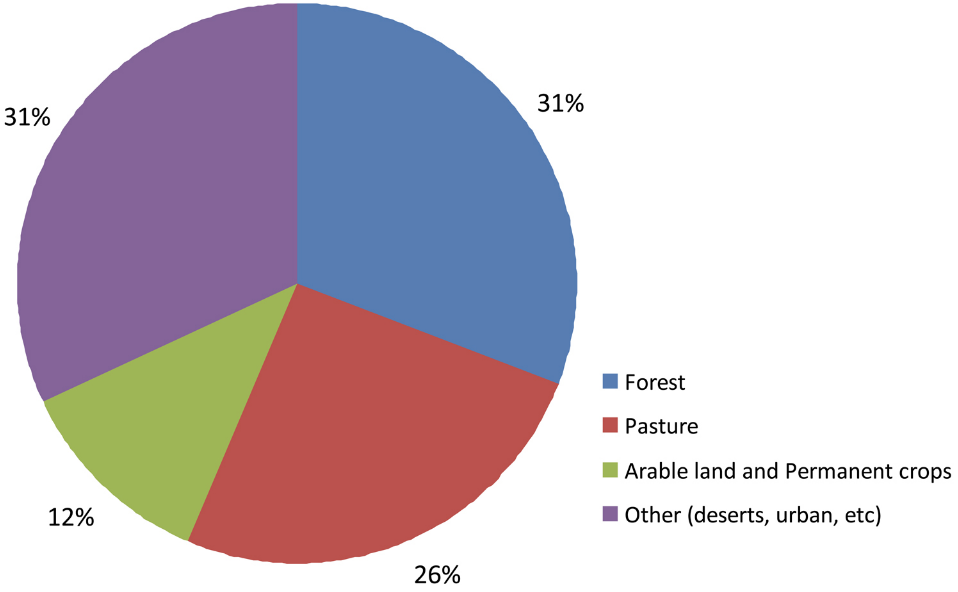

Figure 9.2. Global land use, 2010 (total land area 13.1 Gha; FAOSTAT 2014).

Land demands for food production are of central importance in estimating bioenergy potential. Land demand for fiber and construction materials is also important and forest management is expected to provide significant quantities of biomass for energy provision and other purposes. Of the world's 13 billion ha of land just over 2/3 is biologically productive and nearly 2/5 is actively managed for crops or livestock production (Table 9.1).

Global demand for food and feed is increasing by 2.4% per year (compound growth rate, FAO 2012). Over the last two decades, yields of the crops making the largest contribution to food and feed supply are increasing at slower rates than the previous two decades: 1.6% for maize, 1.0% for rice, 0.9% for wheat, and 1.3% for soy (also compound growth rates; Alexandratos and Bruinsma 2012). Over the previous century, global food prices declined by1% per year as yields outstripped global population growth and per capita demand. Based on population and dietary trends, the FAO projects a net increase in land used to grow food crops by 2050 of about 70 Mha resulting from an increase in land area under agriculture in developing countries of 130 Mha and a decrease of over

Table 9.1. Estimates of land use (Mha) in 2000 and 2010 (FAOSTAT 2014; Lambin and Meyfroidt 2011).

	Land use in 2000			**Land use in 2010**	**Change (2010-2000)**
	(Lambin and Meyfroidt 2011)		**(FAOSTAT 2014; FAO 2006a)**	**(FAOSTAT 2014)**	**(FAOSTAT 2014)**
	Low estimate	**High estimate**	**Alternative estimate**		
Cropland[a,c]	1510	1611	1514	1541	27
Pastures[b]	2500	3410	3420	3353	- 67
Forests	3143	3871	4085	4033	- 52
Planted forests[d]	126	215	161	274	49
Urban, built-up[d,e]	66	351	40	65	25

Notes

'Cropland' here is assumed to = FAO defined 'arable land and permanent crops' which include cultivated pastures and idle cropland

'Pastures' = FAO defined 'permanent meadows and pastures'

Total agricultural area (cropland + pastures combined) declined by 40 Mha over the past decade, primarily due to intensification in more developed nations

FAO (2006) data reflects sum of all reporting nations in the FRA 2010 (http://www.fao.org/docrep/010/ag049e/AG049E03.htm) data Tables; this estimate is not official because not all countries reported in 2000

Lambin and Meyfroidt (2011) estimate 3.3 Mha per year is converted to urban and built up areas, or about 33 Mha increase between 2000 and 2010

60 Mha in developed countries (Alexandratos and Bruinsma 2012). We use this FAO projection for the illustrative scenarios discussed below. It may be noted, however, that some projections feature little or no increase in global land planted with crops due to yield and market dynamics (Ausubel et al., 2012; Lambin, 2012), increasing production within urban areas, or sustainability-motivated dietary changes (WWF/Ecofys/OMA 2011).

9.2.1.2 Current Land Demand for Bioenergy

The IEA (2012a) estimates that c. 50 EJ of bioenergy was supplied in 2009 of which 32 EJ was in the form of traditional biomass, primarily used for household cooking. The IPCC (2011) reports traditional bioenergy in the range of 37-43 EJ for 2008. Recognizing uncertainties and under-reporting in many countries, we have estimated traditional bioenergy to be 40 EJ in 2010. Biomass production and land use in 2010 are summarized in Table 9.2. “Traditional bioenergy” represents 8% of total primary energy but occupies a negligible share of primary land use, being primarily derived from residues, wastes and harvesting from landscapes being managed for other purposes. Some forms of traditional bioenergy are inefficient and unsustainable, for example in systems providing charcoal to urban areas based on harvests that exceed regeneration rates. In fact, traditional bioenergy is now widely believed to be putting unacceptable pressures on the environment including as a driver of deforestation as discussed in Lynd et al. (in press). Despite this, there is a significant potential and need for finding alternatives where modern bioenergy solutions could make more efficient use of the biomass and reduce

Table 9.2. Bioenergy supply, feedstocks and associated land demand estimates for 2010.

	Global Production	**Feedstock**	**Land Occupied**
	EJ		**(million ha)**
Global Primary Energy	520	Predominantly fossil	Not quantified
Total Bioenergy	62	All forms, traditional and modern	c. 50
Traditional Bioenergy	40	Mostly from residues, wastes and harvesting parts of live trees (pollarding)	Not quantified
Modern Bioenergy	21.5		c. 50
• Biofuels	4.2	Agricultural crops	<13
• Heating (domestic and industrial)	13.0	2/3 residues and wastes, 1/3 energy crops (lignocellulosic)	c. 30
• Electricity	4.1	50% from energy crops + 50% from residues and wastes	c. 10

Notes: derived from own calculations based on IEA (2010; 2011a+b; 2012a+b) data. Biofuels (aggregate of national production data for 2010) from F.O. Lichts Interactive Data, (2013). Traditional bioenergy data derived from IEA (2011b) and Chum et al. (2011)

the pressure on the environment (IPCC 2014; Figure 9.11). However, we have not identified reliable estimates of the land areas affected by traditional biomass harvesting. An illustrative estimate of future land demand for bioenergy is provided in Section 9.3.

In order to estimate land use for bioenergy in 2010 we assume there is no land demand associated with the use of wastes and residues and that remaining biomass demand for heat and electricity is sourced from energy crops with a global average annual yield of 10 oven dry metric tons per hectare. For domestic heating (excluding traditional bioenergy) the share of biomass derived from residues was assumed to be 2/3 with 1/3 from energy crops whilst for industrial 'power' 90% of the biomass was assumed to be derived from residues. For biofuels, land demand was estimated based on Langeveld et al. (2013) who calculated individual biofuel and associated co-product yields for each biofuel crop as used by the major biofuel producing countries (Table 9.3). Land demand for biofuels is calculated net of that land associated with co-products.

Table 9.3. Crop, biofuel and co-product yields (metric tons per hectare, as harvested or produced, variable moisture contents).

Region	Feedstock	Crop yield	Biofuel yields		Co-product	
		Langeveld et al. (2013)		This study	Langeveld et al. (2013)	This study
		(t/ha)	(l/ha)	(l/ha)	(t/ha)	(t/ha)
Brazil	Sugarcane	79.5	7200	7200	–	8.7
Brazil	Soybean	2.8	600	600	1.8	1.8
USA	Corn	9.9	3800	3800	4.2	4.2
USA	Soybean	2.8	600	850	1.8	1.8
USA	Corn stover	3.3		819		0.7
EU	Wheat	5.1	1700	1700	2.7	2.7
EU	Rapeseed	3.1	1300	1300	1.7	1.7
EU	Sugarbeet	79.1	7900	7900	4.0	4.0
Indonesia & Malaysia	Palm Oil	18.4	4200	4200	4.2	4.2
China	Corn	5.5	2200	2200	2.9	2.9
China	Wheat	4.7	1700	1700	2.5	2.5
Mozambique	Sugarcane	13.1	1100	1100	–	1.4
South Africa	Sugarcane	60.0	5000	5000	–	6.6

Source: adapted from Langeveld et al. (2013) using biofuel and co-product yields calculated from literature. For this study, US soybean biodiesel yields were revised from more recent data provided in Chapter 10, this volume

9.2.1.3 Land Availability

There is substantial controversy about the future availability of land for food or bioenergy provision (Lambin 2012) with estimates from recent studies of land available for bioenergy in 2050 ranging from less than 250 Mha to more than 1 billion ha (Table 9.4). Many of these studies use a “food and fiber first” approach wherein

Table 9.4. Estimates of land availability for bioenergy crops in recent studies (in 2050).

Reference	(Sustainability) Constraints	Land use types	Land area available (Mha)
Hoogwijk et al. (2005)	Ensuring food security; Protection of biodiversity	Abandoned agricultural land (100%)** Rest land (10 – 50%) #	Abandoned: 600-1500 Rest land: 300-1400
Smeets et al. (2007)	Ensuring food security; Protection of biodiversity; Avoiding deforestation	Surplus agricultural land (100%)	729-3 585
Campbell et al. (2008)	Ensuring food security; excluded all agricultural lands; Protection of ecosystems; Releasing carbon stored in forests	Abandoned agricultural land (100%)	385-472
Field et al. (2008)	Ensuring food security; Protection of biodiversity and ecosystems; Avoiding deforestation	Abandoned agricultural land (100%)	386
Van Vuuren et al. (2009)	Ensuring food security; Consider water scarcity; Protection of biodiversity; Avoiding soil degradation	Abandoned agricultural land (75%) Grassland (25%)	1 500
WBGU, (2009)	Ensuring food security; Protection of biodiversity; Avoiding deforestation; Consider water scarcity and avoid competition for water; Excluded all agricultural land, unmanaged land with a long carbon payback periods, degraded land, wetlands, and environmentally protected land	Remaining suitable land after excluding all agricultural land, unmanaged land, degraded land, wetlands, environmentally protected land, and land rich in biodiversity	240-500
Fischer et al. is it (2009)	Ensuring food security; Excluded forests, sloping land, and low productive land	Cropland not needed for food, feed and fiber supply	700-800

»

Reference	(Sustainability) Constraints	Land use types	Land area available (Mha)
Erb et al. (2009)	Ensuring food security: land needed for food and feed was excluded; Forests and unproductive or uneconomic land were excluded	Cropland not needed for food and fiber supply	230-990
Nijsen et al. (2012)	Ensuring food security; Avoiding deforestation; Excluded forest areas, cropland, pastoral land and urban areas	Marginal and degraded lands	247
Smith et al. (2010)	Bioenergy production on 'spare land' which is cropland or grazing land not required for food production, assuming increased but still sustainable stocking densities of livestock based on Haberl et al. (2011). High bioenergy value: short-rotation coppice or energy grass directly replaces fossil fuels, energy return on investment 1 : 30 dry-matter biomass yield 10 t/ha.yr. Low bioenergy value: ethanol from maize replaces gasoline and reduces GHG by 45%, energy yield 75 GJ/ha.yr (Chum et al. 2011)	'Spare land'	390 (spare cropland) + 490 (livestock grazing area)
Wicke et al. (2011)	Protection of biodiversity; Forests, wetlands and protected areas were excluded	Salt affected lands	971
Lambin & Meyfroidt (2011)	Unused productive land		356 to 445
WWF, Ecofys, OMA (2011)	Rainfed potential (with additional exclusions including 'additional land for biodiversity protection, human development, food demand.')	Rainfed potential land	673

Modified from Batidzirai et al. (2012)

* Estimates are for 18 World regions over a timeframe 2050-2100

‡ Estimates are for 11 world regions

'Rest land' is the remaining land area (from total available land) after taking into consideration 'abandoned agricultural land' and 'low-productive land' and further subtracting/correcting for grassland areas, forest land, urban areas and bioreserves. 'Rest land' includes mainly savannah, shrubland and grassland/steppe. The overall assumption is that energy crop production should not affect food and fiber production, or biodiversity protection

** Percentage values indicate the fraction of the land category that is assumed to be put under energy crops in a respective study

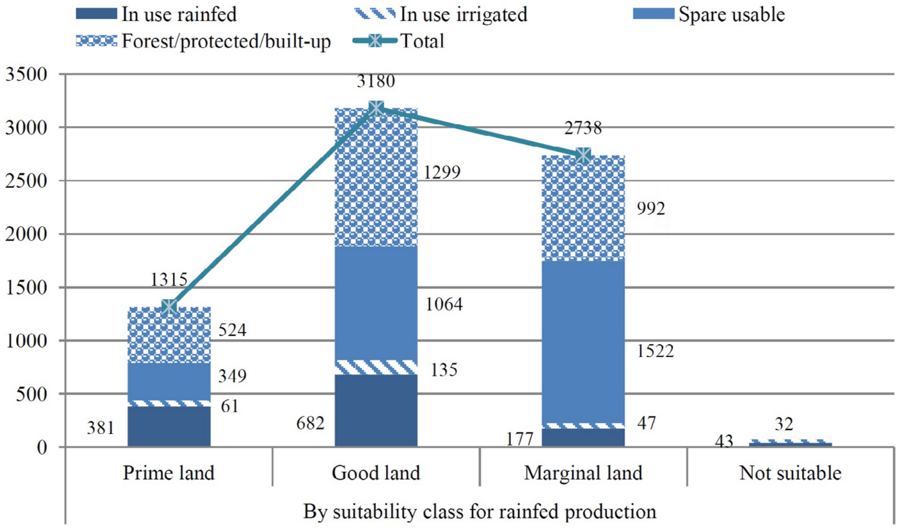

Figure 9.3. World land available (million ha) with potential for rainfed crops (Alexandratos and Bruinsma 2012).

land available for bioenergy is obtained by subtracting projected land required for food and fiber from the total land area considered suitable for bioenergy production. Additional constraints on land may then be layered on top of the land 'available for bioenergy' including infrastructure / urban and biodiversity protection as shown in Table 9.5, further decreasing land availability. This approach is considered in this section – first for land suitable for rainfed agriculture, and then for land that could potentially be used for bioenergy crops but is not suitable for rainfed agriculture.

Land Suitable for Rainfed Agriculture

The FAO (Alexandratos and Bruinsma 2012) estimates that there is about 1.4 Gha of 'prime and good' land and a further 1.5 Gha of marginal land that is 'spare and usable' (Figure 9.3). 960 Mha of this land is in developing countries with much, if not all, of this land currently under pasture / rangeland. This remaining land is unevenly distributed with 'some 85 percent of the remaining 960 million ha in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha); very little or no land remaining in the other regions.' (Alexandratos and Bruinsma 2012).

Of the total 4.5 Gha classified by Fischer et al. (2011) as potential agricultural land, current row crop agriculture uses 1.3 Gha with an additional 70 to 130 Mha likely to be required to meet future food needs. As already noted, FAO (2012) estimates that the net additional land requirement is 70 Mha, with an additional 130 Mha in developing countries and a loss of 60 Mha in developed countries to infrastructure, recreation etc. Forestry, protected lands and urban demands account for a further 1.8 Gha according to Alexandratos and Bruinsma

(2012). Whilst WWF (WWF/Ecofys/OMA 2011) estimate that c. 54 Mha is needed for biodiversity protection Alexandratos and Bruinsma (2012) state that 107 Mha of the total ‘potential’ land is classified as ‘strictly protected land’ with 80 Mha of protected land in the ‘very suitable’ and ‘suitable’ classes of potential agricultural land.

Table 9.5. Current and future land use and demand (Mha; 2010 and 2050) based on FAO (Alexandratos and Bruinsma 2012).

Area (Mha)	**2010**		**2050**		
	Mha	**% share global land**	**Mha**	**% share**	**% share potential agricultural land**
Global Land (total)	13,013	100%	13,062	100%	
Agricultural land	4,894	38%	5,053	39%	
Arable land and permanent crops	1,541	12%	1,661	13%	
Arable land	1,388	11%	1,518	12%	34%
Permanent crops	153	1%	143	1%	
Permanent meadows and pastures	3,353	26%	3,391	26%	
Forest area	4033	31%	3,953	30%	
Land availability for rainfed agriculture[a]:					
Total (Very Suitable + Suitable)	4,495		4,495		
Of this needed for:					
Row crop production	1,260	10%	1,260		28%
Additional agricultural land by 2050 for increased food production			130[b]		3%
Forest, protected and urban	1,824	14%	1,824		41%
Urban and infrastructure			100		2%
Land degradation			87		2%
Forest plantation			109		2%
Of this needed for biodiversity protection			80		2%
Potentially available	1,411		905		20%

Notes

a. VS+S = very suitable and suitable for rainfed agriculture as defined under the Global Agroecological Zones (GAEZ) project. (Fisher et al. 2011)

b. Assumes all new demand for food production (130 Mha increase in land for food by 2050 as estimated by Alexandratos and Bruinsma (2012)) will come from the Very Suitable (VS) + Suitable (S) land categories

By 2050, 1.2 Gha of remaining land could be considered as available for other uses including bioenergy feedstock production (Table 9.5). This can be compared to the estimate by WWF/Ecofys/OMA (2011) of 0.7 Gha of available land using more conservative assumptions. This available land is assumed to come exclusively from pasture lands where there is enormous potential for increased efficiency and intensification of livestock production.

Land not Suitable for Rainfed Agriculture

There is also the possibility to exploit land that is not suitable for conventional rainfed agriculture. Of the 3.2 Gha of land identified by the FAO (Fischer et al. 2011) as having rainfed potential for agricultural production, 1.8 Gha are classified as moderately suitable with an ‘unused’ balance of 1.0 Gha. There are an additional 990 Mha of marginally suitable land of which 600 Mha are classified as currently unused. These lands are assessed by the FAO to be capable of providing 20 to 60% of the maximum attainable rainfed yield of ‘very suitable (prime)’ land. It may be noted, however, that this statement is in reference to food crops and may not apply to bioenergy crops.

Such degraded, marginal and abandoned agricultural land, represents a significant potential for biomass production. However the implications of lower yields and lacking or poor infrastructure on the costs of bioenergy production need to be considered.

Land categories also include saline lands and lands with vulnerable soils i.e. prone to flooding, steep slopes, and where climatic factors limit the length of growing period. Wicke et al. (2011) estimate that there are 970 Mha of salt affected land globally (Table 9.4) and WWF/Ecofys/OMA (2011) estimates that there are a further 2.5 Gha that are ‘not suited’ for rainfed agriculture but might be viable for alternative non-food cropping or soil reclamation through phytoremediation.

These emerging limitations, particularly for some novel oilseed crops e.g. Jatropha and Camelina, have led to the search for alternative crops that have the potential to be highly productive on marginal and degraded lands (see Chapter 10, this volume), including:

- CAM plants (agave),
- Drought tolerant trees, grasses and other crops (cassava, sorghum, camelina, arundo donax, etc.),
- Salt-tolerant crops.

It is therefore clear that with supportive policies and investments very considerable areas of land not suitable for food crop production could be considered for bioenergy feedstock production and which could provide significant amounts of modern bioenergy with clear links to energy access for the rural poor (Table 9.6).

Table 9.6. Estimates of global bioenergy potential on degraded or marginal lands (FAO, UNEP 2014).

Source	Lands included	Area (million ha)	Biomass yield (t/ha/year)	Bioenergy Potential (exajoules)
Van Vuuren et al, 2009	Global degraded lands not in use as forest, cropland, pastoral land or urban	n/a	2.5 - 33	31
Hoogwijk et al, 2003	Abandoned agricultural land and degraded grassland systems	430-580	1 - 10	8 - 110
Tilman et al, 2006	Agriculturally abandoned and degraded lands	500	4.74	45
Field et al, 2008	Abandoned pastoral lands and croplands not in use as urban or forest	386	3.55	27
Campbell, 2008	Abandoned pastoral lands and croplands not in use as urban or forest	385-472	4.3	32-41

9.2.2 Illustrative Example: Brazilian Land Use and Potential Availability

Brazil occupies a uniquely important place in the provision of global food and energy security with bioenergy having been central to its energy planning since the mid-1970s. It is also uniquely important in climate change mitigation and adaptation with a strong track record in using renewable energy but also in terms of managing the emissions from land use change. The carbon stocks that are embedded in the Amazonian forest and the associated biodiversity of its forests and cerados (savanna ecosystems) have focused the world's attention on the land use, energy security and deforestation policies it has developed.

Whilst deforestation continues to be a concern despite the major reductions achieved in deforestation rates over the last decade, over the last three decades Brazil has become a leading exporter of food products and the world's second largest supplier and user of bioenergy after the USA (Nepstad et al. 2014). Its agricultural sector now produces 90 million metric tons of cereals (3% of 2012 global production) including 71 million tons of corn (maize); in addition, 65 million tons of soybeans were produced making Brazil the world's second largest producer. It is also the world's largest sugarcane producer, producing 721 million tons of sugarcane in 2012 (IBGE 2012). From the sugarcane it supplied 25 billion liters of ethanol and from soy oil 2.5 billion liters of biodiesel in 2010, totaling 25% of global biofuels (0.62 EJ biofuel out of 2.5 EJ global). Significant amounts of co-generated electricity were also produced from bagasse, the by-product of sugar and ethanol production. (see Chapter 12, this volume).

Brazil is also a large livestock and meat producer, producing 24 million tons of meat in 2010 (FAOSTAT 2014; IBGE 2012). The country exports agricultural commodities, totaling more than US$ 88.6 billion in 2012 (MAPA 2012). Soybean and its derived products rank first, followed by meat products and products from the sugarcane complex.

Over the last 22 years, the total harvested area increased from 45.9 Mha in 1990 to 63 Mha in 2012. Sugarcane increased from 4.3 Mha in 1990 to 9.7 Mha in 2012. In the same period, soy's harvested area grew from 11.5 Mha to 24.9 Mha, increasing by 117% whilst productivity rose by 50%. Sugarcane's planted area increased by 130%, productivity increased by 20%. Over the last 22 years, Brazil has seen both an increase in total harvested area and in the share of land devoted to soybean, corn and sugarcane. Thus, the expansion in sugarcane and soybean production in Brazil results from a combination of cropland expansion and productivity increases.

Another factor at play in Brazil is the increase in cropping intensity. Alexandratos and Bruinsma (FAO 2012) expect 80% of the projected growth in crop production in developing countries to come from intensification, with yield increases responsible for 73% and higher cropping intensities for 6%. Langeveld et al. (2013) reported a multiple cropping index (MCI) (similar to cropping intensity) of 0.86 for Brazil in 2010 with other developing countries attaining significantly higher MCI's e.g. China 1.45 and Mozambique 1.08. This indicates a potential for increased production in Brazil resulting from increased cropping intensity. This is supported by data on corn productivities in Brazil: from 2003 to 2012, the harvested area increased due to an expansion in double cropping. In 2003, second season corn accounted for 25.3% of total corn harvest. By 2012, this had increased to 51.4% (Figure 9.4).

Projections made in 2012 by the Brazilian Ministry of Agriculture indicate that, by 2022, there will be considerable production increases across most of its main agricultural products (MAPA 2012). The study also indicates that the growth in agricultural production will be based on productivity (yield and cropping intensity) gains rather than area expansion. For example, the total grain crop production (soybean, corn, rice, beans, wheat) is expected to increase by 21.1% although with an area expansion of only 9%. The total agricultural planted area is expected to increase by 7 Mha, from 64.9 Mha in 2012 to 71.9 Mha in 2022. However, sugarcane is considered separately because the government plans to limit its expansion to 63 Mha (Somerville et al. 2010 and Chapter 10, this volume).

In São Paulo, recent sugarcane expansion has occurred over both pasture and annual crop areas (Rudorf et al. 2010). However, in the western part of the state, most expansion occurred in pasture land, because of intensification of livestock production that effectively freed-up pasture land for sugarcane plantations. Agricultural census data show that over the last 7 decades, the average number of heads per ha has steadily increased (Figure 9.6). For instance, while São Paulo, Paraná and Santa Catarina states have more than 1.5 heads per ha, Mato Grosso, Mato Grosso do Sul, Minas Gerais and Goiás, responsible for more than 45% of the nation's cattle herd, show stocking rates ranging from 0.93 to 1.15 head/ha. For Brazil as a whole, according to Martha et al. (2012) the beef yield per ha more than tripled between 1985 and 2006 with stocking density increasing from 0.71 to 1.11 head/ha over that period. Stocking density alone therefore was responsible for less than 50% of the observed

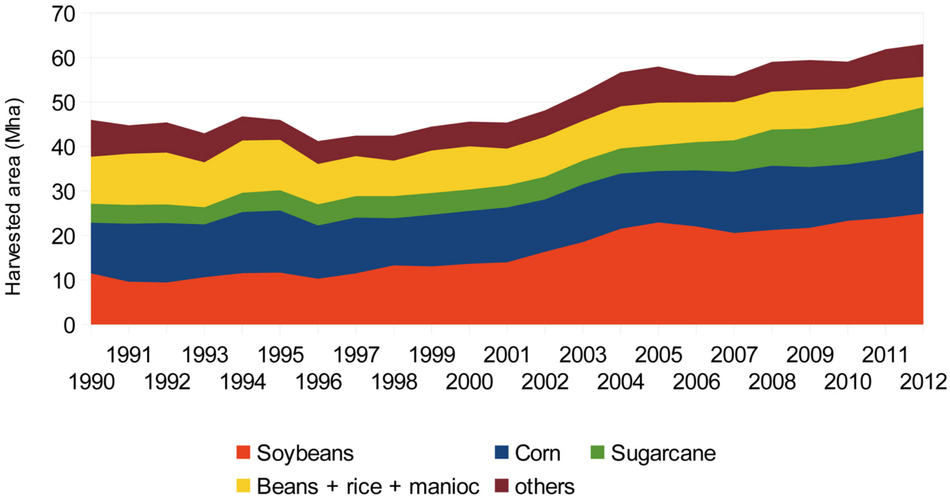

Figure 9.4. Harvested area for soybean, corn, sugarcane, beans + rice + manioc and other crops in Brazil, 1990 to 2012 (IBGE 2012).

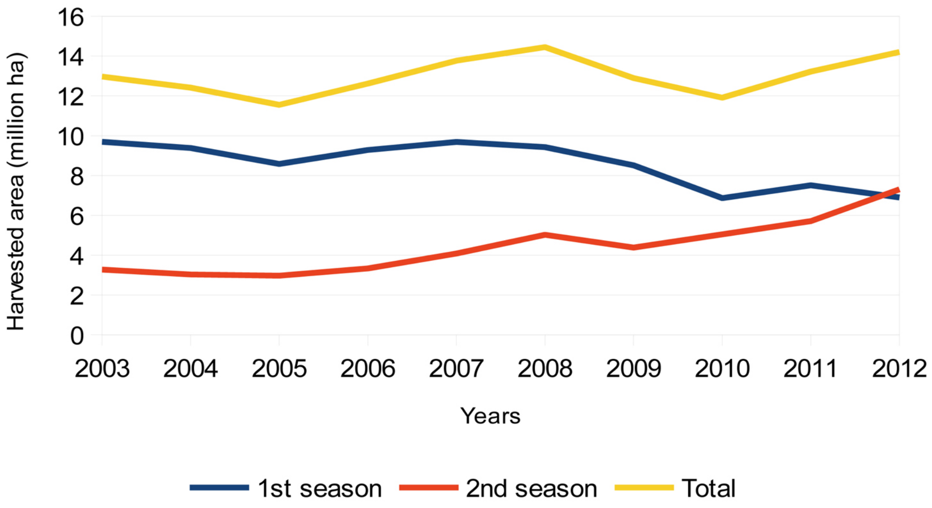

Figure 9.5. Corn harvested area, Brazil, 2003 to 2012. Total harvested area increased due to an increase in second season corn (double cropping), despite a reduction in planted area in the first season (IBGE 2012).

yield gain. At the same time improved animal production performance also helped raise the meat yield from 17.4 to 40.1 kg/head illustrating the interaction between improved pasture land and animal management practices.

FAOSTAT (2014) states that there were 196 Mha of ‘permanent meadows and pastures’ in Brazil in 2010, similar to Europe’s entire pasture area. However, the 2006 Brazilian agricultural census only identifies 102 Mha of planted pastures with 9.9 Mha declared as being degraded planted pastures (IBGE 2007). The National Confederation of Agriculture estimates that there are 140 Mha of pasture in Brazil of which 56 Mha (40%) are considered degraded (Horta Nogueira and Silva Capaz, 2013). Horta Nogueira and Silva Capaz (2013) go on to estimate that 60 to 75 Mha of degraded pasture land could be recovered and Somerville et al. (2010) discuss the potential for generating surplus land through improved pasture management in Brazil. Taking into account the Agricultural Census’ estimates, the degraded pasture area is much larger than the predicted 7 Mha increase in agricultural area estimated by the Ministry of Agriculture. It matches the potential sugarcane production area and proposed limits of its expansion to 63 Mha (Somerville et al. 2010). Thus, actions to improve pasture conditions, along with livestock production intensification, can effectively make large amounts of land available for alternative uses.

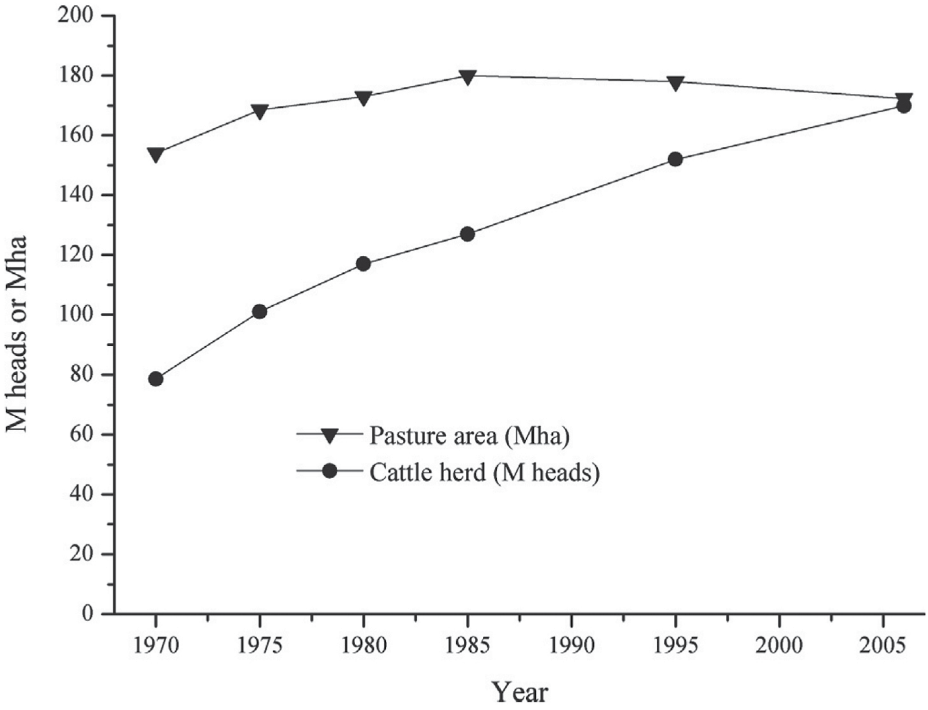

Figure 9.6. The evolution of pasture area and cattle herd in Brazil (IBGE 2007; Horta Nogueira and Silva Capaz 2013).

9.2.3 Land Use Intensities for Bioenergy Supply

Calculating future net land demand for bioenergy, as with food crops, is inherently uncertain. It requires assumptions to be made about the scale of energy demand over time for each bioenergy sub-sector (see section 9.2.4) future yield growth rates for the energy crops, location / climate, land management and inputs and conversion efficiencies. Therefore, the potential land demand for each bioenergy sub-sector needs to be assessed individually as the likely use of dedicated energy crops, by-products or co-products of conventional crops, residues and conversion efficiencies is specific to that sector and location. Direct land demand can then be calculated for each bioenergy sub-sector based on an assumed level of energy demand and an assessment of the appropriate feedstock and their average productivities and conversion efficiencies for given locations. Dynamic global average land use intensities (Mha/EJ) from 2010 to 2050 are derived for each bioenergy sub-sector (biofuels, bioelectricity and bioheat) in the following sub-sections. The use of crop and forestry residues for bioenergy is assumed to have no direct land demand.

9.2.3.1 Biofuels

For biofuels, Langeveld et al. (2013) used a novel methodology for estimating net land demand based on observational land use data from the FAO. Assessing the 34 largest biofuel producing countries[3], which accounted for over 90% of global production in 2010, they found that the increase in biofuel production (2000 to 2010) resulted in a gross land demand of 25 Mha out of a total of 471 Mha arable land. However, nearly half the gross biofuel land area was associated with commercial co-products (primarily animal feeds e.g. distillers dry (and wet) grains; soy and rape meal; Table 9.7) leaving a net direct biofuel land demand of 13.5 Mha (2.4% of arable land area). Despite this increased demand for land for biofuel feedstock production, overall there was a decline in agricultural land area of 9 Mha in the countries evaluated. Increasing cropping intensity was found to have more than compensated for the decline in agricultural land resulting in an estimated additional 42 Mha of harvested area.

Using conventional methodologies for calculating potential land demand the IEA (2011a) estimates likely land demand of 30 Mha for supplying the current (2010) biofuel demand of 1.5 EJ. This is projected to increase to 32 EJ by 2050 with an associated land demand of c. 100 Mha with land use intensity decreasing from 20 Mha / EJ to 3.2 Mha/EJ by 2050 as advanced (including cellulosic) biofuel production systems are commercialized (Table 9.8). We assume that advanced / lignocellulosic biofuels are assumed to be produced using 50% residues and wastes and 50% dedicated energy crops by 2050.

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[3] 27 EU countries plus 7 non-EU countries (Brazil, USA, Indonesia, Malaysia, China, Mozambique and South Africa.

Table 9.7. Biofuel productivity (GJ/ha) by country and feedstock (based on Langeveld et al. 2013).

Country/ Region	Feedstock	Langeveld et al.	This study
Brazil	Sugarcane	152	153
Brazil	Soybean	18	20
USA	Corn	80	81
USA	Soybean	18	28
USA	Corn stover	27	17
EU	Wheat	37	36
EU	Rapeseed	43	43
EU	Sugarbeet	168	168
Indonesia and Malaysia	Palm Oil	90	138
China	Corn	46	47
China	Wheat	36	36
Mozambique	Sugarcane	23	23
South Africa	Sugarcane	107	106

9.2.3.2 Bioelectricity

Bioelectricity provision has important development and energy access dimensions (www.se4all.org). The IEA (2012b) projects bioelectricity generation to increase from c. 0.9 EJ in 2010 (c. 250 TWh) to c. 11 EJ (3100 TWh) in 2050. Assuming a net conversion efficiency of 30% in 2010 would mean a primary bioenergy demand of 3 EJ/yr in 2010, rising to 28 EJ/yr in 2050, with an assumed increase in conversion efficiency to 40%.

In our illustrative scenario, we assume that the feedstocks for bioelectricity provision are derived from 50% dedicated energy crops with yields increasing from 10 odt/ha.yr in 2010 to 18 odt/ha.yr in 2050 (see Figure 9.7 and Chapter 10, this volume, for yield justification). The remaining 50% of the feedstock demand is assumed to be derived from residues and wastes with no associated land demand. The combination of increasing energy crop yields and the use of wastes and residues results in a declining LUI from 2.8 to 1.5 Mha/EJ in 2050 (Table.9.9).

9.2.3.3 Bio-Heat

The role of biomass in heating and cooling is expected to grow considerably in the future. However, in the IEA's World Energy Outlook and Bioenergy Technology Roadmap (2011b and 2012b) it is clear that biomass provides significant amounts of heating energy to both the domestic (predominantly traditional bioenergy in the

Table 9.8. Biofuel and land demand in 2010 and 2050 as estimated by the International Energy Agency (IEA 2011a) and this study (derived from Langeveld et al. 2013).

Year	2010	2050
Biofuel Energy Demand (EJ)		
IEA (2011a)	1.5	32
This study	4.2	40
Land demand (Mha)		
IEA (2011a)	30	100
This study	21.8	115
Land intensity (Mha/EJ) derived from:		
IEA (2011a)	20	3
Langeveld et al. (2013)	7.0	-
This study	7.0	4.7

Notes: IEA assumes a very strong growth in lignocellulosic / advanced biofuels 'The total feedstock required in 2050 to meet the ambitious goals of this roadmap is around 65 EJ of biomass. It is assumed that 50% of the feedstock for advanced biofuels and biomethane will be obtained from wastes and residues, corresponding to 1 Gt of dry biomass, or 20 EJ.'

Langeveld et al. (2013) evaluate historic net land demand for biofuel production between 2000 and 2010 allowing for co-products

This study- Land Use Intensity (LUI) for conventional biofuels assumed to decrease in-line with a projected increase in conventional food crop (cereal) productivity of c. 1% per year and an increase in advanced / lignocellulosic biofuel production growing at 10% per annum from 2015 in the '200 EJ' scenario

rural areas of developing countries but increasingly in wood chip and pellet boilers in developed countries) and industrial and buildings sectors and as high-grade heat to industry. The IEA estimated that 25% of bioenergy in 2009 was consumed in these sectors (IEA 2011b).

Table 9.9. Bioelectricity land demand and land use intensity, 2010 and 2050.

Year	2010	2050
Bioelectricity Energy Demand (EJ)a	4.1	28.9
Bioelectricity Land demand (Mha)	11.4	44.2
Land intensity (Mha/EJ)	2.8	1.5

Notes: assumes 50% of energy is derived from residues and wastes and the remaining 50% is derived from energy crops with yields starting at 10 odt/ha.yr in 2010 and growing at 1.5% per year to18 odt/ha.yr in 2050

a: in the '200 EJ' and '150 EJ' scenarios

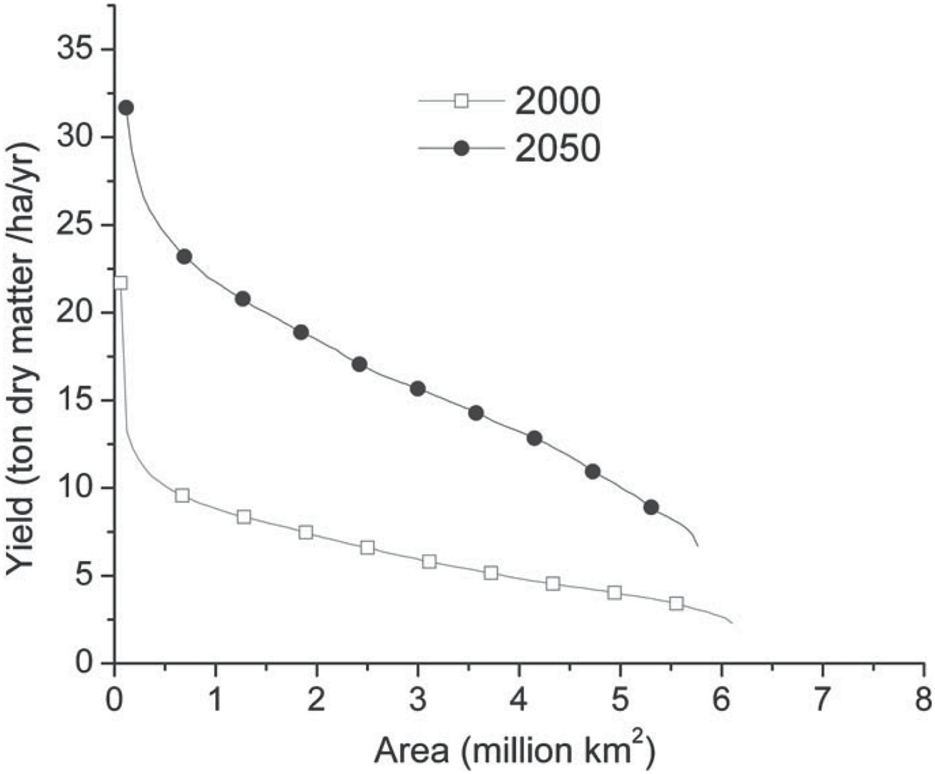

Figure 9.7. Area–yield curve for the OECD reference scenario in 2000 (lower curve) and 2050 (upper curve). van Vuuren et al. (2009).

Important links exist between energy provision for food (and fiber) production and bioenergy that are likely to grow over the coming decades. These linkages are likely to be particularly important for food supply chains which could become increasingly reliant on bioenergy provision for secure and cost-effective energy services at source.

Table 9.10. Estimated bioheat land demand and land use intensity, 2010 and 2050.

Year	2010	2050
Bioheat Energy Demand (EJ)a	13	67
Bioheat Land demand (Mha)	13	44
Land intensity (Mha/EJ)	1.0	0.8

Notes: assumes 2/3 of the energy input is derived from residues and wastes and the remaining 1/3 is derived from energy crops with yields starting at 10 odt/ha.yr in 2010 and growing at 1.5% per year to 2050

[a] 200 EJ scenario

9.2.4 Dynamics of Bioenergy Supply

Illustrative scenarios for the supply of 100, 150 and 200 EJ/yr of bioenergy by 2050 (Figure 9.8) have been developed to investigate the potential scale of land demand for bioenergy under a range of bioenergy sub-sector portfolios projected from 2010 to 2050 (Figure 9.9 and 9.10). In these scenarios, the overall land demand ranges from 50 Mha to 200 Mha with biofuels being the most land intensive sub-sector. Despite traditional biomass energy consuming between 56% and 30% of total bioenergy it has not been possible to estimate its current land requirements and there is considerable uncertainty about the future environmental impacts of its continued and expanded consumption.

Of the total estimated land demand, between 40 and 50 Mha is required to grow the feedstocks for conventional biofuels, which provide between 7% and 17% of primary energy in 2050 (Table 9.11). The land demand for conventional biofuels is thus equivalent to about two thirds of the expected increase in agricultural land demand for food production by 2050 (Alexandratos and Bruinsma 2012). The remaining 10 to 150 Mha of land demand for lignocellulosic biomass from energy crops could be met from a combination of increased agricultural land, pasture land arising from pasture intensification and perhaps dietary change. Additional feedstocks and land for bioenergy could effectively be made available from increased forestry activities where significant fractions of biomass should be harvested from existing forestry

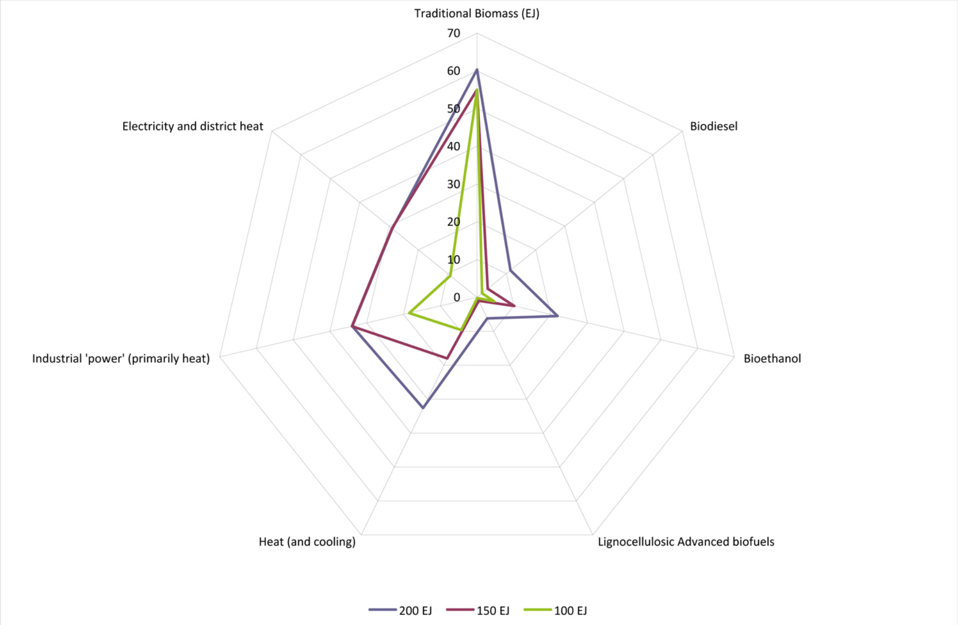

Figure 9.8. Energy provision portfolio in 2050 for each bioenergy sub-sector and bioenergy provision scenario (100, 150 and 200 EJ/yr).

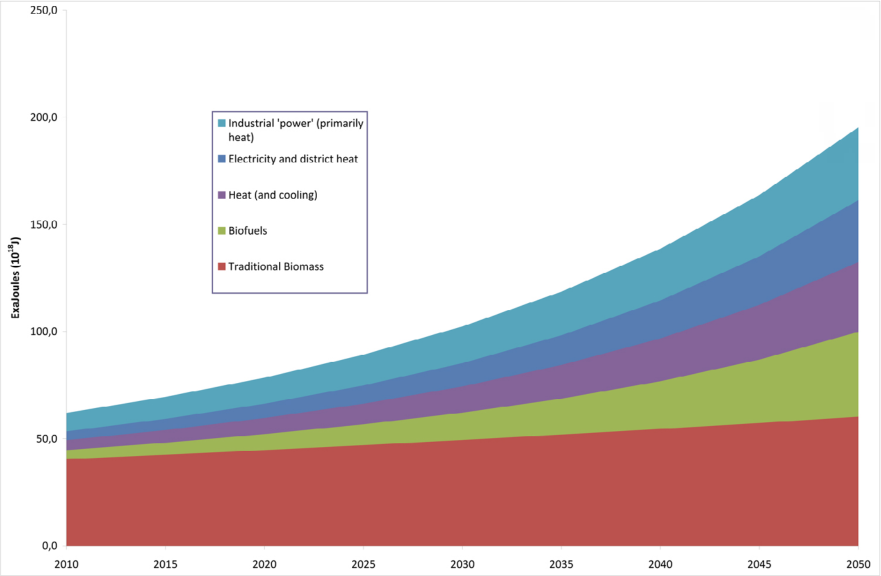

Figure 9.9. Global bioenergy (modern and traditional) demand projections under the ‘200 EJ/yr’ scenario (2010 to 2050).

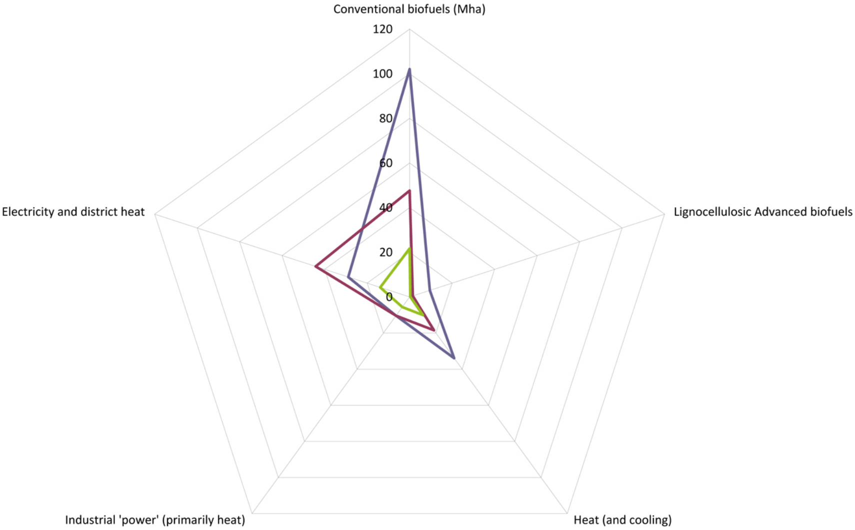

Figure 9.10. Land demand portfolio in 2050 for each bioenergy sub-sector and bioenergy provision scenario, 100, 150 and 200 EJ/yr.

plantations in order to maintain and enhance forestry yields and standing stocks (IPCC 2014).

The estimates for land demand for bioenergy are calculated using a decreasing land use intensity (land required per unit of energy produced) between 2010 and 2050 with overall bioenergy LUI falling from nearly 2 Mha/EJ to 1 Mha/EJ in 2050, primarily as a result of expected increases in yields of conventional and novel energy crops (Table 9.12; see section 9.2.3). Further reductions in land use intensity would be expected through increased cropping intensity and raised supply chain efficiencies for both modern bioenergy supply chains but perhaps more importantly for food supply chains effectively increasing the supplies of bioenergy feedstocks with no net increase in land demand or possibly even a decline as highlighted by Langeveld et al. (2013) for global biofuels, Kim and Dale (2011) and Oladosu et al. (2011) for corn ethanol in the US, and Sousa and Macedo (2010), and Seabra et al. (2011) for sugarcane ethanol in Brazil.

Table 9.11. Land demand for bioenergy and share of total, agricultural and arable land in 2010 and 2050.

	2010				**2050**	
	Land demand	**share global land**	**share agricultural land**	**share arable land**	**Land demand**[a]	**share potential agricultural land**[a]
	Mha	**%**	**%**	**%**	**Mha**	**%**
Biofuels (net; co-products)	14	0.1%	0.3%	1.0%	102, 48, 22	11, 5, 2
Bioelectricity	11	0.1%	0.2%	0.8%	29, 44, 14	3, 5, 2
Bioheat	28	0.2%	0.6%	2.0%	44, 29, 16	5, 3, 2
Total modern bioenergy	53	0.4%	1.1%	3.8%	200, 120, 52	22, 13, 6

Notes

a: for the 200, 150 and 100 EJ/yr scenarios

Increased land demand might be expected for bioenergy where adverse economic and climatic conditions, affect future yield potentials. However, even under such adverse conditions, bioenergy could be developed to provide secure off-take markets for damaged goods or provide some return for crops that have failed or that are contaminated e.g. with mycotoxins. During periods of excess production, bioenergy systems could be configured to provide a productive off-take again setting a price floor for biomass (agricultural and forestry) and enhancing resilience for farmers.

Table 9.12. Land use intensities (Mha/EJ) for biofuels, bio-heat and bio-electricity (2010, 2035 and 2050).

		2010	2035	2050
Basic Land demand calculation	15 odt/ha	3.70	3.70	3.70
Overall LUI		1.99	1.36	1.06
Conventional biofuels		7.01	5.5	4.7
Advanced biofuels	50% Residue share	2.78	1.91	1.53
On-site heat	66% Residue share	1.89	1.30	1.04
Electricity and district heat	50% Residue share	2.78	1.91	1.53

Notes

Conventional biofuels. LUI decreases by 1% per annum in line of forecasts for conventional crop growth

Residues are not used but land associated with co-products (e.g. animal feeds) is subtracted

Advanced biofuels: 50% is assumed to be derived from residues and wastes with no associated land demand

Heat. 66% of energy is assumed to be derived from residues and wastes with no associated land demand

Electricity. 50% is assumed to be derived from residues and wastes with no associated land demand

9.2.5 Biomass Energy Supply: The Answer Depends on How the Question Is Framed

The biomass feedstocks used for energy provision arise from resources ranging from dedicated and exclusive planting and production of crops (including conventional and novel agricultural crops and trees) through to resources currently classified as residues and wastes e.g. from food production. These waste supplies can represent biomaterials that have had multiple uses for example, having been recycled a number of times in some cases (e.g. straw used for chicken litter and then as a feedstock for electricity production). The land demand and perceived and actual environmental impacts arising from bioenergy provision will be increasingly sensitive to which category of resources are used and how quickly the demand increases relative to the scale of the resource base. Three categories of biomass supply estimates are addressed here:

- Residual biomass available from activities undertaken primarily for purposes other than bioenergy production e.g. food and fiber production.
- Dedicated energy crops: Isolated analysis of food and bioenergy production systems. The term “isolated analysis” is used herein to refer to anticipation of food production independent of the emergence of a much-expanded bioenergy industry and based largely on extrapolation of current trends.

- Integrated analysis of food and bioenergy production systems. The term “integrated analysis” is used herein to refer to anticipation of an integrated food and bioenergy system with significant weight given to sustainability objectives.

9.2.5.1 Residual Biomass Arising from Non-Bioenergy Activities

Global production of food and fiber (forestry) will increase through to 2050 and beyond as the population grows, becomes increasingly wealthy, and demands more resources. There are unlikely to be significant gains in the harvest ratio for food crops and so increasing the yields of food crops will inevitably increase the volume of residues. Equally, with forestry, increased management, particularly through thinnings will increase yields of both forestry residues and roundwood for fiber and wood-based materials.

Residues originating from forestry, agriculture and organic wastes (Table 9.13; including the organic fraction of municipal solid waste (MSW), dung, process residues etc.) are estimated at around 100 EJ/yr (Slade et al. 2014; Chum et al. 2011; WWF/Ecofys/OMA 2011; van Vuuren et al. 2009). According to Chum et al. (2011), ‘this part of the technical potential biomass supply is relatively certain,’ but competing applications and other considerations may push net availability for energy applications below the technical potential. How much below depends in significant part on development of technology, and is thus difficult to predict.

Surplus forestry other than from forestry residues, had an additional technical potential of about 60 to 100 EJ/yr (van Vuuren et al. 2009). The potential for improved management of forests has also been recognized by the IPCC (2014) (Figure 9.10) which provides a range of 25 to 75 EJ of potential arising from ‘optimal forest harvesting.’ In addition, there may be a need to remove diseased trees to manage the spread of the disease, as is the case of the pine beetle which is causing major problems in the US and Canada, providing additional forest biomass for bioenergy.

Categories of residual biomass arise from crop production, crop processing (including bioenergy), forestry, and municipal consumption. The total amount of biomass produced by these activities is considerably greater than the amount that could feasibly be used for bioenergy because the economic cost of gathering, storage, and transportation may be too high and because some residues need to be left behind to ensure sustainability in the case of agricultural and forest residues.

Accounting for the minimum bioenergy potentials for each category assessed by the IPCC (2014) there is high agreement in the literature that the combined bioenergy potential for all categories is c. 110 EJ. This can be compared with the residue demand projected in the illustrative scenario of 48 EJ.

Table 9.13. Categories of residues as used for assessing bioenergy potentials.

Agricultural residues
Residues arising in-field e.g. cereal straw, sugarcane tops and leaves
Residues arising from primary processing of food products e.g. husks, hulls, shells, bagasse, etc
Forest residues
Residues arising in-field e.g. thinnings, tops and branches (up to 40% of above-ground forest biomass)
Residues arising from primary processing at saw-mills or pulp and paper factories e.g. saw dust, chips and off-cuts, black liquor
Wastes and secondary residues
Wet wastes (livestock manure, sewage)
Dry wastes (MSW, recovered construction timber, shells and hulls e.g. from nuts and de-husking of grains)

9.2.5.2 Separate Analysis of Food and Bioenergy Production Systems

In the illustrative 200 EJ/yr scenario, nearly 90 EJ is assumed to originate from energy crops for biofuels, heat and electricity generation. Beringer et al. (2011), report a 26 to 116 EJ range for energy crops in 2050 without irrigation (and 52 to 174 EJ with irrigation). A review of the wider literature reports a much broader range in potential bioenergy supplies from energy crops. Perhaps the most severe constraint on future provision of bioenergy from energy crops arises from the perceived competition for land, particularly with food cropping. Byerlee and Deininger (2013) for example, restrict estimates of land availability for bioenergy to areas that have population densities lower than 25 people km^{-2}.

Other constraints in terms of land availability include restrictions to avoid increased deforestation pressure, loss of biodiversity and increased pressure on water resources. Overall estimates of bioenergy potentials are provided by Haberl et al. (2010), who report 160 to 270 EJ/yr in 2050 across all biomass categories. Krewitt et al. (2009), following Seidenberger et al. (2008), also estimated the technical potential to be 184 EJ/yr in 2050 using strong sustainability criteria and including 88 EJ/yr from residues. They project a ramping-up to this potential from around 100 EJ/yr in 2020 and 130 EJ/yr in 2030.

Estimates of potentially available good quality land suitable for rainfed agriculture (see Section 9.2.1.3) range from 250 to more than 900 Mha. Gross estimates of the potential for energy crops on possible surplus good quality agricultural and pasture lands range from 140 to 290 EJ/yr (surplus 'Very Suitable' and 'Suitable' land at 10 and 20 odt ha^{-1} yr^{1}). The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 80 EJ/yr ('Moderately' + 'Marginally Suitable' Land; 5 odt ha^{-1} yr^{-1}).

9.2.6 Integrated Analysis of Food and Bioenergy Production Systems

The vast majority of projections for the development of the food production sector and related land demand have been conceived exclusive of the emergence of a greatly-expanded modern bioenergy industry. Thus activities related to food production have been assumed to develop without impact from, or integration with, development of the bioenergy sector, and bioenergy has been assumed to have access to land that is left over after anticipated requirements for food production, biodiversity protection and infrastructure demands are satisfied. This approach is usually justified based on the observation that food is the highest priority use for land resources managed by humanity, which is strongly endorsed here.

While food is in many situations a high or highest priority, this does not mean that separate analysis of food and bioenergy production is the best approach. Indeed, this is likely not the case. Compared to isolated analysis, integrated analysis is more realistic in that there will surely be interactions between a greatly expanded bioenergy production system and food production. Integrated analysis is also likely to be better at illuminating paths to sustainable biomass provision, whatever the end-uses.

Just as there are attractive integrated systems for the production of crops with livestock (Herrero et al. 2011; Iiayama et al. 2007; Van Kuelen and Schiere 2004), there are likely to be integrated bioenergy-crop, bioenergy-livestock, and bioenergy-crop livestock systems (Bogdanski et al. 2010; Dale et al. 2010). The presence of economically-rewarding technology for bioenergy production will create new pressures and opportunities. Negative interactions will need to be carefully managed. As developed below, there appear to be potentially favorable impacts of bioenergy on food production, which can only be identified and optimized by taking an integrated approach.

Food production agriculture faces challenges independent of bioenergy, among them maintaining and reclaiming soil fertility, preventing erosion, controlling nutrient loss to receiving waters, and enhancing wildlife habitat. There is strong evidence that growing perennial grasses on land formerly used for row crops, or in rotation with row crops, improves soil organic matter and fertility and that this occurs with harvest of bioenergy crops as well as without it (Anderson-Teixiera 2013; Jordan et al. 2007; Lal 2004). In particular, several studies have found that growing perennial grasses in lieu of row crops increases soil carbon stocks at a rate of 1 Mg C/ha.year or more (Gebhart et al. 1994; Penman et al. 2003). Similar outcomes have recently been found for sugarcane when it replaces soy or pasture in Brazil (Mello et al. 2014). Lal (2004) calculate that an increase of 1 ton C/ha in the soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare for wheat and 10 to 20 kg/ha for maize. Such integrated approaches combine adaptation and mitigation whilst simultaneously providing mechanisms to close the yield-gap in major food crops (Hall and Richards 2013; van Ittersum et al. 2013).

Perennials also radically reduce rates of erosion and nutrient runoff as compared to conventional tillage, often by over 100-fold, and are widely recognized as leading management strategies to achieve these objectives (McLaughlin 1996; Chesapeake Bay Commission 2012). Buffer strips along the edges of streams are widely used, and more widely recommended, to intercept pollutants and provide wildlife habitat (Gopalakrishnan et al. 2012; Christen and Dalgaard 2013). A comprehensive study of Midwestern US grasslands found substantial differences between biodiversity indicators for maize and perennial grasslands, whereas indicators were similar for harvested switchgrass and unmanaged prairie (Werling et al. 2014).

Along with the multiple benefits that perennials offer to food production agriculture, they could also produce bioenergy feedstocks on a scale large enough to matter in the context of energy supply at both global and local scales. If, for example, 5% of cropland were planted in perennial bioenergy crops in a combination of buffer strips and long-term rotation, this would correspond to about 60 million ha of land globally, potentially providing over a quarter of the projected land needed to produce 200 EJ of bioenergy by 2050. At a representative yield of 10 odt ha^{-1} yr^{-1}, planting 5% of the area within a feedstock catchment area with a 50 km radius would provide over 1000 oven dry tons per day to an individual processing facility. This is enough to produce about 100 Ml of ethanol per year (30 million gallons), or 4.5 TWh of electricity.

9.2.6.1 Sustainable Intensification

Intensification, increasing output per unit land, is in principle possible for production of goods from cropland, forestland, and pasture. There is broad consensus that sustainable intensification of the world's cropland is necessary in order to meet anticipated food demand (Godfray et al. 2010, Tilman et al. 2011, The Royal Society 2009, Foley et al. 2011, Clay. 2011). Mueller et al. (2012) estimate the difference between potential and actual yields for 18 row crops, with potential yields based on near maximum (e.g. 95th percentile) yields currently achieved under climatically-similar conditions. Based on this analysis, Sheehan et al. (in review) calculate intensification potentials (the potential yield divided by the actual yield) for global maize and wheat land of 1.64 and 1.71 respectively. Future yield increases for crops are widely expected to be needed to keep up with increased food demand (Alexandratos and Bruinsma 2012). Thus, whilst integrating of perennial crops into agricultural landscapes offers potential benefits, the intensification of cropland to make room for production of bioenergy feedstocks may need to be supplemented by other options for the supply of biomass for bioenergy.

Managed forests and residues from the forest products industry make a substantial contribution in many bioenergy scenarios. In the World Wildlife Fund for Nature's 100% Renewables scenario (WWF/Ecofys/OMA 2011), for example, sustainable harvesting of forests contributes 27EJ and forest residues and wood waste provide an additional 25 EJ. Sustainability criteria are applied to these estimates, although not all studies have values as high as the WWF study.

The world's roughly 3.4 billion hectares of pasture (taken here to include rangeland) represents over twice as much land as currently used to grow crops. Although pasture and rangeland is a critical source of livelihood and ecosystem services in many locations, on a global scale it plays a strikingly smaller role than cropland as a source of food. As presented in Table 9.14, grazed land provides about 3% of human dietary protein consumption and about 1% of total dietary calories.

Table 9.14. Contribution of pasture land to dietary calories and protein.

	A	B	C	D	E	F=A*C	G=A*E
Animal Product	**Production from Grazing**	**Animal Product Consumption (kcal/person/day)**	**Percent of Total Calories**	**Animal Protein Consumption (kcal/person/day)**	**Percent of Protein as Calories**	**Total Calories from Pasture**	
Meat	8.4%	252	8.9%	58	17.8%	0.8%	1.5%
Milk	12.0%	127	4.5%	33	10.1%	0.5%	1.2%
Eggs	0.8%	33	1.2%	11	3.4%	0.0%	0.0%
Total		412	14.6%	102	31.3%	1.3%	2.7%
Sources	1	2	2	2	2	1,2	1,2

Note: Human calories consumption: 2,831 kcal/day; Per capita protein: 325 kcal/day

Sources

1. FAO 2006b
2. FAO/FAOSTAT 2009

Data for pasture performance are in general much more limited than for row crops. While there is no global database for pasture yield, the FAO Gridded Livestock Study (Wint and Robinson 2007), provides a global inventory of pastured animals. Using stocking density to represent pasture performance, Sheehan et al. (in review) have developed the first geospatially-explicit estimate of the intensification of global pasture land. Their findings include:

- 43% of pasture land in one of the most widely used land classification schemes (Ramunkutty et al. 2008) does not have livestock on it according to the FAO Gridded Livestock Study. For multiple reasons, much of this land may not be available for bioenergy production. Still, it is notable that the area of pasture apparently not occupied by livestock is nearly equivalent to the area of global cropland.
- Significantly higher animal stocking density (head/ha), and by inference yield of animal products (kg per ha per year), could be realized on the world's pastureland (see section 9.2.1.3). In particular, increasing animal stocking densities to the 95th percentile of their climate-appropriate, currently-attainable, levels would

allow existing pastureland to support 3.8 fold more animals. Bringing the poorest-performing pastures up to 50% of their maximum attainable density would more than double the global stock of grazing animals.

- The potential for intensifying pasture is found to be much larger than that of grain crops determined using a similar approach.

The potential to achieve several-fold intensification of pasture is supported by detailed regional studies (World Bank 2012; Thornton and Herrero 2010). Brazil, the world's second largest beef producer, increased carcass weight per ha by 3.5-fold over a twenty one year period between 1985 and 2006 (Martha et al. 2012). Notably, animal performance (kg per head per year) was a larger contributor to this result than stocking density (head/ha) and thus the intensification potentials calculated by Sheehan et al. (in review) may prove to be conservative upon further study. Reflecting on the causes of intensified production of pastured livestock in Brazil, Geraldo Martha comments that "Prior to the mid-80s, land and animals in Brazil were treated as capital reserves against economic instability, since then there has been a major drive for productivity gains" (Personal communication 2014). Managing pasture land as a capital asset may well be widespread but remains to be systematically assessed. Further information on the intensification of pastureland in Brazil is included in (see Section 9.2.2 and Landers 2007).

Deeper analysis of pasture intensification is a priority. In particular, a detailed sustainability analysis of pasture intensification remains to be carried out. Pasture intensification will likely be accompanied by at least two positive impacts from a sustainability perspective: increased soil carbon storage and decreased methane per unit animal product. Pasture intensification in the presence of a robust bioenergy industry will likely be larger than without such an industry. The relatively small role of pasture in food supply combined with the extensive area it occupies and its apparently large intensification potential make it logical to consider pasture land as a major potential bioenergy feedstock provider. These observations are underscored by Table 9.15, and explain why pasture land is by far the largest land category used to grow energy crops in most scenarios.

9.2.7 Estimates of Bioenergy Potential

The literature includes many estimates for the potential magnitude of bioenergy that could be produced, as well as some excellent surveys that aggregate results from multiple studies (e.g. Slade et al, 2014; IPCC, 2014). Estimates of bioenergy potential are based on a wide range of assumptions. For example, studies differ widely with respect to:

- What categories of land are and are not considered. Few studies consider all of the categories identified in this chapter;
- The operational criteria used for whether land is designated as 'available';
- The extent to which analysis of biomass potential is evaluated using integral or separate approaches relative to food production (see Section 9.2.5.2.).

Table 9.15. Summary properties of the three major land classes that can grow terrestrial biomass.

Land Type	Area1 (109 ha)	Potential win-win integration options	Potentially competing priorities	Food Production	
				Importance	Intensification potential
Cropland	1.6	Perennials improve sustainability metrics	Food	Very large	Moderate, likely needed for food
Forestland	3.9	Selective harvest, thinning	• C storage • Habitat	Almost zero	---
Pastureland	3.4	• Sustainable intensification • Crop-livestock-bioenergy systems	Less apparent	Very small	Large, likely in excess of food needs

[1] See Table 9.1 and Lambin and Meyfroidt 2011

Given these differences, it is not surprising that estimates for bioenergy potential vary widely.

Among the two most comprehensive aggregated studies are those by the IPCC (2014) and Slade et al. (2014). The IPCC study considers the global bioenergy potential originating from industrial organic residues, forest and agricultural residues, dedicated crops and optimal forest harvesting, while also projecting reduced demand for traditional biomass for energy purposes (Figure 9.11).

The wide variation in bioenergy supply estimates, previously noted, is evident – particularly with respect to energy crops, for which estimates vary from 25 to 675 EJ. Summing the minimum value in every category gives about 110 EJ. Slade et al. (2014) aggregate results from 28 studies that provided over 120 estimates for the future contribution of biomass to global energy supply into categories of energy crops, wastes and residues, and forestry (Figure 9.12). As with the IPCC 2014 study, estimates vary widely and the highest estimates of potential are for energy crops.

9.3 Discussion and Conclusions

Based on dynamic considerations, we calculate a gross land demand for modern bioenergy of 45 Mha in 2010, and indicatively between 50 Mha and 200 Mha by 2050. Whilst highly uncertain, this scale of land use delivers about 20 EJ/yr of modern bioenergy in 2010, and between 44 and 135 EJ/yr of modern bioenergy in 2050. In all our indicative scenarios, traditional biomass remains the single largest bioenergy sub-sector, providing between 55 and 60 EJ/yr in 2050. Sensitivity analysis suggests that

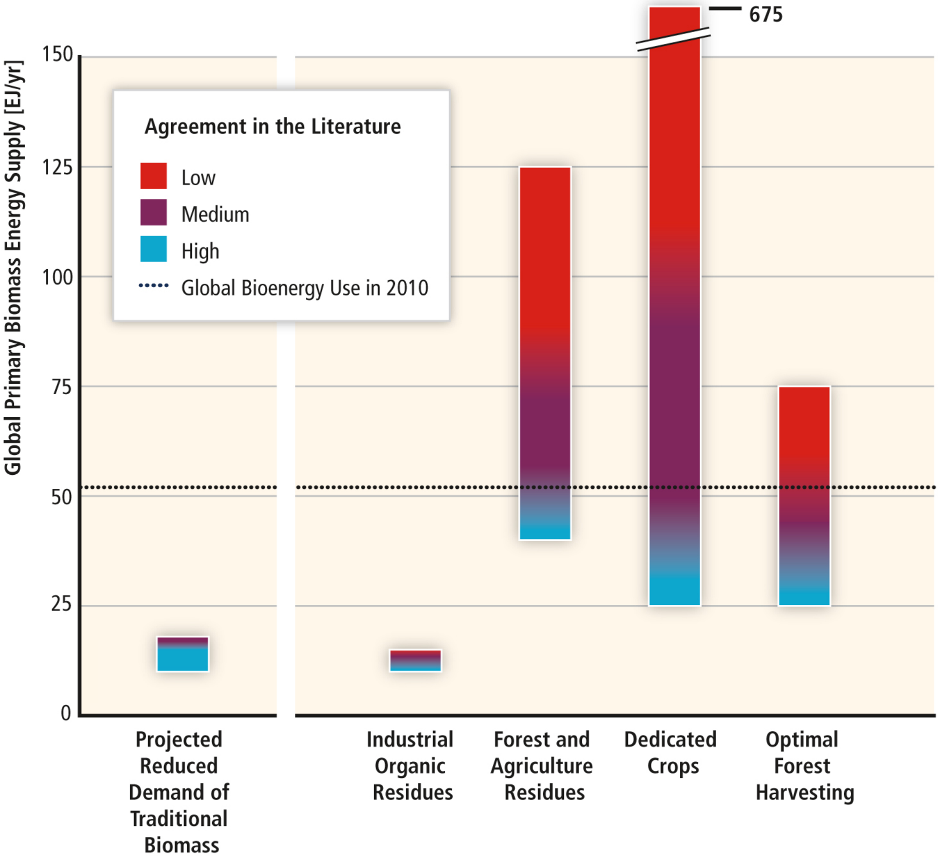

Figure 9.11. Bioenergy potentials (ranges based on expert opinion). The medium to high potential range was 100 to 300 EJ (IPCC 20 14).

independent of the specific scenario considered, e.g. with respect to the distribution of bioenergy products, approximately 0.7 EJ per Mha is a reasonable ballpark land use intensity for production of modern bioenergy at a scale in the order of 80 to 160 EJ in the 2050 timeframe. In practice the overall land demand for bioenergy is likely to be lower than these estimates as a result of integrational co-benefits with food and fiber production, but precise numbers are difficult to calculate.

Most global studies of land availability for bioenergy in 2050 exceed 500 million ha after allowing for food production, protected areas, urban expansion, and increased biodiversity protection (Table 9.1). The FAO (Alexandratos and Bruinsma 2012), for example, estimates that there is currently about 1.4 Gha of 'suitable to moderately suitable' land that is currently unused or 'spare' and that has rainfed cropping potential. Taking into account the sources reviewed and considering all categories of potentially available land, and not just land suitable for rainfed cultivation of row crops, we find this estimate to be quite reasonable.

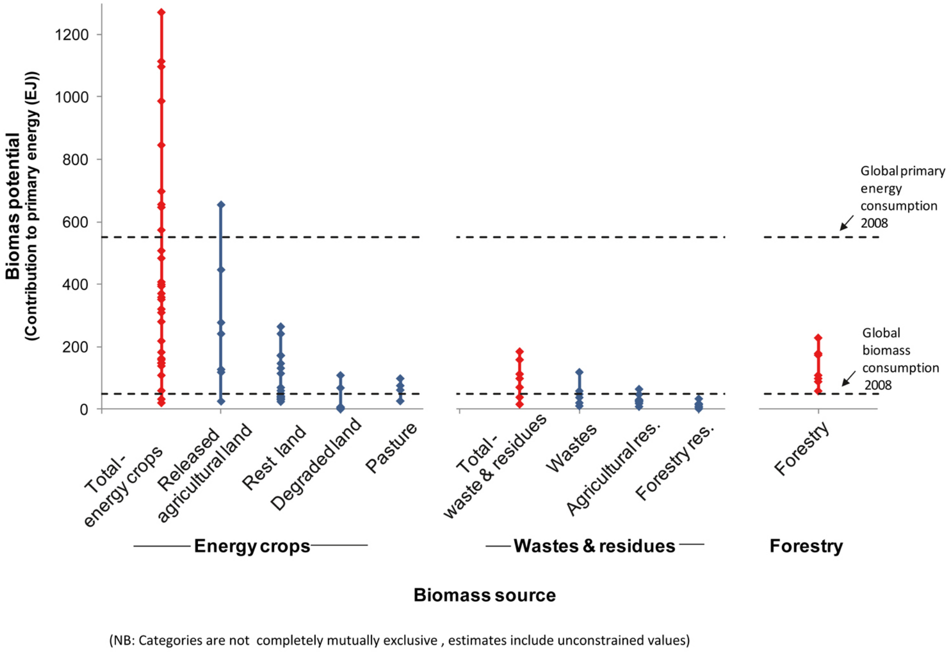

Figure 9.12. Bioenergy supply potentials based on meta-analysis of 28 global studies (Slade et al. 2014).

Our estimates for the land demand of bioenergy are lower than other estimates because of the inclusion of key factors supported by recent analysis: the ability of bioenergy to recycle biomass through the use of wastes and residues and support crop yield growth through investments in infrastructure and development capacity in agriculture and forestry. Furthermore, the potential to use alternative crops and in particular to increase the area of perennial cropping will diversify agricultural landscapes and provide novel and productive tools to manage and ameliorate the impacts of intensified food cropping.

Land potentially available for bioenergy includes:

a) Land suitable for rainfed agriculture expected not to be needed for other purposes (Section 9.2.1.3),

b) Degraded land (Section 9.2.1.3),

c) Land not suitable for rainfed agriculture but potentially suitable for energy crops (Section 9.2.1.3, not easily distinguished from degraded land),

d) Land made available by pasture intensification (discussed in Section 9.2.5.2).

Whilst not quantified here, we note that increasing cropping intensity, including double cropping (Langeveld 2013; Feyereisen et al. 2013), is already increasing biomass production on existing cropland with considerable potential for further expansion, as highlighted in section 2.6.

It is not currently possible to clearly distinguish between these categories of land, which represent a key knowledge gap (see below). If available land is estimated assuming that land in category a) includes land in categories b), c), and d), the resulting estimate will be conservative – that is lower than the actual amount of land available. If on the other hand, available land is estimated by summing categories a) through d), the estimate will be too high and will involve some double counting.

Taking the more conservative approach, Figure 9.13 compares only the land areas considered suitable for rainfed agriculture and that is potentially available for bioenergy production (905 Mha), with the 200 Mha estimated to be required for production of 135 EJ of modern bioenergy in a scenario that delivers 200 EJ/yr of bioenergy (modern + traditional) by 2050 as defined in Section 9.2.4). As presented in Section 9.2.1.3, Table 9.5, potentially available land is exclusive of anticipated demands for cropland, natural forests and forest plantations, urban land (including allowance for expansion), and increased land for biodiversity protection as recommended by the World Wildlife Fund (see Section 9.2.1.3). Most of this potentially available land is currently categorized as pasture, although not all of it has livestock on it, and is managed at very low intensity if at all.

In practice, accessing land for bioenergy production will be a function of diverse local biophysical, economic, cultural and political factors, requiring widespread public and political support to enable the needed investments in infrastructure and human capacity. The underpinning science needed to provide the evidence base to enable the public and political support is currently lacking and more work is needed to reduce uncertainties, remove data gaps and provide guidance on beneficial rather than detrimental pathways for substantive modern bioenergy provision.

As illustrated in Figure 9.13, a small (0% to 11%) portion of potentially available land considered suitable for rainfed agriculture is required for energy crops. We note that bioenergy crops currently under investigation or development are able to access wider categories of land than considered as ‘very suitable’ or ‘suitable’ for rainfed agriculture. When land categories classified as ‘moderately’ and ‘marginally’ suitable for rainfed agriculture are included, an additional 1 billion ha of land could be considered for bioenergy crops. We therefore conclude that there is vastly more land than necessary in order to produce in excess of 100 EJ of modern bioenergy, consistent with low carbon energy scenarios. Long before the world reaches any significant fraction of 100 EJ of modern bioenergy, we will have ample opportunity to be guided by experience rather than projection.

Given this novel perspective on land availability for bioenergy, we consider that the critical question is not one of managing a competition for land between energy and food, but rather whether and how bioenergy production can be gracefully incorporated into human and natural systems. The authors believe the answer to this question to be yes, but leave detailed consideration to other chapters in this volume.

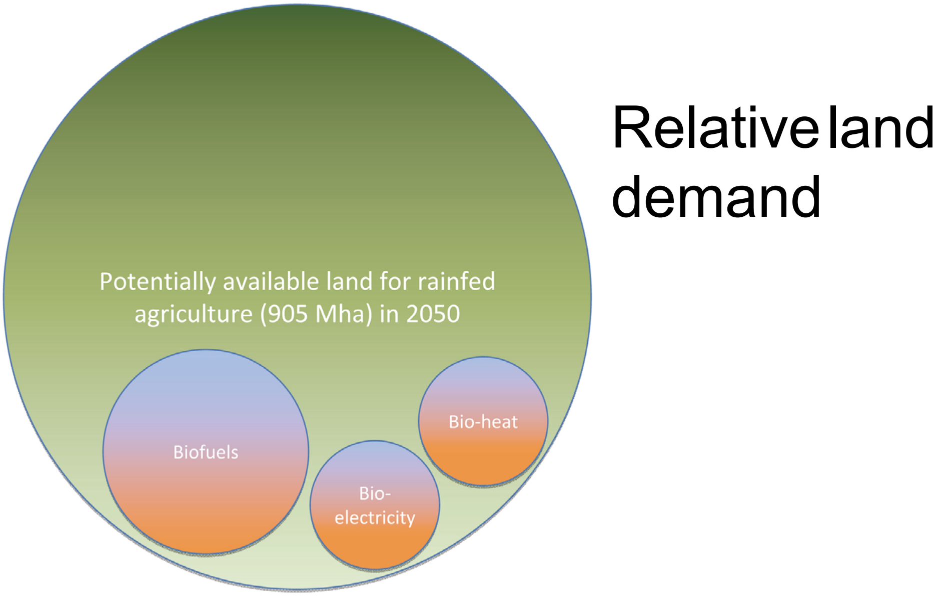

Figure 9.13. Indicative share of potentially available rainfed agricultural land (Alexandratos and Bruinsma 2012) occupied by bioenergy crops (22%) under a scenario where bioenergy (modern and traditional) delivers 200 EJ/yr in 2050.

9.4. Recommendations

The need for a significant expansion of modern bioenergy provision and better understanding of the systems that must be developed to ensure the sustainable provision of biomass to supply the new bioenergy demand urgently needs addressing. As a result of the spatially distributed nature and heterogeneous technological options of bioenergy pathways the underpinning research capabilities will also need to be distributed and broadly based with integrative global science programs, closer integration with the global food research system and the private sector. More specific recommendations include:

- Support the development of new markets for modern bioenergy systems;
- Develop better understanding of the catalytic role of bioenergy in promoting economic and agricultural development;
- Develop capacity to develop regionally-responsive, spatially explicit, new conversion processes and supply chains, and cropping systems;
- Stimulate efforts to understand, monitor and assist poor people to gain access to modern bioenergy services and technologies. The role and scale of traditional bioenergy remains heavily under-researched;

- Significant effort is needed to better understand the role of biomass in the provision of high-grade heat to industry (including agro-industry) and domestic / residential space heating;
- Better data and improved understanding of the actual land use impacts of modern and traditional bioenergy is urgently required;
- Develop integrative perspective of bioenergy with agriculture, livestock and forestry production systems;
- Support the investigation, demonstration, and synergy maximization for integrated bioenergy and food production systems.

9.5. The Much Needed Science

Substantial uncertainty remains in the understanding of land availability, the dynamics of its use (particularly temporal dynamics) and in the potential impacts of climate change on crop productivity and production. The role the very broad range of bioenergy cropping systems could play in ameliorating these impacts is not well recognized or understood and substantial interdisciplinary and international science programs are urgently required to reduce the uncertainty in land availability estimates and the potentials for integrative cropping.

- Supporting this macro-level understanding, new science is needed to understand the potential and need for:
- Increased cropping intensity, evaluating novel crop rotations including winter cover crops, pasture – arable – perennial bioenergy cropping systems. In particular, evaluating the impacts and management potentials to modify:
- Site-specific environmental (biophysical, biochemical and biological) characteristics of soils / land, including soil organic matter and soil carbon, soil and above ground biodiversity, nutrient status / retention, soil management particularly with regard to erosion, hydrology including modified soil water holding capacity; potential for bioenergy cropping to remediate degraded / damaged soils;
- Socio-economic, including; land planning, land tenure, access, long run productivity / productivities for multiple rotations / seasons.
- Potential for and practical implementation strategies that result in sustainable pasture intensification;
- Novel integrated land management options arising from a better understanding of the interlinkages between pasture intensification, food crop production and bioenergy cropping;
- The local level socio-economic drivers and policy linkages needed to provide the markets and regulatory frameworks to promote integration and sustainable intensification.

- Improved data provision across the range of bioenergy service provision including, heating and cooling, electricity, transport / mobility and their implications on the associated land demands.
- A particular focus is required on understanding the scale, and impacts (environmental, health, etc.) of traditional biomass use for energy. Current understanding and data on consumption is limited and the driving forces underpinning the demand for traditional bioenergy are dynamic e.g. rural and urban population growth in developing countries, particularly African countries.

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chapter 10

Feedstocks for Biofuels and Bioenergy

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Highlights

- Currently only a few crops supply the bulk of biofuel and bioenergy production globally, however many crops and even as yet undomesticated plants have the potential to become important feedstocks, with major opportunities to offset greenhouse gas (GHG) emissions from the use of fossil fuels.
- It is important that expansion of any existing or newly developed crop for feedstock production does not lead to unacceptable socioeconomic or environmental consequences. However, holding bioenergy feedstocks to higher standards than existing food and forestry crops will delay major opportunities to realize important renewable energy opportunities and mitigation of current GHG emissions.
- Increasing the productivity of current and emerging bioenergy crops per unit land area is not only critical to economic viability, but also to biodiversity by minimizing the total land area needed. Land sparing is found far more effective than land sharing in strategies to realize bioenergy.
- Organic post-consumer waste and residues and by-products from the agricultural and forest industries, which contribute a major part of biomass for energy today, will not suffice to meet the anticipated levels of longer term biomass demand. Thus, much of the bioenergy feedstock will have to come from dedicated production.
- Global demand for wood has been increasing by 1.7% per year. Meeting future demands will require investment in energy tree breeding and enabling policies that tackle the environmental concerns surrounding forest management, new plantings and residue removal.
- Maize ethanol, often portrayed as the villain of the piece in the food versus fuel debate, may in fact have been key in stimulating yield improvement, including through genetically modified (GM) traits, that has resulted in increased exports of grain from the USA while providing a buffer in drought years.
- Of the four largest sources of biofuels: maize, sugarcane (bioethanol), soybean and rapeseed (biodiesel), only sugarcane appears to have a secure future although in the case of maize this will depend on the rate of yield improvement that could be achieved.
- With the exception of oil palm, the yields of biodiesel crops (soybean and rape/canola) are too low to contribute significantly to future energy supply. However,

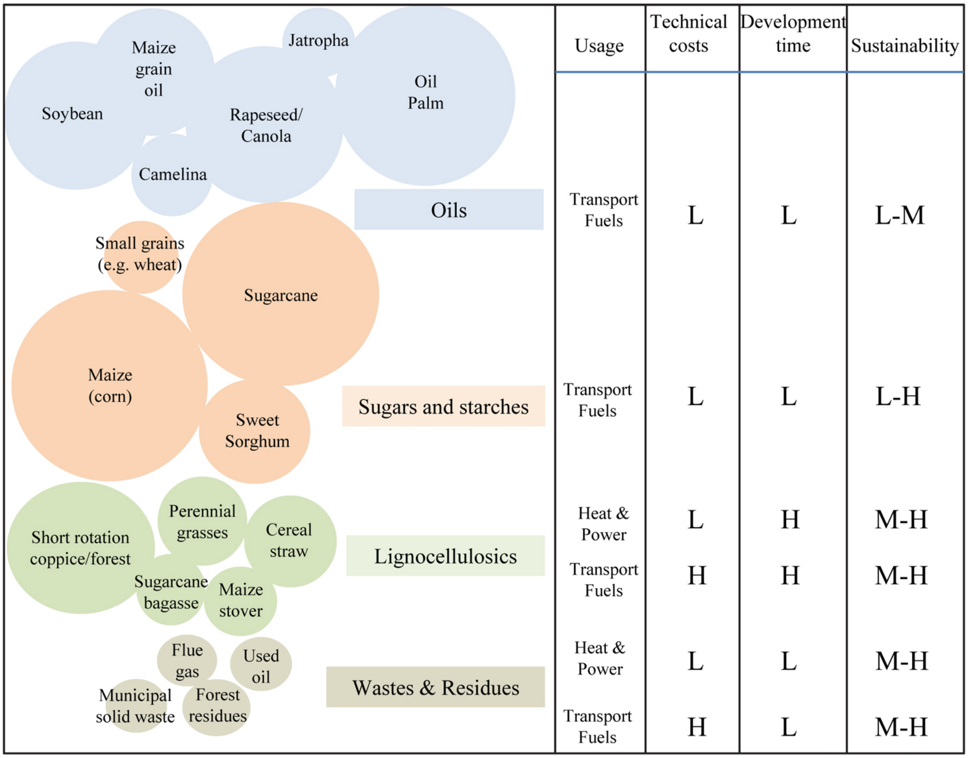
breakthroughs in engineering accumulation of oil in vegetative tissues may provide an alternative with the potential of developing a sugarcane that accumulates oil in place of sugar.

- The claims that large-scale microalgae production will meet future energy needs have not been substantiated and at best, these systems could contribute to high value products or have value when combined with wastewater treatment.
- Using high productivity perennial feedstocks, a substantial contribution to global energy needs, can be made using land unsuited to food crop production. This will require a large expansion of trials on marginal land, and coupled agronomic research and breeding on land unsuited for food crop production, as well as improved definition of land unsuited to food crop production.

Summary

Bioenergy and biofuels are recognized globally as crucial elements of the future energy matrix, without which the reduction in greenhouse gases needed to reduce the acceleration of global warming and climate change will not be achievable. Yet, in 2012 the oil equivalent production of biofuels was less than 2% of the amount of oil produced from geological reserves. The bulk of these biofuels came from two countries; USA and Brazil and from two crops; maize and sugarcane, respectively. Perennial lignocellulosic feedstocks provide an important opportunity to meet further growth in demand in more sustainable ways, compared to maize and other food crops. Similarly, less than 10% of the world energy use for heat and power is bioenergy, most of which is wood-based, although other crop wastes and residues, particularly sugarcane bagasse, are also used. Future supplies will be increasingly from managed (and planted) woodlands and fast-growing energy trees to relieve pressure on existing natural forests. There are many energy crops that are currently grown in low amounts that will be an important part of the future feedstock mix. However, exploitation of these emerging feedstock crops will require investment in breeding and agronomy to further enhance yields and adapt varieties to a wider range of environments, including future climates. Many concerns surrounding biofuels, in particular, relate to feedstock production. However, with improved knowledge of the different crops and where these crops should be grown and with improved varieties and management practices, these concerns can be addressed. By utilizing and developing the full range of feedstocks available, the challenge of increasing feedstock supply in sustainable ways can be met but only with secure, consistent and sensible policies that will achieve both environmental and economic sustainability.

Abbreviations and definition of key terms in the context of this Chapter and derived in part from Karp and Shield (2008): Bioenergy - any form of renewable energy from biological sources; Biomass – biological mass from which energy can be produced, including residues; Bioenergy crops - a generic term embracing crops grown for heat, power and transport fuels; Biofuel, Biopower, and Biomass Crops –subsets of Bioenergy crops grown for liquid transportation fuels, heat and power, and any renewable use, respectively; Bl - billion liters; C3 photosynthesis – basal form, in which the first product of CO_2 assimilation is a C3 compound; C4 photosynthesis – the first product of CO_2 assimilation in the light is a C4 compound, this avoids photorespiration; CAM photosynthesis – CO_2 is assimilated into C4 acids at night, which are decarboxylated to provide an internal supply of CO_2 to photosynthesis during the day; EJ - 10^{18} J; Feedstocks – specific sources of bioenergy; GHG - greenhouse gases; GJ – 10^9 J; Lignocellulose – a subset of plant biomass that comprises the structural components, primarily the cell wall polymers cellulose, hemicelluloses, lignin and pectins; Mt - million metric dry tons; SRC - short rotation coppicing, SRF - short rotation forestry; t – dry metric tons.



	Usage	Technical costs	Development time	Sustainability
Oils	Transport Fuels	L	L	L-M
Sugars and starches	Transport Fuels	L	L	L-H
Lignocellulosics	Heat & Power	L	H	M-H
	Transport Fuels	H	H	M-H
Wastes & Residues	Heat & Power	L	L	M-H
	Transport Fuels	H	L	M-H

Figure 10.1. Summary diagram of the major crop feedstocks, their uses, technical costs, development time and sustainability. H=high; L=low. Circles are indicative of relative importance of different feedstocks at the present time. For details see Table 10.1.

10.1 Introduction

Biofuel production in 2012 in oil equivalent was 52 Bl , or 2.2 EJ, compared to 3534 Bl, or 118 EJ of oil from geological reserves. The three largest producers of these biofuels were USA, Brazil and Germany at 45%, 23% and 5% of this total, respectively (BP 2013; EIA 2014). Despite the seemingly small amount, just under 2% of oil equivalent for the globe as a whole, biofuels represented almost 10% of the volume of gasoline used in vehicles in the USA and about 40% in Brazil, showing that large-scale displacement is possible within major markets (RFA 2013). While the bulk of production in the USA and Brazil is ethanol from maize and sugarcane respectively, most German production is of biodiesel from rapeseed. Globally, in 2012, ethanol represented 69% of the total and biodiesel 31% (BP 2013), with maize and sugarcane accounting for most ethanol and rapeseed/canola and soybean accounting for most biodiesel.

Biopower is predominantly from wood, which accounted for circa 36.2 EJ of the world energy needs in 2007; ~30EJ from traditional fuel, 3EJ from charcoal and only 1EJ from modern solids (pellets and chips). Proportions of usage and contribution to energy differ greatly between countries and continents (Asikainen et al. 2010). In Africa 90% of total roundwood production was used for biopower, whereas only 21% was used in Europe (Asikainen et al. 2010; see also Chapter 13, this volume). Net global bioenergy trade in wood grew six fold from 56.5 PJ (3.5 Mt) to 300 PJ (18 Mt) between 2000 and 2010 (IEA 2014) and global demand for wood has been increasing by 1.7% annually (Fenning and Gershenzon 2002). Wood pellets are the dominant commodity. Trade streams for wood waste, roundwood and wood chips are smaller and mostly limited to Europe. Europe remains the key region for international solid bioenergy trade, accounting for two thirds of global trade in 2014 (IEA 2014).

Table 10.1 gives the biomass, biofuel and bioenergy yields per hectare of the different feedstocks considered here in major regions of current and potential production. Much attention has been given to use of biodiverse systems for expansion of bioenergy production, with the concept that they could serve both biodiversity and production (Tilman et al. 2006). However, analysis of this land sharing concept finds that because of the large areas required by these less productive systems (Heaton et al. 2008), for most areas of the globe, high productivity monocultures are ironically more effective for biodiversity by sparing land through high productivity (Anderson-Teixeira 2012). For example, mixed-grass prairie would require 6x the land area of an unfertilized Miscanthus system to deliver the same amount of bioenergy (Heaton et al. 2008; Table 10.1). A particular focus of this article is therefore high yielding feedstocks and opportunities to increase production, as well as sustainability.

In this Chapter we examine existing feedstocks for bioenergy including biofuels, and those that may be emerging. The first sections deal with the two current major biofuel feedstocks - maize and sugarcane, followed by emerging perennial grass feedstocks, oil crops, woody feedstocks and algae.

Table 10.1. Overview of amounts of biofuel and bioenergy that could be produced per unit land area, based on current yields of each crop in specific regions.

Feedstock **Common and latin binomial name (region of measurement)**	**Total Dry Biomass Yield (t/ha)**	**Grain/ seed/sugar yield (t/ha)**	**Easily accessed biofuel (GJ/ha)**	**Cellulosic (GJ/ha)**	**Combustion of residue (GJ/ha)**	**Sum of previous three columns**	**Combustion of Total Biomass (GJ/ha)**
Annuals							
Maize *Zea mays* (USA)	18.4	9.2	72.8a	40.4	27.6	140.8	331.2
Wheat *Triticum aestivum* (EU28)	8.8	5.3	34.9a	19.4	13.2	67.6	159.0
Rapeseed *Brassica napus* (EU28)	5.6	2.8	33.2b	12.3	8.4	53.9	112.9
Soybean *Glycine max* (USA)	4.7	2.8	21.2b	20.5	5.6	47.3	96.1
Herbaceous perennials							
Sugarcane *Saccharum officinarum* (Brazil)	38.0	12.0	156.8a	167.0	113.9	437.7	684.0
Napier Grass *Pennisetum purpureum* (El Salvador)	84.0	0.0	0.0	738.2	503.5	1241.7	1512.0
Miscanthus *Miscanthus x giganteus* (Illinois)	22.0	0.0	0.0	193.3	131.9	325.2	396.0
Switchgrass *Panicum virgatum* (Illinois)	10.0	0.0	0.0	87.9	59.9	147.8	180.0
Reed Canary Grass *Phalaris arundinaceae* (Denmark)	12.0	0.0	0.0	105.4	71.9	177.3	216.0
Mixed Grass Prairie (Minnesota)	3.7	0.0	0.0	32.5	22.2	54.7	66.6
Agave *Agave americana* (Arizona)	8.0	0.0	33.0a	35.2	24.0	92.1	144.0
Woody perennials							
Oil Palm *Elaeis guineensis* (Indonesia)	34.0	17.0	128.8b	149.4	50.9	329.2	685.4
SRC Willow *Salix* “hybrids” (Sweden)	10.0	0.0	0.0	43.9	30.0	73.9	180.0
SRC Poplar *Populus* “hybrids” (Italy)	14.0	0.0	0.0	61.5	42.0	103.5	252.0
SRF Eucalyptus *Eucalyptus* “hybrids” (Brazil)	18.2	0.0	0.0	80.0	54.5	134.5	327.6

Yields of sugarcane, maize, wheat, rapeseed, soybean and oil palm, are averages for the stated country in 2011 (FAOStat, 2013). Miscanthus and switchgrass yields are averages for 7 unfertilized sites in Illinois over 8-10 years (Arundale et al. 2013a). Mixed grass prairie yields are from Tilman et al. (2006). Napier grass, Reed Carnary Grass and Agave yields are from Beale & Long (1985); Kandel et al. (2013); and Davis et al. (2014), respectively. Yields of SRC and SRF are averages for specific countries of existing commercial trials (from de Wit et al. 2013). It should be noted that yield ranges for all crops are very large and are variety, site and management dependent. It is assumed that 536, 380 and 342 liters of ethanol can be produced from 1 tonne of sucrose, lignocellulose and maize grain, respectively, and that dry sugarcane stem and agave shoot is 33% sugars. The oil contents of rapeseed, soybean and oil palm are assumed to be 36%, 23% and 30%, and that 80% of the lipid can be recovered as biodiesel. Cellulosic fuel is assumed to be manufactured from the cellulosic residue in the case of seed, grain and sugar crops, and from the total biomass in the case of trees and perennial grasses, other than sugarcane. It is then assumed that the residue (lignin) at 30% of the lignocellulose can be combusted to provide heat energy. The final column gives the bioenergy combustion value of the total annual biomass yield for each crop.

10.2 Maize and Other Grains

Currently, maize in the USA provides more than half of all fuel ethanol produced in the world (IEA 2013). In the last few decades maize in the USA has seen a larger increase in yield per hectare than any other major crop (Long and Ort, 2010; FAOSTAT 2013; USDA-NASS 2013; Figure 10.2). Production in 2013 is estimated at 335 Mt compared to 70 Mt in 1953, and yet the total area planted to the crop has changed little (USDA-NASS 2013; Figure 10.2). Although earlier increases in yield corresponded to increased fertilizer rates, particularly nitrogen (N), the average rate of N application to maize in the USA has remained constant at about 140 kg ha^{-1} since 1979 (USDA-ERS 2013), yet average yields per hectare have increased more than 80% over this period. In effect the amount of N used to produce a metric ton of maize grain has declined from 0.75 kg t^{-1} to 0.42 kg t^{-1}. Further, over most of the cornbelt, soybean is rotated with maize, to which no N is typically added, the soybean crop being supported by residual N from the preceding maize crop and its symbiotic relationship with N fixing rhizobia. In effect, this average 140 kg ha^{-1} of N application supports two years of crop production. The continued increase in yields approaching 30% per decade inevitably drove down prices, in real terms; in turn driving down the area planted to maize in the early 1980s (Figure 10.2). Beginning at this time, ethanol production as a petroleum oxygenate was incentivized with a blenders' credit in the USA. This also served as a means to give price support to maize by removing some of the surplus production relative to demand (Ferris 2013). Over the past two decades ethanol production has consumed a significant portion, but not all, of the continued increase in yield achieved by US farmers (Figures 10.2 and 10.3).

Today the world produces more maize than any other grain or seed. Of the global 880 Mt of production, the USA accounts for just over 40%, but grown on just 20% of the land planted to this crop globally (FAOSTAT 2013; USDA-NASS 2013). US production of maize grain from 2006-10 averaged 311 Mt yr^{-1}, of which 94 Mt yr^{-1} was used for ethanol production and 54 Mtyr^{-1} exported (Figure 10.3). This compares to 207 Mt yr^{-1}, 11 Mt yr^{-1} and 45 Mt yr^{-1}, respectively in the first half of the 1990s (calculated from: USDA-NASS 2013; USDA-ERS 2013). In addition, 26 Mt yr^{-1} of dried distillers grains (DDGS) were produced on average between 2006 and 2010, compared to just 2 Mt yr^{-1} between 1990 and 1994 (USDA-ERS 2013). So while ethanol production now accounts for a large proportion of the total US maize crop, it has not prevented a 20% increase in exports and a 24% increase in use by all other domestic uses. Indeed the increase in exports of 8 Mt yr^{-1} over this period accounts for most of the 10 Mt yr^{-1} net increase of total US exports of primary foodstuffs, making the USA by far the largest net exporter of all primary foodstuffs at almost 110 Mt yr^{-1} (FAOSTAT 2013). Over the same period the EU28's deficit has almost doubled resulting in it becoming a net importer of over 20 Mt yr^{-1} (FAOSTAT 2013). These facts have to bring into question the media blame that has been placed on US maize ethanol production as the cause of increased global costs of primary foodstuffs (RFA 2013). Indeed, maize ethanol may have acted as a buffer to grain prices during the severe drought across the corn-belt in 2012 which lowered production by 40 Mt compared to 2011 (USDA-NASS 2013). Substantially less maize was used for domestic ethanol production following the drought with many

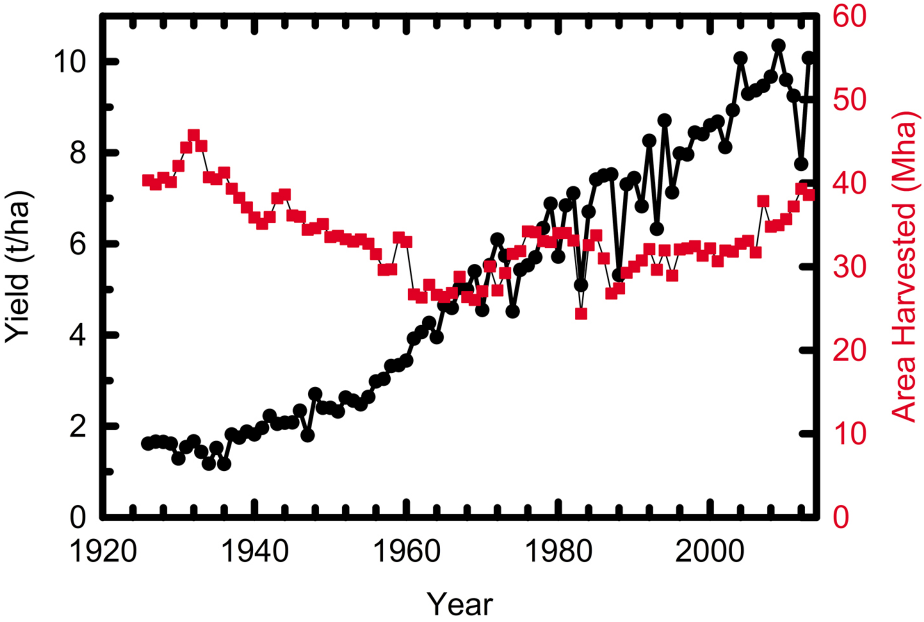


Figure 10.2. Historical progression of the yield of maize grain per unit land area in the USA and the area of the country committed to the crop. Data source: USDA-NASS (2013).

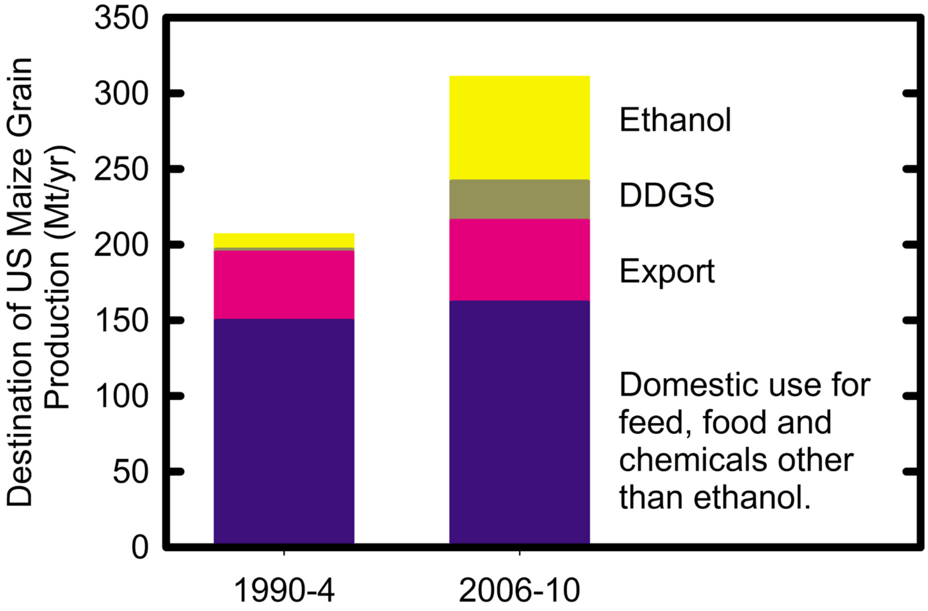


Figure 10.3. Destination of US maize grain production averaged over two 5-year periods. DDGS represents part of the grain diverted to ethanol production, but is shown to illustrate the amount returned to the feed market. Calculated from USDA-ERS (2013).

ethanol plants mothballed (EIA 2014). Indeed economic analysis has suggested that for producer countries with significant animal feeding or biofuels industries, options to protect the consumption of the most vulnerable globally from droughts and other harvest shocks are more cost-effective than emergency reserves. That is, maize ethanol can be seen as providing a reserve (Wright 2011). In the event of a shortfall, it would require some relaxation of national blending requirements for this buffer to be effective. This suggests that maize ethanol might be viewed as a partial reserve of grain, which during periods of shortage can be diverted away from ethanol production while use for ethanol production during periods of surplus would provide a floor on price that would continue to incentivize the agricultural production system to continue to grow and improve the crop (Wright 2011).

What underlies the continued increase in maize yields per unit land area, and can this be expected to continue? Maize seed supplied to farmers is almost all hybrid seed. This differs from wheat, rice and soybean, the crops which rank 2nd through 4th in the world after maize (FAOSTAT 2013). Unlike these other crops, seed of maize cannot be saved by the farmer and used the next year, as the progeny will vary widely, with the yield advantage of the original seed largely lost. Therefore new seed must be purchased annually, giving the seed supplier/developer greatly increased incentive to focus on the crop. Maize, unlike the other major seed and grain crops uses C4 photosynthesis giving it a higher theoretical maximum efficiency of conversion of sunlight into biomass, as well as a higher efficiency of water and nitrogen use (Zhu et al. 2010; Long and Spence 2013). Maize breeders have also effectively altered plant architecture to maintain per plant productivity while increasing planting densities (Duvick 2005; Lobell et al. 2014). In the US, maize is now available with more biotechnology (GM) traits than any other crop. The proportion of the US crop with at least one *Bacillus thuringiensis* gene expressing an insecticidal protein (Bt) has risen from 2% in 1996 to 76% in 2013 while the amount carrying at least one transgenic herbicide tolerance (HT) gene has risen from 2% to 85% over the same period (USDA-ERS, 2013). This has greatly decreased losses to the European corn borer (Hutchison et al. 2010), maize rootworms, and also to weed competition compared to non-transgenic crops (Nolan and Santos 2012). The Bt insect resistance traits decrease damage to leaves, stems and roots, making the crop more drought tolerant. This is evident late in the growing season as crop moisture levels are significantly higher (Traore et al. 2000). Conventional breeding will also have increased yield over this period. So how much, if any, of the increase is due to the introduction of GM traits? A recent analysis of 164,000 trials showed that GM caused a statistically significant increase in yield over this period accounting for 29% - 33% of the total increase over the past decade (Nolan and Santos 2012). The recent release of additional Bt and HT traits suggest an accelerating rate of addition of transgenes to farmers' options. The first physiological trait, Droughtgard™, was tested by 250 growers on the Western Plains in 2012 and was reported to result in a 0.3 tha^{-1} improvement over untransformed material (Monsanto 2013). This transgene codes for a bacterial cold tolerance protein that allows continued growth in plants under mild water stress. It provides one of many potential examples of how yield tolerance to stresses may be improved. The year-on-year increases in maize yields per hectare in the USA have depended on a series of technological innovations from the Haber-Bosch process for production of nitrogen fertilizers and large-scale production of uniform hybrid seed to molecular marker assisted breeding and production of GM lines, in concert with agronomic adaptation and improvement. The completion of the maize genome, its functional annotation, the rapid growth in capacity for deep sequencing of transcriptomes, and resequencing of multiple genotypes are all factors opening the way for further technical innovation both in conventional breeding and GM traits. Inevitably, resistance in pests and weeds to GM traits will emerge. Continued value in, and acceleration of, the contribution of GM will depend on the emergence of policies that recognize the safety of these products, and decrease the current prohibitive costs and administrative hurdles involved in taking new GM products to market.

The average annual increase in maize yield in the USA between 1983 and 2013 was 0.17 t ha^{-1}yr^{-1}, i.e. the average slope of the line over this period, as shown in Figure10.2. From the above, we may expect that further breeding with addition of improved traits and improved agronomy will continue to increase yields at this rate for some time into the future. If we assume that the area of the USA devoted to this crop stays constant at the 2013 level of 38.6 Mha (million hectares), then total production would rise from 355 Mt in 2013 to 457 Mt by 2030. This additional 102 Mt (ca. 29%) could support a doubling of the amount of maize used for ethanol and DDGS production, while still allowing further increases in exports and in other domestic uses. This would also mean that the US goal for 2030 of replacing 30% of the volume of transportation fuel that it used in 2007, with ethanol, could be achieved from maize grain alone without diminishing exports and supply to other domestic uses. While yield has been continually increased, water use efficiency has not. Assuming current patterns of rainfall into the future, water availability might be expected to cap further increases around the middle of this century (Ort and Long 2014). Further gains in ethanol production could be achieved by alteration of grain composition. High starch, low protein and low oil germplasm are available that could be used to develop cultivars that would yield more ethanol per metric ton of grain and also demand less nitrogen in growth (Moose et al. 2004). However, yield of DDGS and maize oil would be lower and the opportunity to sell grain into other markets may be affected. Maize offers two further renewable fuel opportunities. First, maize grain contains oil in the form of triacylglycerols (TAGs) that may be converted to biodiesel (EIA 2014). Industrial plants with wet grind facilities separate out the oil prior to digestion of the starch, while at those with dry grind facilities, the oil may be separated out by centrifugation of the thin stillage on completion of fermentation. As it is a by-product that requires little additional energy to extract, the resulting fuel qualifies as low carbon, which has incentivized retrofitting many ethanol plants for oil extraction (Cantrell and Winsness 2009; EIA 2014). Secondly, the stover, i.e. stripped cobs, stems and any remaining leaves from the maize crop may provide a ready feedstock for production of cellulosic ethanol or other fuels. The first commercial production of cellulosic ethanol from maize stover was expected to begin operation in Iowa in 2013 (Biofuels Digest 2013). By contrast to wheat and rice, the harvest index of maize has remained at about 50% since the 1950s (Lorenz et al. 2010). Therefore future increases in grain yield might also continue to be accompanied by similar increases in the availability of stover. Stover is however a valuable source of organic matter for maintaining soil structure and fertility. It was estimated that soil quality could be maintained if 50% of the stover were removed (Wilhelm et al. 2004). Since the effect on fertility will depend on the absolute amount of stover, the proportion that needs to remain could arguably become progressively less as yield rises. However, if we assume a fixed removal of 50%, then by 2030 this would amount to 228 Mt, and at an estimated 380 liters of ethanol that could be produced from the cellulose and hemicellulose in a dry metric ton of biomass, this would provide an additional 86.6 Bls of ethanol. There are two further advantages of maize in the context of cellulosic fuels. First, harvest equipment could be modified to collect stover or a portion of the stover at the time of grain harvest (Shinners et al. 2012), the single operation minimizing the additional energy required for collection. Secondly, the depth of knowledge of gene function is likely to facilitate cell wall modifications to improve saccharification faster than in any other crop. Indeed, non-GM and GM modifications have already been identified to support increased efficiency of enzymic saccharification (Park et al. 2012; Pauly et al. 2012; Torres et al. 2014).

Some 150 years of cultivation of the rich cornbelt soils is suggested to have resulted in the loss of about 50% of the carbon in the top 15 cm of soil (Nafziger and Dunker

2011). Various measures were introduced to arrest or slow this decline. These include no-till and minimal till cultivation, contour ploughing and removal of the most vulnerable lands from production as conservation reserve (USDA-NRCS 2013). Because soil C is distributed in a spatially highly heterogeneous manner and the C-content of most corn-belt soils is relatively high, detecting a statistically significant change due to management is challenging. Indeed failure to detect significant effects led to questioning of the value of no-till and minimal till cultivation for maintenance of soil C (Wander et al. 1998; Puget and Lal 2005). The development of eddy-covariance techniques, that combine 3-D air velocity with open-path infra-red gas analyzers, now allow monitoring of net carbon exchange between a crop field and the atmosphere for every second of every day. The ability to average over a large area circumvents the problems of small-scale heterogeneity in soil C content. Using this method and correcting for the carbon removed in the harvest, Bernacchi et al. (2005) showed that in side-by-side tilled and non-tilled fields of the same maize cultivar there was a net accumulation of 1.6 t C $ha^{-1}yr^{-1}$ under no-till while the tilled field showed a net loss of 0.2 t C $ha^{-1}yr^{-1}$ to the atmosphere. Assuming that the large productivity gains in maize also result in more root biomass, even with partial stover removal, carbon gain by the soil may be expected to increase substantially. Further, just as genetic traits have been exploited to develop stem biomass that is more easily digested to release sugars for fermentation, so it is feasible that the depth of knowledge of genetics in maize could allow the development of germplasm with less easily degraded biomass. By use of root specific promoters it is feasible that root biomass could be made less easily degraded to favor accumulation of C in the soil.

The long-term economic viability of using maize for ethanol is uncertain. Increasing global population and changes in diets are demanding more maize, mostly for animal feed. From these trends, Ray et al. (2013) predict that the world will require 1700 Mt yr^{-1} by 2050. Even if historical rates of maize yield improvement are maintained throughout the intervening 36 years, global supply will only rise to 1451 Mt yr^{-1} giving a major shortfall relative to demand. By contrast increased production of oil and natural gas in the USA could lead to a slower or zero rate of increase in the cost of liquid transportation fuels (McElroy and Lu 2013). This could make use of maize grain for ethanol progressively less profitable relative to sales into other markets. If however, the goal turns increasingly to decreasing the carbon footprint of transportation fuels, rather than fuel security, maize grain is less attractive than other biofuel feedstocks because of its much smaller carbon benefit relative to perennial feedstocks, including sugarcane. A recent and highly detailed well-to-wheels analysis of life cycle greenhouse gas (GHG) emissions concluded that relative to the use of petroleum, ethanol from maize grain, sugarcane, maize stover, switchgrass and Miscanthus would reduce emissions on average by 34%, 51%, 97%, 87% and 108%, respectively (Wang et al. 2012). Although maize gives the smallest advantage among these, this 2013 estimate is a significant improvement over a 2006 estimation that it was roughly equal to the use of petroleum (Farrell et al. 2006). Inevitably at the scale of maize ethanol production, learning by doing is progressively decreasing carbon losses from well-to-wheels. Further gains will come from increased productivity per unit land area, increases in nitrogen use efficiency through both precision agriculture and improved genetics, and utilization of the oil from the grain in addition to starch for fuel. Much larger gains will be achieved if stover, or a part of it, is used for the production of cellulosic fuels. Gains could also come from using bioenergy to provide heat and power to the processing plant, in place of fossil fuels.

Of course any source of starch or sugars can be used for fermentation to ethanol and other fuels, and alcoholic beverages have been made from almost every species of grain, fruit and root crop. Excluding sugarcane ethanol, maize accounts for more than 95% of fuel ethanol production today, most within the USA (EIA 2014). Wheat is being used increasingly for fuel ethanol in the EU28, with significant new capacity in the UK (Jessen 2013). This appears to have less long-term economic viability than maize, however. While large increases in maize yield per unit land area are being achieved globally, wheat yield improvement has stagnated with no increase in yield per hectare over the past decade (Long and Ort 2010, Ray et al. 2012). Even if it is assumed that the historical rates of improvement seen in the Green Revolution years are regained, wheat global supply will fall more than 20% short of forecast global demand by 2050. Indeed, even today, the difficulty of meeting food and feed demand for wheat has caused a doubling of price over the past 7 years and accounts for the growing price separation between maize and wheat, with the latter approaching double the cost while yielding half the ethanol per unit land area (Balat and Balat, 2009; USDA-FAS 2013). As with all crops, account must be taken of co-products, in particular the protein rich feeds provided by the DDGS. This is particularly important as yields of DDGS per hectare from these sources approach yields obtained from soybean as, currently, the most common protein source used in animal feeds. Various root crops have also been explored as sources of starch for ethanol production, in particular cassava. Substantial cassava to ethanol programs have been established, for example in China and Thailand (Dai et al. 2006; Nguyen et al. 2007). Given that cassava is also among the most important sources of calories for some of the world's poorest communities great care would need to be taken with this crop to avoid affecting food supply to some of the most vulnerable, while recognizing that this would be a highly location specific issue (Naylor et al. 2007).

10.3 Sugarcane

Sugarcane is a major crop grown in the tropical and subtropical regions of the world, producing 550Mt dry biomass in 2012,, assuming 70% moisture in reported yields (FAOSTAT 2013; De Souza et al. 2014). Sugarcane is produced for its sucrose, which may be used as a sweetener, a feedstock for various chemical syntheses or for fermentation in the production of alcoholic beverages or fuel bioethanol (Amorim et al. 2011). Bagasse, the lignocellulosic residue produced after sucrose extraction, is combusted to provide electricity that is used to power sugarcane mills and bioethanol production, with the excess being sold on the electricity grid. Brazil accounted for 39% of the world's harvest of sugarcane in 2012. Brazil's sugarcane production has increased more than 10-fold in 50 years and doubled in the last 10 years (FAOSTAT 2013 Figure 10.4). Although most yield increase is accounted for by expansion of the planted area, yield per ha has also doubled over the last 50 years (Figure 10.4). Over a similar period unit production costs of sugarcane ethanol, in real terms, have declined 67%, most driven by technological improvements in the overall process (Chen et al. 2014).

Sugarcane has a well-established agricultural production system and processing infrastructure to make it among the most advanced feedstocks for bioenergy. More importantly, it has a positive net energy balance across a range of production systems and environments and releases considerably less CO_2 than petroleum when used to produce transportation fuel (Wang et al. 2012). With the emergence of second generation (2G) bioenergy platforms to convert lignocellulose to liquid fuels, the energy output from, and GHG benefit of, sugarcane could increase significantly (De Souza et al. 2013a).

Brazil is considered to have developed the world's first sustainable biofuels economy and in many respects is the biofuels industry leader (De Souza et al. 2014). This reputation is based largely on its sugarcane industry. The main reason for Brazil's success in biofuels has been synergy between the global sugar market, electricity production, governmental support, and geography (Nass et al. 2007). Brazil's resources are sufficiently abundant to support massive agriculture, including both a large biofuel industry and traditional agricultural production of food, fiber and feed while still fostering conservation of biodiversity. Biodiversity can be preserved while maintaining sugarcane production in regions where it is most abundant when appropriate strategies are employed (Buckeridge et al. 2012).

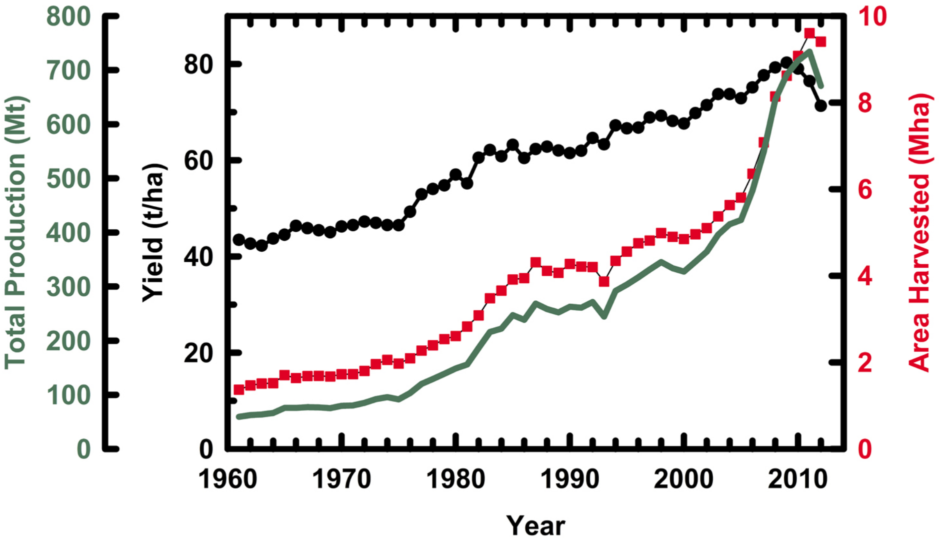


Figure 10.4. Historical progression of the sugarcane yield per hectare, total area harvested and total production in Brazil. Data source: FAOSTAT (2013).

The ability of Brazil's sugarcane industry to support demands for both sweetener and bioenergy gives flexibility in the market place and has reached the stage where, depending on the price of petroleum, approximately half of Brazil's sugarcane crop goes into sugar and half into bioethanol for bioenergy (Amorin et al. 2011; De Souza et al. 2014). When the price of petroleum is high, more of the sugarcane crop is processed to bioethanol as a substitute for petroleum, and vice-versa. This market situation can result in less sugarcane being processed to sugar with the consequence that the world price of sugar rises; the converse is also true. Thus the percentage of the sugarcane crop going to sugar or bioethanol is in constant flux. While some of Brazil's bioethanol is exported, approximately 85% remains in Brazil, 90% of which is used for transportation fuel and the remaining 10% for industrial uses (Nass et al. 2007).

Today, there is an increasing awareness that sugarcane can be used for many applications, not only as a biomass feedstock for energy production but also for bioprocessing in a biorefinery to a wide range of chemicals including a variety of polymers. Life cycle analyses indicate that sugarcane would be highly competitive with other crops as a preferred feedstock for a biomass-based industry (Tilman et al. 2006; Renouf et al. 2008).

Taking account the need to protect the Amazon, conservation of biodiversity and avoid conflict with food production, the Brazilian Government has mapped 63.5 Mha suitable for sugarcane production. This would not require the clearance of natural ecosystems, but would require significant expansion onto pasturelands, largely Cerrado, with low stocking density. This would need to be compensated by improving the remaining pasture to support an increase in the number of heads per hectare. This land area could allow the production of 800 Bl of ethanol by 2030, which in energy terms would be equivalent to 15% of total global liquid fuel use in 2009, while the bagasse could provide 30 GW of electricity (Somerville et al. 2010). This expansion of sugarcane production is likely to be incentivized by the long-term rise in petroleum prices and by climate change driving a demand for biofuels with low net GHG emissions. However, it will require development of new varieties capable of production under marginal, warmer and drier environments, as well as substantially different soils. Maintaining yield in these new areas will be important to minimize land demand. Brazil has been a leader in the development of genomic tools for both the development of molecular tools to support breeding of improved cultivars, as well as genetic engineering of sugarcane, to aid varietal improvement for this expansion (Hotta et al. 2010). A recent analysis adds further value to this expansion. Whereas the conventional practice of residue burning would have depleted carbon in these Cerrado soils, the modern practices in Brazil using mechanical harvesting are predicted to result in soil carbon at or above those in native Cerrado (Brandani et al. 2014). Another important limiting factor to sugarcane expansion could be global climate change. Although sugarcane is expected to respond positively to the increase in atmospheric CO_2 (De Souza et al. 2008), the uncertainty of precipitation forecasts made from climatic models could inhibit some expansion into new areas.

Approximately one-third of the total energy in the above-ground biomass of today's sugarcane cultivars is captured in the sucrose fraction present in the stalk while another third is present in the bagasse and the last third is in field trash which with mechanical harvesting of unburnt cane is left in the field (Table 10.1; Buckeridge et al. 2012; Leal et al. 2013). While this trash can form a mulch and recycle nutrients - it may also inhibit early season growth in the cooler part of the growing region and can harbor diseases. Much recent research has investigated how much trash should be removed, and by what means. Leaving stem tops on the field, returns most of the nutrients to the soil, while removing lower leaves as trash provides a large harvest of additional biomass (Cantarella et al. 2013; Cardoso et al. 2013; Fortes et al. 2013; Franco et al. 2013). The calculated average energy content of the total above-ground biomass of current Brazil sugarcane is 7,400 MJ t^{-1} of cane, Therefore, an average crop of around 38 t ha^{-1} yr^{-1} could deliver >600 GJ ha^{-1} yr^{-1} (Table 10.1; Leal et al. 2013).

If increasing energy output of sugarcane is the primary goal, one needs to increase the crop's lignocellulosic fraction and more fully utilize its higher energy density compared to its sugar fraction. Using conventional breeding to increase the energy content of new sugarcane varieties has been projected to potentially increase Brazil's sugarcane bioenergy yield to 1228 GJ ha^{-1} yr^{-1} over the next 20 years (Landell et al. 2010; Table 10.2). Current advances in bolting on 2nd generation technology to Brazil's existing bioethanol plants may enable this goal even sooner. Realizing this potential will also require more investment in understanding interactive effects of genotype and environment on production and quality (Sabatier et al. 2014).

Table 10.2. Projected yield and sustainability components for energycane improvement. From Landell et al. (2010).

Energycane component	Year		
	2010	2020	2030
Culm (fw t ha^{-1})	81	111	130
Trash (dw t ha^{-1})	14	19	24
Sugar (%)	15	13	12
Fiber (%)	12	18	23
Total Energy (GJ ha^{-1})	628	940	1228
Output/input energy	8	12	14
Environmental impact	High	Med.	Low

Is there opportunity to replicate Brazil's production of sugarcane elsewhere? While the area of sugarcane and its productivity have risen sharply in Brazil, this has not been seen elsewhere. Most notably the Caribbean produced more sugarcane than Brazil in 1971; 82 Mt on 1.8 Mha, compared to 24 Mt on 0.7 Mha today. Most of the land abandoned from sugarcane has dropped out of agricultural use (FAOSTAT 2013).

Bringing this land back into production could allow significant bioethanol without any impact on food production. Many other areas of the globe would be suited to replicate Brazil's success in developing an environmentally and economically sustainable sugarcane bioethanol industry. The key will be identifying abandoned or under-utilized land resources where this model could be replicated without damaging local food supply or other ecosystem services.

10.4 Perennial Grasses

Perennial grasses, including sugarcane, offer many advantages over the use of annual food crops for bioenergy, including liquid fuels. Their perennial nature avoids the need for annual cultivation and their rhizome and root systems bind the soil and add carbon to the soil, as shown by the fact that soils under perennial grasslands contain more carbon than those under forests (Guo and Gifford 2002). Perenniality also allows them to cover the ground for a longer period than annual crops, allowing greater capture of the available solar radiation. Many perennial grasses use C4 photosynthesis, which in a given environment provides a higher potential efficiency of light, water and nitrogen in carbon capture (Long and Spence 2013). Perennial C4 grasses include the most productive plant species yet known - *Echinochloa polystachya*, which on the Amazon floodplain was shown to yield 100 t $ha^{-1}yr^{-1}$ (Piedade et al. 1991). Within the wet tropics and subtropics, sugarcane is already a major bioenergy feedstock and Napier grass (*Pennisetum purpureum*) is a highly productive grass used for forage, currently being actively evaluated for bioenergy (e.g. Rengsiriku et al. 2011). Forage stands in El Salvador have been shown to yield 84 t $ha^{-1}yr^{-1}$ (Beadle and Long 1985). However, because these crops grow year-round, they must be harvested green, and so as in annual crops, the harvest will include their nutrients, in contrast to autumn and winter harvested crops of perennial temperate grasses such as switchgrass and Miscanthus. These tropical crops will therefore require large fertilizer inputs to maintain their productivity. Their large and perennial root systems though make them considerably more efficient in nutrient capture than annual crops, and by binding the soil they are suitable for areas that might be eroded in annual cultivation. In regions that may be too cold for effective production of any current C4 grass cultivar, the C3 perennial reed canary grass can produce quite high yields for use in various bioenergy projects (Table 10.1; Kandel et al. 2013).

In areas of the globe where production is seasonally limited by cold or drought, perennial grasses that dieback during this period provide a second advantage. As winter or the dry-season approach, these plants mobilize their nutrients from the senescing annual leaves and stems and transfer them to their perennial root and rhizome system (Heaton et al. 2009; De Souza et al. 2013b). If the dry dead shoots are harvested as a bioenergy feedstock the bulk of the nutrient reserves of the plant remain in the perennial underground organs and soil, making these potential feedstocks particularly sustainable. Plants using this strategy in temperate and cold climates that are being considered as bioenergy sources or utilized commercially on a small scale include: Miscanthus (*Miscanthus x giganteus*), Switchgrass (*Panicum virgatum*), Cord-grasses (*Spartina pectinata* and *S. cynosuroides*), Giant Reed (*Arundo donax*) and Reed Canary Grass (*Phalaris arundinacea*). The first three of these are C4, and include some of the most cold-tolerant C4 plants known and the second two are C3 (Long and Spence, 2013). To date, there is very limited commercial experience with these crops, however experimental trials and limited commercial production suggest considerable promise.

Of these, there has probably been more experience with switchgrass than any other, and to the extent that there are well established breeding programs. These have resulted in increased yield potential and regionally adapted cultivars (Casler et al. 2004; Parrish and Fike, 2005; Schmer et al. 2008). *Miscanthus x giganteus* is a sterile hybrid, and most trials and commercial deployment appear to be with a single clone, termed the “Illinois” clone in the USA (USDA-NRCS 2011). Despite this name, the clone probably originated from a single plant collected in Honshu, Japan and transferred initially to Denmark, from where it was distributed to various botanical gardens in Europe and the USA (Hodkinson and Renvoize 2001). Until recently, most experience of this clone was within the EU, where it proved more productive than most potential bioenergy crops from southern England and Denmark southward (Jones and Walsh 2001). Early trials in SE England showed a peak biomass of 30 t ha^{-1} and a harvestable biomass of 20 t ha^{-1}, with a substantial addition of root and rhizome mass below ground (Beale and Long 1995). Grown over fifteen years in Rothamsted in SE England and 20 years in Foulum in Denmark the crop showed no significant response to addition of N fertilizer, confirming the anticipated sustainability of its growth habit coupled with C4 photosynthesis (Christian et al. 2008; Larsen et al. 2014). The first replicated trials of this clone in the USA, conducted in Illinois, showed even higher yields averaging over 38 t $ha^{-1}yr^{-1}$ 3-5 years after planting and although the shoots contained 400 kg[N] ha^{-1} during active growth, 90% of this had been translocated or leached from the biomass at the time of harvest (Heaton et al. 2008; 2009; Dohleman et al. 2012). However, after 8-10 years yields declined to an apparent plateau level of 22 t $ha^{-1}yr^{-1}$ (Arundale et al. 2013a). This pattern of a peak around year 5 after planting followed by a ca. 40% decline to a plateau level has also been observed in long-term trials in the EU (Larsen et al. 2014). This decline is observed even when the effects of inter-annual variation in weather are removed. The basis of this decline, which parallels ratoon decline in its close relative sugarcane, is unclear but can only be partially overcome with fertilization (Arundale et al. 2013b). Occasional disking to break-up the rhizome mat and overcome soil compaction has been shown to reverse this decline (Jorgensen, pers. comm.). Even at the lower yield of 22 t $ha^{-1}yr^{-1}$ and assuming that 380 l of ethanol may be produced from 1 t of dry biomass, the Renewable Fuel Standard mandate of the USA of 60 Bl by 2022 could be met on 6.8 Mha. This represents, just under 0.7% of the total land surface area of the 48 contiguous States. Particularly important in these long-term studies was the finding that yields were similar on land classified as having poor capability for crop production, as well as on good sites (Arundale et al. 2013a,b). This is important evidence supporting the contention that such perennial energy crops could minimize or avoid competition for land with food production (Valentine et al. 2012). Miguez et al. (2009, 2012) developed a mechanistic model of Miscanthus production from the BioCro platform, which was successfully validated against extensive EU trials. BioCro predicted yields achieved in Illinois very effectively. It predicted that high rain-fed yields (>24 t ha^{-1}) could be achieved over large areas of the eastern USA that are currently not used for crop production (Figure 10.5).

In Illinois a similar pattern of long-term yield decline was observed in switchgrass, but this could be fully restored by adding N fertilizer. A meta-analysis (Heaton et al. 2004) and a modeling analysis (Miguez et al. 2012) using yields of regionally adapted switchgrasses suggest that *M. x giganteus* would substantially out-yield this crop at most locations (Figure 10.5). Throughout side-by-side trials at seven sites on contrasting soils across Illinois, *M. x giganteus* proved at least twice as productive as the locally adapted switchgrass cultivar “Cave-in-Rock” (Heaton et al. 2008; Arundale et al. 2013a). Maize achieves some of its highest yields globally in central Illinois, yet, in side-by-side trials, *M. x giganteus* produced 60% more biomass, without addition of N-fertilizer. This increase is due to the fact that *M. x giganteus* produces functional leaves earlier in the year and maintains them later into the year, allowing it to capture 60% more solar energy which it converts into biomass at the same efficiency rate as maize (Dohleman and Long 2009). This results from an unusual capacity among C4 species, not shared by maize or sugarcane, to form an efficient photosynthetic apparatus and maintain it at chilling temperatures, i.e. temperatures above freezing but below 15 °C (Long and Spence 2013; Spence et al. 2014). A disadvantage of *M. x giganteus* is that as a sterile hybrid there is no seed, and fields must be planted with

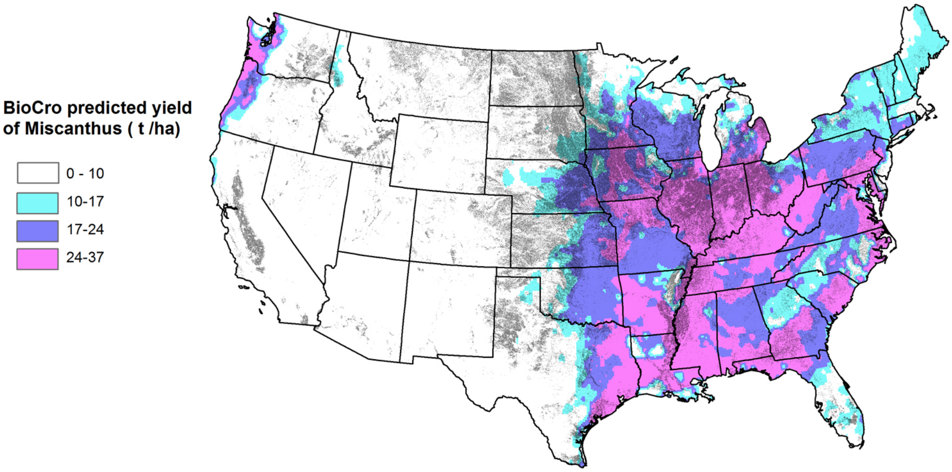


Figure 10.5. Annual average non-irrigated dry biomass yields predicted from gridded soil and daily weather data over from 1978-2010 for mature stands (fourth year) of *Miscanthus × giganteus* “Illinois” clone. Grey spots indicate fields currently used for production of other crops. Adapted from Miguez et al. (2012) and USDA-NASS (2013).

rhizomes or stem sections. However, this is not an insurmountable barrier given that the world's 26 Mha of sugarcane are planted in a similar way. Many years of experience in gardens and long-term trials in Europe, and now Illinois, have shown no evidence of this hybrid becoming invasive, which is not perhaps surprising for a sterile and self-incompatible plant with rhizomes that spread very little. In this respect its sterility is an advantage over fertile forms of Miscanthus and many other perennial grasses. However, one highly productive clone is clearly sub-optimal for all environments, and although no epidemics have been observed it is clearly a vulnerability that will increase as plantings increase. If it is to emerge as a major crop, creating more sterile clones from crosses of the parent species to increase the genetic and adaptive diversity of *M. x giganteus* will be critical. This will be aided by the rapid emergence of genomic tools for the parent species, and improved understanding of genomic variation across their native ranges in E. Asia (Gifford et al. 2014; Clark et al. 2014).

Cord grasses, *Spartina cynosuroides* and *S. pectinata* are C4 rhizomatous perennial grasses that are native to the N. American prairie, and like *M. x giganteus* can show a strong chilling tolerance of their photosynthetic apparatus (Long and Spence 2013). These species have proved productive in trials in the EU (Potter et al. 1995), the Dakotas and Illinois (Lee et al. 2011). Commercial seed of one cultivar is available and new productive cultivars are being identified (Voigt et al. 2013). One genotype originating from Illinois has proved particularly productive with yields similar to those of *M. x giganteus* (Voigt et al. 2013). These cord-grasses have two attributes that would allow them to use land unsuited to switchgrasses and *M. x giganteus.* They can withstand and grow under long periods of flooding or even permanent waterlogging. As a result of salt glands in their leaves they can also survive and grow well on saline soils. This would allow re-use of land that has been lost from agricultural use by salination (Boe et al. 2009).

Two C3 perennial grasses are also being trialled and used as bionenergy sources. Reed canary grass is productive in climates too cold for the effective cultivation of *M. x giganteus* and switchgrass (Lewandowski et al. 2003; Sahramaa et al. 2003; Casler et al. 2009; Table 10.1). It is not competitive with these species in warmer climates. However, a second C3 perennial grass, giant reed (*Arundo donax*) is native to the Mediterranean and given adequate water and nitrogen can be very productive in the warm temperate zone, apparently producing up to 74 t $ha^{-1}yr^{-1}$ (Borin et al. 2013). Experience with this species as a bioenergy crop is limited. It has proved invasive in California, where it was introduced, due to its fertile wind-blown seed (Goolsby and Moran 2009). Its high productivity may result in part from an unusually high stomatal conductance, which allows a high concentration of CO_2 within the leaf, which will decrease photorespiration, but at the expense of increased water loss in transpiration. Indeed, the crop has been shown to use 9 mm of water per day (Watts and Moore 2011). Over a 9-month growing season this would amount to some 2500 mm! This physiological attribute while supporting high productivity will also cause a poor water use efficiency and so water demand per unit biomass will be very much higher than in the other species.

10.5 Agave

Agave species are characterized in part by their use of Crassulacean Acid Metabolism (CAM). This photosynthetic pathway results in the highest known water use efficiency, i.e. amount of carbon gained per unit of water lost to the atmosphere. In hot semi-arid and arid environments such as the desert southwest of the USA, productivity is by definition limited by water. Production in these areas will therefore be largely determined by precipitation and water use efficiency, rather than radiation use efficiency. A key factor here is photosynthetic pathway. Biochemical differences between the C3, C4, and CAM photosynthetic pathways affect affinity for CO_2 and timing of CO_2 assimilation, resulting in intrinsically different water use efficiencies (WUE). To a first approximation C3 plants which include all trees, small grains, and oil crops are the least water use efficient. They have an intrinsic WUE, which is about 60% of that of C4 plants. Since, as in C4 plants, CAM plants assimilate CO_2 via PEP carboxylase localized in the mesophyll cytosol, a similar WUE might be expected (Borland et al. 2009). However, obligate CAM plants open their stomata almost exclusively at night, and as a result realize a higher WUE; why?

The air within a leaf is saturated with water vapor. The saturated water vapor pressure (e_s) is determined by temperature, rising exponentially with temperature. The vapor pressure deficit (VPD) is the difference between e_s and the water vapor pressure of the ambient air (e_a). While e_a will vary little between night and day, e_s will be much lower at night, because leaf temperature is lower. This diurnal variation is most pronounced in hot deserts where daytime maxima can be 10 - 30°C higher than nighttime minima. Nocturnal gas exchange, typical of CAM plants therefore occurs when VPD is much lower and allows a higher WUE than in C4 photosynthesis.

Using average monthly weather data for Oct. 2012-Oct. 2013 in the Sonoran Desert region (Maricopa, Arizona, USA) VPD during day and night was calculated (Davis et al. 2014). Averaged over these twelve months, daytime temperature was 27 °C and VPD 3.0 kPa, compared to nighttime values of 17°C and 1.3 kPa, with a total precipitation of 201mm. Assuming a loss of one third of precipitation to run-off, deep drainage and soil surface evaporation, the remaining precipitation could support the production of 2.0 t ha^{-1} for C3 crops and 3.6 t ha^{-1} for C4. If we assume the same WUE for CAM, as C4, but apply the night-time VPD, since stomatal opening here is nocturnal, then the same low level of precipitation would support 8.9 t ha^{-1}, almost 2.5x the productivity that C4 photosynthesis could support (Davis et al. 2014). Rigorous agronomic trials to establish that such yields can be obtained on arid lands in the absence of irrigation are lacking. However, a replicated trial of *Agave americana* was established in 2012 to test this prediction (Figure 10.6).

Agave species are also characterized by a thick wax covering the leaves and retractile roots. In a severe drought the roots retract leaving an air gap between the root and soil surface while the leaf stomata remain shut. This locks in the plant's moisture allowing

Figure 10.6. First field trial of *Agave americana* in Maricopa, Arizona, USA.

survival over months of drought. Although potential yields are likely less than those for sugarcane, Miscanthus and switchgrass, *Agave* spp. can be cultivated on land where these crops could not grow. With arid lands covering 30% of the Earth's land surface, there is much apparent potential.

There are two commercial industries that have historically exploited *Agave* spp.: the tequila and fiber production. The high concentration of soluble carbohydrates in the plant tissue is ideal for fermentation to alcohol. The rigid leaves that yield high-quality natural fibers are high in cellulose, and some species have much lower lignin content than many of the widely studied lignocellulosic feedstock crops. Recent changes in the fiber industry have resulted in widespread abandonment of *Agave* plantations that might be brought back into production and repurposed for biofuel. In sum, the physiology, tissue composition, and land availability is a unique combination of traits favorable for bioenergy production (Davis et al. 2011b).

Agave species are sugar-rich but are not typically food crops, although historically some foods and beverages have been sourced from these plants in Mexico. Between 55 and 90% of the mass of a mature agave stem can be soluble carbohydrates, primarily hexose with an energy yield, before conversion to fuel, of 79 to 220 GJ ha^{-1}. The total mass of sugar in commercially produced *Agave* spp. is between 5 and 14 t

ha^{-1}. Including the hexose that would result from cellulose degradation, a sugar yield of 11 to 23 t ha^{-1} is possible. This equates to ethanol yields ranging from 360 l t^{-1} (8 GJ t^{-1}) to 600 l t^{-1} (14 GJ t^{-1}). Estimates from life-cycle assessments indicate that the energy output in biofuel from *Agave* feedstock would be 4.6 to 6.1 times greater than the energy required to produce the fuel (Yan et al. 2011).

Although there are over 200 species of *Agave*, there have been no field trials conducted for most. Some of these species that have been untested in plantation production have traits that would potentially lead to improved yields across a broader range of environmental conditions than those achieved with the commercially grown varieties. For example, *A. americana* has not been grown commercially in the past, but has cold-tolerance lacking from the species used for tequila and fiber production. Cold-tolerance is a necessary trait in the southwestern U.S. where there are large areas of marginal semi-arid agricultural land that could serve the growing biofuel demand in the country without competition with food crops. As noted above, the first field trial of *A. americana* in the U.S. was initiated in 2012 (Figure 10.6). Other species are undergoing field trials in Mexico and Australia. Cold tolerance is less of an issue for these countries and a recent analysis suggests that using *A. fourcroydes* on 0.7% of Australia's land surface could provide 28.9 bl yr^{-1} or 0.62 EJ of ethanol on land where there would be no conflict with either food crop production or biodiversity (Owen and Griffiths 2013). Australia consumed 40 bl or 1.67 EJ of crude oil in 2013 (EIA 2014). Taking account of the lower energy content of a liter of ethanol, *Agave* from this analysis could replace over 37% of the country's current oil use.

10.6 Oil Crops

Oil crops serve as feedstocks for the production of biodiesel fuels. In terms of cost and energy efficiency, the conversion of oil crops to biodiesel is far more efficient than the conversion of starch or lignocellulosic crops to bioethanol. The triacylglycerol storage oils (TAGs) of these plants are mainly based on easily extractable C16 and C18 chain length hydrocarbons that are chemically similar to diesel hydrocarbons. Vegetable oils can be used in raw form as part of a diesel blend in some engines but this can reduce engine lifetime and almost all commercial biodiesel is produced today by transesterifying TAGs to their methyl ester derivatives, termed fatty acid methyl esters or FAME. Depending on the acyl chain length and degree of unsaturation, different crop oils have different freezing points, which allow them to be blended together to produce various types of biodiesel fuel. For example, higher melting point blends are more suitable for vehicle fuel use in winter conditions while more unsaturated lower melting point blends perform better under warmer conditions. These oils can also be catalytically hydrogenated to produce high performance blends that meet specifications for aviation fuel and advanced diesel engines. Several international airlines and the US Navy have made successful test flights with these fuels (Serrano-Ruiz 2012).

In 2013, biodiesel accounted for about 31% global biofuel when its estimated global production was 24.7 Mt or 1.0 EJ (Biofuels Digest 2013a; BP 2013). This is a 12-fold increase in the decade since 2003 (Licht 2012). Three oil crops supply the vast majority of biodiesel, soybean (7 Mt), oil palm (6.3 Mt) and rapeseed/canola (6.0 Mt). Most soybean biodiesel is both produced and consumed in the major centers of soybean cultivation: Brazil, USA and Argentina. Although oil yields per unit land area are low relative to other sources, it should be appreciated that in the case of soybean the oil is a by-product, the crop is grown largely as a protein source for animal feeds. In contrast, the European Union uses both domestically produced canola biodiesel and imported palm biodiesel, mainly from Indonesia. Malaysia is increasing biodiesel production but almost all of it will be used domestically to meet the mandatory 7% blend in all vehicle diesel fuel that is being rolled out by the government (Reuters 2013). Global biodiesel production is expected to expand in the short-to-medium term, mainly driven by demand-promoting policies, to reach 37Mt or 1.55 EJ by 2022 (OECD-FAO 2013). This amount would require 15% of world vegetable oil production to be diverted to biodiesel. Over the next decade, the European Union is expected to be by far the largest producer and user of biodiesel while other significant producers/users include Argentina, USA, Brazil and Indonesia.

Although current biodiesel crops are potentially more efficient in terms of conversion of the harvested product relative to bioethanol crops, biodiesel can only supply a small fraction of current global requirements for liquid fuels because of low absolute yields - with the exception of oil palm (Table 10.3). Even if all vegetable oil production was used for biodiesel, it would only provide 5% of current liquid fuel use while this would create a huge shortage of food calories because vegetable oils are currently the second most important source of edible calories for human populations across the world. A major problem with the current temperate oilseed crops, such as soybean and canola is their relatively low productivity in terms of oil yield. For example, Table 10.3 shows the large areas of land that would be required simply to grow sufficient oil crops in the USA to replace its 2008 usage of aviation fuel. This table also includes Camelina (*Camelina sativa*), a relative of Arabidopsis, and canola that has been proposed as a new biodiesel crop (Groeneveld and Klein 2014). However, its yields are very low and even a 2-3

Table 10.3. Yield of oil for different crops and the land area that would be needed to provide the 62 Billion liter of Jet fuel used in the USA in 2008.

Crop	Liters ha^{-1}	Area of land required (Mha)
Camelina	438	136
Soybean	857	73
Canola	1,358	45
Oil Palm	5,724	10.6
Hypothetical “Oil Cane”	13,740	4.4

Average US yields (USDA-NASS 2013), except oil palm (FAOSTAT 2013), are combined with the assumption that oil is 36% of Camelina and Canola seed, and 23% of Soybean seed, and that the energy content of sugarcane recovered as sucrose could in the future be recovered as oil in the hypothetical “Oil cane” fold increase in the future would only place it on par with canola. Further, even the untransformed crop fails the Australian Weed Risk Assessment (WRA) that is being widely used to evaluate invasive species risk for new crops globally (Davis et al. 2011a).

In contrast, oil palm is potentially a much better prospect with respect to yield of biodiesel per hectare of land. In 2012 the estimated global production of total palm oil was almost 65 Mt, of which 58 Mt was mesocarp oil and 6.8 Mt was kernel oil (USDA 2012). Typical average yields of palm oil on a global basis are in the region of 4 t ha^{-1}. This figure far outstrips the yield of the major temperate annual oilseed crops where yields range from 0.3 to 1.2 t ha^{-1}. This high yield means that the current global output of 65 Mt palm oil requires cultivation of only 15 Mha, which contrasts dramatically with the 194 Mha needed to produce just 87 Mt oil from the temperate annual oilseed crops (Table 10.3). Therefore, in terms of total oil yield (kernel + mesocarp oil) per hectare, oil palm is already more than 6.5-fold more efficient than the average combined yields of the temperate oilseed crops. Palm oil is limited to tropical wetland regions and its expansion onto natural tropical peatland forests in SE Asia, has rightly attracted much criticism (Danielsen et al. 2009). However, this has distracted attention from the possibility of expanding production elsewhere onto abandoned and degraded lands or to displace plantations of other trees that are no longer economically viable. For example, there is increasing interest and opportunity for the establishment of new oil palm plantations in non-forested areas in West/Central Africa and Central/South America (Murphy 2014).

A second tree or bush, Jatropha or Physic nut (*Jatropha curcas*) has been promoted as a productive tropical oil seed that can be grown on marginal land (Openshaw 2000). However, there is little peer reviewed literature to support these claims. While 10 t ha^{-1} has been reported on good soils, more typical yields are around 2 t ha^{-1}, and even with its high oil content, this would still be a very small amount of oil per hectare. There are further practical problems. Fruits on the plant mature at very different times and the mixture of unripe, ripe, and overripe fruits borne at the same time precludes mechanized harvesting. The oil of most cultivars is highly carcinogenic, raising serious handling issues. The crop also has a harvest index of just 10% and oil production decreases on acid soils, eliminating the crop from much marginal land (Kant and Wu 2011). However, it should not be overlooked that established crops may have had many parallel problems in their early domestication. With modern breeding techniques it should not be ruled out that these problems could be addressed (SGBIOFUELS 2013).

All vegetative tissues of plants are continually producing and metabolizing TAGs. This has encouraged much bioengineering effort to up-regulate biosynthesis and down-regulate catabolism to force vegetative tissue to accumulate TAGs as an oil source. In several recent studies a combination of the ectopic overexpression of oil-regulating genes such as WRI1 and DGAT1 with the suppression of TAG breakdown by lipases, has enabled leaf tissues to accumulate TAGs (Fan et al. 2013; Kelly et al. 2013). If this TAG is enclosed in a proteinaceous coat of modified oleosins, the oil can be accumulated in a stable manner without potentially poisoning key metabolic processes such as photosynthesis (Winichayakul et al. 2013). Already, Arabidopisis leaves have been engineered to accumulate as much as 8% of dry weight as oil while roots can accumulate up to 17% oil. These breakthroughs could open the way to engineering highly productive plants, such as sugarcane, to form and accumulate TAG in its mature stems. This might be achieved by coupling the changes found effective in Arabidopsis to late stem promoters. If the energy currently accumulated in sugar, could be accumulated as TAG, then based on current yields, over 13,000 liters of oil could be obtained per hectare (Table 10.3).

10.7 Forests and Short Rotation Coppice (SRC)

While it is anticipated in earlier sections of this paper that a range of herbaceous perennials could become viable sources of biomass on land unsuited to food crops, this is an established fact for the many pulp and round wood supply operations that meet ISO 14001 sustainability standards (ISO 2014). Wood is the fifth most important product in world trade. The market in wood based products increased from $60 billion to $257 billion in the 20 years up to 2008 and is estimated to be $450 billion by 2020 (Gardiner and Moore 2013). In 2008, global wood usage amounted to around 4.6 billion cubic meters. The dominant traditional use is solid/sawn timber (for house building and furniture) and fibers (for pulp, paper products and boards). However, wood also represents a key sink for atmospheric CO_2, and is considered the most important natural, renewable source of energy, with around half of wood consumed today used for wood fuel (FAO 2010).

In 2006 global production of wood pellets was between 6 and 7 Mt worldwide (not including Asia, Latin America and Australia). In 2010 it reached 14.3 Mt or 0.26 EJ (including these countries) while consumption, predominantly for biopower, was close to 13.5 Mt, representing an increase of more than 110% in 4 years (IEA 2012b). Production capacity from pellet plants has also increased worldwide, reaching over 28 Mt yr^{-1} by 2010 (Goh et al. 2013). The European Union (EU) is the main market for wood pellets, but the gap between European production and consumption has grown to become 8 fold (IEA 2012b).

The increased use of industrial pellets has been mostly associated with co-firing and driven by policy frameworks supporting green electricity, whilst market expansion in heat has been incentivized via support for installations, as well as feed-in tariffs. It has stimulated large investments in new pellet plants and an increase in exports of pellets, particularly from Canada but also the US and the Russian Federation. In countries with well-developed forest industries, much of the wood-based energy generation takes place within sawmill and pulp sectors, often using waste-industrial by-products for fuel. Whilst pulp and paper markets have declined, global energy prices have risen, offering new opportunities for diversification as well as for reducing production costs.

The main raw material for pellets is sawdust but availability of traditional sawmill residues has decreased and difficulties in sourcing feedstock at competitive prices has resulted in a lower utilization by many pellet mills. Large - scale pellet consumers (such as European or North American power plants) are increasingly looking for longer term supply agreements with well - defined volumes and prices that mirror their domestic feed-in tariffs. This conflicts with the volatile supply situation of the residue stream of the saw milling industry. Larger pellet manufacturers, and some energy producers, are thus moving up their supply chains to secure a more diversified and longer term feedstock base. Pellet producers have begun to source alternative woody feedstock, including wood chips from saw mills, round wood, residues, bark, used wood and wood from managed plantations (IEA 2012a, IEA 2012b).

In comparison with pellets, currently less than 10% of annual trade in woodchip is bioenergy-related. In the EU usage is exclusively driven by the industrial sector where chips are combusted in dedicated co- and mono-firing installations. Supplies are as chips, crushed (waste) wood, or roundwood which is chipped at the plant. International trade in woodchips for energy is not predicted to increase substantially. The key constraint is economic viability influenced by production and transport costs and also by feedstock prices (IEA 2012a). Use of roundwood, forest residues and salvage wood is likely to increase but can only supply a portion of requirements. There is a paucity of knowledge on risks associated with biomass extraction in this way but residue removal will need to be managed if negative impacts on soil productivity and nutrient balances are to be avoided (Davis et al. 2009; Lamers et al*.* 2013).

The complex chemical makeup of wood (cellulose, hemicelluloses, lignins, pectins and extractives) makes it a good potential raw material to replace petrochemical-based fuels and chemicals. The massive all-year-round supply needed for new installations of gasification and synthesis plants (Fischer-Tropsch), lignocellulosic plants and biorefineries represents a logistical challenge but potentially huge market (Heinimo and Junginger 2009). In the US, woody feedstocks currently account for approximately 30% of lignocellulosic biomass (Limayem and Ricke 2012).

Where is wood currently sourced to meet these markets and how will future demands be met? Demand for wood is currently met from around 30% of the world's natural forest area, whilst another 50% of natural forests are considered nominally protected or too remote to harvest (Fenning and Gershenzon 2002; Gardiner and Moore 2013). The maximum sustainable rate of timber extraction from natural forests is only ~2m^3 $ha^{-1}yr^{-1}$ (Fenning and Gershenzon 2002). Dependency on natural forests will decline because of the increasing recognition of the need to protect them for their ecosystem rather than provisioning services and because only planted forests will be able to supply enough wood sustainably. Many tree species are grown in managed plantations for bioenergy. Depending upon geographic location, primary softwoods include pines, firs and spruce whilst the principle hardwoods are eucalypts, poplars and willows. Bioenergy trees are usually grown as short rotation forestry (SRF) in 7-15 year rotations, or as short rotation coppice (SRC) in 2-4 year rotations that are more akin to arable production (Figure 10.7). At 10 Mha globally, SRF Eucalyptus is the most widely grown, achieving dry wood yields of 30 t $ha^{-1}yr^{-1}$ over a 7-year rotation. Poplar and willow are grown in more temperate

Figure 10.7. SRC willow: harvested rows can be seen alongside the remaining uncut rows of circa 7m high willow during winter harvest in a three-year coppicing cycle.

climates as SRC (both) and SRF (poplar), yielding on average 10 t $ha^{-1}yr^{-1}$ but cover much smaller areas in comparison, although as outlined below, a doubling of these yields is likely possible, with investment, over the next two decades (Karp and Shield 2008).

An advantage of bioenergy trees is that their efficient growth strategies, in which nutrients are largely recycled, and low-input cultivation, mean that plantations can be located on lower grade and more marginal land than is used for food production (Karp and Shield 2008). Moreover, crops like SRC willow provide natural filters and can be used to manage flooding, remove excess run-off of nitrogen from farmed land and for bioremediation of wastewater, sewage sludge or agricultural washings. As trees continue growing year after year they provide a “living inventory” of available biomass which can be harvested after several years and at different times, reducing storage and inventory holding costs and mitigating against the risk of annual yield fluctuations due to drought, disease and pest pressures (Hinchee et al. 2011). SRF can be used on land too sloped for food crop cultivation, in the absence of terracing, opening another land resource unsuited for food production.

A major limitation to biomass yield in forests and managed plantations is the available water content of the soil. Moreover, with high rates of biomass productivity, there is a risk that water resources may be adversely affected in areas where there is insufficient effective rainfall, thus reducing yield from water-supply catchments. Awareness of water balance-vegetation interactions at the stand scale is important to allow groundwater recharge to be estimated (Upham et al. 2011). When removing high biomass volumes from an area of land, there is also a risk of soil nutrient depletion (Upham et al. 2011). Impacts will be species-related. For example, Eucalyptus has caused particular concerns but SRC willow stands can be used for soil remediation and is beneficial to biodiversity, hence their inclusion for greening in the CAP reform of the EU. The largest threats to trees are, however, pests and diseases, compounded with impacts of climate change. Recent outbreaks, such as ash dieback and mountain pine beetle, have had devastating impacts on tree populations. Similarly, rust (caused by *Melampsora* spp), can reduce yields of poplars and willows by 40% reduction, and even cause plantation death. Breeding, or genetically engineering in resistance, is the only sustainable way of protecting forests (see below). Once diverse genotypes are available, mixtures can be used to better manage pests and diseases, and minimize the risk of devastating epidemics.

What are the future prospects for increasing biomass supply from trees? The potential for additional woody biomass appears huge. A recent analysis of the eastern US brought together representatives of foresters, biologists, conservation groups, analyst groups and economists. They estimated that if woody feedstocks were cultivated with a combination of intensive management on abandoned lands and partial harvests of standing forest were conducted, with amounts removed depending on condition and conservation value, it was estimated that 176 Mt yr^{-1} could be produced sustainably (Davis et al. 2012). A second detailed analysis of the potential for SRC willow on marginal land in Saskatchewan, Canada, shows the possibility of producing 34 Mt yr^{-1}, while sequestering 3 Mt C yr^{-1} into the soil (Amichev et al. 2012). For increasing productivity per unit land area, the typically long generation cycles, large space requirements, and outcrossing nature of trees make them particularly difficult to breed compared with arable crops but for these very reasons molecular markers and biotechnology have even more to offer by way of accelerating selection (Hanley and Karp, 2013, Harfouche et al. 2012). Further, with very limited past efforts in breeding improvement compared to the major food crops, large returns might be expected for investment at this stage. For example, although good yields of current production willow cultivars in short-rotation coppice trials average 10 t ha^{-1} yr^{-1}, new triploid hybrids are already now achieving 17 t ha^{-1} yr^{-1} (Serapiglia et al. 2014). Using mapping populations, with either linkage or association genetics, both quantitative trait loci (QTLs) and genes have been identified that influence key traits, such as pest and disease resistance, stem morphology, drought tolerance, biomass yield, composition and wood quality. Such tools are available for Douglas fir, loblolly, Monterey pines, spruces, Eucalyptus, poplars and willows. Whole genome sequences are also either already available or in production for many of these trees. Efficient means to produce transgenic plants displaying improved modified traits have also been generated in many species. Coupled with advanced management practices, productivity gains have been evident, with a doubling of yields achieved in many species over the past 20-30 years (Karp and Shield 2008).

Faster and cheaper next generation sequencing has led to the development of new promising approaches for genetic improvement. Large numbers of individuals can now be screened at very large numbers of loci for as many phenotypes as possible in genome-wide association studies. Interesting variation present at very low frequencies can be detected using strategies such as ‘Breeding with Rare Defective Alleles’ which are independent of the gene targeted or tree species (Vanholme et al. 2013).

In genomic selection (Grattapaglia and Resende 2011), a “training population” is established and data from intensively phenotyping and genotyping this population is used to develop a model, which is then used to predict the “genomic breeding value” of progeny in future generations. Based on these prediction models, genomic selection could be used to select superior genotypes early in the breeding process and could considerably reduce the length of time required for completing a cycle of genetic improvement in trees (Grattapaglia and Resende 2011; Harfouche et al. 2012). The emergence of mechanistically rich models of plant growth has opened the door to identifying optimum trait values for maximizing production and resource use efficiency in a given environment *in silico.* This is providing a further tool for accelerating selection (Drewry et al. 2014). Genetically modified feedstocks would undoubtedly accelerate improvement, especially in pest resistance (Hjalten et al. 2012). Long experience in research trials of genetically modified trees has shown that ecological impacts are no different from those of genetic change through conventional breeding and inter-specific hybridization (Strauss et al. 2001). Indeed, pest and disease resistance could decrease need for use of chemicals, besides increasing yield and certainty of supply. It is time policy recognized this fact.

Production forests could in theory meet much of the world’s need for sustainable energy (equivalent to half to 2/3’s of current fossil fuel consumption at current levels of productivity). However, in spite of past increases in productivity, plantations currently only supply *circa* 12% of the total amount of wood consumed. It is still usually cheaper to harvest trees from the wild and current planting and replacement rates are far below that needed to sustain future demand (Fenning and Gershenzon 2002; see also Chapter 13, this volume). Advances in woody feedstock production can only be exploited if policies surrounding both existing forest management and new plantings are in place. These policies will need to tackle environmental concerns associated particularly with monocultures and overcome some misunderstandings and misconceptions about the use of forests and plantations (Sutton 2013). They will need to consider the use of genetically modified trees and the need to incentivize investment. Managed sustainably, forests and plantations could reduce reliance on fossil fuels, help mitigate climate change and bring many environmental benefits (Sims et al. 2006). However, over-utilization and unsustainable practices risk the loss of forest ecosystems and societies dependent upon them. Energy policies have to be based on the principle of sustainable development and should plan for economic and environmental longevity of woody feedstocks, which could follow the model developed by Davis et al. (2012).

10.8 Algae

As productive as palm oil trees may be, in one of the most highly cited reviews of microalgae as a source of biodiesel, Chisti (2007) claimed that microalgae would produce 45x more oil per unit ground area per year, i.e. 13.7 l m^{-2}. Such remarkable potential has been frequently noted (Vonshak 1990; Chisti 2007; 2013; Silva et al.

2014). Such high yields would mean that despite the much greater infrastructure costs, relative to cultivation of plants, economic viability would be strong (Chisti 2013, Wijffels and Barbosa 2010; Silva et al. 2014). Unfortunately there is a large discrepancy between such claims, based on predictions and extrapolations, as compared with actual experimental data, pilot plant experience and simple theory. While the concept of using microalgae as a biodiesel feedstock has been explored extensively over the past several decades, a scalable, commercially viable system has yet to emerge (Hu et al. 2008).

Are the claimed yields of oil thermodynamically possible? Algal, like plant biodiesel contains about 34 MJ l^{-1}. So Chisti's (2007) claim would represent 466 MJ m^{-2} of oil yield. Zhu et al. (2010) show from theory, considering all steps in the photosynthetic process and in the complete absence of respiration and photorespiration, that the maximum theoretical conversion efficiency of solar radiation into biomass energy is 6.5%. Average daily solar radiation in the desert southeast of the USA is among the highest at the ground surface in the world, at 7200 MJ m^{-2}. If all of this radiation is intercepted by the algae and converted at 6.5% efficiency every day of the year and if the alga is 70% oil, as assumed by Chisti (2007), this would yield 397 MJ of oil. So even if we assume the algal suspension absorbs 100% of the radiation, loses no energy in respiration and operates at maximum theoretical efficiency without a single interruption over 365 days, the claim still exceeds what is thermodynamically possible by almost 20%. This also ignores the fact that in practice, oil accumulation is a nutrient limitation response, which requires a period in which photosynthesis is zero or severely restricted by stress (Hu et al. 2008).

Claims made for algae are focused around their: fast growth, higher photosynthetic efficiency, ability to increase oil content to 70% of mass, ability to grow in saline or brackish water, and capacity (as in C3 crops) to fix more carbon in high CO_2, as well as ability to produce high value chemicals that could subsidize the cost of biodiesel production (Chisti 2007). Some of these individual claims are supported by experimental data obtained under laboratory and short-term small-scale field measurements. But, attention must be paid to the fact that these experiments were performed with an algal species or strain that met one of these goals, but it is almost impossible to have all of these properties in a single strain. For example, many of the algal species with higher potential photosynthetic efficiencies than C3 crops, achieve this by an internal, energy driven, CO_2 concentrating mechanism (Giordano et al. 2005). However, this precludes any further response to increased external CO_2 concentration, and would make the algae less, not more, efficient than a C3 crop in high CO_2. Some of the claims in what amount to "sales pitches" ignore problems for which there is no clear solution. For example, a plus that is often given is the ability to use saline water in deserts and semi-deserts. However, when grown in out-door open ponds, high evaporation rates will produce a brine that may cause severe environmental issues when the water is disposed. As demonstrated above, claims of high photosynthetic efficiency can overlook the theoretical maximum efficiency that cannot be exceeded in practice and ignore problems of the observed down-regulation of the photosynthetic activity (Vonshak and Guy 1992; Vonshak et al. 1994; Day et al. 2012), paralleling those of crop plants (Zhu et al. 2004; Murchie and

Niyogi 2011). More critical analyses of the true photosynthetic efficiency and limitations to algal biodiesel production are explained and justified in other reviews that are not receiving the attention they deserve when evaluating the true potential of these systems (Hu et al. 2008, Walker 2009, Tredici 2010, Lundquist et al. 2010).

Many claims that potential microalgal production systems can be a commercially viable alternative source of energy are based on assumptions that high productivity can be achieved easily in large scale production and be equivalent to that obtained under laboratory controlled conditions. High figures of productivity obtained from model predictions, short-term laboratory or small-scale short-term field studies are then used to estimate maximum potential in large-scale field production facilities (Guterman et al. 1990; Chisti 2007). Unfortunately, there is nothing to support those assumptions and extrapolations (Hu et al. 2008). While this is also an issue with agriculture, there is a great deal more experience in translation with agriculture than there is with algal culture. Yet, the complexity and engineering of large-scale algal culture is orders of magnitude greater (Lundquist et al. 2010). Claims that micro algae have a better, or more efficient, photosynthetic machinery are at the best incorrect and in many cases reflect the misuse of terminology. All algae and plants use the same Calvin-Benson pathway to assimilate CO_2. Many algae have energy driven mechanisms to concentrate CO_2 at the site of Rubisco, so minimizing losses in photorespiration, but this only makes them more efficient than C3 plants under conditions of low CO_2 and not more efficient than C4 plants. Different photosynthetic pigments allow some algae to capture some wavelengths of solar radiation with higher efficiency while the absence of heterotrophic organs will also improve net efficiency. However, none of these factors allow algae to escape the thermodynamic maximum efficiency explained above. On the negative side, the tumbling nature of algal suspensions moving through photo-reactors or raceways prevents the light acclimation possible in plant canopies, where investment into components of the photosynthetic apparatus can be optimized for the prevailing light conditions (Zhu et al. 2010). In practice, the current productivity in large-scale facilities based on photoautotrophic growth does not exceed 15 g m^{-2} d^{-1} on an annual basis, which is less than the annual average of 23 g m^{-2} d^{-1} achieved by the C4 bioenergy feedstock Napier grass under rainfed (see the section on perennial grasses). A detailed analysis, suggests 22 g m^{-2} d^{-1} as an achievable maximum in ponds (Lundquist et al. 2010), which even so is still very similar to that achieved by productive crops. Short-term higher productivities may be achieved as in crops, depending on stage in the growth cycle, the season of the year and location of the site (Beadle and Long 1985; Vonshak 1987). Even if a perfect site with ideal climatic conditions can be found; yield would be 40-50 Mt ha^{-1} yr^{-1} of dry biomass, when downtime for maintenance and replenishment of the culture is taken into account. It has to be noted that even this estimated productivity is yet to be rigorously demonstrated, since it assumes that there will be no contamination with other algae, introduction of pathogens and that lipid production can occur without the need to induce this via the currently necessary nutritional stress, which halts any further energy gain by the algae (Vonshak 1987; Hu et al. 2008; Lundquist et al. 2010). A further claim is about the fact that algal feedstocks can be genetically engineered far more rapidly than crops. While unquestionably correct, GM algae would need to be contained since in open cultivation the alga may easily escape. However, enclosure would incur massive energy costs in maintaining temperature in raceways at viable levels, given that they may have to dissipate as much as 20 MJ m^{-2} s^{-1} of incoming solar radiation.

How do algae compare with respect to cost, technology and life cycle analysis? Today there are only four algal species that are produced in large scale in an economically viable manner. The first two are grown for the sale of their total biomass with very little further processing: Spirulina (*Arthrospira platensis*) about 15 kt yr^{-1} and Chlorella (*Chlorella vulgaris*), about 5 kt yr^{-1}. Grown mainly in open ponds with a bulk selling prices of $10– 25/kg for dry biomass of Spirulina and $20– 40/kg for Chlorella. These are sold into the health food/supplement market. Predicted production cost is about 60-80% of the wholesale price. The cost of drying is about 1.0 $/kg and might be a good indication for the production cost of algal biomass for biodiesel. The two other algal species, *Dunaliella salina* and *Haematococcus pluvialis*, are used for extraction of carotenoids (beta-carotene and astaxanthin, respectively) for the health supplement market. They are produced in much smaller amounts but sell at far higher prices. The higher price reflects the higher production cost due to the need to induce accumulation of the carotenoids. This process parallels the process that would be needed to induce lipid accumulation in algal biodiesel feedstocks (Hu et al. 2008). It is very difficult to see how significant reduction in production costs may be achieved without a major breakthrough leading to orders of magnitude improvement in the efficiency of production. Yet this will be necessary to make biodiesel or jet fuel economically viable at open market prices. The current production costs are the result of 30 years of continuous improvement in efficiency through engineering and downstream processing, via learning by doing, yet is still far from being viable for the fuel market (Lundquist et al. 2010). At present it is not clear how such gains could be achieved on less than a multi-decadal timescale. Although closed photo-bioreactors incur significant extra costs in construction and energy input, they are providing a platform for gaining better insight as to the improvements required to gain some improvement in efficiency (Stephenson et al. 2010; der Veld 2012; Woertz et al. 2014).

The claim that microalgae will solve the world’ s energy problem or even contribute significantly to reducing the dependency on fossil fuels is unfortunately at this stage not foreseen as viable. The potential of microalgal biofuels will be realized only by addressing the real issues of productivity, strain selection and efficient use of resources in large-scale production facilities. A focus on high-value products, perhaps high value lubricants, may be a better platform for the evolution of more efficient systems and knowledge as to whether algal biofuel production has a viable future in the longer term (Hu et al. 2008).

One area where viability may be possible is in wastewater treatment. Although not a new idea, algal waste treatment offers a means to counteract the high costs of anaerobic technologies, by allowing nutrient capture and bioenergy production. A recent analysis suggests that these combined benefits could lead to energy positive and economically viable photoautotrophic wastewater treatment in areas with year round high insolation (Shoener et al. 2014).

10.9 Conclusions

A range of different crops will be required to provide feedstocks for bioenergy and biofuels, as specific needs for light, temperature and water availability restrict the geographic ranges of individual feedstocks. The large volume of feedstocks required for bioenergy and biofuels to make a difference has resulted in both novel use of existing crops and the development of novel crops. Support should be given to efforts aimed at continuing to improve yields (sustainably) of both traditional and novel crops through breeding enhanced by genomics and biotechnology integrated with agronomic improvement. Expansion into land that is sub-optimal for food production should be encouraged but will require the selection of cultivars and appropriate agronomy adapted to perform well in these environments. It is also essential that adequate testing in target environments be carried out before any large-scale plantings are initiated.

Currently, the predominant feedstocks for biopower (heat and power) are woody species, including forests, managed woodlands and energy trees, although straws and other crops residues are also used. The current primary feedstocks for biofuel are food crops but use of the lignocellulosic (non-food) fraction and development of non-food crops is also underway.

At present, biomass accounts for only a small fraction of current liquid fuel use, ca. 2%, and about 8% of total global energy use - however most of this is traditional combustion of wood. Natural forests are still the major source of wood but this will decline under pressures to protect the valuable ecosystem services they contribute to and because only planted forests will be able to meet the rising demands. Biofuels have replaced a very substantial proportion of gasoline use in Brazil and in the USA. Of the four largest sources of these biofuels - soybean, rapeseed, maize and sugarcane, only the latter appears to have a secure future. Soybean and rapeseed produce far too little fuel per unit land area to remain competitive without mandates and subsidies (Table 10.1). The progressive divide between increase in demand and increase in production suggests that maize ethanol will lose long-term economic viability, unless the already high rate of yield per hectare improvement can be accelerated yet further. Emerging perennial crops and woody feedstocks that may be grown on marginal land, i.e. land unsuited to arable crop production or semi-arid land could allow large-scale replacement of fossil fuels. However, this will require the implementation of policies that favor these new land uses and policies that support the realization of the potential of producing cellulosic fuels or/and acceptance of bioengineered crops. Generally, re-establishment of biodiverse systems such as mixed grass prairie as a biomass source, are not viable because of their low yields. Both macro and micro algae have also been developed and promoted as alternatives to crops, which have the advantage of no or minimal land requirement. However, claims that they will make major contributions have yet to be upheld and they may be better confined to use as feedstocks for high-value renewable products.

Crop feedstocks for bioenergy and biofuels are different from coal and oil as new chains require establishment and expansion time before sufficient quantities can be supplied and all crops feedstock chains involve many different players, and often different localities (see Chapter 11, this volume). Many of the concerns surrounding biofuels relate to feedstock production and the challenges of ensuring that bioenergy and biofuels produced with these feedstocks really do reduce greenhouse gases and result in environmental benefits, as noted in other Chapters of this volume. Considerable advances have been made in the improvement of crop yields and in the understanding of the key criteria that need to be met for sustainable production, which crops best meet these criteria and the further changes needed to improve sustainability further. The challenges of meeting feedstock supply through yield improvement and expansion of feedstocks in sustainable ways can be met, but only with secure and prolonged support and sensible, easily adoptable policies that recognize the environmental as well as the economic goals. However, the need to move swiftly has become urgent. These policies are needed now, so that strategies for increasing feedstock production in sustainable ways can be implemented immediately. Climate change is already impacting on crop production and human societies. A detailed technical and global analysis using IPCC methodology, showed that bioenergy crops could provide up to 22 new EJ yr^{-1} by 2025, mitigating 2070 Mt CO2 equivalent yr-1 in GHG emissions when taking account of build-out times (Sims et al. 2006). This chapter shows many further potential bioenergy options, but the question remains: Will policy-makers move quickly enough to release this potential in a timely enough manner to fight global climate change? Current policy on bioenergy and genetically modified crops is almost certainly a realization of the proverb “the perfect is the enemy of the good”. Without change, the significant opportunities for realizing bioenergy shown here will remain just opportunities.

10.10 Recommendations and Much Needed Science

- Genetic improvement of perennial energy crops through conventional and marker-assisted breeding and GM approaches to enhance yields, increase resource use efficiency and resilience to future climates;
- More extensive trials with a range of agronomies of these emerging crops to test the assumption that these will be high-yielding and sustainable on marginal land and other areas unsuited to competitive food crop production;
- Modeling approaches to identify optimal locations for energy crops using yield models and GIS-based opportunity mapping and constraint mapping;

- Development of policies that encourage sustainable energy crop production through recognition of multiple environmental benefits;
- Social research into barriers to adoption of new and emerging crops by farmers;
- Holding emerging bioenergy to higher standards than current agriculture and forestry will inhibit, not aid, emerging and more sustainable opportunities.

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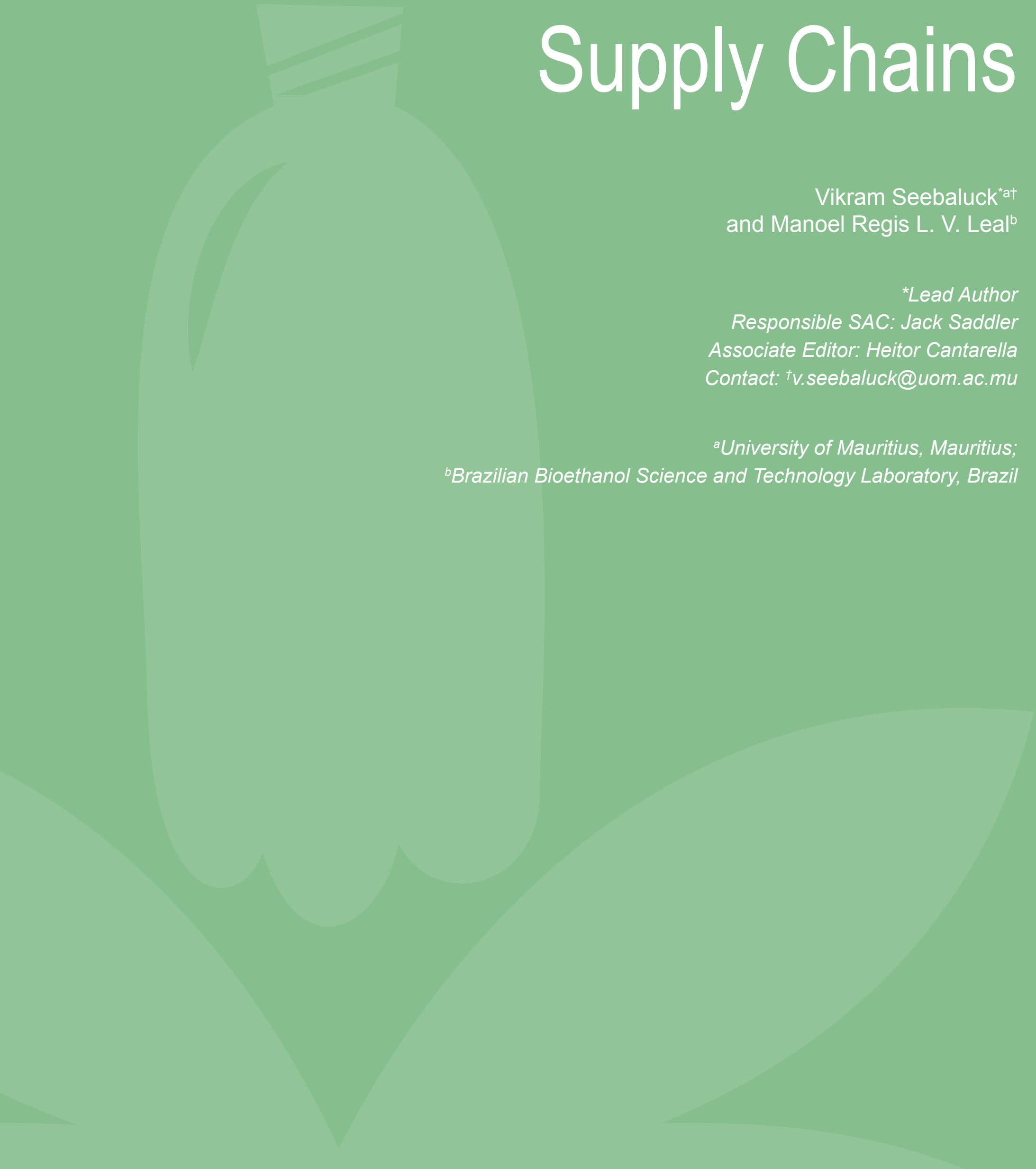
chapter 11

Feedstock Supply Chains



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Highlights

- Feedstock supply chains bridge biomass production in fields to industrial processing. Although it will be influenced by the type of crop, the chain will typically include harvesting, collection, baling, transport, drying, storage and pre-treatment, all of which should be efficiently and cost-effectively designed to enhance the overall sustainability of bioenergy projects.
- Except for some large-scale commercial crops such as sugarcane or corn, biomass supply chains for bioenergy production are currently underdeveloped despite the fact that significant improvements could be achieved by modernizing the logistic operations to make them more efficient. Capitalization, replication or adaptation experiences could be derived from the existing commercial biomass supply chains.
- Modern biomass supply chains offer significant possibilities for gathering all types of biomass and synergizing their physico-chemical properties with subsequent energy conversion processes.
- There is good potential to develop alternative options to provide stable and continuous supply of suitable feedstocks to processing plants. Potential improvements include storage, biomass densification, use of complementary fuels available over the year, and multi-fuel processing.
- Scale of bioenergy crops production is crucial in the choice and development of suitable supply chains. Mechanical operations are generally favored by large-scale production, as it is the case with sugarcane or corn. However, given that the availability of bioenergy crops may be scattered in situations like its cultivation in marginal areas, there is the need to determine the minimal or reasonable cultivable area on which mechanization or at least partial mechanization could be efficiently and cost-effectively undertaken. This is vital in tapping the maximum available and suitable land for bioenergy crops production as well as the associated socio-economic benefits.
- Scientific innovations and practical experiences, together with the collaboration of equipment manufacturers would largely contribute in cost-effectively and efficiently transferring different types of biomass from fields to factories.
- Appropriate policies in synergy with those on crop production and conversion processes (the immediate nexus of biomass supply chains) would support the development of region-specific efficient feedstock supply chains; there is a need for technical and financial supports as well as capacity building.

Summary

Bioenergy expansion is nowadays gaining momentum with commercial scale and modern production systems gradually being developed worldwide. One of the key lessons learned in such developments is that the long-term economic success and sustainability of bioenergy projects depend on the proper management of the overall energy system, which includes supply chain operations as a key determinant. Biomass supply chains thus form part of the knowledge-based bio-economy of the future which is needed for replacing traditional fossil resources that are becoming costly and environmentally destructive. This chapter reviews the biomass supply chain operations with case studies of typical commercial energy crops in view to provide an insight of progress achieved so far and future prospects. There exist some large-scale biomass supply chains which could be further optimized to provide key lessons to quickly develop or adapt them to new bioenergy feedstocks having substantive market penetrability. However, given the rather varying context in which bioenergy projects are evolving in different regions, a more coordinated approach for technical and financial supports as well as for capacity building would assist in developing efficient biomass supply chains for bioenergy production. Scientific innovations would contribute in cost-effectively and efficiently transferring different types of biomass from field to factories. These would require the assessment of field experiences to scientifically develop efficient logistics in close collaboration with equipment manufacturers. Thus, appropriate policies in synergy with those on crop production and conversion processes between which supply chains are squeezed in should be promoted to meet the need to increase the share of modern bioenergy in the global energy supply. Such developments would bring benefits for the climate, energy access or security and developmental opportunities.

11.1 Introduction

This chapter focuses on feedstock supply chains that bridge biomass production or availability to its industrial processing into bioenergy. Except for some crops such as sugarcane, corn, soybeans and rapeseed, large scale biomass supply chains for bioenergy production are underdeveloped and are new or emerging for many potential bioenergy feedstocks; this is due to the quite recent rapidly developing market for energy biomass (Vakkilainen et al. 2013) and the growing need to convert waste biomass into useful energy products in the quest for diversifying renewable environment-friendly energy resources. The know-how and expertise in this area thus need to be strengthened while capitalizing on the experience acquired so far with some feedstocks such as sugarcane or corn. Besides reviewing the biomass supply chains for energy production, the key factors influencing the logistic operations as well as the impacts and nexus with the overall biomass to bioenergy cycle are also presented in this chapter. The technology gaps, challenges and opportunities for improving and developing new biomass supply chains for bioenergy production are given together with an overview of the commercial supply chain operations for four different biomass sources, namely sugarcane (a food and fuel crop), eucalyptus (a tree species), miscanthus (a new crop for power generation) and oil palm (an oil crop). These examples provide insight for capitalization, replication and adaptation opportunities for bioenergy production from other types of biomass available or produced in different world regions. Corn is a major feedstock used for ethanol production in the US for use as oxygenate in gasoline. Corn supply chains are modern with long standing experiences while options for harvesting and supply of corn stover are being developed (Klingenfeld 2008; Gonzalez et al. 2011; Darr 2012; Gutesa 2013; Shah 2013) given its significant availability and potential for bioenergy production. However, this feedstock is linked to considerable debate on its sustainability for biofuel production, the land use change impacts and ‘food versus fuel’ issue. Bioenergy from corn is presented in other chapters of this book.

11.2 Key Features of Biomass Supply Chains

Biomass supply chains are mainly characterized by their design, cost and sustainability among other features. The growing portfolio of bioenergy feedstocks differ in their physico-chemical properties and availability, thus requiring specific logistics designs adapted to the characteristics of the materials handled and the scale of production. The need for pre-treatment prior to storage or processing may impose an additional complication on the supply chain. The operations are thus normally designed taking into consideration the quality of the available biomass as well as the subsequent energy conversion processes or storage needs, which usually requires that the biomass is pre-treated to be technically convenient to the processing configurations or for storage and re-transportation purposes. Optimization of the structural flow pattern, including the functioning of the biomass supply chain steps with adjustments to specific conditions of production systems (e.g. climate and topology, feedstock, technologies, infrastructures, energy end uses, etc.), can largely contribute in improving the viability and cost-effectiveness of the bioenergy system. Any incremental improvement at each logistics step should be tapped given that supply logistics have a significant bearing on the total delivered cost of biomass to an energy plant which can go up to around 40% of the cost of the biomass production (Johnson and Seebaluck 2012). From the sustainability perspective, it eventually becomes important to green the supply chains through the use of properly selected approaches and energy efficient logistics steps to improve the energy and environmental balances of the bioenergy system. Additional factors, such as weather conditions, can affect the yield and quality as well as the harvesting and collection time, while real time knowledge can improve communication between the factory and raw biomass suppliers to ensure coordinated and constant supply of quality biomass to the processing plant.

11.3 Biomass Crops and their Supply Chains

Supply chain operations primarily depend on the types of biomass to be harvested or collected which are broadly classified into oil or sugar/starch-bearing crops or lignocellulosic feedstocks. Globally, there are around 350 oil-bearing crops identified as potential feedstocks for biodiesel production (Atabani et al. 2012) out of which crops like oil palm, soybeans and rapeseed have reached commercial processing. Harvesting of oil seeds is undertaken manually or is semi-mechanized with power cutters and picker type lifts, but fully mechanized systems, which exist only for a few crops, still need to be developed or addressed as a technological gap (HREDV 2009). Modified mechanical harvesting equipment for other crops have been proposed for harvesting of crops like jatropha but these still need to be fully developed. On the other hand, lignocellulosic biomass in the form of energy crops, agricultural wastes and forest residues represents the most abundant source of renewable biomass with production of $1x10^{10}$ metric tons annually, which is about half of the biomass produced in the world (Alvira et al. 2010). It is the future feedstock for the biofuel and bio-based industry; it could produce up to 442 billion liters of bioethanol per year due to its high diversity around the world (Darjanaand and Mirjana 2013). However, second generation cellulosic ethanol conversion technologies which has to emerge would be needed to realize this potential. To maintain the viability and sustainability of bioenergy production worldwide, there are growing interests in the production of energy crops such as perennial grasses which are attractive in terms of their high production yield, low input requirements, high content of lignin and cellulose, ability to adapt to marginal land and rain fed conditions, and their generally anticipated positive environmental impacts. Factory biomass wastes produced from traditional food and forage crops are equally increasingly being used for bioenergy production. For instance, sugarcane, a common crop grown in more than 100 countries worldwide, offers both field and factory wastes for energy generation. Lignocellulosic feedstocks supply chains may be manual to semi-mechanized as well as fully mechanized systems. For instance, sugarcane resources offer diverse mature commercial applications of these alternative systems while the supply chain operations of other emerging energy crops like *Arundo Donax* are generally learnt and extrapolated from sugarcane, but need to be adapted and optimized (Seebaluck 2012).

The supply chains are generally less costly for factory derived waste biomass (e.g. sugarcane bagasse), while the cost for collected biomass is higher depending on the complexity of the operations (e.g. sugarcane agricultural residues). On the other hand, dedicated energy crops are generally associated with specifically designed supply chains that usually bear higher cost but which could be reduced depending on the scale of production and technology applications. It must also be highlighted that around three quarters of the biomass used for food, feed, industrial wood and traditional fuel wood is not fully exploited at some point in their harvesting, transport and processing (Nielsen et al. 2007) thus providing opportunities for optimization of these logistic operations.

11.4 Typical Layout of the Biomass Supply Chains

Generally, depending on the biomass and fuel type, the supply chains would include harvesting, collection, baling, transport, drying, storage and pre-treatment prior to conversion to bioenergy products. These steps are interlinked and should be planned from a total chain perspective rather than separately to obtain an efficient and cost-effective biomass supply. The typical general layout of biomass supply chains is given in Figure 11.1. It is therefore natural that many attempts have so far been made to simulate and optimize specific biomass supply chains on the understanding that cost reductions could originate from more efficient logistics operations.

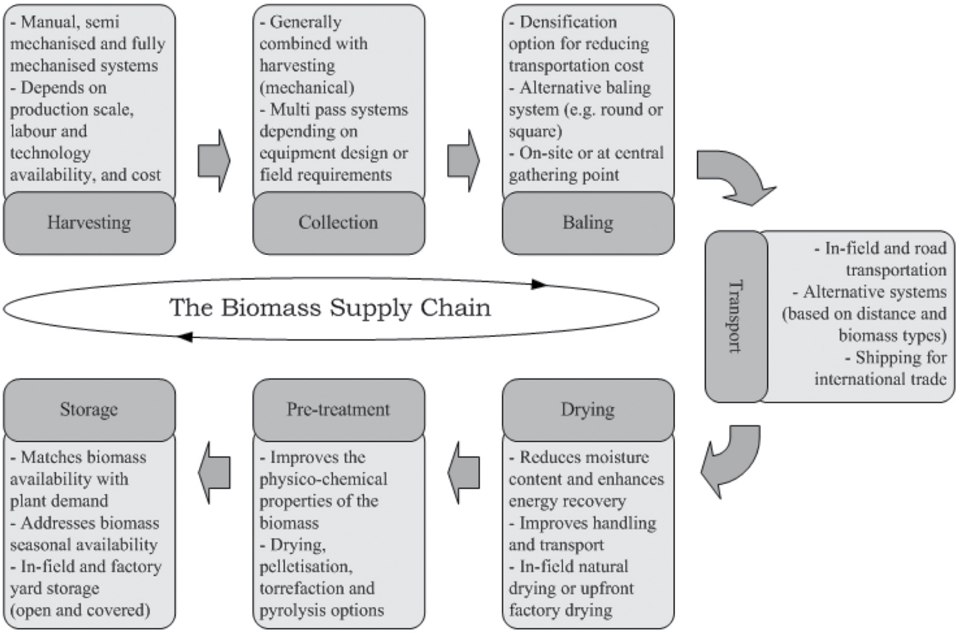

Figure 11.1. Typical layout of biomass supply chains.

11.4.1 Harvesting and Collection

Harvesting and collection depends on the type of biomass (e.g. grass, wood, crop residues or seed crops) and it represents one of the significant cost factors in the production of biomass energy crops (McKendry 2002; Gonzalez et al. 2011). It may be undertaken manually or mechanically depending on production scale, labor and technology availability, and cost. Multi-pass or single pass or whole crop harvesting are generally used for harvesting oil seed crops while lignocellulosic grassy biomass are usually mechanically harvested with equipment like combine, mower, shredder, rake, baler (square or round), windrower, loafer[11] and forage harvester which have different speed of operation and efficiency (ASABE 2006), making the process energy intensive. New harvesting techniques are constantly being developed with single or multi-pass system (Bentini and Martelli 2013). Harvesting and collection generally introduce extraneous matter (e.g. soil), which contaminates the feedstock and leads to process operational problems. The soils are also generally affected with mechanical operations which results in lower yields over the crop cycle.

For crops like sugarcane, a combination of manual, semi-mechanical and full mechanization is practiced in different regions worldwide. For low-density biomass, loafing offers an attractive option since collection, densification and transport can be done with a single piece of equipment. For wet biomass, a field shredder is generally employed to cut the materials into pieces and spread on the field for drying, which is subsequently cut by a mower and placed in swath for immediate bailing. Baling is a conventional key technology used for improving the bulk density of harvested biomass to make handling and storage easier while it simultaneously reduces the risks of deterioration (Forsberg 2000; Gold and Seuring 2011; Stelte 2011; Pirraglia et al. 2012; Lim et al. 2012; Idah and Mopah 2013). Mechanical logging in particular thinning operations are generally opted for harvesting forest biomass (Damen and Faaij 2006; Mabee et al. 2006; Rauch 2007; Gold and Seuring 2011). Cut trees are generally left at harvesting sites for a few months which enables significant reduction in moisture content through natural drying (Yoshioka et al. 2005; Ayoub et al. 2007; Gold and Seuring 2011). Gold and Seuring (2011) reported that baling and chipping can generally be undertaken at harvesting sites or at centralized collection platforms (Thornley et al. 2008) after which the chipped biomass is usually directly processed into bioenergy or converted into pellets for long distance transportation (Hamelinck et al. 2005; Uslu et al. 2008).

11.4.2 Transportation

Transportation (in-field and road) is influenced by many factors including technical, social and environmental impacts as well as the legal and infrastructural framework considered in the management of the supply chain. It is linked to the characteristics of the material, the carrying capacity of the vehicles and the distance to storage areas and the processing plant. Considering the typical locations of biomass fuel sources (farms or forests), the transport infrastructure is mainly road transport which favors short distances and greater flexibility compared with other modes such as train or ship, generally considered for long distance biomass transport.

One of the main economic variables of transport is the travel time which is influenced by distance and speed (Gronalt 2007); distance is related to the routes travelled as well as

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[1] Loafing refers to stack handling which involves collecting residual straw, as an alternative to baling, allowing paddock siding of the material.

the proportion of tilled land and its biomass yield for infield transport (Perpiná et al. 2009; Gold and Seuring 2011) while speed is influenced by road properties and infrastructure, and mode of transportation. Infield transportation moves the biomass to the roadside where it is loaded to road transportation vehicles for conveyance to the factory.

Baling is generally recommended for low-density biomass as a means of reducing costs of transportation, handling and storage (Petrolia 2008). Else, the transportation cost becomes significant in the bio-energy system (Mayfield et al. 2007; Searcy et al. 2007; Gasol et al. 2009; Gold and Seuring, 2011). Gold and Seuring (2011) reported that maximizing truck cycle capacity through increase in biomass bulk density (Hess et al. 2007) and optimizing the utilization of vehicle payload (Möller and Nielsen 2007) are useful options for reducing transport costs.

From an environmental point of view, transportation causes emissions such as particulates matter, nitrous oxide and carbon dioxide which are directly influenced by the distance travelled. The overall legal and infrastructural framework and road properties influence the functioning of a bioenergy supply systems particularly in developing countries where poor road infrastructures may deter investors.

11.4.3 Storage

Storage matches biomass supply with designed plant demand. Thus, the availability of the biomass for year round processing would determine any storage requirement. Most agricultural biomass is available seasonally during the crop harvesting period (Caputo et al. 2005) thus giving a limited time frame for collecting large amount of biomass. This leads to significant seasonal needs of resources, both in equipment and workforce, leading to an increase in the cost of obtaining these resources including their suboptimal utilization, in particular the storage space. For some crops and regions, a single annual harvest may under-utilize the logistics machineries and equipment (Uslu et al. 2008) while requiring more labor compared to perennial harvesting (Thornley et al. 2008; Gold and Seuring 2011).

Biomass storage provides a buffer to the continuous supply of biomass to the processing plant, in particular for feedstock characterized by short harvesting periods. Seeds are typically stored in sealed bins or silos while biomass is transformed into bales or pellets for storage. Gold and Seuring (2011) reported that both open and covered storage may be suitable for baled biomass; round bales can however tolerate only certain levels of exposure to rain and weather compared to square bales which need to be stored in covered areas given that they are more prone to weather damage (Haq and Easterly 2006). Critical choice of the type of storage is needed since storage location and duration of storage are associated with expenses and risks such as biomass quality degradation and dry matter losses (Van Belle et al. 2003; Damen and Faaij 2006; Hess et al.2007; Ayoub et al. 2007; Caniëls and Romijn 2008). This can be done on field, at intermediate storage location or at the processing plant, but the most common type of storage is on-field biomass storage which is usually the cheapest option. On-field storage is however associated with significant biomass losses and uncontrollable moisture leading to technical problems and reduced efficiency in power plants. There are also often health and safety issues, such as danger of spores and fungus formation and self ignition as a result of increased level of moisture in the biomass. Intermediate storage location involves transportation of the biomass twice by road transport vehicles resulting in higher delivered cost. This may add 10–20% to the delivered costs, as a result of the additional transportation and handling costs incurred (Allen et al. 1998). Storage of biomass at factory sites can favor its upfront drying by making use of boiler exhaust heat or flue gas (Rentizelas et al. 2009) prior to their conversion into energy products.

11.4.4 Pretreatment

Pretreatment is generally undertaken to improve the physico-chemical properties of the biomass for enhanced energy productivity and adaptability to the subsequent conversion process, while it also provides a safe option for long-term biomass storage and export. Common pre-treatment techniques are drying and pelletization while torrefaction, pyrolysis and gasification are promising alternatives currently under development.

Drying enables reduction in moisture content of the material, enhances combustion efficiency and improves its resistance to decay and fire risks, while it also reduces handling and transportation costs due to the significant weight reduction that is achieved (Hamelinck et al. 2005; Deswarte et al. 2007; Gold and Seuring 2011). Natural drying such as in-field or ambient drying is less costly compared to upfront factory drying where suitably designed equipment and a source of energy are needed. However, the applicability and effectiveness of natural drying largely depends on climatic conditions (Dunnett et al. 2007). Pelletization results in both moisture reduction and increase in bulk density (Haq and Easterly 2006; Perry and Rosillo-Calle 2008; Uslu et al. 2008; Seebaluck and Thielamay 2010; Gold and Seuring 2011). It also leads to high heating value e.g. wood pellets (Hamelinck et al. 2005; Junginger et al. 2008). Biomass pellets can be kept longer with reduced losses in dry matter (Junginger et al. 2008). However, higher costs are associated with pellets production compared to baled biomass (Haq and Easterly, 2006). Biomass densification technologies are nevertheless receiving considerable attention for their technical refinement and for improving their cost-effectiveness. The quantity of wood pellets traded has significantly increased over the past decade (Vakkilainen et al. 2013) which would most likely intensify in the future to offer possibilities of pellets cost reduction.

The size, moisture content and also the percentage impurities are key factors that determine whether the biomass needs to be pre-processed. Boilers in power plants are often designed for a specific moisture range for optimum efficiency and thus the raw material has to be pre-processed accordingly. Also, whenever co-firing or co-combustion[2] is practiced in the same furnace, a drop in efficiency is usually recorded

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[2] Co-firing or co-combustion is the burning of two different types of materials at the same time. It is generally used to improve the combustion of fuels with low energy content while it provides many other advantages such as reduced emissions, improved efficiency and reduced corrosion, erosion and scaling of boiler equipment.

thus requiring proper design based on the optimum raw material properties. In some emerging processes like the low pressure catalytic depolymerization process for biodiesel production, the biomass moisture needs to be reduced to less than 20% which poses formidable challenges to such projects (Seebaluck 2012). Densification techniques such as briquetting and pelletization thus offer commercial options for increasing the bulk density of the material, as well as for reducing the moisture and size of the materials thereby providing important gains in energy efficiency. However, due to cost constraints, low cost natural field or yard drying options are sometimes practiced. However, they are usually affected by climatic conditions. Emerging techniques such as pyrolysis need further work to define its economic and technical benefits (Jahirul et al. 2012) but carry good prospects for improving biomass energy productivity. There are studies on how to improve the characteristics of specific biomass types for transportation and trade (Sheng Goh et al. 2014) and many others are in progress. On the other hand, impurities such as alkali metals that are normally found in annual and fast-growing crops, can lead to technical problems in power plants. To avoid such situations, the biomass first needs to be pre-treated using a crushing, washing and dewatering process to remove the undesirable impurities to permissible design limits (Seebaluck and Seeruttun 2009).

It has also been shown that biomass moisture varies with the time of harvest and is generally higher for immature crops. Thus, moisture content management can potentially lead to economic and environmental advantages. Models such as the Integrated Biomass Supply Analysis & Logistics model (IBSAL) (Sokhansanj et al. 2006), which uses a dynamic moisture sorption routine, are generally employed to determine daily moisture changes during harvesting operation.

11.5 Challenges, Best Practices and Key Lessons in Biomass Supply Chains

The main challenges in biomass supply chains are the seasonal availability of biomass in varying quantities at rather scattered locations, particularly agro-forestry residues. These make harvest operations costly, for instance biomass characterized by annual single short harvesting periods lead to the utilization of relatively more logistics machineries and equipment over a short period of time thus increasing operational costs, while the material should also be properly stored for year-round processing which again incurs additional cost. These challenges naturally lead to the need for designing cost-effective supply chains operations including proper storage systems in view to ensure continuous supply of suitable feedstock to bioenergy plants.

The topography is an important consideration in supply chains, particularly for modern systems where mechanization is favored. Appropriate available and suitable areas should thus be identified for bioenergy crops cultivation together with suitable machineries developed for the logistic operations. In many cases, the experience acquired from existing crops such as sugarcane can be replicated and adapted to the new bioenergy resources. For marginal areas where bioenergy crops could be potentially grown, appropriate logistic operations should be developed taking into consideration factors such as land slope, soil rock density or types.

Natural drying should be favored as far as possible to reduce the complexity of integrating a front-end drying factory process. This leads to less boiler operational constraints, important gains in energy productivity, improvement in the overall energy balance of the biomass to bioenergy process and reduced production costs. For instance, cut trees are usually left for a few months at harvesting sites for drying while other biomass may be left for around two weeks for natural moisture reduction.

The concept of multi-biomass utilization (biomass co-firing or co-combustion) can offer multiple benefits, leading to total system cost reduction. Biomass co-firing is currently undertaken in many plants globally and its full potential has yet to be fully tapped (Vakkilainen et al. 2013). Significant savings can be realized with respect to storage as the inflow of biomass throughout the year is smoother with multiple biomass thereby putting less pressure on the supply chain, both for equipment and labor. For instance, the simultaneous use of straw and reed canary grass was investigated and a 15–20% cost reduction was obtained simply by using the two biomass sources instead of one (Nilsson 2001). The logistics can however become quite complex, especially when a variety of biomass streams are involved. However, this can be addressed by growing and harvesting selected biomass crops that require similar logistical operations. Crops having almost similar characteristics and fuel properties are also preferred for co-combustion given their adaptability and efficient joint processing in the same energy conversion process. A typical practical example of such application would be the co-combustion of cane bagasse (factory waste) and cane agricultural residues (field waste) in the same furnace (boiler). This would reduce or avoid the use of coal as complementary fuel during sugarcane off-crop season in existing commercial cogeneration power plants, as it currently occurs in Mauritius. It also has a high potential in countries like Brazil where cane agricultural residues are largely available. However, the price of the biomass derived energy has to first be made more attractive.

11.6 Case Studies of Biomass Supply Chains

11.6.1 Sugarcane

Sugarcane is a global commercial agricultural crop that supports the developmental and societal needs of the many tropical and subtropical countries that grow this crop. Traditionally it has been exploited for the production of sugar as a sweetener. However it is now being grown at a large commercial scale to generate multiple products, particularly bioethanol and cogenerated electricity. It has today become the world's most economically valuable bioenergy crop with its potential for producing over 100 metric tons of biomass per hectare annually which is used for the production of food, feed, fuel, fiber and various specialized products (Johnson and Seebaluck 2012).

Harvesting and delivery of sugarcane is a complex and costly operation which requires extensive coordination, especially for large-scale production; it constitutes approximately 40% of the operating cost of cane production with transport accounting for 14% in South Africa (SACA 2010). Sugarcane is unique in that a large amount of fiber is moved to the factory in the course of sugar production, although this fibrous residue is used for power generation. Cane supply management usually involves four types of operators: growers, harvest contractors, hauliers and the mill itself. The logistic operations extend from manual to semi-mechanized as well as fully mechanized options: they generally include burning (for manual harvesting), cutting, loading, in-field transport, trans-loading, road transport, offloading and feeding to the factory. For efficiency improvement, integrated and centrally coordinated processes are favored rather than managing them separately. However, the whole chain can be affected by any change occurring to the individual processes, for instance, harvesting of unburnt cane results in lower cutting rate (in the case of manual harvesting) and higher loading and transport requirements due the additional amount of cane residues, but more fiber is made available in the factory for power generation while the environmental air pollution from cane burning is avoided.

Cane grown in many countries such as in South Africa is burnt prior to harvesting and is generally manually harvested (Purchase et al. 2008). However, environmental regulations together with the increasing importance of cane fiber for electricity generation suggests that reduced burning and increased gathering and use of crop residues will become increasingly common in the coming decades. Such trends are already observed in countries like Brazil, Mauritius and India, where bagasse cogeneration is now viewed as a strategic energy asset. Green cane harvesting with the use of chopper harvesters (full mechanization) favors the availability of sugarcane agricultural residues, but it is generally undertaken in suitable topographies and where upfront appropriate land preparation and cane cultivation have been done. Such an option is possible for large growers or grouped planters. On the other hand, based on figures reported by Meyer and Fenwick (2003), it is found that cutter output is higher for burnt cane by around 25% while it was found that manual harvesting is more expensive than mechanical harvesting (Ahmed and Alam-Eldin 2014). Thus, the use of manual, semi-mechanical or mechanical harvesting would highly depend on cost of labor besides land suitability and the environmental regulatory framework.

Cane supply chains are mainly influenced by the topography: large vehicles enter the fields in flat areas whereas in difficult topographical areas small in-field trailers transfer the biomass to larger road vehicles at loading zones. Tractor-drawn field trailers, rigid chassis and articulated trucks with payloads ranging from 5-30 metric tons are used for cane transport and efforts are geared towards improvements in vehicle utilization through the use of appropriate software. Rationalization of transport equipment and improved coordination can reduce production costs and is a current focus area of industry development efforts. Furthermore, to remain competitive in cane production, its cultivation is being moved from marginal areas to more appropriate land. However, within the production system, the high-cost areas of harvesting and transport could be improved by introducing a logistics benchmarking system and vehicle scheduling software, while emphasis on the design of haulage vehicles is also likely to increase productivity (Johnson and Seebaluck 2012).

Cane residues provide many agronomic benefits (soil protection against erosion, weed control, nutrient recycling and increase in soil carbon) and a few problems (risk of fire, delay in ratoon sprouting and difficulties in some agricultural operations) when left in fields. Burning before harvest may result in long-term decline in productivity, especially for highly erodible and infertile soil. The issues of cane burning, left-over, or collection of the cane residues have received major attention in many cane producing countries and have been assessed with respect to the benefits, soil impacts and economics for energy generation (CTC, 2005; Hassuani et al. 2005; Leal and Hassuani 2006; Purchase et al. 2008; UNDP 2009; Seebaluck and Seeruttun 2009; Johnson and Seebaluck 2012). Harvesting of cane residues requires additional changes to harvesting and transport systems, thus requiring cost assessments that include the economic value of residues and recognize local and regional differences. Assessments based on short-term economics may give different results from those that take long-term crop yield effects into account, but there is normally scope for harvesting of some portion of the non-stalk components of cane without adverse long-term effects.

In an analysis of the electricity generation potential of cane agricultural residues in Mauritius, Seebaluck and Seeruttun (2009) concluded that burning a mixture of 70% bagasse with 30% cane residues is optimum and would involve collecting 35% of the total residues while the rest could be left for preserving the agronomic benefits to the soil. In Brazil, several studies have been conducted on sugarcane straw impacts on soil organic matter (SOM) (Canellas et al. 2003; Razafimbelo et al. 2006; Galdos et al. 2009; Cerri et al. 2013) demonstrating that there is a significant positive impact of the straw on the ground. This was also verified for Australian conditions (Wood 1991). Based on specific field experiments, Braunbeck and Magalhães (2010) showed the importance of straw on soil erosion and soil water retention. Nevertheless, to date, there are no agreed to minimum values of straw biomass to be left in the field as this depends on soil topography and climate.

Straw recovery routes have been evaluated in several field tests and incipient commercial operation in some mills, but the technologies are still in the developing stage and need to be optimized while taking into consideration the local conditions. Three basic systems have been used in these tests: baling, whole cane transport (straw and cane are transported together and separated at the mill in a dry cleaning station) and hay harvester (Hassuani et al. 2005; Leal and Hassuani 2006). The latter approach has been discontinued due to high maintenance costs. Doubts persist about the best system, but there is a tendency to accept that harvester and whole cane system are good systems whereas baling may be better for longer distances (Hassuani 2013). Another advantage of baling is the low straw moisture content of around 10-15% while whole cane system delivers straw with moisture content of the order of 35-40%. The main disadvantages of baling are high ash content (up to 10%), availability of short period for baling after harvest, soil compaction and ratoon damage by the baling machine.

The recovery costs have not yet been consolidated with the literature indicating a wide range of values. Hassuani et al. (2005) indicated costs of US$ 18/t straw (dry basis) for baling and from US$ 14-31/t straw (dry basis) depending on the amount of straw recovered. Perea (2009) gave the recovery cost of straw delivered at the mill gate as R$ 58-63/t (~27.0-29.3 USD/t) for hay harvester, R$ 69/t (~32.1 USD/t) for baling and R$ 31/t (~14.4 USD/t) for whole cane system. However, it was found that sugarcane residues represented a significant amount of biomass that could be made available at the mill at an attractive cost. This material could then be used for surplus power generation, second generation biofuels or other biomaterials production.

11.6.2 Eucalyptus

Eucalyptus is among the fastest growing hardwood plantations widely cultivated for bioenergy in many countries with practical cases in Australia, Brazil, Hawaii, Ireland, South Africa, Uruguay, and Venezuela (Gonzalez 2008). Its conversion technologies are mature and well understood while several others are being developed (Rockwood and Alan 2008). Generally, for wood plant species to be economically viable, it should produce high (or moderate) density wood that easily dries, having suitable chemical characteristics and be easily harvested using appropriate machinery all year round. Eucalyptus largely meets these criteria as it has a high productivity potential over short rotations. It tolerates a wide range of soil types, commonly exhibits straight stem forestry production and, unlike other trees, it does not have a true dormant period and it retains its foliage which enables growth during warm winter periods. However, efficient harvesting of eucalyptus remains a challenge and cost-effective harvesting machinery has yet to be improved in leading eucalyptus producing country such as Brazil (Couto et al. 2011).

Eucalyptus is highly productive in temperate forestry and has yields of 18 m^3/ha/year over 12-year rotation with single species clones (AFOCEL 2003) and up to 35 m^3/ha/year with hybrid clones in France (AFOCEL 2006). Field trials in the US gave rotation length and yields for pulpwood of 5 to 8 years with a mean annual increment of 19.8 to 39.5 green metric tons/ha/year or 10 to 20 dry metric tons/ha/year (Gonzalez et al. 2011). Wood density is important as it largely determines the calorific value per unit volume (Neilan and Thompson 2008) and eucalyptus has denser wood than other species utilized for biomass production over short rotations: Short rotation coppice willow has a wood density of 0.4 Mg/m^3 (Nurmi and Hytönen 1994) whereas Eucalyptus nitens grown on two sites in Australia has a density of 0.471 Mg/m^3 and 0.541 Mg/m^3

respectively (Greaves et al. 1997) while Eucalyptus Gunnii grown in the Midi Pyrenees in France has a density of 0.5 Mg/m^3.

Eucalyptus plantations may yield wood fiber at a competitive cost if the harvesting operations are optimized (Spinelli et al. 2009). Currently motor-manual tree harvesting techniques (using chainsaws) still dominate in eucalypt plantations worldwide. The projected increasing trends and competitiveness in commercial wood supply of eucalyptus create demands for the mechanization of forest harvesting operations as labor becomes increasingly scarce and expensive. Even where motor-manual harvesting techniques are still competitive, there is a general interest to mechanize operations to streamline the timber harvesting process and anticipate future labor shortages.

There are two main options for harvesting and transport of eucalyptus, namely cut-to-length (CTL) and whole-tree (WT) harvesting. The former includes harvester-debarker, CTL timber forwarder and roundwood truck whereas the later is generally comprised of WT feller-buncher, WT forwarder, delimber-debarker-chipper (DDC) and chip lorry. The CTL system is popular in Europe while the WT system is favored in the US (Spinelli et al. 2009). Mechanical felling-processing is the highest cost item in CTL harvesting, representing around 40% of the total delivered cost whereas in WT harvesting, chipping and transportation each account for roughly 36% of the total delivered cost (Spinelli et al. 2009). In Australia, the optimization of the transport scheduling of woodchips for in-field chipping operations was examined and it was found that significant savings could be made in transport and chipping operations (Acuna et al. 2012). Hence, optimization of these process stages could maximize returns.

A WT harvesting system is generally less costly than a CTL harvesting system with the delivered cost being about 20 euro/green metric ton of bark-free pulp chips compared to CTL harvesting which is around 25-30 euro/green metric ton of debarked pulp roundwood (Spinelli et al. 2009). WT harvesting may allow for additional revenues by saving the cost of chipping at the plant and by favoring the cost-effective exploitation of logging residues as a boiler fuel. However, the WT system has its own weaknesses, such as the need for large landing space for parking the DDC unit and the high cost of the equipment.

11.6.3 Elephant Grass/Miscanthus

Miscanthus, a C4 perennial grass, is a promising resource for use as solid combustion fuel given its high yield potential, low requirements for soil tillage, weed control and fertilization as well as the long crop cycle of up to 25 years (Clifton-Brown et al. 2008). It is a fast growing plant with growth rates as high as 40 tons of dry biomass per hectare per annum and can be harvested up to four times a year which makes it a prospective crop for energy use (Strezov 2008). An energy analysis of the crop gave a high energy ratio of 45.3 (Angelini et al. 2009) showing its high bioenergy potential, although the analysis did not take into consideration the conversion of the biomass to energy. *Pennisetumpurpureum*, commonly known as Elephant grass, is equally a potential crop having high biomass productivity that can be used for energy production through combustion (Morais et al. 2009; Morais et al. 2011); it has an average gross calorific value of 18 MJ/kg (Flores et al. 2012). Even if the crop is mainly intended for combustion, there has recently been interest in utilizing it as a feedstock for lignocellulosic biorefining technologies (Haverty et al. 2012; Melligan et al. 2012). However, options for the future use of the crop depend on the economics and environmental performance of its production, supply and processing.

There are two harvesting systems for miscanthus, namely self-propelled forage harvester that harvests and chops the biomass and then blows it into a trailer, and pull-type harvester-baler that delivers large bales. Both harvesting systems are presently used for the collection of miscanthus in Devon (UK), where large-scale commercial production of herbaceous energy crops is undertaken (Smeets et al. 2009). However, the standard method of harvesting involves mowing and baling (Richard et al. 2012). According to OMAFRA (2010) and based on the expected peak yield of miscanthus, the cost of mowing and baling is estimated to be $356/ha.

Storage for an average of six months is required for the continuous availability of miscanthus in power plants. Storage is possible in farm buildings or open air (without covering) or covered with plastic sheets or organic materials. The cheapest and most common option is open air storage with plastic sheeting (Jones and Styles 2008) which is also commonly applied to store silage. Storage in new buildings is expensive, unless existing buildings are used. Open air storage without covering is problematic due to the loss of biomass from decay, whereas open air storage covered with organic material is only attractive when suitable and cheap organic wastes are available, which may not always be the case. According to Lewandowski (2000), covered outdoor storage of chopped or baled miscanthus was adequate to bring moisture content down to less than 20% thereby avoiding costly forced drying of harvested biomass (Gigler et al. 2000) before it could be utilized in small-scale boilers.

Transportation of harvested miscanthus by trucks is the most cost effective option for distances of 100 km or less (Perlack et al. 2002). According to OMAFRA (2010), the costs of hay production, loading, transportation, and unloading of the bales is $61.44/ha whereas the cost of chopping/shredding prior to combustion is estimated based on the use of a hammer mill (Mani et al. 2006).

11.6.4 Palm Oil

Oil palm is an important oil-bearing crop of the tropics with a high outturn of oil per unit area. World palm oil production is on a steep rising path and it is the highest yielding plant among major oil crops producing on average about 4-5 metric tons of oil/ha/year, about 10 times the yield of soybean oil (Choo et al. 2005). In the world market, Malaysia and Indonesia account for 90% of the palm oil export and they will likely remain the key players in the palm oil sector accounting for 28.5 million metric tons or 85% of the world's palm oil production (Sumathi 2008). Besides producing oils and fats, there is increasing interest for oil palm renewable energy namely bio-diesel production.

Crude palm oil is found to be the most attractive feedstock for industrial production of biodiesel (Vanichseni et al. 2002;Sumathi 2008). The attractiveness of palm lies in its high yield of oil which by far exceeds that of other vegetable oils. Moreover, its production cost is lower than other vegetable oils (Tan et al. 2009; Basiron et al. 2004; Boons and Mendoza 2010). Palm oil production is rapidly expanding due to the food sector increasing demand in developing countries mainly India and China while a minor fraction of around 12% is used as biodiesel.

Fresh fruit bunches (FFB) of oil palm can be harvested mechanically but are mostly harvested manually with some machinery and farm equipment while trucks are used for its transport. The first harvest is generally undertaken after five years of the plant cycle which is more than 30 years; however, it is generally replanted after 25 years because it starts getting too tall for convenient harvesting (Thapat 2008). Young palms are harvested with a chisel whereas along-handled sickle is used for tall palms and there is no fossil energy input to harvesting (Shabbir 2009). Workers usually carry the bunches to the road and load them in trucks for transportation to processing units. Pleanjai and Gheewala (2009) estimated the transportation fuel energy to be 7 GJ/ha.

Palm oil mills are generally located close to the planting areas to allow transport of harvested fresh fruit bunches within 24 hours to avoid excess generation of free fatty acid and to have a reasonably high oil extraction percentage (Shabbir 2009). During the process of oil recovery, waste biomass in the form of empty fruit bunches, fibrous fraction and shells can be used as fuel for the boiler house.

11.7 Concluding Remarks

Biomass supply chains involve critical elements that influence the viability of biomass to bioenergy projects. Some crops, such as sugarcane, provide useful experience regarding biomass supply for bioenergy production, although it is likely that further optimization in the logistic operations can bring added improvements. Thus, given the key multiple roles that bioenergy development could play in many world regions and its pressing need, key lessons could be derived from existing commercial biomass supply chains. This would be done to capitalize, replicate or adapt them to new and emerging bioenergy crops or for the desired modernization of the logistic operations of many energy crops that are so far underdeveloped. Generally, the main issue for an optimum biomass supply chain is to ensure a stable and continuous supply of suitable feedstock at competitive prices. This will require correctly designed cost-effective sustainable biomass supply chains. Scales of bioenergy crops production play a crucial role in the development of efficient and cost-effective supply chains as well as the overall bioenergy systems. However, given that bioenergy crops could also be potentially grown in rather smaller land areas, appropriate logistics operations should be developed to tap such potential as well as the associated socio-economic benefits. Therefore, it becomes important to provide technical and financial supports to innovate efficient biomass supply systems that are fully compatible with different production scales, the feedstocks quality and their processing.

11.8 Recommendations

- Existing biomass supply chains for bioenergy production should be modernized and optimized to improve the competitiveness of bioenergy projects.
- Key lessons should be learnt from existing efficient and cost-effective supply chains, and disseminated for application to other energy crops.
- Emerging tools (e.g. Agro-Ecological Zoning (AEZ)) should be used for identifying appropriate land for bioenergy production. Appropriate topographies would facilitate use of mechanized operations, which are appropriate for large-scale production. For marginal areas where bioenergy crops could be potentially grown, appropriate logistic operations should be developed, particularly in areas where the scale of production would be rather smaller but which may be associated with important socio-economic benefits.
- The overall legal and infrastructural framework necessary for the proper functioning of a bioenergy supply systems should be enhanced in particular for developing countries where poor road infrastructures may deter investors.
- The synergies or nexus of supply chains with other steps involved in biomass to bioenergy production (mainly agriculture and industrial processing) should be developed and optimized, for instance by adopting appropriate agricultural practices or by delivering raw materials that could be directly processed without pre-treatments.
- To alleviate the challenges of crops seasonality, adequacy of raw materials and year-round use of equipment and labor, appropriate cost-effective storage systems should be designed while other more practical options like multi-fuel processing (co-combustion or co-firing) in energy plants should be enhanced.
- Natural biomass drying should be favored as far as possible to avoid complex energy-intensive and costly front-end processing in factories which would also affect the overall energy and environmental balance of energy production from biofuel crops.
- Appropriate simulations and software should be used to facilitate the optimization of the structural units in the supply chains and improve the cost-effectiveness of the bioenergy system.
- All fractions of biomass crops (harvested part up to field residues) should be fully utilized as far as possible. The appropriate mass, energy and environmental balances should be undertaken to assess the potential and benefits.
- Technical and strategic options for decentralizing the activities involved in biomass supply chains should be developed to provide small scale entrepreneurship opportunities such as biomass densification (briquetting, pelletization or torrefaction) for sales to power plants.

- Efficient transportation systems that use less fuel, reduced fleet size as well as producing less GHGs emissions through the use of renewable fuels (bioethanol or biodiesel) should be promoted; it would improve the overall energy and environmental balances of the bioenergy project.

11.9 The Much Needed Science

- Specific tools using GIS and AEZ should be developed to identify suitable and available areas for bioenergy crops cultivation including subsequent efficient crop handling.
- Alternative modes of harvesting and transportation should be investigated in terms of energy use, environmental impact and their economics to indicate the best options for different world regions having different economical context. Typical supply chains for bioenergy crops production in marginal areas should be developed taking into consideration the specificity of the lands.
- The socio-economic impacts of scale of bioenergy crops production on the development and design of appropriate supply chains and the overall sustainability of bioenergy systems should be investigated given that small to medium scale bioenergy projects would much likely contribute in tapping the full bioenergy potential in many world regions.
- The internal or captive use of renewable energy, in particular biomass based fuels, as is the case in bioenergy processing plants, should be investigated and promoted in biomass supply chains to make the overall biomass to bioenergy system sustainable.
- Appropriate biomass densification techniques and equipment that can handle multiple types of biomass should be developed and deployed for field operations to improve transportation and storage for upfront processing. Other techniques such as pelletization should be deployed while emerging ones like torrefaction should be investigated with respect to its technical performance and economics.
- The appropriate fraction of biomass residues that should be left in fields for preserving the agronomic benefits should be investigated for specific crops to provide opportunities for collecting part of it for bioenergy production. The nutrients obtained in the form of ash or sludge in processing plants should be investigated for their potential reuse or recycling to fields as good sustainable practices.
- Multi-fuel processing (e.g. co-combustion or co-firing of several biomass types in a single furnace) in flexible plants should be investigated based on the physico-chemical properties of biomass collected, handled and sent to processing plants.

- Low cost in-field biomass drying options should be investigated in an attempt to reduce any equipment and energy-intensive upfront processing in bioenergy processing plants; on the other hand moisture tolerant conversion technologies should be developed.

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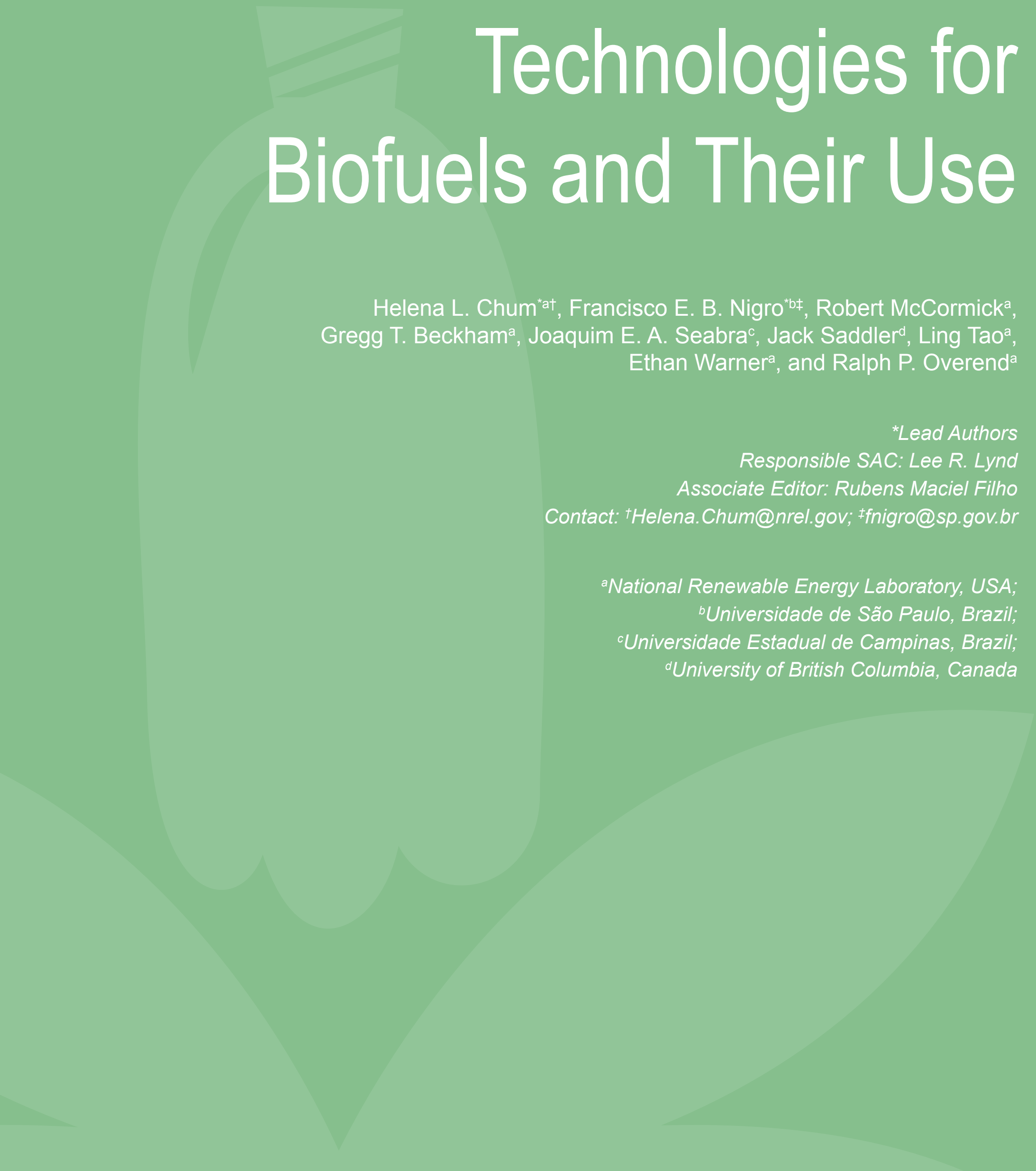
chapter 12

Conversion Technologies for Biofuels and Their Use



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Highlights

- Commercial biomass conversion technologies are improving, with respect to efficiency of resource use, and environmental impact mitigation and economic performance.
- Existing processes are addressing bottlenecks and improving on-stream performance in terms of operating hours at designed conversion plant capacity performance or better.
- Many processes are evolving from single outputs toward the biorefinery, with multiple products increasing the economic returns as in the Brazilian sugar industry producing electricity and combined heat and power with electricity export to the grid, and in other countries.
- Likewise, the corn dry milling process for ethanol reached into animal feed, while using the corn oil for biodiesel production, and is starting to bring in corn fiber for additional ethanol production. The industry that matured in less than a decade, increased production volume five-fold from 10 billion liters in 2003, increased average yield of corn and ethanol produced, increased energy efficiency, and decreased process environmental impacts.
- Ethanol, an octane enhancer, is blended with gasoline at low to higher level blends, or used as a neat fuel. Engine systems modifications are established for E10 level, and at higher levels they vary between countries. The environmental performance is generally good. In the two main user countries, engines are not optimized to take advantage of the fuel ethanol properties but to accommodate a range of blends. More than 50 countries use E5 to E10 gasoline. Overall ethanol consumption in 2013 was 1.8 EJ.
- Biodiesel, fatty acid methyl esters (FAME), come from many vegetable oils and a variety of waste cooking oils, animal fats, and greases, containing fatty glycerides reacted with methanol in small to large plants and are produced in many countries in small to large conversion plants. Overall consumption reached 0.87 EJ in 2013. Fuel quality in relation to feedstock and conversion process increased with process improvements. Many environmental performance improvements in the performance of 2 to 20% blends with diesel in road transport use were observed. Some distribution and infrastructure issues remain.

- A more recent commercial biofuel entry, using the same feedstocks as biodiesel, is hydrotreated vegetable oil (HVO), also called renewable diesel, evolving toward fuel products of the petroleum system, with no loss of performance in road transport, and produced, in part, by oil refining companies in commercial processes. In less than five years this fuel reached 0.12 EJ of consumption in 2013 (11% biodiesel mass; from 4.5% in 2011) and is growing fast. In petroleum refining processes, multiple ranges of products are made to generate the final fuels sold commercially, including gasoline, diesel, maritime, and jet fuels. Developers have qualified the jet biofuel fraction for commercial flights by reaching certification of the fuel. But much more needs to be done. Costs are still high so development continues to reduce costs in conversion processes and in feedstocks. Improving the logistics of lowest cost waste oil supply, reducing its costs, and certifying the supply chain to validate its origin are ongoing.

- Meanwhile, recent reviews of literature indicate that biofuels from lignocellulosic biomass such as herbaceous and tree crops, biomass residues, or municipal and other organic wastes could provide more benefits overall than biofuels currently derived from annual crops. Many of the benefits of lignocellulosic biofuels and systems are projected from pilot plant data and need to be assessed from data from operating commercial plants. Portfolios of conversion technologies are emerging to use these feedstocks making current biofuels and the suite of products made from petroleum, chemicals, and novel products, including animal feeds.
- A blend of biomass gasification-technologies-derived fuels and fossil fuels is producing jet fuel for aviation that is certified for in-flight use and has been tested but costs need to be reduced to reach commercial application.

- Novel biochemical technologies are using sugar and syngas resources to produce high quality fuels suitable for aviation fuel, and ethanol, isobutanol, and other products but costs have to be reduced. Recycling of CO_2 in biofuels, such as algae or other organisms, is also emerging.
- Steady investment and development so far has allowed lignocellulosic resources such as straw, corn stover, wood, and waste materials to produce ethanol, now at the pioneer plant scale in several continents, integrated with the existing corn, sugarcane, or forest products refineries, and also on a standalone basis. In parallel, approaches to make value added chemicals and materials are occurring from sugar, synthesis gas, or other intermediates from biomass.
- The use of the residues from crop production at sustainable levels reduces the need to expand crop production, and has the potential to lower environmental impacts, and reduce land use impacts of the final fuels.

- Development and commercialization of these technologies is moving at a slower pace than anticipated by governments or by the private sector for many reasons. Developers of the conversion technologies and their partners had to establish chains for:
    1. biomass production,
    2. logistics for biomass collection, storage, and delivery to the
    3. conversion facility for biofuel manufacture with agreements of purchase for
    4. fuel distribution and use, and to reach
    5. fuel product acceptance.
- More work is needed to bring the cost of these technologies down and to integrate all the elements of the value chain, including assessments of environmental performance and overall system sustainability (environmental, social, and economic) in the context of the specific location, its landscape and watershed.
- The positive outlook of advanced biofuels is conditional on accelerated deployment of whole supply chains. Accelerated deployment would help achieve: process stability, reliability, and availability that can lead to production costs falling to competitive levels. In conjunction with evaluation of multiple sustainability parameters over time and continuous improvement across the value chain it can propel the industry further.
- A complement to large-scale conversion plants described above is small-scale conversion systems to use multiple feedstocks available in smaller quantities and promote sustainable development opportunities in many countries, communities, and households. These developments use the economies of volume by manufacturing small plants in large quantities.
- Many examples of advanced small modular systems are emerging that can provide multiple benefits to the local communities, including improvements in soil quality, fuels, and local development. Such developments should be fostered and disseminated.
- All commercial liquid biofuels are increasingly being traded internationally; so are solid biomass pellets and other densified materials that enable transport at longer distances to supply a variety of markets, such as power generation and cogeneration for district heating and power. Many biofuels and feedstocks were exported and received sustainability certification according to criteria and principles defined by several sustainability schemes accepted by the EU Renewable Energy Directive.

Summary

This chapter describes the progress in the commercial development of biofuels and its use in transport in the context of the environment, sustainability, climate change, and existing and developing biomass uses. Three decades of investment and development have resulted in a budding bioeconomy, improved commercial systems, many using food feedstocks, and new ones employing various lignocellulosics feedstocks in many countries. In 2013, the total consumption of three liquid biofuels was 2.8 EJ, namely ethanol at 1.8 EJ, biodiesel or fatty acid methyl esters at 0.87 EJ, and hydrotreated vegetable oil (EU) called renewable diesel (US) with 0.12 EJ. There are smaller amounts of other biofuels such as methanol, dimethylether, and some hydrocarbons.

- **Ethanol**. Major commercial ethanol biorefineries have improved. The United States (U.S.) dry corn mill industry increased average yield and energy efficiency, and decreased environmental impacts while producing animal feed, biodiesel, and other products. The sugarcane to ethanol processes increased biomass use efficiency and developed electricity generation as a main industrial coproduct in several countries.
- **Biodiesel.** The use of biodiesel made from vegetable oils, used cooking oils, greases or fats and methanol continues to grow and improve product quality. Conversion plant scales go from small to larger in many countries.
- **Hydrotreated vegetable oil or renewable diesel.** Processing the same fatty-oil feedstocks or wastes in petroleum refining hydrotreating facilities generates hydrocarbons, generically called renewable diesel, with high acceptance and compatibility with diesel. These renewable hydrocarbon fuels reached 11% of the biodiesel mass consumed in 2013, (10% in 2012, from 4.5% in 2011).

All three biofuels are traded internationally among many countries. Increasingly all three fuels are certified with respect to their carbon dioxide (CO_2) emissions and other criteria as defined in accepted sustainability schemes by the European markets and participate in different subsidy schemes in operation in many jurisdictions. In addition:

- **Gaseous biofuels** have made advances as methane for transport in some countries and even had a higher impact inserted into the natural gas grid or in minigrids in many countries for various applications. Conversion of liquid residues or mixed materials to biogas, further upgraded to methane, is the most common source and from biomass gasification followed by catalytic upgrading to methane is entering local markets. Biogas fuel advanced in the developing world for applications of cooking, heating, and lighting while decreasing the environmental impact of low-efficiency cooking with primitive stoves. Overall, methane contributed with more than 1.7 EJ to these various applications in 2011.
- **Solid pellet fuels** enabled large-scale power and cogeneration applications with global trade of these solid densified fuels reaching 23.7 million tons in 2013 or 0.42 EJ (from 0.26 EJ in 2009).

Recent reviews of the literature following multiple lines of sustainability assessments indicate that biofuels from perennial and tree crops, biomass residues, or municipal wastes could provide more benefits overall than biofuels currently derived from annual crops. Many of the benefits of lignocellulosic biofuels and systems are projected from pilot plant data and need to be assessed from data from operating commercial plants. The emergence of portfolios of conversion technologies from lignocellulosic biomass to biofuels indicates possible pathways for decoupling bioenergy from food crops. However, the integration of conversion processes across multiple systems is necessary for successful sustainable outcomes to the economy, society, and environment. These outcomes are needed at small to large scales—from the specific facility, to regions, and globally. In addition to conversion systems for manufacturing biofuels and/or heat, power, products, food, feed, and fiber, consideration must be given to biomass production, the logistics and delivery of raw or processed feedstocks to the conversion facilities, and integration of these products with their distribution systems.

We describe the progress across the technology development curve for several processes in conversion portfolios. Initial classifications separated thermal, chemical, and bioprocesses but more hybrid systems are emerging and couplings of various types of processes because of advances in multiple fields of science, translational science, engineering, systems engineering, and advanced manufacturing.

Project-specific context within the value chain(s) has a significant impact on costs and sustainability considerations, and can introduce additional costs and/or incentives that are variable and in continuous flux, bringing uncertainty for additional private investment. Current experience shows that the longer testing is conducted at pilot scales solving integration issues at small scale, the more successful developers are at successful further scale-up. Better criteria for selecting processes to scale-up can decrease technical and commercialization risks.

Initial first-of-a-kind plants coupled with conventional biofuel production take advantage of the existing infrastructure set up, help solve waste problems in specific areas, and test new models of deployment. One development model includes adapting the size of the conversion facility to the supply of feedstock in a flexible manner (e.g., modular). Another approach is to focus supply chain design and logistics to enable larger scale conversion plants. We summarize with existing and developing examples of systems integration for biofuels production to road and air transport. While road transport applications can accept oxygenated liquid fuels by adaptation of existing or new engines and of fuel distribution infrastructure, such adaptation for aviation fuels is severely constrained. There is a pressing need for high-energy density carbon fuels with renewable carbon content that match the stringent fuel mixture properties and distribution requirements.

Advanced biofuels from lignocellulosic feedstocks are just beginning to be produced at industrial scales in plants that are undergoing normal de-bottlenecking to reach their design capacity. Between 2013 and 2014 several first-of-a-kind integrated commercial plants started operations in several continents coupled with existing established refineries or stand-alone systems. Developers are identifying multiple products for the biorefinery, improving the overall biorefinery economics through production of energy and a variety of chemicals/products with applications in multiple markets.

The positive outlook of advanced biofuels is conditional on accelerated deployment of sustainable whole supply chains. Accelerated deployment would help achieve: process stability, reliability, and availability that can lead to production costs falling to competitive levels. In conjunction with evaluation of multiple sustainability parameters over time and continuous improvement across the value chain it can propel the industry further. A very large number of families of patents have and are being developed by multiple partnerships to explore product applications.

Partnerships are global, fostered by national and regional governments, and multilateral bodies, associations, and associated supplier companies in many fields. The major portfolio pathways are indistinguishable within the uncertainties of public cost knowledge. These technologies have to be tested with the feedstocks and conditions of the actual sites because of the inherent variability of plant-based systems and infrastructures for supply and product distribution, unless research on uniform feedstocks succeeds on delivering reliable, cost effective, and sustainable supplies.

The design of the sustainable biomass value chains benefits from multiobjective optimization that can be achieved through the systematic analysis of the integrated system. Such an integrated assessment includes production of feedstock, conversion, and products utilization at the specific landscape and watershed of biomass production, and in the specific economic system.

Integrated assessment studies are beginning to take place in both developed and developing countries. Initial frameworks for understanding sustainable systems exist. The frameworks need to be expanded beyond greenhouse gas (GHG) emissions and energy balances historically used in conversion processes. Small- and large-scale developments are needed because various countries have diverse feedstocks and potential supplies. Additionally, significant science and technological innovation needs to continue—not only in individual parts of the value chain but also in integrating feedstock and conversion systems. Increased availability of site-specific spatial and temporal sustainability assessments data from actual implementation of projects will go a long way to facilitate dissemination of best practices and growth of the bioeconomy.

12.1 Introduction

Biomass such as the organic material contained in plants (such as trees and agriculture) and animal residues have been used as an energy source since the emergence of humans about one million years ago. In the Industrial era, the use of biomass for energy has taken divergent paths:

- There is still the traditional and indeed largest use of wood biomass for cooking and industry in developing countries.
- Meanwhile there is a rapidly growing biofuel and bioenergy industry in many countries around the world.

The traditional use relies on inefficient combustion technology at generally small scales of individual household use, however 2.8 billion people rely on this with its attendant health risks that make it the third most important cause of death and disability in developing countries according to the assessment by the World Health Organization (WHO) for 2012 (WHO 2014). Biomass is the primary energy resource for the foreseeable future for one third of that population inhabiting the 49 least developed countries in Africa and Asia (IPCC 2014). There are also social and wider regional impacts of the air pollution generated by the artisanal stoves, although impacts decrease with properly designed and culturally adapted cooking systems (Anenberg et al. 2013; IPCC 2014). The work of governments, multilateral organizations, and the Global Alliance for Clean Cookstoves has, so far, kept pace with the increased population, as metrics are increasingly used to track global progress (Banerjee et al. 2013). Some leading experts in the public health field consider that the replacement of this use of biomass by clean fossil- or renewable-derived fuels such as liquid petroleum gas (LPG) or methane provides more sustainable systems solutions (Subramanian 2014). WHO is also updating household indoor air quality guidelines for household fuel combustion, which considers new health impacts data.

In the mainly industrial countries, biomass combustion is conducted at large scales with very significant gains in efficiency, which coupled with modern emissions control technology, results in very clean energy delivered to industrial processes, power generation, and district heating. The range of more convenient biomass energy carriers includes pelletized wood fuels, gaseous fuel from anaerobic digestion, and liquid transportation fuels. There is also a growing renewable chemicals sector, beyond specialty products and pharmaceuticals. Figure 12.1 illustrates the relationships between the terrestrial part of plant production, the logistics and processing chain, and the use of biofuels or bioenergy. Between 2005-2013, there was a three- and four-fold increase in production of wood pellets for electricity, heat, or combined heat and power (CHP), and of liquid fuels for transport (also shown in Figure 12.1) (IPCC 2014; REN21 2014). Gaseous fuels are used locally or regionally and the average growth rate was 15%/yr while liquid fuels were growing at a 12% annual rate between 1990 and 2008 (Chum et al. 2011).

12.1.1 Environmental and Sustainability Context

As the biofuels markets scaled up, the sector has come under scrutiny for environmental sustainability, as well as the social consequences of the interaction of the energy sector with the food and fiber production system as shown in Figure 12.1. Issues of land use in agriculture, forestry, and land use change were not new. They have been addressed

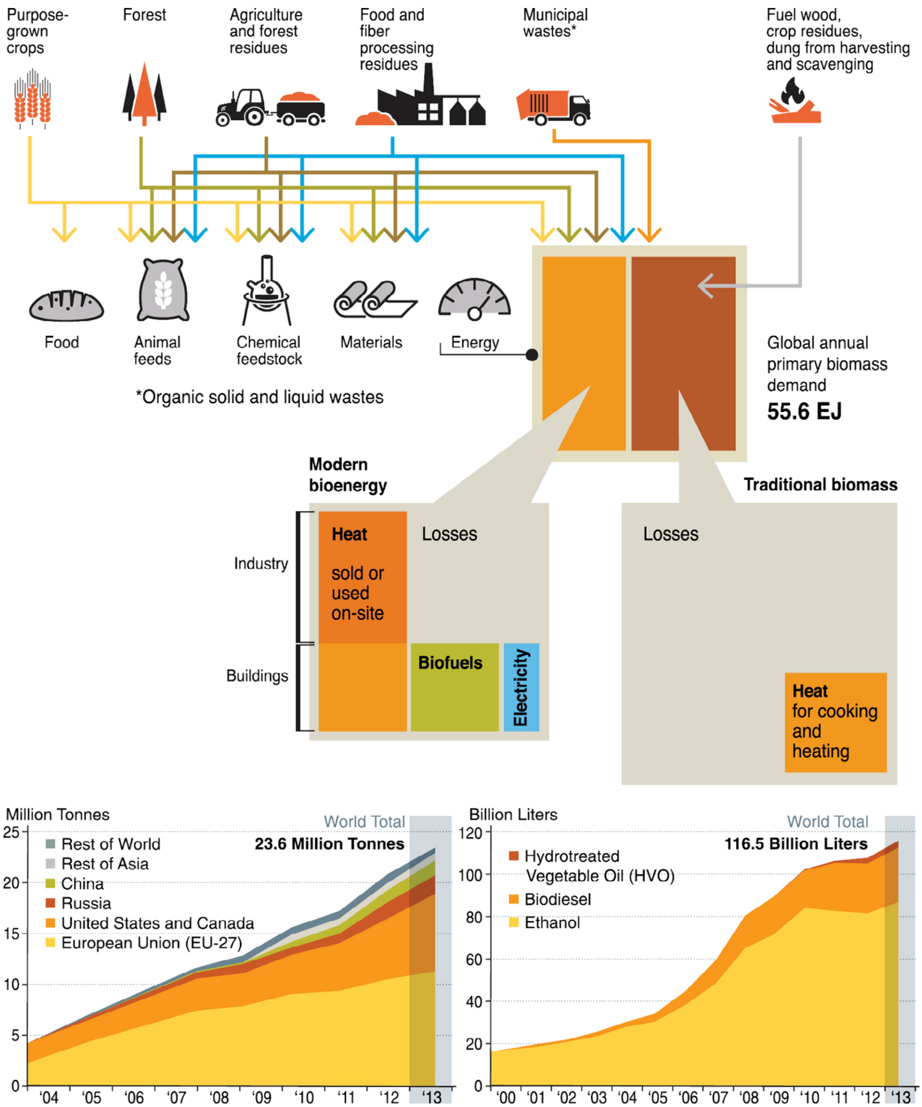

Figure 12.1. Shown at the top of the figure, breakdown of the useful bioenergy from multiple biomass resources employed in various sectors and of the associated energy losses in two major groups of traditional and modern bioenergy. Shown at bottom left, more convenient, denser solid energy carrier (wood pellets) are being used in cold climates for district heating and widely for coproducing heat and power. Shown at bottom right, commercial production of oxygenated liquid fuels, ethanol, and biodiesel, and the more recent hydrocarbon fuels from hydrotreated vegetable oils (HVO) (Modified from the 2014 Renewables Global Status Report with permission from REN21 (REN21 2014)). Gaseous fuels derived from anaerobic digestion had similar high growth rates (Chum et al. 2011).

by the Intergovernmental Panel on Climate Change (IPCC) since the nineties and are issues for all uses of biomass and land (IPCC 2000).

Bioenergy applications at the industrial scale got their start by using residues associated with particular biomass processing industries with energy needs, such as the pulp and paper sector in which the paper product uses only part of the harvested wood leaving copious residues. This provided a large technology base especially in combustion technology, as well as in the logistics and handling of what is a low-energy density fuel. Commercial biofuels started as byproducts of chemical pulping of wood over a century ago; however, the major growth has been through the use of agricultural crops (sugarcane, maize, wheat, and oil seeds). Commercial biofuels and wood pellets are traded globally with production increases resulting from policy decisions followed by legislation, regulation, and government programs in many countries that mobilized private sector investment (Chum et al. 2011; Chum and Overend 2003).

The linkage of biomass, bioenergy, and biofuels and the sustainability of the system in which they operate, has been the subject of research reviewed from multiple perspectives recently in several chapters of the IPCC 5th Assessment Report and other references (Chum et al. 2011; Creutzig et al. 2014; IPCC 2014; Scovronick and Wilkinson 2014). The energy supply and use are coupled with each other through material stocks and flows leading to feedbacks and delays. Policies to accelerate production of biomass and biofuels interacted with energy supply and use as well as with the systems of Figure 12.1. Policies often had multiple objectives such as energy security, economic development, and specific environmental goals such as climate change mitigation.

Multiple lines of analytical frameworks were developed to understand complex relationships of these systems and to investigate climate mitigation and sustainability science. Each framework has significant assumptions, limitations, and methodological issues, causing experts of each field to come to divergent viewpoints on the bioenergy potential and GHG emissions mitigation, principally when used at large scales (IPCC 2014[1, 2]). Sustainable development indicators and metrics are being proposed and tested with available literature for biofuels (Martins et al. 2006; Sikdar 2003; Mata et al. 2013) but care is needed when comparing and interpreting metrics for prospective technologies relative to commercial industrial systems, which could be current or retrospective (Herrmann et al. 2013; Herrmann et al. 2014; Hertwich, 2014).

Life cycle assessments were used as one of the most common tools to derive the GHG emissions in setting frameworks for legislative actions, and are used to assess other environmental impacts (see Box 12.1 for examples of impacts; for uncertainties see references (Herrmann et al. 2013; Herrmann et al. 2014; Hertwich 2014). One example shown in Box 12.2 illustrates another methodology where materials production and

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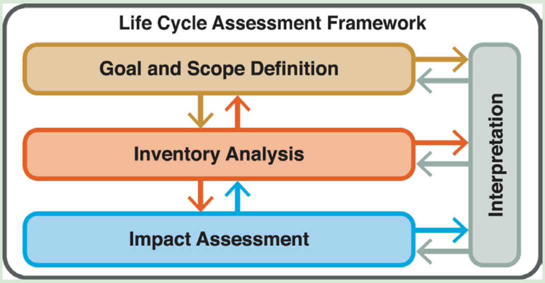
[1] Fleurbay et al., Sustainable Development and Equity, in working group 3 (WG3) in IPCC, 2014, http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter4.pdf

[2] Krey et al., Metrics & Methodology, section A.II.6 Material flow analysis, input-output analysis, and lifecycle assessment in WG3 IPCC, 2014, http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_annex-ii.pdf

consumption are linked to GHG emissions (climate) and overall environmental degradation (environment), in the various economic sectors. Analyzing their flows and impacts, the most impactful areas are identified. Box 12.2 is region-specific—the European Union (EU 27), where the use of animal and fossil fuel products that scale proportionally to consumption, generated the biggest impacts on climate and environment, relative to all other products used. Another methodology extends the materials flow analysis coupled to human-environment systems, such as the "human appropriation of net primary production" (HANPP). HANPP assesses human-induced changes in biomass flows in terrestrial ecosystems (Haberl et al. 2007; Vitousek et al. 1986), which is applied to assessing feedbacks in the global land system to production and consumption of food, agricultural intensity, livestock feeding efficiency, and bioenergy potentials thus impacting both residue potentials and land area availability for energy crops (Erb et al. 2008; Haberl 2013; Haberl et al. 2011).

Box 12.1. Major environmental impact categories and common characterization methods[1]



The figure illustrates that life cycle impact assessments follow elementary flows across the boundary limits of the bioenergy chain.

1. **Acidification:** Accumulated excess, characterizing the quantity of acidifying substances, and the specific location of the emissions in relation to sensitive areas in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.

2. **Climate change:** Global warming potential calculated from the radiative forcing over a 100-year time horizon, used to express GHG emissions in CO_2 mass equivalent.

3. **Depletion of abiotic resources:** Quantity of resources used relative to quantity in reserve. Applies to minerals, fossil fuels, water, etc.

4. **Ecotoxicity:** By examining the potentially affected fraction of species integrated over time and volume per unit mass of a chemical emitted (terrestrial, aquatic, air).

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[1] Acero et al. 2014; EMPA 2012; Hellweg and Milà i Canals 2014; Powell 2010

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5. **Eutrophication:** Accumulated exceedance—a site dependent category based on quantity of a nutrient emitted, relative to the background level; in fresh water (P considered limiting factor), marine (N considered limiting factor), terrestrial (varies depending on the sensitive area involved).

6. **Human toxicity:** Expressing the estimated increase in morbidity in the total human population by the chemical(s) involved separated into carcinogenic and non-carcinogenic effects.

7. **Land Use:** Soil organic matter (SOM) based on changes in SOM carbon, measured in kg/ha.

8. **Ozone layer depletion:** In the stratosphere over a 100-year time, sum of ozone depleting chemicals, expressed in CFC-11 equivalents.

9. **Particulate matter:** By quantifying the impact of $PM_{2.5}$ and PM_{10} in terms of premature death or disability.

10. **Photochemical ozone:** Quantity of volatile organic compounds (VOCs) and NO_x, may be expressed in ethylene equivalents. They react in the atmosphere to form smog.

Box 12.2. Resource efficiency and climate change mitigation studies

Studies to understand how economic growth can be decoupled from environmental degradation explored materials flows analysis, for instance, of a basket of products produced (includes imports) and consumed, coupled to life cycle assessment in the EU. The results shown in the figure below indicate that consumption of animal products and fossil fuel products (for energy and materials) at 5% and 20%, led to 35% and 25% of the global environmental degradation, while contributing to 20% and 60% of GHG emissions, respectively. Crop production at about 12% consumption contributed 20% and 10% to environmental degradation and GHG emissions. The forestry sector in this analysis showed low impacts in both areas compared to consumption. This approach fosters considerations of resource efficiency—how to achieve desired products or energy efficiently in addition to GHG emissions for that specific geographic location, its economic characteristics, and values in characterizing the protection of humans, ecosystems, and resources in their economy. In addition to climate change impacts by GHG emissions, priority pressures and impacts included

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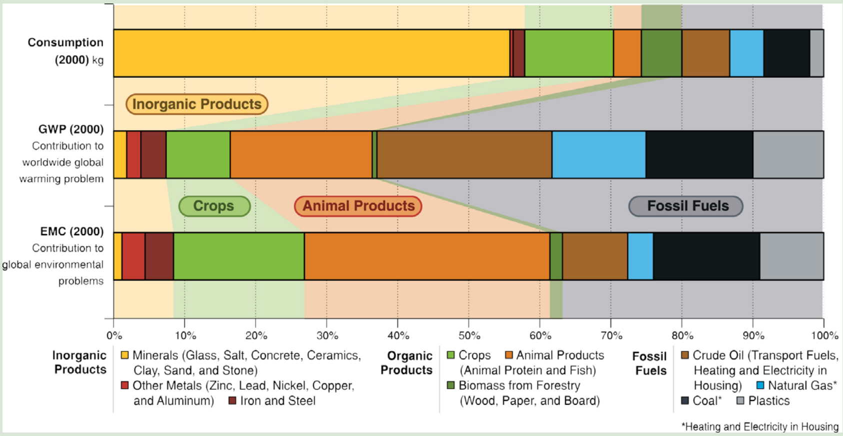
eutrophication caused by pollution with nitrogen and phosphorus by over-fertilization; human and ecotoxic effects caused by urban and regional air pollution, indoor air pollution and other toxic emissions; relative to resource use the depletion of abiotic resources (fossil energy carriers and metals) and of biotic resources (notably fish and wood); and habitat change and resource competition due to water and land use. These results were obtained by the International Panel for Sustainable Resource Management of the United Nations Environment Programme (UNEP) (UNEP et al. 2010).



The figure indicates the normalized contribution to Global Warming Potential (GWP) of material flows and Environmentally-Weighed Material Consumption (EMC) for the EU 27 + 1 region (UNEP et al. 2010). Note that in the EMC, values are assigned to different groups of indicators to reduce multiple variables to single numbers, a practice not globally accepted.

The UNEP Panel is currently working on managing and conserving the natural resource base of economic and social development. They are helping frame Sustainable Management of Natural Resources in the United Nations Sustainable Development Goals for Equity, Environment, Economics for a Sustainable Future, including land use management [1].

For small-scale bioenergy, a strong consensus propels increased efficiency of traditional biomass combustion while fostering sustainable biomass supplies. Sustainably managed feedstock supplies in many developing countries today vary from 35%-85% of the feedstocks used (IPCC 2014; Smith et al 2013). Generic statements become more difficult to make because bioenergy is site specific. Often favored are perennials such as sugarcane, miscanthus, and other herbaceous crops, short rotation woody crops, and the use of residues. Overall outcomes depend, among others, on (a) governance of land use, (b) increased yields of production of biomass for bioenergy, agriculture, and forestry, and (c) deployment of best practices in agricultural, forestry and biomass production (Creutzig et al. 2014), among others. A fundamental component to decrease the yield gap between developed and developing countries is basic research in photosynthesis to further increase yields in terrestrial and aquatic biomass production (Hall and Richards 2013; van Ittersum et al. 2013). The various models, systems, and networks of methodologies are increasing the understanding of products and supply chains (including the less studied bioenergy and biomass supply chains for conversion), helping identify “hot spots” in environmental and cost performance, and increasingly considering social aspects. The sustainability assessment field is starting to move from static comparisons of inventories (snapshots) to dynamic (temporal) and spatial analyses (flows) at landscape and watershed levels, to decrease the uncertainties of climate change mitigation of large-scale bioenergy (Creutzig et al. 2014; Hellweg and Milà i Canals 2014; IPCC 2014) and more accurately reflect all climate change global and local effects (IPCC 2014).

Selecting from the wide range of biomass feedstocks, conversion processes, and uses (heat, power, fuels—gaseous or liquid) and determining which combinations are the most appropriate for a specific location requires a framework with specific assumptions. A study conducted by the European Environmental Agency (EEA) compared the current policies, which use market ready technologies, with a scenario requiring high resource use efficiency in all applications with built-in climate considerations. The study restricted land areas to protect biodiversity and excluded areas of high soil organic carbon (e.g., peat lands). In addition, it required sustainable feedstock production practices, and small/medium size conversion facilities with small carbon environmental footprints. Feedstock included EU-produced agriculture, forest, waste biomass, and imports. The details of the scenarios studied and methodologies are described by EEA (EEA 2013). Bioenergy comprises 68% of the renewable energy, with 48% being wood and its residues, and the remaining other biomass crops and residues (AEBIOM 2013).

The conversion technologies investigated are shown in Figure 12.2 for power, heat, and biofuels. The net efficiency of conversion of biomass to the energy products on a life cycle basis, from harvested biomass to bioenergy use, is shown for a range of high and low overall net efficiency conditions for specific technologies (EEA 2013). Figure 12.3 summarizes the results for the two scenarios indicating the following changes in proportions: increased electricity, less heat, and half biofuels. However, instead of generating 79 kg CO_2eq/GJ of biofuel, the GHG emissions from lignocellulosic biofuels energy crops would produce nearly zero emissions and be more resource-productive than current rapeseed biodiesel production in the EU 27. Figure 12.4 shows the current crops used for biofuels and the projected environmentally compatible with higher resource efficiency crops based on this framework. The specific European situation, geographic area, and economic conditions show that increased resource efficiency makes more energy product per unit of land area used, and reduces the amount of biomass needed because these are high product efficiency routes for power, heat and biofuels. In this story line, the overall high resource productivity generates low levels of waste and pollutants to air, water, and land (Petersen et al. 2014).

Each country/region would need to analyze its own situation to select combinations of biomass for food, feed, fiber, and biomass for energy most suitable to their circumstances including socio-economic parameters, scale of operations, supply chains, and environments (Kostin et al. 2012; Mele et al. 2011; van Eijck et al. 2014).

Models for using land more efficiently for animal feed production (e.g., leaf protein, pre-treated crops, and double crops) from the same land area, project maintaining domestic food production and agricultural exports, while increasing soil fertility and biodiversity in the context of the U.S. agriculture (Dale et al. 2010). This view is illustrated in Figure 12.5. The model projects a 670 Tg CO_2 eq/yr using a third of the total cropland for a biofuel. Other resource efficiency considerations were not investigated. Borders of perennial energy crops or short rotation woody crops could provide buffer zones for commercial crop production and reduce environmental emissions by absorbing run off fertilizers and pesticides (Gopalakrishnan et al. 2012). The integration of bioenergy systems into agriculture and forest landscapes can improve land and water use efficiency and help address concerns about environmental impacts (Creutzig et al. 2014).

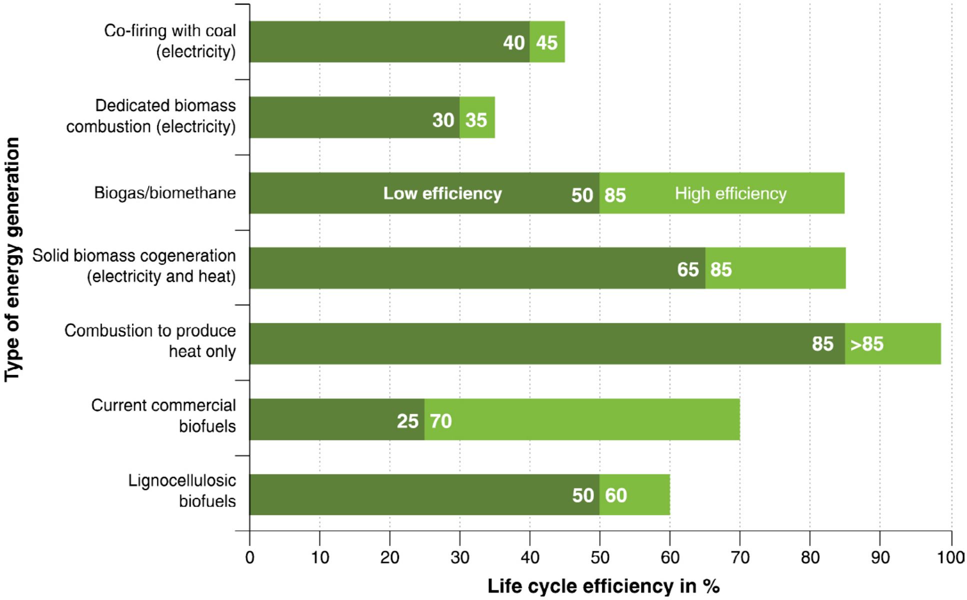


Figure 12.2. Net efficiency range of biomass-to-energy pathways on a life cycle basis from harvested crop to power, heat, and biofuels considered by the (EEA 2013) for current applications and developing lignocellulosic biofuels. Reproduced with permission from EEA.

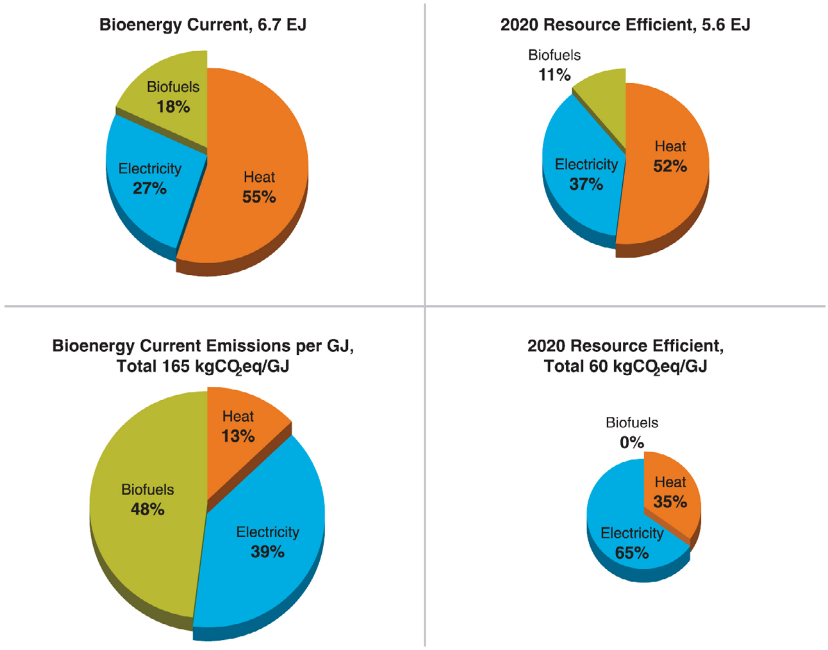


Figure 12.3. Current bioenergy in GJ compared to a 2020 projection emphasizing resource efficiency for all biomass applications including climate change mitigation using EU-produced and imported biomass. Also shown are the average GHG emissions for current commercial technologies for heat, electricity, and biofuels and a 2020 projection with advanced biofuels from lignocellulosic energy crops (EEA 2013).

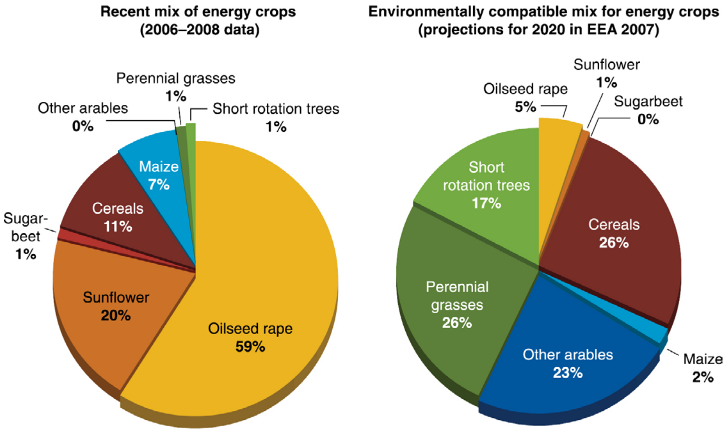


Figure 12.4. Mix of energy crops used in Europe from 2006–2008 (left) and the 2020 EEA modeled crops for high yield of products per unit area used, low waste and pollution, including low ecosystems impacts and high GHG emissions reductions in 2020 (right) (EEA 2013). Reproduced with permission from EEA.

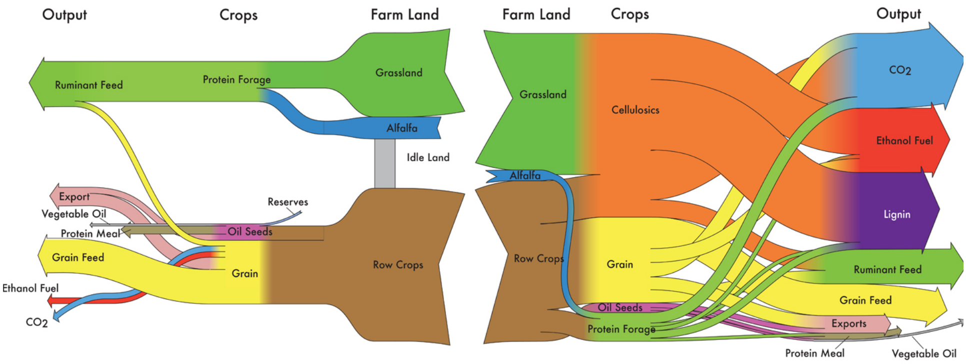


Figure 12.5. The current allocation of 114 million hectares in the U.S. is shown on the left. Modeled annual mass flows from a land efficient allocation (right) showing major crops and outputs for a scenario of maximum ethanol production. The CO_2 listed is biogenic carbon released during fermentation (Dale et al. 2010); reproduced with permission.

12.1.2 Technology Development and Deployment Context

This chapter addresses improvements in commercial biomass and commercial biofuels production and use. Current use situations span the range from (a) existing distribution and transport infrastructure with vehicle manufacture adjusted to the biofuel and (b) adapting a massive infrastructure in place to different levels of biofuels occurring at the same time that regulation lowers vehicle emissions, which also requires increases in overall vehicle efficiency. These use situations provide important lessons that can help countries develop their resources and infrastructure, or adapt infrastructures to climate change.

Lignocellulosic biofuels technology development is linked with the simultaneous establishment of the feedstock production and logistics to provide sustainably produced biomass to conversion facilities. These efforts are starting in conjunction with existing corn ethanol refineries or sugarcane ethanol as the product storage, distribution, and use, are established or coupled to urban residue collection. Detailed examples of setting the feedstock infrastructure for sustained supplies, their specific environmental assessment and management systems—developed with many sustainability considerations—have been performed as described in [2]. Instead of an exhaustive coverage of conversion technologies and multiple uses, the chapter shows examples. The examples include building systems, learning impacts of rates of penetration from their establishment, and environmental aspects including of fuel use. Production of biomass-derived hydrocarbon fuels that serves road transport and the more regulated and constrained fuelling infrastructure system for air transport. Power and heating infrastructures are more mature and established, although we show examples of improved cogeneration opportunities in the existing commercial industry.

Many biofuels and bioenergy developments are already producing commercial products in bio-based materials and renewable feedstocks for the chemical industry around the world (IEA-ETP 2013; Singh 2010; Vennestrøm et al. 2011). Iles and Martin (2013) describe current examples of commercial bioplastics that were built using business models that linked producers and customers through the development of new technologies and products at DuPont, BASF, and BRASKEM (Iles and Martin 2013); 25 "hot molecules" are under various phases of development [3]. This trend is reinforced in the U.S. by the lighter oil products from shale hydrofracturing that will result in a decreased supply of C-3 to C-5 hydrocarbons for chemicals, making the renewable derivatives such as ethylene, isoprene, and para-xylene as well as specific biomass-derived chemicals such as 2,5-furandicarboxylic acid, isosorbide, and farnesene especially attractive as their costs decline (Hackett 2014) with continued technology development [4].

An S-shaped curve in Figure 12.6 characterizes technology developments in many fields, including renewable energy (Chum et al. 2011; Junginger et al. 2010), biofuel from corn production (Hettinga et al. 2009; Resch et al. 2013), and sugarcane (van den Wall Bake et al. 2009; Chen et al. 2014). The cost per unit of product (e.g., feedstock or biofuel) decreases from the original costs by a fraction at each doubling of cumulative production, i.e., a learning rate that follows a power law (Junginger et al. 2010). Learning rates of 32% and 45% described progress in sugarcane (van den Wall Bake et al. 2009) and corn feedstocks production (Hettinga et al. 2009), respectively from 1975-2005 in Brazil and in the U.S. For the conversion process, the learning rates were comparable at about 20%. As the technology matures, learning rates decrease unless significant innovation occurs across the value chain. This progress is roughly represented by the blue range in Figure 12.6. The performance is an index including product quality, capital investment, operating costs, and environmental performance.

Lignocellulosic biomass conversion processes to ethanol, other biofuels and chemicals, land-efficient animal feed, or power are represented schematically by the red line and adjacent hatched areas. Many advanced biofuels and bio-based products processes are at various stages of development and include many innovations or adaptations to the existing industry technology that span the range from the red to the green line. To arrive at the point of commercial production, development work at various scales is conducted on individual components of the process, prior to their integration into a process. Therefore, process integration is another important area, as the many individual steps are either not yet optimized or have not been optimized in a fully integrated process (Chum et al. 2011), usually involving many organizations. More specifically, research is needed at kilogram per hour (kg/h) scales to identify main characteristics of concepts; then at multiple metric ton per hour (t/h) of feedstock to identify detailed characteristics, operating the facilities to identify issues and solve problems. At the same time developers collect products and with the data obtain process performance information in continuous operation for a significant number of hours to enable prediction of performance for further scale-up. With increased confidence in the process performance, technical risk decreases and further scale-up proceeds to gain confidence in decreased risk of capital investment in larger demonstration or first-of-a-kind commercial facilities [2] (see also Table 6.2 in chapter 6, this volume).

Fuels markets, like power markets, could require hundreds of large-scale facilities while chemicals at large scale do not require as many (Brown and Brown 2013; Vennestrøm et al. 2011). Premature scale-up toward commercial scale increases operation costs significantly and has caused many failed projects (Kirkels and Verbong 2011), significant delays, and increased costs [5]. Developers and their networks of suppliers of equipment and engineering and construction firms who succeed in the systematic development through various stages to reach a performance point that can be warranted have easier access to regular financing. This is the case, for instance, of the development of small- [6] to medium-scale gasification for heat and CHP applications [7](IEA Bioenergy 2010). Large-scale operations still have too high a cost of capital and risk for private investment, and require targeted public policies such as values for carbon markets to drive technological change. This is described in innovation studies of gasification RD&D (Hellsmark and Jacobsson 2009, 2012). This chapter provides examples of commercial and developing technologies and highlights some of the science and technology advances, using notes as further information and records of commercialization progress from companies' announcements, which change with time, and websites and references for permanently retrievable materials.

Taking Figure 12.6, we illustrate conversion facility sizes adapted to the small feedstock supply of a location and approaches that increase the feedstock supply with logistics and pre-processing so that economies of scale in regular or larger scale conversion facilities can be used. How to optimize economic, environmental, social, and sustainable development?

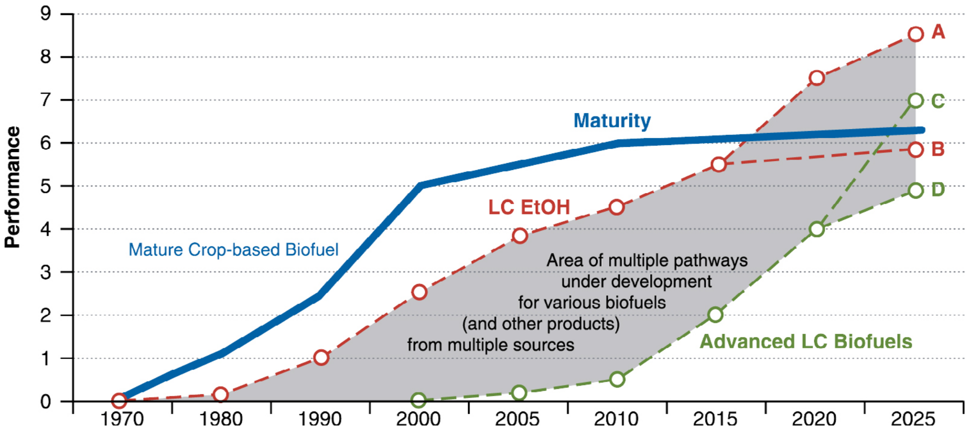


Figure 12.6. Hypothetical S-shaped curve for technology development of biofuels to commercialization and maturation, and advanced technologies that could surpass the performance of incumbent technologies. Performance index includes product quality, capital investment, operating costs, and environmental performance. LC = lignocellulosic.

For instance, Route A for lignocellulosic biomass at scales of current dry mills (or <1,000 t/day) could become Route B by increasing the supply of sustainable lignocellulosic feedstock to be equivalent to that of a few of the largest corn wet milling facilities in the U.S., with scales near 20,000-30,000 t/day (closer to those of refinery operations of 150,000-200,000 bbl/day). The necessary innovation is in feedstock supply, preprocessing, and logistics to enable much larger storage facilities. For instance, densification is already enabling a stable and storable material to be produced and then shipped or transported to a larger centralized storage and distribution center (e.g., similar to a grain storage facility). These can then support conversion facilities operating at the needed scale (Egbendewe-Mondzozo et al. 2012; Eranki et al. 2011). The scales were modeled for other feedstocks up to 10,000 t/day, a small refinery size (Argo et al. 2013). Densification is already used in combination with maritime shipping so wood pellets (Lamers et al. 2014; Searcy et al. 2014) can reach coal-fired plants or heat and power applications in Europe from North America (Faaij et al. 2014; Goh et al. 2013). As shown in Figure 12.1, 23.6 million metric tons were traded in 2013. Advanced technologies such as mild pyrolysis (torrefaction) (Batidzirai et al. 2014) of wood could enable even larger scales and project environmental benefits (Wilson et al. 2011) but have not been demonstrated at scale yet.

Another Route B uses a lower feedstock cost, for instance, from smaller plants located close to high density urban centers that generate waste. For instance, a 100 to 170 t/day could lead to 20-35 million liters fuel facility for small cities. Such technologies help municipalities attain large diversion rates from landfills as was achieved in California in the eighties (Chum and Overend 2003) and continues to be pursued. Depending on the route, around 100 million liters could be produced with 1,000 t/day at sites where this supply is available.

Route C could be reached in a location where the cost differential could be absorbed by a higher value coproduct where appropriate size markets can support this cost difference over time. Route D could be reached with flexible manufacturing of different coproducts. Such multiproduct facilities could have smaller scale and are being pursued as potential routes in Europe, for instance, coupled to pulping processes (Modahl and Vold 2010; Rødsrud et al. 2012), or, as the example of the European study described in Section 12.1.1, small to medium size facilities to decrease the environmental footprint and overall resource use. Some are being designed to be flexible and support small-scale fuel production (for an urban center) or make multiple chemical or specialty products (Vennestrøm et al. 2011). These are examples of integrated biorefineries.

In bioenergy today, one size does not fit all situations and both small- and large-scale conversion plants are necessary to match the multiple feedstock and development opportunities. Appropriately sized conversion technologies can be developed in different countries and communities. Advanced manufacturing, automation, and process controls progress could favor smaller plants. Major sources of commercialization status used are:

- Information provided by The International Renewable Energy Agency (IRENA 2013), Bacovsky (2013) database, databases of pilot, demonstration, and first commercial plants of the International Energy Agency (IEA) Bioenergy Agreement task 39 (Bacovsky et al. 2013), literature (Brown and Brown 2013), and trade association data such as Biofuels Digest. IRENA and the various working tasks of the IEA Bioenergy publish frequent updates on technologies, integration, and commercialization, including on biorefineries (task 42).[3]

- Reviews of developments in the EU and the U.S. (Balan et al. 2013) with consistent and diverging U.S. and EU developments (Monti and Berti 2013; Zegada-Lizarazu et al. 2013) including biofuels demonstration and commercialization efforts (Balan et al. 2013; Janssen et al. 2013).

The production of biofuels for use in road and air transport is the major thrust of this chapter, including environmental performance examples, and gaseous biofuels. Feedstock production and logistics are the subjects of Chapters 10 and 11, this volume respectively; social aspects, environmental impacts on biodiversity, water and hydrology, GHG emissions and indirect land use impacts, and sustainability certification of bioenergy are addressed by chapters 15 to 19, this volume.

12.2 Key Findings

Commercial Biofuels

- Ethanol: The dry mill corn refining industry matured, producing ethanol, feed, biodiesel, and other products and increased average yield, increased energy efficiency, and decreased process environmental impacts (12.2.1, 12.2.1.1.1, see Chapter 10, this volume for parallel feedstock improvements). Mature sugarcane to ethanol conversion processes increased feedstock use efficiency and developed electricity generation as a main coproduct in Brazil and in other countries (12.2.1, 12.2.1.1.2).
- Hydrotreated vegetable oil or renewable diesel started production at commercial scale, has high acceptance, and with more reasonable cost if produced from waste oils, fats, and greases (12.2.1.4, 12.2.2.4.1), it enables the use of higher volume fraction in blends. Several of these products have received sustainability certification. It is projected to be the fastest growing biofuels segment with additional production coming from tall oil (12.2.1.6) and other fats and used cooking oils.
- Ethanol and biodiesel matured as biofuels in commerce with significant trade among producing and using countries (Pelkmans et al. 2014) (12.2.2.1, 12.2.2.3). Blends are the most common use but straight ethanol and flexible fuel vehicles are marketed. Biofuels exported to the EU had sustainability certification according to criteria defined by several sustainability schemes accepted in that market (see Chapter 19, this volume).

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[3] http://www.ieabioenergy.com/wp-content/uploads/2014/09/IEA-Bioenergy-Task42-Biorefining-Brochure-SEP2014_LR.pdf

Advanced Biofuels

- A large number of process configurations are possible to convert lignocellulosic biomass to fuels, products and energy. Portfolios of conversion technologies are being tested, some of which are moving toward commercialization.
- Convert the carbohydrate portion (about 75%) with improvements in pre-treatment and microorganisms (natural and engineered) and enzymes to fermentable sugars to ethanol, while using the lignin fraction for process heat and electricity (e.g., in Italy, U.S., Brazil) (12.2.1.1.4).
- Use low cost waste biomass to produce clean syngas using advances in engineering and catalyst development in thermochemical gasification. Catalytic Fischer-Tropsch (FT) processes using microchannel reactors after plasma gasification are undergoing simultaneous scale-up to assess small-scale developments to synthetic gasoline, diesel, jet fuel, and waxes (e.g., U.S., U.K.) using economies of volume for small manufactured plants. Many gasification commercial developments for cogeneration of power and heat are operating commercially. Other catalytic processes yield dimethylether, also being tested for transport (e.g., Sweden) (12.2.1.5.1). Clean gas upgrading is also occurring in bioprocessing such as fermentation by acetogenic organisms, natural and engineered, at room temperature to ethanol or other fuels and chemicals (e.g., U.S., New Zealand) or catalytic conversion to methanol (e.g., Canada) (12.2.1.5.2).
- Three first-of-a-kind commercial plants using biochemical conversion to ethanol have been designed and constructed in the U.S.; the feedstock supply chains for corn stover and other lignocellulosic materials have been contracted for reliable delivery at about 700-1,000 Mg/day each and two started operations by October 2014. As expected, initial commercial conversion plants have higher capital costs than the mature conventional ethanol plants. Sustainability criteria for the systems were built into the design and continue to be evaluated. At the start of operations, plants undergo normal de-bottlenecking to reach their designed capacity (12.2.1.1.4).
- One first-of-a-kind commercial project using mixtures of agricultural residues to ethanol and power started operations in 2013 in Italy and a similar type of commercial project started operations in Brazil at twice the scale using sugarcane bagasse and field residues in 2014.
- Many process configurations are being tested in pilot and demonstration stages around the world. For very large-scale conversion approaching petroleum fuels-scales with lower processing costs, new logistics of feedstock supply models are under development through densification and preprocessing to stable and storable feedstocks. At the same time, size-adapted conversion plant scales to feedstock supplies is also under development for urban centers of distributed production or community or household (12.2.1.1.3, 12.2.1.5, 12.2.1.6, 12.2.1.7).

- Diversification of biofuels—type and coproducts—characterizes the new biorefineries. These pathways use scientific developments from synthetic biology, metabolic engineering, and construction of designed strains, among others, to build higher alcohols (e.g., butanols such as isobutanol) or more complex hydrocarbon structures such as contained in natural rubber, to make farnesene ($C_{15}H_{24}$). Others are using heterotrophic algae as catalysts in dark fermentation of sugars to make a variety of oxygenated oil products or hydrocarbons. The desired traits and functions are built into yeasts for industrial production that is starting. Further conversion of each of these products can make gasoline, diesel, and jet fuel substitutes and coproducts. Purely chemical pathways are also under development at various scales for all fuel products. Significant progress is also being achieved in catalysis for thermochemical and catalytic conversion of biomass and its upgrading to fuels and chemicals (12.2.1.1.4, 12.2.1.2 to 12.2.1.7).
- Pathways to commercialization include retrofitting commercial ethanol plants (either corn or sugarcane) to produce significant quantities of materials for testing for performance, lower costs, and risks, of going directly to lignocellulosic materials. Parallel development of multiple fuel and chemical products of higher value or food/feed products is a major strategy moving forward paving the way to biofuels commercialization (12.2.1.1.4, 12.2.1.2, 12.2.1.5, 12.2.1.6).
- A myriad of conversion routes are being researched, then a large number is being explored at pilot and demonstration scale, including pyrolysis of biomass to oils, which can be upgraded in standalone configuration in catalytic processes to produce fuel blend fractions, or sent to petroleum refineries for upgrading. Biomass pyrolysis also produces biochar which is being sold in some locations as organic soil amendment. Developments are occurring both at small- and large-scale conversion plant sizes covering the multiple existing or developing feedstock production and logistics systems highlighting opportunities and challenges (12.2.1.7, 12.2.1.1.3).
- The coordinated development of the biomass and biofuel supply system and its utilization is occurring in the aviation sector. Aviation has no substitute power systems for the foreseeable future, so biomass can help fill a gap with low-carbon profile fuels. Biofuels that passed ASTM certification have been tested, as 50% blends are hydrocarbons derived from biomass gasification and commercial FT processing to jet fuel, and hydrotreated vegetable oils, waste, fats, and greases; and at 10% jet fuel blend with farnasane. Alcohols to jet fuels, pyrolysis and upgrading to fuels and chemicals production, and others continue to be tested to pass certification to enable actual testing in commercial flights. Costs are still high and several coordinated approaches by multiple sectors, public and private, are being employed globally to facilitate cost reductions and the necessary further testing to commercial products (12.2.2.4).

12.2.1 Biofuels and Sustainability Are Systems Dependent: Scale, Nature and Location

The major biofuels systems by 2013 were:

1. Ethanol from corn or other cereals, sugar beet, and sugarcane, primarily in the U.S., Brazil, EU, China, and Canada (97% of 87 billion liter (L) produced) with the total ethanol consumption of 1.8 EJ[4],
2. Biodiesel production from rapeseed, soybean, palm oils, waste oils and greases, and animal fats in the EU, U.S., Brazil, Argentina, and Indonesia (85% of 23 million metric tons produced) with a total biodiesel consumption of 0.85 EJ.
3. Biogas from waste management and animal husbandry, which is the major gaseous biofuel produced in most countries and its application globally produces twice the energy of biodiesel [8] (REN21, 2014) or about 1.7 EJ.
4. Renewable diesel, also called HVO, at an estimated 2.7 million metric ton production in the EU, Singapore, and U.S., is consumed mostly in the U.S. and EU [9] or 0.12 EJ. In addition, smaller quantities of other biofuels are produced.

Cost trends of commercial biofuels and bioenergy were reviewed for many countries and expressed as levelized cost of biofuel—a function of feedstock cost (Chum et al. 2011). For biodiesel, the oil feedstock costs contribute 80% to 90% of the estimated production cost, unless derived from wastes. For ethanol from corn and sugarcane, the feedstock contributed 60% to 80% of the cost. The 2012 estimated production cost and producer prices in Brazil and the U.S. are shown in Figure 12.7 (IRENA 2013).

The ethanol price variations from food commodity feedstocks shown in Figure 12.7 are linked to oil prices and other factors, which are not seen to the same extent in lignocellulosic feedstocks, principally for residues and pellets; for comparison, wood at $70/t (dry) corresponds to $3.8/GJ while corn at $197/t corresponds to $9/GJ.

Although most of the literature on environmental impacts is based on considerations of GHG emissions, fossil energy use per unit of output fuel produced, and sometimes air impacts—the broad range of life cycle impact assessment categories shown in Box 12.1 (data for the specific location and time of production (Ridley et al. 2012)) have been less studied. Some models include toxicological data using prior databases versions which are updated as more compounds are tracked. Corn ethanol in the U.S. has lower ozone layer depletion, particulate matter emissions; higher impacts in acidification, eutrophication, photochemical oxidation; and decreased Global Warming Potential (GWP) (Yang et al. 2012).

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[4] Global and major countries consumption and production data were supplied by F.O.Licht Interactive Database with permission (March 2014). Data were supplied in cubic meters for ethanol and million tonnes for diesel and hydrotreated vegetable oils and converted to EJ. Values used for conversion were in MJ (lower heating value)/kg: 26.8, 37.7 (average), and 45.5 (supplier value) for ethanol, biodiesel, and hydrotreated vegetable oil, respectively. Note that average gasoline and diesel in the U.S. are 43.1 and 42.8 MJ/kg, respectively.

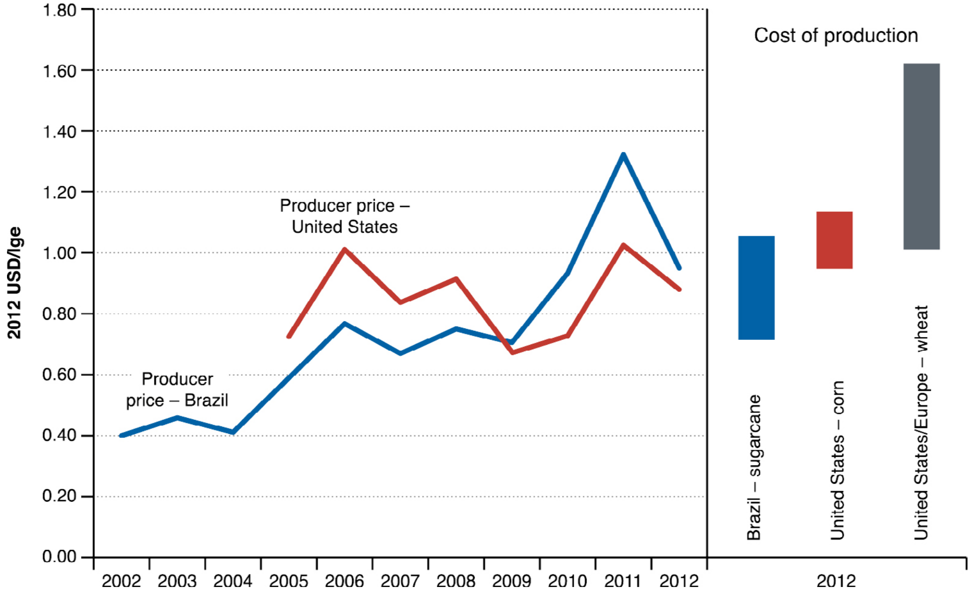

Figure 12.7. Average producer prices from 2002 to 2012 for commercial ethanol are expressed in liters of gasoline equivalent energy from commodity crops and 2012 estimated production cost ranges (IRENA 2013) in major producing areas. Reproduced with permission from IRENA.

The environmental performance of U.S. commercial ethanol industry has improved with time. Specific vintage plants—2001, 2005, and 2010—were analyzed for indicators related to human health carcinogenicity and fresh water ecotoxicity for corn ethanol production. Figure 12.8 shows the potential human impact on the left and the potential ecosystem impact on the right and the ranges indicate the producing states (from lower to upper values). Conversion contributed over time to a smaller fraction of the life cycle impacts across the value chain and this trend was mostly associated with power generation. While in 2001 overall conversion had about the same order of magnitude of impacts by petroleum processing, in 2010 human carcinogenic impacts were halved. The bulk of the impacts came from the distributed biomass production with phosphorus contained in the fertilizer being the major source. As the types of regulated pesticides changed with time, so did their ecotoxicity impacts (as shown in the figure on the right) and by 2010, the conversion process had minimized emissions. The comparison is with modern gasoline produced in very large commercial plants that are highly regulated because of the toxicity of chemicals involved and concentrated in a specific location. Within the errors of these measurements, the potential human health carcinogenic impacts are similar. The potential for freshwater ecotoxicity is higher than that of gasoline because it primarily derives from feedstock production using pesticides over a wide geographic area of production.

These impact studies are preliminary and need additional research and measurements with increased spatial resolution at landscape and watershed levels. Such resolution is beginning to emerge in air emissions of ethanol use compared to gasoline (Hill et al. 2009; Tessum et al. 2012), which is often concentrated in the urban centers. Frameworks for analysis of the lignocellulosic biofuels impacts are being developed and tested, such as corn stover removal for bioenergy and watershed impacts for advanced biofuel production (Gao et al. 2011; Gramig et al. 2013).

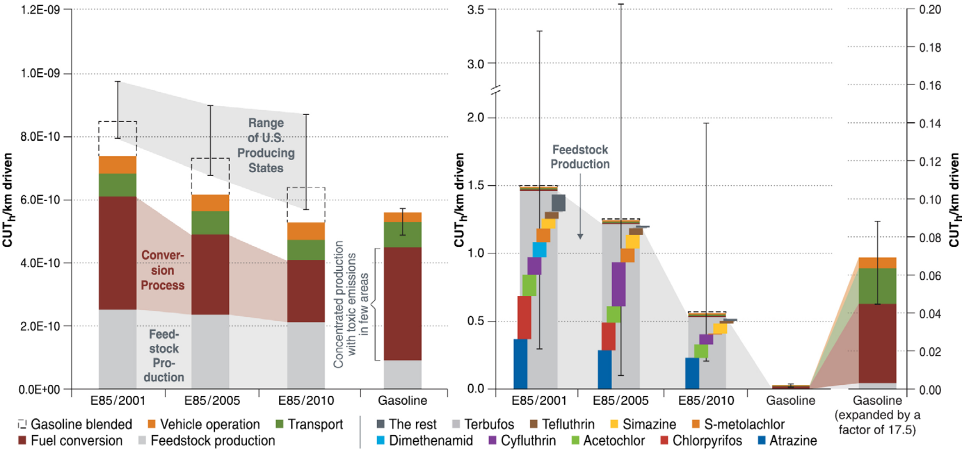

Figure 12.8. Trend in human carcinogenic toxicity of E85 (85% ethanol/15% gasoline blend) from corn ethanol in the U.S. from 2001 to 2010 (left) and freshwater exotoxicity impacts (right). Units are Comparative Toxic Units per km driven, which represent potential increase in human morbidity (or aquatic toxicity), calculated using the USEtox model and TRACI 2.0 [10]. Error bar represents the range from highest to lowest values for corn-producing states (Yang 2013). Note that the conversion process over time minimized emissions with recycling and wastewater processing solutions decreasing its ecotoxicity impacts (Yang 2013). Reproduced with permission.

Several specific configurations of corn ethanol processes powered by natural gas with cogeneration, or anaerobic digestion gases in the U.S. have received sustainability certification for the EU Renewable Energy Directive (EU RED) (RED 2003) system to meet 35% GHG emissions reductions by the International Sustainability and Carbon Certification and have been exported [11].

In one example of an integrated corn-based biorefinery, an analysis of sustainable process development guided the subsequent stages of the company's development from a stover commercial plant to ethanol in collaboration with academic and government laboratory partners (Alles and Jenkins 2010). (See [2] for environmental impact assessments for three examples of first-of-a-kind commercial plants in the U.S. setting feedstock supply systems with multiple sustainability parameters and conversion systems for fuels and power).

Sugarcane ethanol in Brazil presents lower impacts than gasoline in terms of GWP, fossil depletion, and ozone layer depletion , and higher impacts in acidification, eutrophication, photochemical oxidation, and agricultural land use categories. Human health toxicity values are similar to those of gasoline (Cavalett et al. 2013). Ethanol from sugarcane refineries that use mechanical harvesting of unburned cane and configure the process to efficiently generate power receive the U.S. EPA Advanced Biofuel category (meeting the 50% threshold level) and receive a 50% reduction in the EU RED system (RED 2003). An economic input-output life cycle assessment analysis of the sugarcane ethanol system with mechanization comes to similar conclusions, emphasizing the need to improve agricultural management to decrease fuel, fertilizer, and herbicide consumption (Caldeira-Pires et al. 2013).

A number of multiobjective studies optimizing the products of the sugarcane biorefinery are available, including various uses of bagasse for fuels, chemicals, and power generation with the latter having the lowest impact in several areas (Dias et al. 2013a; Dias et al. 2012; Dias et al. 2013b). In the framework studied, only power generation was available; the others were developing technologies, so the emissions performance is based on projected data from pilot or early demonstration work, as data for commercial practice are not available but guide RD&D.

Environmental performance of biodiesel production in various countries is shown in Table 12.1 for selected life cycle impact assessment indicators, harmonized by the Swiss Federal Laboratories for Materials Science and Technology organization (EMPA) (EMPA 2012). Additional data points from China (Hou et al. 2011) illustrate results from two different allocation of coproducts impacts [12] in the life cycle methodology used that was adapted to that country's conditions. Note that differences of 10% to 25%, depending on measurement types, may show equal performance within the errors of measurements and models used, or use generic data if specific locations lack them. Data gaps for many countries need to be filled.

Environmental legislation in the U.S. had parameters for considering global market mediated land use changes in the development of pathways that set the limit of GHG emissions relative to gasoline at the time of legislation enactment. The EU legislation set restrictions for the use of high carbon soils and various types of land with high value for biodiversity, and considered indirect land use change (iLUC) as another parameter to consider along with results of the a static life cycle assessment analysis. We provide some recent examples, but recent publications provide many more (Chum et al. 2011; Creutzig et al. 2014; IPCC 2014; Pelkmans et al. 2014; Smith et al. 2013) showing conditions under which overall sustainability can be improved for specific sites and with appropriate governance of land use.

In the case of palm oil biodiesel, the Roundtable on Sustainable Palm Oil enabled process and system improvements with anaerobic digestion of mill effluent wastewater to generate power and also pelletized empty fruit bunches for power generation in combustion boilers for process and for nearby communities, with improvements in GHG emissions and environmental indicators [14].

Specific sustainability studies compared jatropha biodiesel from decentralized smallholders and a centralized plantation and conversion facility using data from producing facilities in Tanzania. Both models investigated could lead to positive socio-economic and environmental impacts. The smallholder model scores better on land rights, GHG balance, and biodiversity, and reached out to more people. Whereas the

Table 12.1. Ratio of Impacts: Biofuel/Fossil Fuel. Environmental impact indicators from life cycle impact assessments for select criteria show data as ratios of biofuel impacts divided by petroleum diesel fuel impacts by EMPA (EMPA 2012) and Hou et al. (Hou et al. 2011). INT and EXT refer to intensive or extensive crop production and CONV refers the conventional process in the database used [13].

Plant Oil Feedstock	**Biodiesel Production and Plant Oil Production Location** (unless noted)	Climate change	Freshwater eutophication	Marine eutrophication	Acidification	Ozone depletion	Photochemical ozone formation	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Particulate matter	Ionizing radiation, human health	Mineral, fossil & ren. resource depletion	Source	Lifecycle allocation methodology
Rapessed	Switzerland (INT)	0,8	2	15	3,9	0.5	1,2	1.2	29	1	1,3	1,1	EMPA 2012	
	Switzerland (EXT)	0,8	1,6	17	5,5	0.6	1,2	1.1	33	1	1,3	1,1		
	CONV/ Germany	0,6	1,9	3.4	1,6	0.4	1,2	1.2	1	0,7	1,1	1,1		
	CONV/France	0,8	2,6	10	3,5	0.4	1,2	1.3	3	1	1,2	1,1		
Soybean	Brazil	3,1	1,7	8,6	1,6	0.3	2	1.2	-9	1,3	1,1	14		
	United States	0,5	1,6	7,6	1,2	0.3	1,2	1.1	-9	0,6	1,1	1,1		
	China	0,5		4,2	3,0	0.1	2,3					0,3	*Hou et al.2011*	*Mass*
		0,8		8,6	5,7	0.2	4,2					0,6		*Energy*
Jatropha		0,2		2,4	1,9	0.0	1,9					0,2		*Mass*
		0,3		3,1	2,4	0.0	2,5					0,2		*Energy*
	India (EXT)	-0,8	1,6	12	4,4	0.3	1,6	1.2	27	1,3	1,1	9,2	EMPA 2012	
	India (INT)	0,5	2,6	8,6	13	0.6	1,6	2.5	33	2,5	1,5	2,8		
	Africa (fence)	-0,1	1,1	2	0,9	0.2	0,8	1.0	0,9	0,6	1,1	1		
	Africa (EXT)	-2,6	1,3	7,6	1,2	0.2	0,9	1.1	12	0,7	1,1	-3,0		
Palm	Malaysia	1,2	1,3	7,1	1,7	0.3	1,3	1.1	1,7	1,4	1,2	5,7		
	Colombia	0,3	1,2	1,8	1,5	0.3	1,2	1.1	3,9	1,2	1,0	1,6		

plantation model creates more employment and higher (local prosperity) benefits spread to a smaller number of people, and could lead to higher yields (van Eijck et al. 2014). Both models could be made to provide benefits. More field measurements are needed (van Eijck et al. 2014)—a persistent conclusion from this and other studies in developing countries, especially least developed countries (Creutzig et al. 2014; IPCC 2014).

For conversion technology processes, initial sustainability guidance includes materials utilization, energy use, water use, toxics dispersion, pollutants dispersions, and GHG emissions [15], as used by the chemical industry, including the many categories of environmental impacts discussed in Box 12.1. Countries and organizations have developed guidance and context, as have global companies (Efroymson et al. 2013) [16]. A review of taxonomy for conversion technologies process development R&D summarizes global developments (Ruiz-Mercado et al. 2011a), discusses data needs (Ruiz-Mercado et al. 2011b), and applications (Ruiz-Mercado et al. 2012; Ruiz-Mercado et al. 2013). From incoming feedstocks to outgoing fuels (products), these researchers identified 66 environmental, 26 efficiency (materials), 33 economics, and 15 energy indicators to analyze their interdependencies and guide process development toward commercialization. The efficiency indicators are listed in Table

12.2 and carbon and atom efficiency are main indicators. A process that is better—in terms of the environment, efficiency, energy, and the economy—will most likely be sustainable, although one can expect that trade-offs will need to be made. The tool, “Gauging Reaction Effectiveness for the Environmental Sustainability of Chemistries with a Multi-objective Process Evaluator” (GREENSCOPE), was tested with one commercial biodiesel production (Ruiz-Mercado et al. 2013), and could be helpful in continued development of biofuels and biorefinery technologies (Smith and Ruiz-Mercado 2014).

Table 12.2. Sustainability Indicators for Efficiency (Materials) in Chemical Processes. These indicators, along with environment, economics, and energy indicators contribute to selecting sustainable processes (Ruiz-Mercado et al. 2011a).

Indicator	Description	Indicator	Description
1	Reaction yield	**14**	Carbon efficiency
2	Atom economy	**15**	Material recovery parameter
3	Actual atom economy	**16**	Solvent and catalyst environmental impact parameter
4	Stoichiometric factor	**17**	Physical return on investment
5	Reaction mass efficiency	**18**	Renewability-material index
6	Total material consumption	**19**	Breeding-material factor (Mass of product per Nonrenewable mass input)
7	Value mass intensity	**20**	Recycled material fraction
8	Mass intensity	**21**	Mass fraction of product from recyclable materials
9	Mass productivity	**22**	Mass fraction of product designed for disassembly, reuse or recycling
10	Environmental factor	**23**	Total water consumption
11	Mass loss index	**24**	Fractional water consumption
12	Environmental factor based on molecular weight	**25**	Water intensity
13	Effective mass yield	**26**	Volume fraction of water type

A simplified subset for sustainability assessment is shown in Figure 12.9, comparing country-specific hydrocarbon fuels production pathways in petroleum refineries, with possible substitute processes based on coal (Yang et al. 2013) gasification to liquids (commercial catalytic FT process), or biomass, or coal and biomass coprocessing in China. Here the technical maturity is specifically highlighted as well as relatively simple proxies for the various indicators (aggregation) (Yang et al. 2013). Just looking at indicators one by one, determining which system is better will vary; but examining the multiple indicators is much more likely to provide robust information for trade-off analyses. The same can be concluded from analysis of specific indicators in other systems (Choudhary et al. 2014).

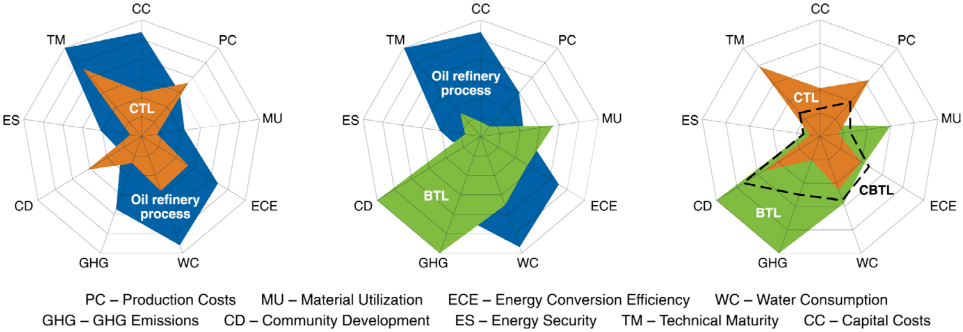

Figure 12.9. Comparison of parameters for sustainability assessment of liquid fuels routes from existing oil refinery process with developing alternatives based on gasification of coal, biomass, and coal/biomass to liquids using the commercial Fischer-Tropsch catalytic processes (Yang et al. 2013).

At the same time, simpler tools that aggregate results from multiple and complex indicators into simpler indices using multivariate analytical methods are under development to uncover major variables responsible for the overall impacts (Sikdar et al. 2012; Sikdar 2003). Methodologies are being developed that do not require specific values to be assigned to groups of indicators but use all the individual information collected (Ingwersen et al. 2014a; Ingwersen et al. 2014b); value-based methodologies are employed in European countries (EMPA 2012).

Company-specific aggregate indicators include various types which are used alone (one dimension) or in combination such as: product focus life cycle impacts; eco-efficiency indicators; and process cradle-to-grave costs; one full combination includes also the overall impacts on the environment, society, and related costs to help manufacturer in product selection (e.g., BASF's Seebalance^R). A framework and guide for people engaging with the complex and evolving sustainability literature reviews the development and application of sustainability assessment tools led by CSIRO (Australia) for the World Economic Forum's Global Agenda Council (O'Connell et al. 2013).

12.2.1.1 Ethanol

The current market-dominant biofuel ethanol is made primarily from corn and sugarcane, although cereal grains including wheat and sugar beet also contribute to production in the EU.

12.2.1.1.1 Maize and Other Grains—Dry Mill Corn Refining Industry Emerged for Ethanol, Feed, and Biodiesel

As discussed in the Introduction section (12.1) of this chapter and in Chapter 10, of this volume, ethanol production and use in the U.S. was a response to energy, environment, agriculture, alternative fuel infrastructure and vehicles, and economic development policies over time [17]. Policies successfully increased total ethanol production from 2005 to 2011 by a factor of nearly three and that of the lowest environmental impacts dominant process by a factor of ten.

Two primary processes for converting maize into ethanol are wet and dry milling. The wet milling technology coproduces starch, syrup, oil, sugar, and byproducts such as gluten feed and meal resulting in hundreds of products and byproducts. In the U.S., dry milling technology was responsible for 30% of the ethanol production in 1990, but became the major process for fuel ethanol production by 2004 (Hettinga et al. 2009). This technology matured (80% to 90%) during the rapid growth period of 2004 to 2010. Dry milling maize grains allows enzymes to have easier access to starch for hydrolysis to glucose, fermented by yeasts to ethanol; hydrolysis and fermentation can be conducted simultaneously (Mueller and Kwik 2013). The coproduct, distillers' grain with solubles, is a highly valued and nutritious livestock feed that replaces the use of some soybean and corn (see Section 12.2.2) and thus the same planted corn area produces ethanol and animal feed.

In the nineties, conversion plants were designed for beverages with 35 million liters per year (L/yr) capacity. Biofuel conversion plant size doubled by 2005, and has more than doubled again since 2005. This is due to economies of scale and the integration of better designs (Hettinga et al. 2009; Hettinga et al. 2007) as the industry reached the full legislated capacity and anticipated performance ahead of time (U.S. EPA 2007)—with many mills meeting the EU RED (RED 2003) legislation. Using technology vintage- and specific-data, Figure 12.10 displays selected energy and environmental parameters over time. The improvements in the average corn ethanol dry mill decreased GHG emissions by nearly half; fossil energy consumption decreased by 54% through enhanced energy efficiency (Wang et al. 2012); and land use decreased by 44% resulting from improved crop genetics and agronomic practices in 2010, respectively, compared to 1990 (on a life cycle basis discounting land not needed for soy; see Chapter 10, this volume) (Chum et al. 2014). In the nineties, each liter of ethanol used six liters of water in the process. By 2007, only three liters of water were used, (Chum et al. 2014; Wu 2008), and by 2012, water use decreased further by 10% (Mueller and Kwik 2013). The 2012 corn average yield is 420 L/t (up from 327 L/t in 1990), a value that incorporates feedstock improvements (see Chapter 10, this volume).

The process industry achieved enhancements in yield through:

1. More efficient separation of plant components

2. More efficient conversion of these components use advanced preparations of commercial enzyme mixtures for starch hydrolysis that also operate at lower temperature [18]
3. The use of more efficient engineered yeasts that consolidated multiple processes to increase ethanol production [19]
4. Advanced process configurations enabling separation of corn oil from the thin stillage for biodiesel production (Chum et al. 2014), or even earlier in the fractionation process (Mueller and Kwik 2013).

Recovering corn fiber became possible, and some companies are adding cellulase enzyme mixtures to increase ethanol production [20].

EU biofuels production was spurred by the EU (RED 2003). EU RED considers ethanol, biodiesel, biogas, methanol, dimethylether, ETBE (ethyl-tert-butylether) based on bioethanol, MTBE (methyltert-butylether) based on methanol from biomass, synthetic biofuels, biohydrogen, and pure vegetable oil as biofuels. Production is located close to the end market and designed to use multiple feedstocks such as wheat, maize, barley, rye, and sugar beet derivatives. The total weight of grain feedstocks processed is the same as that for beet derivatives used for a total production of about 4.5 billion L/yr, which, with imports, totals 4.5% of the EU gasoline use [21] (AEBIOM 2013). Wheat-to-ethanol processing starts with a malting step, and either enzyme or acid hydrolysis leading to sugars for fermentation. These processes improved as in the U.S. Ethanol plants initially averaged about 50 million L/yr (2006-2008) and doubled in size from 2009 to 2011 [22]. Because energy prices are higher in the EU compared with the U.S., energy efficiency improvements were implemented quickly compared to the U.S. (AEBIOM 2013).

12.2.1.1.2 Sugarcane Biorefineries Make Ethanol, Sugar, and Power the Grid (mostly based on Walter et al. 2014)

Sugarcane ethanol was produced in Brazil since the early 20th century with increased production in the mid-1970s aiming at substituting 20% of the gasoline. During the first phase of the Proalcool program, the priority was to increase ethanol production with little concern for process efficiencies. After 1986, however, the industry competed with gasoline under adverse conditions of low oil prices and a lower level of subsidies. Several less efficient mills were pushed out of the market or consolidated. Competition led to important improvements in sugar production and, in the 1990s, the industry began its trajectory to become the world’s main sugar exporter (Walter et al. 2014).

Table 12.3 summarizes the results of this technology development. In Brazil, ethanol can be produced either from cane juice, molasses, or (in most cases) from mixtures of juice and molasses. Most mills are sugar mills with adjacent distilleries, enabling an important operational synergy. Within the distillery, the largest area of sugar losses was (and still is) the fermentation. The use of cane juice in the autonomous

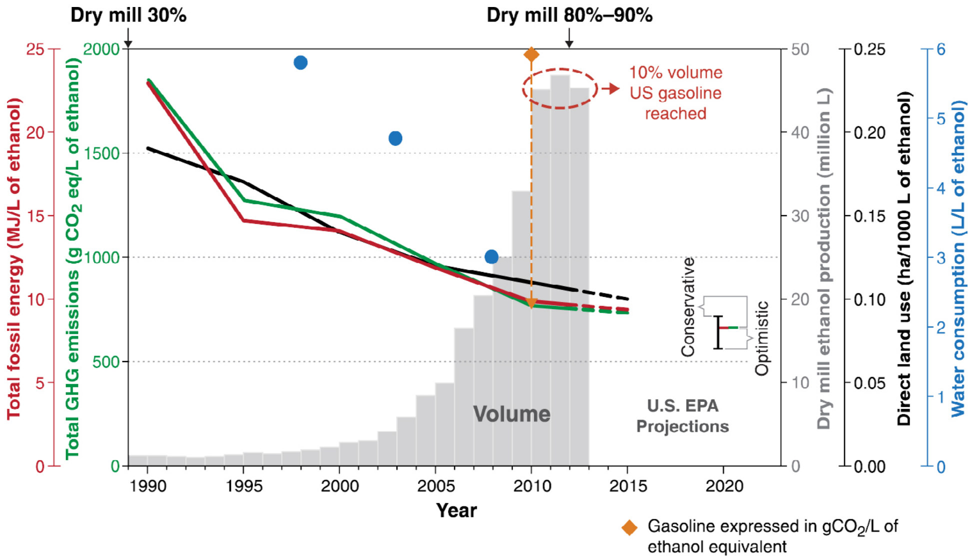

Figure 12.10. Life cycle improvements, using time-specific technologies for conversion and feedstock production for corn ethanol production in the U.S. Shown are total fossil energy used, GWP (100 year), water consumption, and direct land used per liter of ethanol (discounting land not needed to plant soy for feed). Grey blocks show produced annual volume. Adapted from (Chum et al. 2014) with permission.

distilleries was a novelty for most plants at the beginning of the Proalcool program. Improvements areas were: juice treatment, beer centrifugation, microbiological control, yeast treatment and recycling, and use of selected yeasts in fermentation. The prevailing system includes fed-batch fermentation with yeast recycling even though some continuous fermentation systems are in use. The distillation and dehydration technologies were imported as integrated systems adapted to the Brazilian conditions of beer quality and fuel ethanol specifications (Walter et al. 2014). Today, the average yield of the process is around 82 liters of ethanol per wet metric ton of cane (Seabra et al. 2011).

The transition from being electricity grid purchasers to becoming energy self-sufficient relied on installing more efficient equipment and redesigning the process for energy efficiency from 1975 to 2000. With the Brazilian deregulation of the power sector in 1999, an accelerated modernization process started, substituting high-pressure boilers (>40 bar) and turbo-generators for the old machinery. Simultaneously, approaches to reduced processes steam demand were pursued. The progress of the sugarcane industry-wide electricity generation is shown in Figure 12.11. Using this configuration, more than 60 kWh/t cane surplus electricity is generated from bagasse fuel only. The implementation and evolution in the cane straw recovery will eventually lead to much higher levels of surplus electricity. On average, the current levels of electricity surplus are around 10 kWh/t sugarcane (Seabra et al. 2011) and are expected to increase rapidly in the next years (the level of efficiency could be higher but at increased costs).

Table 12.3. Technological Evolution of Brazilian Sugar Mills and Distilleries Since 1975 (Finguerut 2005; Walter et al. 2014; Olivério 2008).

Unit Operation	1975	2005
Milling capacity of 6 milling units of 78” width (tc h^{-1})	5,500	15,000
Sugar extraction efficiency (%)	93	97
Fermentation time (h)	16	8
Fermentation efficiency (%)	82	91
Distillation efficiency (%)	98	99.5
Overall distillery efficiency (%)	66	86
Boiler efficiency, Lower Heating Value (%)	66	89
Turbo-generator efficiency (%)	50	75

12.2.1.1.3 Scale—Large and Larger, with Small-Scale Ethanol Production Evolving

Sugarcane and corn ethanol production enjoy economies of scale that have favored production scales greater than 100 million L/yr. Customizing small scale production with automation, process controls, and advanced manufacturing could enjoy economies of volume with increased number of plants in many locations.

Examples:

- Downscale beverage-sized facilities: 9 million L/yr from 250 t/day of cassava has operated for six months at 60% capacity at a commercial facility, with improved yields of cassava plants and farming practices [23].
- Commercial ethanol plant supplier customized a 1 million L/yr plant installed and operated in Mozambique with local operators [24]. Challenges included training and qualifying local personnel in cassava chips production and delivery to the fuel plant and for the operation of the facility. Capacity building in the local communities is necessary to enable complex technical operations.

The current corn biorefineries already use the wet stream of pure CO_2 by drying, compressing, and delivering through pipelines to commercial applications (carbonated beverages, freeze drying, etc.), and also commercial enhanced oil recovery for facilities in close proximity. This part of the technology could be coupled with CO_2 capture and storage (CCS) technologies under development globally for potential negative emissions should the needed coupling of technologies be tested,

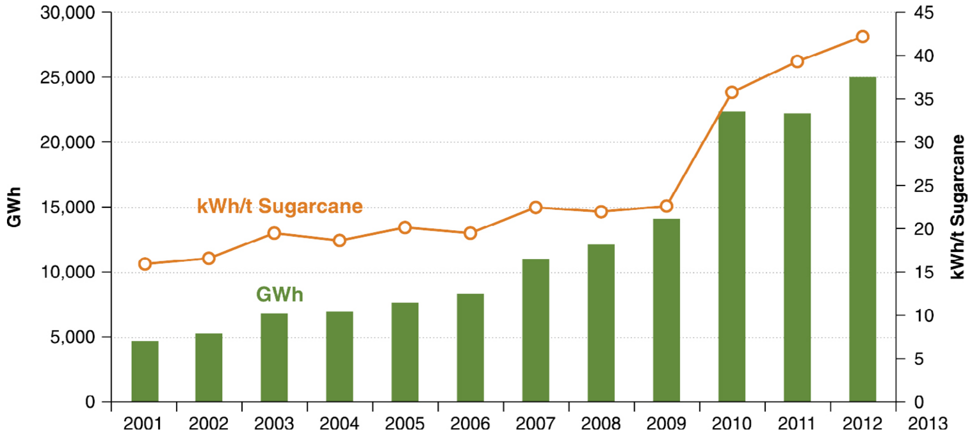

Figure 12.11. Brazil's sugarcane industry-wide electricity generation nearly doubled since 2006-2009, according to data from EPE (EPE 2013) and MAPA (MAPA 2010).

monitored, verified, and become commercial (Creutzig et al. 2014); see Chapter 7 in IPCC (2014) and [25]. One project is operating sequestering GHG emissions to onshore deep saline formations in the Illinois Basin to a final 1 $MtCO_2$/yr capacity, testing performance over time [26]. All bioenergy technologies that emit streams of CO_2 as a product are part of the family of technologies called bioenergy-CCS, with potential to sequester atmospheric CO_2 producing negative emissions, which could become important strategies in climate change mitigation if proven (GEA 2012; IPCC 2014). The larger the scale and the proximity to appropriate geologic storage sites, the more likely the technologies are to be used. Both the U.S. and Brazil have appropriate geologic sites in proximity of current biorefineries (IEA-ETP 2013).

12.2.1.1.4 Lignocellulosic Ethanol Using Bioconversion Processes in Biorefineries

The challenge of biochemical conversion approaches is the use of a series of steps (Figure 12.12). Biomass pre-treatment is intended to separate the durable polymeric matrix of sugar-derived cellulose and hemicelluloses, and lignin, an alkyl-aromatic polymer, thus more difficult to process than grains or sugar crops. Figure 12.12 lists 14 leading pre-treatment options. Ethanol was the major product focus of biochemical conversion, with concentrations and rates varying depending on catalysts, temperature, and time, as well as reactor selection and process integration conditions (Chundawat et al. 2011; Galbe and Zacchi 2012; Saddler and Kumar 2013; Tao et al. 2011; Wyman 2013). Another important consideration is that pre-treatment optimization conditions vary from one feedstock to another (Elander et al. 2009; Tao et al. 2013b), thus generating many process configurations and technology companies and multiple partnerships based on the specific selection of steps and their optimization. The status of this field is similar to biomass gasification technology development compared to coal analyzed by Kirkels and Verbong in 2011 (Kirkels and Verbong 2011). Proprietary information from the various competing routes is shown by the rapid increase in patents applied and received.

Biochemical conversion technologies that employ pre-treatment processes of various types (Mosier et al. 2005; Pedersen and Meyer 2010; Wyman et al. 2005), enzymatic hydrolysis (Himmel et al. 2007) and fermentation to ethanol, have now been demonstrated at the pilot scale; and multiple industrial-scale plants utilizing various configurations of this general technology are being constructed and coming online worldwide (Bacovsky et al. 2013; Balan et al. 2013; Janssen et al. 2013). Pre-treatment and enzymatic hydrolysis processes typically remain the most costly portion of the conversion processes due to high enzyme cost, although costs have been reduced over time (Hu et al. 2013; McMillan et al. 2011; Tao et al. 2013a; Tao et al. 2013b; Tao et al. 2013c). Issues with wastewater treatment when acid or base catalysts are present can also increase cost. Some pre-treatments require corrosion resistant materials, thus increasing capital costs. New pre-treatment media such as ionic liquids (Werner et al. 2010) can be expensive and require very high recovery efficiency for low cost products (Kroon et al. 2013; Peralta-Yahya et al. 2012) although could eliminate the need for enzymes for hydrolysis (Sun et al. 2013). Other process configurations

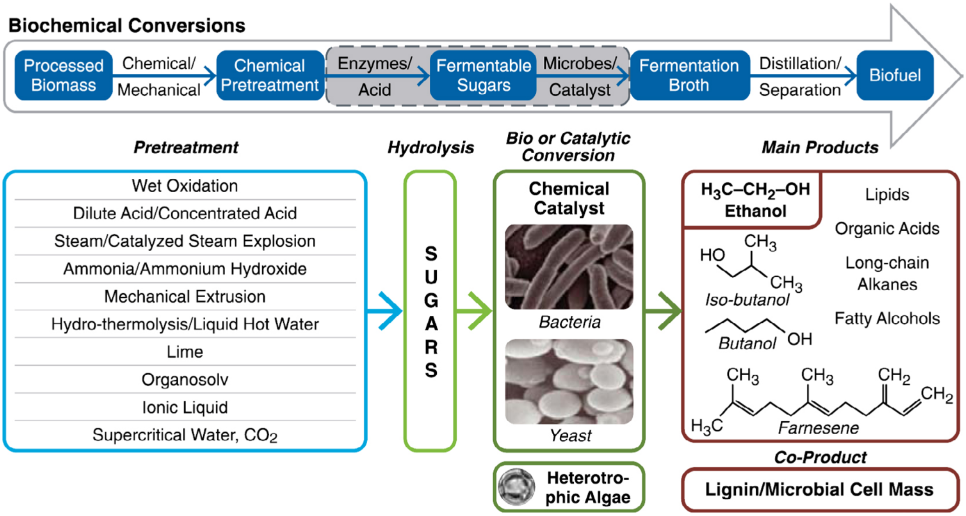

Figure 12.12. Biomass pretreatments alone or in combination with hydrolysis lead to sugars that can be fermented to ethanol and other products as indicated. The most common application for the lignin is process heat and electricity although many others are being developed. Examples of other biofuels discussed in the next section include: other alcohols, microbial products using tools of synthetic biology (Alonso et al. 2013; Peralta-Yahya et al. 2012; Yoon et al. 2013), or fatty alcohols via heterotrophic algae in dark fermentation (Perez-Garcia et al. 2011) that are also undergoing parallel technology development. Modified from Balan et al. (Balan et al. 2013) with permission.

liquefying biomass first and then conducting the enzymatic hydrolysis are also under advanced development (Galbe and Zacchi 2012).

Conversion of soluble sugars to fuels such as ethanol has traditionally been limited by the robustness of the fermentative organism against inhibitors commonly produced during pre-treatment and by competitive organisms (Parawira and Tekere 2011). The discovery of new detoxification methods and, more robust fermentative organisms is addressing this problem. More robust fermentation organisms that can tolerate molecules typically considered as inhibitors (e.g., furfural or 5-hydroxymethylfurfural) will enable harsher pre-treatment conditions, which in turn will enable lower enzyme loadings.

One pilot-scale example (see Box 12.3) completed multi-thousand hours of operation at the Kalundborg industrial symbiosis site integrated with heat and power and animal feed production. In this facility, performance evaluation was conducted of various commercial cellulase and hemicellulase enzyme cocktails based on *Trichoderma reesei* fungus [27][28] or other engineered advanced yeasts that can ferment both five and six carbon sugars [29]; further commercialization steps are described in [30] to [32]. The importance of this step in industrial bioprocessing developments was summarized by Lane (Lane 2014). By 2014, in industrial conditions, enzymes cost contribution to lignocellulosic ethanol is described by industry as seven- to ten-times higher than in the mature starch ethanol production [33]; costs are expected to decrease with increased operational time of industrial-scale plants and continued improvements in cocktails by enzyme manufacturers.

An integrated facility with annual capacity production of 50 million liters of ethanol and 13 megawatt (MW) power capacity started operation in Crescentino, Italy (10/2013). Mixtures of agricultural residues (200,000 t/yr) are processed by steam to reduce viscosity; enzymes are added for hydrolysis and yeasts for fermentation (Janssen et al. 2013). Operations started at 60% of capacity; other facilities using similar technology are under development in several countries [34][35].

Using similar integrated technology, an industrial cellulosic bioethanol plant started operations (9/2014) in São Miguel dos Campos, Alagoas, Northeastern Brazil. The production capacity per hectare is projected to increase by 50% using both bagasse and agricultural straw residues with the system developed to harvest, store, and process 400,000 metric tons of straw per year with an initial production capacity of 82 million liters of ethanol per year. The associated Caete power plant is expected to generate about 135,000 MWh/year [36].

Another standalone integrated facility using corn stover as feedstock to produce about 100 million liters of ethanol and 21 MW of power capacity (fully operated on biomass energy) of which 4 MW is for the community in Hugoton, Kansas, U.S. started operations in 10/2014 [37] (Janssen et al. 2013). With similar production capacity, two integrated biorefinery plants co-located with conventional ethanol plants, sharing infrastructure and trade by-product streams, were constructed in the U.S. near Nevada [38] and near Emmetsburg [39], both in Iowa, U.S. and started commissioning operations. These plants include validated data on five years of feedstock nutrient management at the site and prior history with recommendations from independent researchers on residue removal quantities [40] [41]. To set up integrated corn stover biorefineries, the lignocellulosic feedstock supply chain had to be developed over about five years each using best management practices (Janssen et al. 2013); in parallel design and construction of the conversion technology facilities (about 700 t/day) continued [2] [42].

The Emmetsburg facility began converting baled corn cobs, leaves, husk, and stalk into cellulosic ethanol by 9/2014, and is moving forward toward continuous operation. At full capacity, it is projected to consume 285,000 tons of biomass annually from a 45-mile radius of the plant. About 25% of the residue per unit area will be used to produce ethanol at a rate of 80 million liters per year, and later to full capacity of 100 million liters per year [43].

Co-optimization of pre-treatment and enzymatic processes or development of one-pot, high efficiency conversion processes (Lynd et al. 2005) will be required to continue to lower the cost of the biomass deconstruction. The development of enhanced enzymes combining novel activities (Quinlan et al. 2011; Vaaje-Kolstad et al. 2010) and complementary enzymatic paradigms (Resch et al. 2013) has recently been reported. Further improvements in biological solubilization are critical for cost effective biochemical conversion processes to be an economic reality at large scale (Brunecky et al. 2013).

Consolidated bioprocessing (Lynd et al. 2005) also offers the ability to produce enzymes *in situ* via the fermentative organism. Significant challenges exist in terms of heterologous expression of effective cellulolytic enzymes, which undergo post-translational modifications that are of significant importance for enzyme activity (Beckham et al. 2012). Industrial development utilizes genetically modified yeast and bacteria to convert cellulosic biomass into high-value end products in a single step that combines hydrolysis and fermentation [44].

Consolidated bioprocessing is also being pursued with many strains, one example being bacteria that can withstand radiation and very harsh conditions such as *Deinacoccus radiodurans* (Leonetti and Matic 2011). French researchers found that these hardy bacteria, also used for environmental detoxification, exhibit both xylanolytic and cellulolytic abilities, withstand high ethanol concentration, and have high productivity because of their genes' ability to self-repair (Daly 2009). Development of fuel and chemicals as applications for antibiotics and other medical uses is continuing [45].

Lignin offers potential additional value streams from an integrated biorefinery (Zakzeski et al. 2010). Moreover, lignin conversion to chemicals or materials offers a broader product slate to produce renewable aromatics, which are common building block molecules produced currently from fossil fuels. Evidence increasingly indicates the need for value added coproducts to establish the cellulosic ethanol industry (Davis et al. 2013; Ragauskas et al. 2014) [46].

Supercritical water processing to rapidly solubilize in two stages five-carbon sugars from six-carbon sugars is being tested at small scales at high temperature and pressure [47]; whether this testing can translate into a commercial process is unknown. However, if high throughput plants can be mass produced at small to medium scales, their environmental footprints could become smaller and the cost may be reduced sufficiently for chemicals applications. This chemical/thermochemical pre-treatment can also be coupled with a variety of chemical catalysts to produce drop-in hydrocarbon fuels and a variety of approaches have received significant research attention in the last decade.

Promising chemical strategies include aqueous-phase and mixed-phase catalytic strategies to go through carbohydrate-derived intermediates (Cortright et al. 2002; Huber et al. 2005; Kunkes et al. 2008). From various pretreatments integrated catalytic upgrading can also lead to hydrocarbons in the jet, diesel, and gasoline range in addition to other chemicals (Bond et al. 2014) also undergoing development and commercialization [48]. Traditional lines between biochemical and catalytic conversion will continue to be significantly blurred with the development of processes combining aspects of biological, catalytic, and thermal treatments of biomass to produce renewable transportation fuels (see 12.2.1.5.2).

Box 12.3. Industrial Symbiosis and Bioenergy Demonstrations at Kalundborg, Denmark

One example of multiple systems' integration operates at the eco-industrial park in Kalundborg, Denmark. Industrial symbiosis evolved there over fifty years (see figure below) [49]. Multiple co-located companies exchange streams; a waste stream becomes a feedstock for another company's process including heat used for industrial processes and municipal facilities heating. Kalundborg partners foster industrial symbiosis globally.

The power company spearheaded several projects. Ethanol from wheat straw facility with a 100 t/day processing capacity was built (Inbicon); wheat straw is pre-treated followed by enzymatic hydrolysis and fermentation, with the lignin fraction pelletized and used in the power plant. The five-carbon molasses make an animal feed (Janssen et al. 2013). Production runs delivered the first batch of ethanol to the oil company in 10/2010 for blending and distribution; this was the first part of the 1 million liters delivery contract over time. Tests of the blends started with distribution to 100 fuel stations [50]. Another project supported produced 270,000 liters delivered by 12/2013 using mixed sugars with reported increased yields by 40%, and qualified a third enzyme supplier [51].

Support of a 6 MW output energy gasifier demonstration project using wheat straw and other wastes at a 1.5 t/h was also part of the efforts of the power plant. The gasifier supplied high quality gases for cofiring with the high efficiency combustor at the power station (>>90% efficiency thermal and electric) [52].

The industrial park in Kalundborg, Denmark was established based on human relationships and fruitful collaboration between the employees

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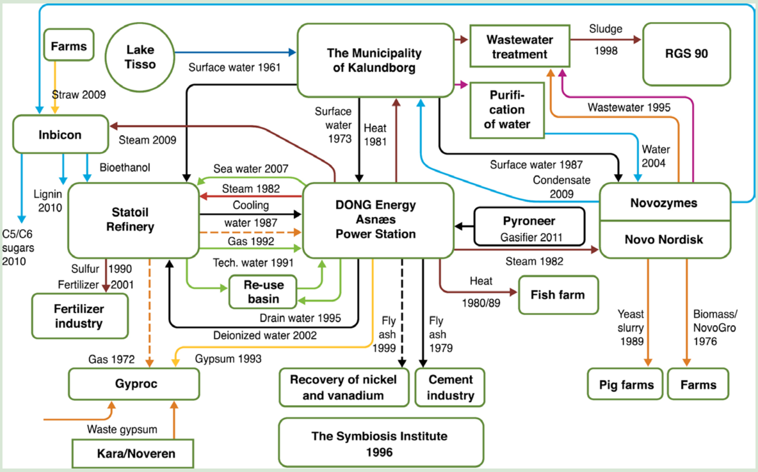

(Symbiosis Center 2014) [49]. Many companies and demonstration plants have been added over time as indicated by the figure starting dates with companies and municipality buildings spreading over 7 km.

12.2.1.2 Other Alcohols, Fuel Precursors, and Hydrocarbons from Biochemical Processing

Recent progress in omics[5] is facilitating the analysis of microorganisms based on bioinformatics data for molecular breeding and bioprocess development as seen in the previous section applied to ethanol production. Systems metabolic engineering, a new area of study, has been defined as a methodology in which metabolic engineering and systems biology are integrated to upgrade the ability to design industrially useful microorganisms for a wide range of products. Rational design of metabolic networks targets production by flux balance analysis using genome-scale metabolic models. Also, evolution engineering helped by omics analyses created stress-tolerant microorganisms with the desired phenotypes (Furusawa et al. 2013). For instance, a variety of alcohols can be made from the pathways shown in Figure 12.13, depending on the metabolic pathways selected (Rude and Schirmer 2009). Acetone-butanol-ethanol (ABE) fermentation by *Clostridium spp* of many sugars produces acetone, butanol, and ethanol in a ratio of 3:6:1 (Zheng et al. 2009).

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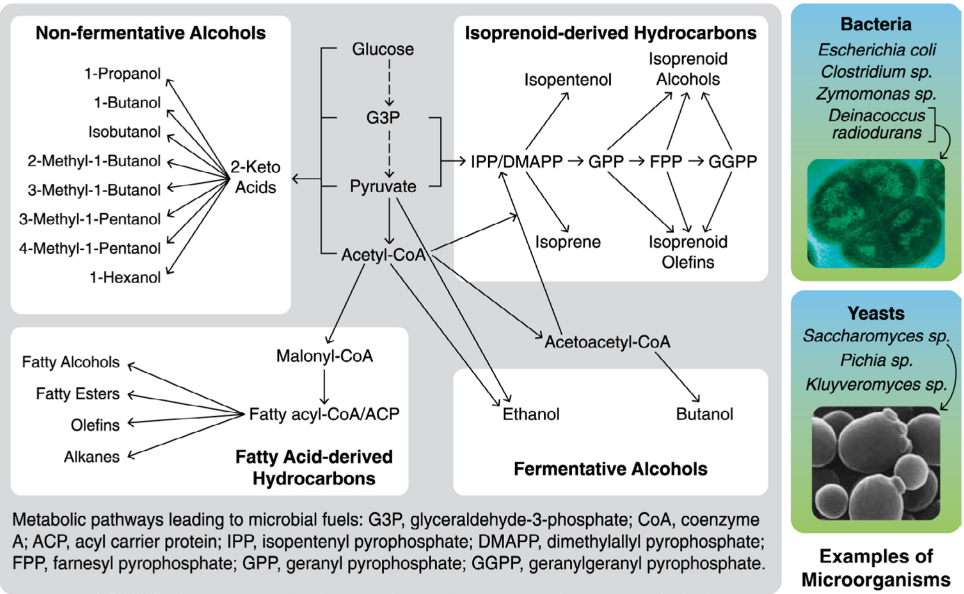
[5] "Omics is a general term for a broad discipline of science and engineering for analyzing the interactions of biological information objects in various 'omes'. […] The main focus is on: 1) mapping information objects such as genes, proteins, and ligands; 2) finding interaction relationships among the objects; 3) engineering the networks and objects to understand and manipulate the regulatory mechanisms; and 4) integrating various omes and omics subfields." http://en.wikipedia.org/wiki/Omics and Nature http://www.nature.com/omics/about/index.html



Metabolic pathways leading to microbial fuels: G3P, glyceraldehyde-3-phosphate; CoA, coenzyme A; ACP, acyl carrier protein; IPP, isopentenyl pyrophosphate; DMAPP, dimethylallyl pyrophosphate; FPP, farnesyl pyrophosphate; GPP, geranyl pyrophosphate; GGPP, geranylgeranyl pyrophosphate.

Figure 12.13. Examples of metabolic pathways leading to microbial fuels from Rude and Schirmer (2009) and examples of bacteria and yeasts. Reproduced with permission[6].

ABE has been practiced for 100 years. Isobutanol has been produced by engineered *Escherichia coli* (Atsumi et al. 2008; Atsumi et al. 2010) or by *Bacillus subtilis* and *Corynebacterium glutamicum* (Blombach and Eikmanns 2011), typically with co-products such as acetate, ethanol, acetone, or isopropanol.

Many microorganisms such as microalgae, bacteria, yeast, and fungi are available, or can be engineered, to produce biofuels, chemicals, and polymers. A variety of biofuel molecules (or their precursors) can be derived from the fatty acid biosynthetic pathway by using the metabolic capabilities of native microorganisms and by engineering novel strains. For example, fatty acid esters and alkanes (Fortman et al. 2008; Keasling 2010; Peralta-Yahya et al. 2012), and fatty alcohols and alkenes (Steen et al. 2010) were produced using engineering microbial strains from fatty acid synthesis pathway (Figure 12.13 bottom left).

Fatty acids are the foundation of triacylglycerides, which become the primary energy storage molecules for many species of algae, fungi, and bacteria (Shi et al. 2011). High yields of lipid precursors can be achieved using (a) oleaginous microbes (e.g., the yeast *Rhodotorula graminis* and the alga *Chlorella sorokiniana*) that naturally accumulate and store lipids, or (b) metabolic engineering to convert well-known and well-characterized microbes (such as engineered *E. coli*) to produce lipids (Howard et al. 2013; Rude and Schirmer 2009). One key difference among these microbes

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[6] "Deinococcus radiodurans" Credit: TEM of D. radiodurans acquired in the laboratory of Michael Daly, Uniformed Services University, Bethesda, MD, USA. http://www.usuhs.edu/pat/deinococcus/images/tgy1bbar.jpg

is whether lipid or free fatty acids are secreted (i.e., *E. coli*) (Lennen et al. 2013) or intracellularly accumulated (yeast and algae). Additional extraction and purification steps may apply for intracellular lipid products and add costs to the process.

Figure 12.13 top right shows how isoprenoid-based biofuels are produced from two basic C5 (five carbon) precursors (Lange et al. 2000; Peralta-Yahya et al. 2012; Pitera et al. 2007). The feasibility of using the isoprenoid biosynthesis pathway for biofuels has been shown by fermentation of sugars to isoprene (Keasling 2010; Lange et al. 2000; Peralta-Yahya et al. 2012; Rude and Schirmer 2009), terpene (C10) (Keller et al. 2005; Koksal et al. 2011; Peralta-Yahya et al. 2011; Zhang et al. 2011), and farnesene (C15 – Figure 12.12) (Renninger and Mcphee 2008; Rude and Schirmer 2009). Mild hydrogenation of farnesene saturates the double bond and produces farnasane, a diesel substitute and partial jet fuel additive [53] (see Section 12.2.2.4).

Substitution of the whole barrel of oil products became a driver for aligned civil and military government offices (U.S. DOE 2013) air transport associations, companies in multiple sectors, national and international organizations (FAPESP 2013; International Air Travel Association 2013), [54], other governmental organizations (IEA 2011), and the voluntary EU program [55]. A few examples of developments to commercialization are highlighted here and in other sections. The engineered microorganisms have to be permitted to operate in the specific countries in the industrial setting, as is the case of the examples below.

The production of farnesene (Figure 12.12) derived hydrocarbons has been tested at industrial sugar fermentation scale to tailored diesel substitute in Brotas, São Paulo, Brazil and the fuel is being tested in bus fleets and as jet fuel [56]. These industrial scale efforts follow the testing of the synthetic biology principles that resulted in a commercial anti-malarial product (Paddon et al. 2013). The ability of these processes to work in the presence of complex lignocellulosic sugar streams to produce farnesene was shown on a small scale. The C5 sugars required xylose isomerase addition to lead to high quality diesel fuel blendstocks [57]. Scale-up considerations such as the fermentation mode (aerobic and anaerobic), carbon efficiency, and biological productivity of the molecule of interest, toxicity effects, and separation must be considered for technical and economic feasibility to produce fuels in parallel with metabolic engineering.

The branched and symmetric alcohol isobutanol (see Figure 12.12) production was scaled up in a retrofitted corn dry mill in Luverne, Minnesota, U.S., with the alcohol registered by EPA as a fuel additive. The product can be catalytically upgraded to hydrocarbon fuels in gasoline, diesel, and jet fuel range of properties, and is being tested [58]. Several companies pursue this alcohol and four other carbon alcohols as well as catalytic hydrotreatment to hydrocarbon fuels essentially equivalent composition to those of fossil fuels (see 12.2.2.4) as well as routes to monomers for plastics by catalytic dehydration to olefins (e.g., butenes). The dehydration route of ethanol to ethylene and subsequent polymerization to polyethylene is already practiced commercially in Brazil (Iles and Martin 2013).

Renewable algal oil production started in a fermentation facility coupled to a corn mill plant in Clinton, Iowa, U.S. [59]. Heterotrophic cultures of microalgae (Perez-Garcia et al. 2011) illustrated in Figure 12.12 convert glucose in an advanced (dark) fermentation plant, into a variety of biofuels, chemicals, specialties, food, and cleaning products by designing specific compositions. Developers project to ramp up to annual production capacity of 20,000 Mg by 2016 [60].

12.2.1.3 Biodiesel—Chemical Processing of Plant Oils or Fats Matures—Small and Large Plants

The production of oil seed crops like soybean, rapeseed, canola, or from trees such as oil palm or jatropha are described in detail in Chapter 10, this volume, with their geographic distribution in the world.

Biodiesel is produced through a transesterification, by combining plant oil with a large excess of methanol and a catalyst (sodium or potassium hydroxide) to produce glycerol and a mixture of fatty acid mono-alkyl methyl esters (FAME) that is designated as biodiesel (Atadashi et al. 2013; Demirbas 2009; Luque and Melero 2012). About 50% of the biodiesel plants are smaller than 35 million liters per year capacity because they use a variety of waste feedstocks in many locations (e.g., used cooking oil, greases), while the other half ranges in size from 40 million to more than 150 million liters per year of capacity, using oil seed feedstocks, with the larger sizes being of integrated soybean production and biodiesel plants (e.g., Indiana) [61]. European size plants tend to be smaller than in the U.S. because of feedstock availability. Globally, a large number of suppliers of smaller size production capacities range from one t/day to 500 times that, include modular configurations, and deal with the various waste feedstocks such as animal fats, waste cooking oils and greases, and some non-food oils.

Processes start with the oil and methanol with the base catalyst, usually in batch operations, that produce two phases, the lower rich in glycerol, and the upper containing the biodiesel (Luque and Melero 2012). Methanol has to be recovered from both fractions and water washed. The presence or production of free fatty acids impacts product quality. Process intensification advances include reactive extraction in-situ transesterification, methods to improve mass and energy transfer (e.g., oscillatory baffle reactors), heterogeneous catalysts, biocatalysts, such as lipases (Itabaiana et al. 2013), among others (Harvey and Lee 2012). In addition, continuous operations capable of processing mixture of these feedstocks are evolving with process controls. Methanol as a reactant is one of the safety issues of production, principally in small-scale production.

As presented in the previous section, the same type of oil compositions or a tailored one can be made from sugars using modified organisms including heterotrophic algae that can utilize various sources of carbon. The larger group of photoshynthetic organisms such as microalgae and cyanobacteria use sunlight, $CO_{2,}$ and water to generate similar fatty acids from which biodiesel or other hydrocarbon products can be produced (Blankenship and Chen 2013; Melis 2013). Significant research is ongoing in these organisms that can use brackish waters and land that do not conflict with food production, but they require water and engineering to lead to sustainable systems (Work et al. 2012).

12.2.1.4 Renewable Diesel—Hybrid Chemical and Thermochemical Processing from Plant Oils or Fats to Hydrocarbons

Renewable diesel is the commercial hydrocarbon biofuel introduced in 2007 reaching 10% of biodiesel mass by 2013. It is also referred to as hydrotreated vegetable oil (HVO),"green diesel", or hydrogenated esters and fatty acids (HEFA); it is produced from fatty acids (fats, oils, and greases) or vegetable oils or tall oil from trees, by hydroprocessing and hydroisomerization technology used in petroleum refineries. In hydroprocessing, the feedstock is reacted with hydrogen under elevated temperatures and pressures and in the presence of a catalyst in order to remove oxygen, sulfur, and nitrogen and saturate double bonds. The triglyceride-containing oils can be hydroprocessed either as a co-feed with petroleum or as a dedicated feed. The products consist predominantly of isoparaffins with some residual normal paraffins and proportions can be adjusted for diesel fractions or jet fuel fractions; technoeconomic analyses and size of production are different depending on the feedstock and coproducts (Miller et al. 2012; Smagala et al. 2012).

12.2.1.5 Hydrocarbons, Alcohols, Ethers, Chemicals, and Power from Biomass and Waste Gasification—Flexible Biorefineries to Multiple Products

Gasification is a process which converts carbonaceous solids, liquids, and gases to a mixture of fuel gases ,e.g., CH_4, CO, H_2, and higher hydrocarbons. After purification, these can be converted into syngas ($CO + H_2$) which is a versatile resource for upgrading to chemicals and fuels. The gasification process is endothermic and thus requires heat supplied either from external sources, or from combustion of part of the feedstock with substoichiometric amounts of oxidants such as oxygen/steam or air. When air is used, the nitrogen remains in the product gas (aka producer gas), and dilutes the energy content from the approximately 12 MJ/m^3 of synthesis gas, to a range of 4-6 MJ/m^3 (at standard temperature and pressure). Gasification is commercial at very large scales using natural gas in FT synthesis, and with coal and petroleum feedstocks for integrated gasification combined cycle power generation (IGCC), while at much smaller scales plasma assisted partial oxidation and air oxidation are commercial with municipal solid waste (MSW) and biomass for CHP and power generation at the village scale. Gasification is also used to convert biomass to co-fire with coal in large power stations (Kirkels and Verbong 2011; Ahrenfeldt et al. 2013; Matas Guell et al. 2013).

Biomass gasification takes place in a temperature range of 700°C-850°C, depending on the type of gasifier, which can consist of moving beds in which the oxidant flow is either co-current (sometimes called downdraft) or counter current. Fixed beds are limited to scales up to about 5 MW of thermal input. Larger scale units are usually fluidized beds (FB), either bubbling FB or circulating FB, for which there is no significant scale limitation (Noureldin et al. 2014). Unlike some of the typical coal feedstocks, or gaseous and petroleum feedstocks, one feature of biomass gasification is the production of condensible organics “tars”, which requires considerable efforts to either remove, or catalytically reform them to more gas (Deshmukh et al. 2010; Kumar et al. 2009).

12.2.1.5.1 Catalytic Upgrading of Syngas—Commercial and Developing Processes—Could Lead to CO_2 Capture and Storage

Figure 12.14.1 illustrates the flow from the biomass feedstock that has to be dried to a moisture mass fraction of <15% through to clean syngas and a synthesis stage such as FT (de Klerk 2000) to hydrocarbon fuels. The general catalytic metals are indicated in Figure 12.14.2. In the FT process a catalytic polymerization and hydrogenation of CO produce a synthetic crude oil that has naphta (gasoline), diesel, or kerosene and waxes, as well as combustible gases like propane and butane products and is practiced at very large scales requiring very high capital costs. Changing catalysts, the clean syngas produces: ethanol, other alcohols, ethers such as dimethylether, also a transport fuel, and chemicals (Figure 14.12.2) (Alonso et al. 2010; Dayton et al. 2011; Dutta et al. 2011; Magrini-Bair et al. 2007). One of the interesting synthetic catalytic products is methane or synthetic natural gas (SNG), which can be supplied to the natural gas pipeline network for distribution and use. SNG from biomass is, of course, biogenic and after combustion will have a very small CO_2 equivalent GHG gas contribution if the feedstock is sustainably produced. Due to catalyst limitations, the specification for syngas is quite strict with essentially less than 1 cm^3/m^3 level of critical contaminants such as H_2S being allowed. Even for SNG there are also limitations on the higher hydrocarbons that are allowed. However, once syngas from biomass has attained the needed criteria, the already wide range of catalysts that have been developed for fossil feedstocks are available.

In multiproduct biorefineries based on gasification (Haro et al. 2014) or other technologies, the product diversification can increase the total energy and materials recovery over the single product strategy. A simple illustration is CHP, which in the case of an advanced IGCC coupled with a district heating system, could easily get >90% high-heating value based efficiency. Other configurations use the excess heat from FT production for electricity and CHP to gain very high energy and carbon utilization efficiencies and for multiple products (Haro et al. 2014; Meerman et al. 2011). Also, there are continued efforts to adapt catalysts or design new approaches for chemicals, or separation of CO2 for sequestration (Meerman et al. 2013).

One opportunity for the gasification-based electricity or synthetic-fuels pathways, which can provide significant high concentration CO_2 that is produced in many industrial streams, is to capture this stream with, for example, amine absorbers, and to sequester the CO_2 in suitable media. Since the CO_2 is biogenic, this not only avoids the release of CO_2, but also acts as a carbon pump drawing down the atmospheric CO_2 captured by photosynthesis in biomass—the negative CO_2 emission can be quite large. Emissions from systems of this type are illustrated for power and fuels in Figure 12.15 (Creutzig et al. 2014; IPCC 2014). The figure shows estimated emissions that vary with biomass feedstock and conversion technology combinations, as well as life cycle GHG calculation boundaries. It shows each part of the life cycle as well as the biogenic emissions and

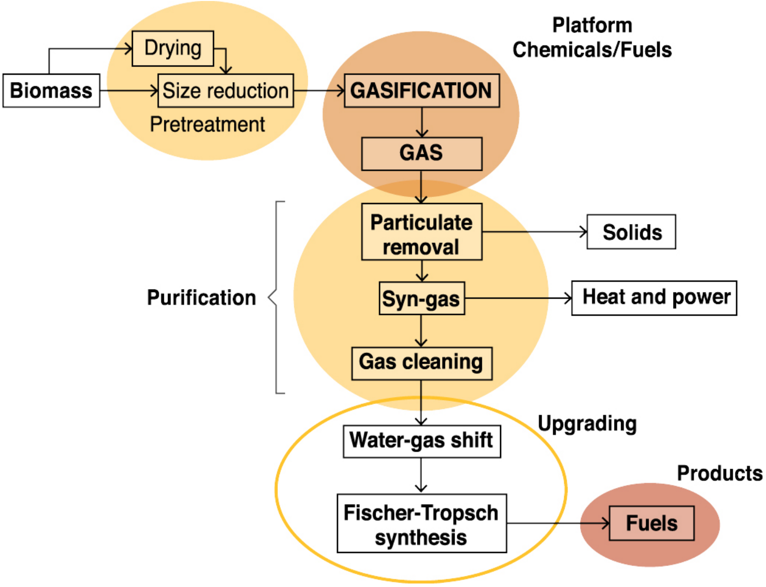


Figure 12.14.1. Biomass gasification steps to fuel synthesis using FT catalysts for integrated fuels, heat, and power production (modified from figure in (Alonso et al. 2010) with permission).

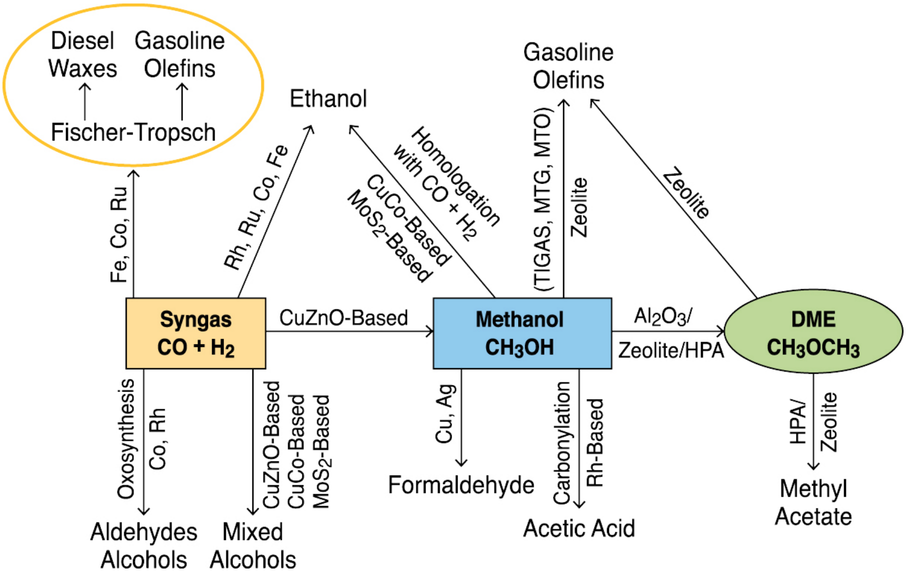


Figure 12.14.2. shows the general composition of catalysts for various conversion pathways from syngas to many fuels and chemicals.

stored emissions. Significant net negative emissions could be possible in these systems, but the uncertainties in the data are high because these systems have not operated in an integrated manner, although individual parts of the system have been.

For policy relevant purposes, counterfactual and market-mediated aspects (e.g., iLUC), changes in soil organic carbon, or location-dependent changes in surface albedo need also to be considered, possibly leading to significantly different outcomes in either direction (Creutzig et al. 2014). Surface albedo changes are significant using biomass sourced from temperate and boreal managed forests which would be snow covered for a significant time after removal of the carbon from the land (Cherubini et al. 2012; Cherubini et al. 2011; Cherubini and Strømman 2011; Guest et al. 2013). The cooling effect caused by the reflection of sunlight can offset warming for periods of time that depend on the location and change with time. To model the climate impact of these long rotation systems, it is necessary to consider the timing of emissions, specific albedo effects, and counterfactuals (Guest et al. 2013; Cherubini et al. 2012). Use of shorter rotation trees or perennial crops would have fewer of these impacts.

Combinations of coal or natural gas with biomass in gasification can thus enable production of power and of a variety of hydrocarbon fuels or oxygenated fuels and chemicals at very

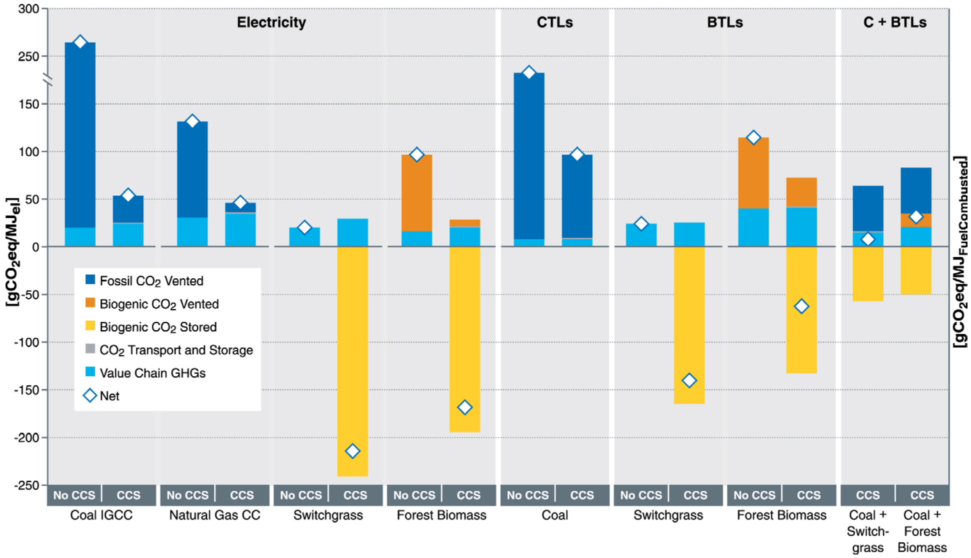


Figure 12.15. Illustration of the sum of CO$_2$-equivalent (GWP100: Global Warming Potential over 100 years) emissions from the process chain of alternative transport and power generation technologies both with and without CCS. Values are uncertain and depend on the production chain as well as what and how biomass is sourced and its original location. Units: g-CO$_2$-eq/MJ el (left y-axis, electricity); g-CO$_2$-eq/MJ combusted (right y-axis, transport fuels). Direct CO$_2$ emissions from energy conversion ('vented' and 'stored'). iLUC not considered. For detailed explanation and references see (Creutzig et al. 2014). Reproduced with permission from IPCC 2014.

large scales (Baliban et al. 2013; Soimakallio 2014; van Vliet et al. 2009). On the other hand, progress in small scales for biofuels is also occurring and taking advantage of innovation in FT processes using microchannel reactors (Almeida et al. 2013; Deshmukh et al. 2010), which allow compact reactors with heat integration and a much smaller footprint (process intensification), and the use of a variety of biomass residues. Combinations of gasifiers operating at very high temperatures with microchannel reactors are advancing for waste conversion to biojet fuels in a variety of settings close to airports [62].

12.2.1.5.2 Bioprocessing Upgrading—Hybrid Processing

The conversion of syngas into biofuels can be performed by a variety of microbial catalysts, including those containing acetogens in Figure 12.16, using the reductive acetyl-CoA pathway (Latif et al. 2014). In this coupling, biomass is more fully utilized, including lignins, and a wide variety of waste streams, including CO and CO_2 containing streams of industrial origin (e.g., steel making). The microbial catalysts tolerate a wide range of $CO:H_2$ ratios in bioreactors operating at ambient conditions. Some will also convert the CO_2 into products, depending on the organism. Gas-liquid mass transfer properties of the gaseous substrates are being addressed with better reactor designs fermentation, syngas quality, microbial catalysts activity, and product recovery. These issues are being addressed by researchers and several companies in order to make syngas fermentation more economically feasible (Mohammadi et al. 2011; Munasinghe and Khanal 2010; Liew et al. 2013).

Two-stage fermentation processes to overcome the gas-liquid mass transfer issues were studied in the early nineties (Klasson et al. 1991); technology development continued to identify robust organisms and reactor and process development with many patents (e.g. Gaddy et al. 2011). A pilot plant at 1.5 t/d operated since 2003 on various woody and organic waste materials which are gasified and cleaned up. The cooled syngas is fed to the continuous stirred tank reactor to achieve a proper mass transfer when mixed with the microorganism *Clostridium Ljungdahlii,* yielding a 2% ethanol solution initially [63]. The concept proceeded with a joint venture using green waste gasification, the gas cleaned up, and the biosyngas is biochemically converted to ethanol (20 million liters), integrated with a 6 MW external power capacity when operating at full capacity, in Vero Beach, Florida, U.S. [64]. This fuel was qualified as a cellulosic fuel by EPA [65]. Details of the project environmental assessment are found in [2].

Process development for syngas fermentation can improve further with understanding of the fundamental biology of these microbes with tools that are now available (Latif et al. 2014). Other examples are highlighted by Daniell et al. (2012) and [66], including the work conducted in New Zealand up to demonstration scale with off gases from steel-making operations that reduce the carbon footprint of these mills by converting $CO/CO_2/H_2$ into ethanol or higher value products such as 2,3-butanediol, by select and modified *Clostridia* microorganisms with appropriate pathways [67] and reusing these gases. Scale-up of this concept is ongoing in Chinese steel mills [68] (Daniell et al. 2012; Liew et al. 2013). The production of this biofuel received RSB certification for complying with this voluntary standard principles and criteria [69].

12.2.1.6 Liquid Fuels from Biomass Pyrolysis—Multiple Scales for Centralized and Decentralized Production of Bio-Oils and Upgrading

Pyrolysis is thermal decomposition of biomass in the absence of oxygen that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil), and a gas product (Bridgwater et al. 2003). The relative amounts of the three co-products depend on the operating temperature and the residence time used in the process. High heating rates (fast pyrolysis) of the biomass feedstocks at moderate temperatures (450°C to 550°C) result in oxygenated oils as the major products (60% to 75%), with the remainder split between a biochar and gases. Slow pyrolysis, also known as carbonization, produces about 35% of charcoal, 30% of tars/oils, and gas. At medium heating rates, about 50% of pyrolysis oil formed has lower oxygen content than those from fast pyrolysis, and about 20% char and gases (Laird et al. 2009).

Pyrolysis oils typically contain a significant amount of reactive, oxygenated species including organic acids, aldehydes, ketones, and oxygenated aromatics (Elliott et al. 2012b). These oxygenated species present significant challenges for use in transport applications (Elliott 2013). Biomass pyrolysis technologies are advancing toward the production of liquid fuels for transport applications. Figure 12.17 illustrates the steps to one approach to reach upgraded products in a standalone hydrotreating refining situation (Arbogast et al. 2013; Elliott et al. 2012a). Biomass pyrolysis is commercial for the manufacture of flavor compounds from wood with the residual oils being co-

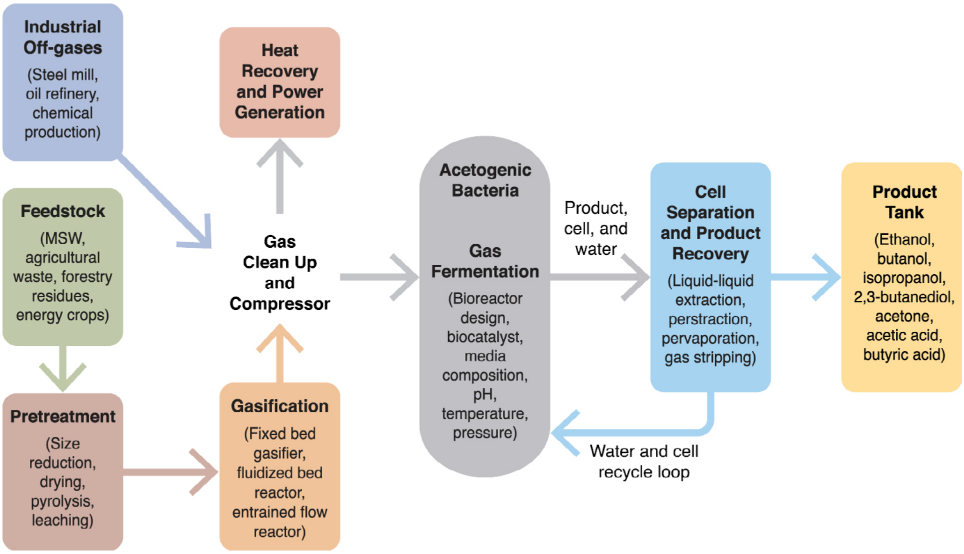


Figure 12.16. Schematic of biomass-derived syngas fermentation to ethanol and a variety of oxygenated products from Liew et al. (2013) reproduced with permission from Intechopen. Also converted are industrial off-gases containing CO and CO_2.

fed in boilers for power production (Stuart and El-Halwagi 2012); bio-oils can be used in commercial heating and several combustion systems (Harmsen and Powell 2011; Venderbosch and Prins 2010).

One catalytic pyrolysis and upgrading of yellow pine to hydrocarbons was scaled up rapidly to commercial scale and produced 3.5 million liters of total fuel, 41% gasoline, 37% diesel, and 22% fuel oil [70] operating at a fraction of capacity.

Developing technologies are the upgrading to drop-in hydrocarbon fuels and chemicals recently reviewed (Talmadge et al. 2014). Upgrading can be conducted as a stand-alone operation to generate blendstocks from uncatalyzed pyrolysis oils or, as above, from catalytic pyrolysis. Many process configurations and catalysts are currently being developed. Alternatively, the pyrolysis oils can be co-processed directly with appropriate petroleum refinery feeds in fluidized catalytic cracking units (de Rezende Pinho et al. 2014). These are areas of significant research, development, demonstration, and initial commercialization (Zacher et al. 2014). Pyrolysis approaches have lower capital costs compared to gasification for the production of diesel fuels as projected in (IRENA 2013). Today's projected costs are the same but could decrease faster for pyrolysis than gasification based on the anticipated future yields at the sizes considered. Pyrolysis scaleup to the large scales is under way by multiple developers.

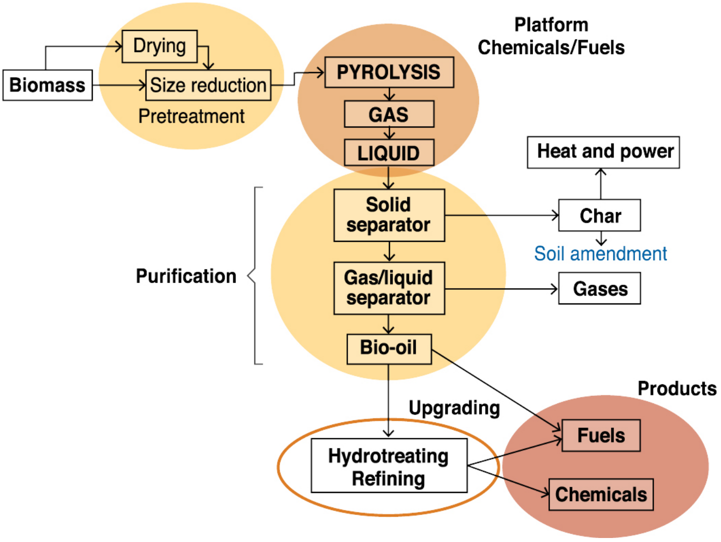


Figure 12.17.1. Fast pyrolysis of biomass process steps to liquid, solid char, and gaseous fractions, followed by upgrading of the bio-oils to liquid hydrocarbon fuels and chemicals (modified from figure in (Alonso et al. 2010) with permission).

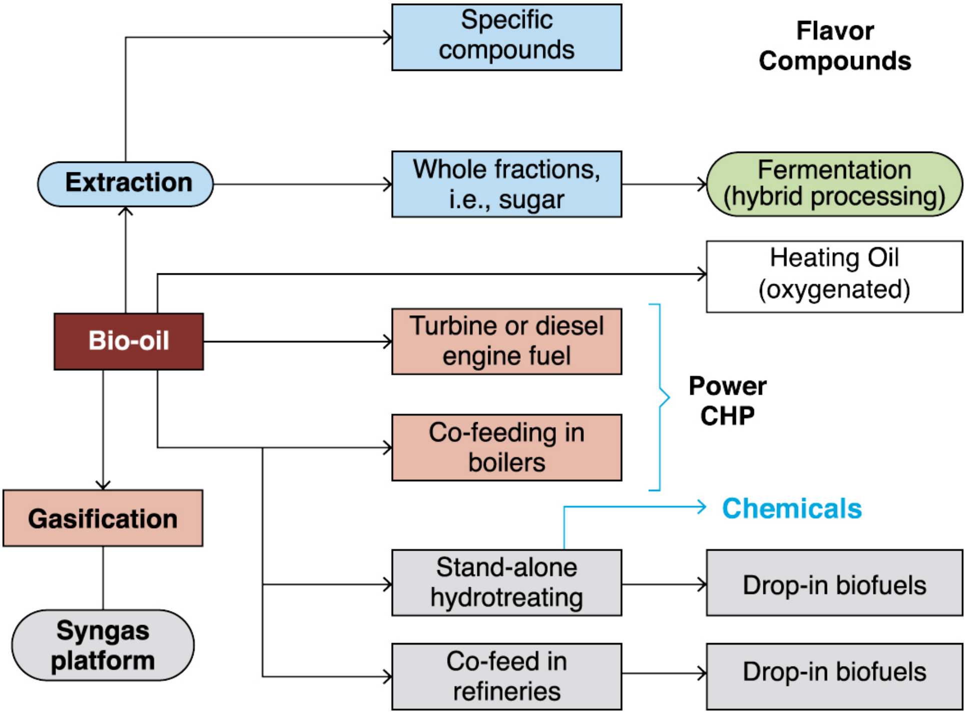


Figure 12.17.2. Multiple pyrolysis biorefineries under development with parts already commercialized.

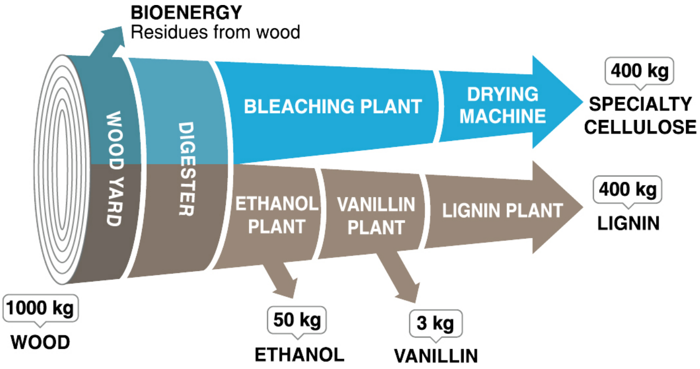
A pyrolysis technology-based very small modular concept using wood residues is operating at small scale in California and started demonstration phase in Alexandria, Louisiana, U.S. as part of an economic development program that includes local capacity development as a first integrated system [71]. The oil is projected to be upgraded to a blend stock for gasoline and the biochar has been developed into a soil amendment with organic certification in California [72]. The integrated concept has the potential to generate negative carbon emissions for the system overall, and has added benefits if coupled with continuous improvement of degraded soils with the biochar. Biochar can improve water moisture retention and increase plant yields and provide the basis for rural or urban high yield production of vegetables, among others [73].

Using other business models and developments on a larger scale than the previous concept, premium fuels from palm and bagasse residues are being generated in Malaysia. The operations proceed through a long-term purchase agreement between developers and users of bio-oil to replace petroleum-based heating oil [74].

12.2.1.7 Biofuels from Forest Products and Pulp and Paper Biorefineries—Old and New

A pulp and paper based biorefinery can take various forms, derived from pulping processes. The Kraft (sulphate) and the Sulphite (dissolving) pulp processes produce packaging and writing paper and chemical/polymer feedstocks (such as rayon), respectively. The development and marketing of novel polymer materials such as Crystalline NanoCellulose and NanoFibrilated Cellulose are also being pursued at demonstration level in Canada, Sweden, Norway, and the U.S. The third area, producing biofuels and biochemicals from the wood derived sugars (such as pre-extraction of the hemicellulose sugars prior to pulping) (Amidon et al. 2013), is an active research area but, as yet, has not evolved to the demonstration and commercial scales. However, the conversion of tall oil to renewable diesel has reached commercial scale production in Finland [75] and development in Sweden [76].

Ethanol from the hemicellulose component and additional ethanol fuels from some cellulosic biomass is being integrated in Norway along with the production of lignin products for a variety of applications. Examples of products and applications are shown in Figure 12.18 (Modahl and Vold 2010; Rødsrud et al. 2012).



Specialty cellulose	Lignin	Vanillin	Bioethanol
Construction materials	Concrete additive	Food	Car care
Cosmetics	Animal feed	Perfumes	Paint/varnish
Food	Agrochemicals	Pharmaceuticals	Pharmaceutical industry
Tablets	Batteries		Biofuel
Textiles	Mining		
Filters	Oil field chemicals		

Figure 12.18. An integrated biorefinery emerged from a paper mill in Norway with basic products and their applications (Rødsrud et al. 2012) with improved environmental impacts (Modahl and Vold 2010).

12.2.1.8 The Commercialization of Advanced Biofuels and Biorefineries

The preceding sections described science and technology advances including examples of about 50 companies and venture partnerships. Many more exist because the industry of advanced biofuels and biorefineries is expanding, albeit at a slow pace, not surprising given the complexity of the systems involved described earlier. Figure 12.19 shows a snapshot of global developments in 2013, from the database of ongoing bioenergy and biorefinery projects with pilot, demonstration, and industrial facilities (Bacovsky et al. 2013) led by the IEA Bioenergy Agreement, which along with the literature (Balan et al. 2013; Janssen et al. 2013) change rapidly; the database is updated periodically.

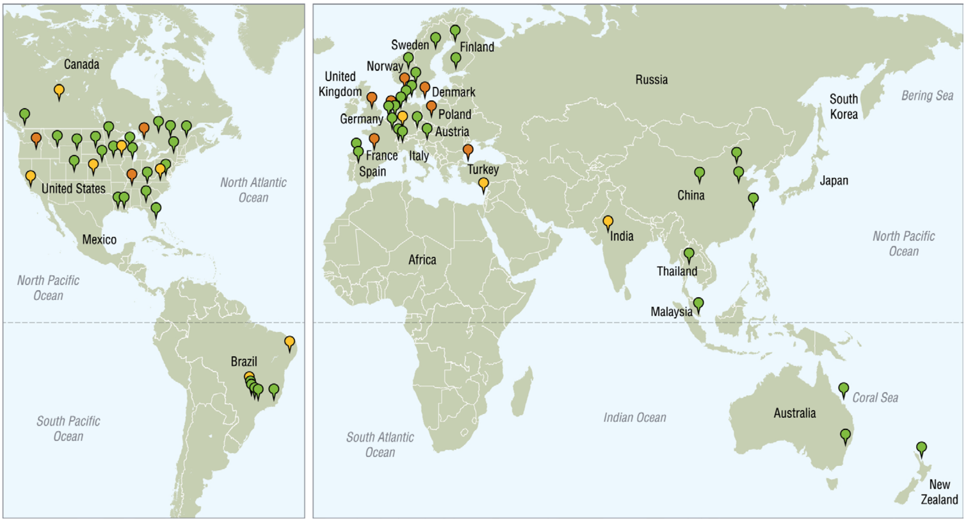


Figure 12.19. Examples of pilot, demonstration, first-of-a-kind industrial projects from IEA Bioenergy Agreement including only member and associated countries as of 2013 (Bacovsky et al. 2013) accessible at http://demoplants.bioenergy2020.eu/.

One approach used to decrease the risk of commercialization is creating multiple partnerships for the development of each of the potential product applications from the core technology invention, including high value products. These activities facilitate biofuels/bioenergy commercialization—as developers and their suppliers/partners gain experience in plant operations to reduce production costs—by de-bottlenecking the technology at smaller scales (Hellsmark and Jacobsson 2009). Existing biomass industries also use another approach: expanding their product portfolio by forming partnerships with other companies such as petroleum processing companies. The biotechnology and the catalyst developers are major participants. Many developments reach technical successes, but fail to move to commercial successes as companies transition from the technological to the commercialization

Valley of Death (Clean Energy Group and Bloomberg New Energy Finance 2010; Jenkins and Mansur 2011).

12.2.1.8.1 Partnerships Created Across the Globe Demonstrate Multiple Technically Feasible Options for Advanced Biofuels and Many Types of Biorefineries

Partnerships have formed among multiple entities through: government programs, e.g., U.S. Department of Energy (DOE) directly [77], or indirectly through the European Technology Platforms [78], multicountry-multiagency collaborations such as the IEA Bioenergy [79], trade and professional associations, conferences, tailored journals, academia, industry, and partners along the supply chain (e.g., biotechnology suppliers) (Thelwall et al. 2010). These loosely linked activities, up to 2009, can be seen through a Webometrics site linkage analyses (Zhao and Strotmann 2014) illustrated in Figure 12.20. Webometrics provides policy-relevant insights (Zhao and Strotmann 2014), principally in the early stages. The advanced biofuels analysis provided evidence of networking and extent of mutual awareness among partners through a process that: (a) identifies the participants, (b) tracks the early, mainly prepublication development of biofuels research funding initiatives, and (c) assesses the role and impact of intermediary organizations and gaps (Thelwall et al. 2010). Figure 12.21 illustrates each of these aspects; starting from the 45-node subnetwork, a four-node subnetwork and four two-node subnetworks indicate a loosely connected association, and then describe the main connections among the various players as types of organizations and countries.

The network has increased substantially with significant additional industry-to-industry and multiparty networks since 2010. Government programs continue to foster efforts from basic research to pilot, demonstration, and first-of-a-kind commercial plants—in the U.S. case through coordinated federal programs of the government (Energy, Agriculture, Defense, Transportation Departments and the National Science Foundation, the Environmental Protection Agency, and the Federal Aviation Administration) [80]. In the European case, multiple projects address the bioeconomy for the European Technology Platforms, managed by partnerships including industry, with great emphasis on biorefineries [81], with member countries that have aligned investments. On the private sector side, a measure of growth is the Biofuels Digest Index[7] of 30 publicly traded biofuels companies; the Digest tracks the daily field activities of biofuels, chemicals, and power, and also conferences around the world. Other trade associations and magazines around the world cover the field. Publications have increased significantly—particularly on the sustainability of the various supply chains to biofuels and bioenergy, along with all other uses (Creutzig et al. 2014).

One of the challenges has been financing, but both private and government sources are being utilized (Janssen et al. 2013). Private sources include internal corporate funds and

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[7] http://www.biofuelsdigest.com/bdigest/category/biofuels-digest-20-index-bdi/

debt offerings, and venture capital. Some government sources include the U.S. federal government, the EU, European national governments, the Brazilian and other governments—including many local governments (Bacovsky et al. 2013). Private sector actors involved are in many fields, financing community, sustainability standards organizations, academia in multiple fields of science, engineering, equipment manufacturers, and many others.

Figure 12.20. At the top, the 57 connected advanced (also called second-generation) biofuels websites show the links from government programs (yellow) elements, red indicates the nonprofit technology platforms of research funded by European government programs, green are the various industries operating in one or more countries, and the blue circles indicate the public science as performers of RD&D or conferences or associations. At the bottom left, are the linkages between the major types of organizations and the links between countries are displayed on the right (Thelwall et al. 2010).

12.2.1.8.2 Estimated Production Costs of the Porfolios of Advanced Technologies

The capital costs of advanced technologies, so far, have been estimated at factors of four to five higher than commercial ethanol plants, so they will contribute more to the advanced biofuel production cost, depending on the conversion plant size, among other factors.

Chum et al. (2011) project the 2020-2030 ranges of estimated production cost for families of processes based on literature data of processes at different stages of development, assuming that projected costs of a first-of-a-kind plant would be reduced based on the industry experience of many pioneer plants to that of the nth plant (Chum et al. 2011). To succeed at scale requires accurately estimating cost and performance at smaller scales. Plant cost growth correlates with the level of process understanding (integration issues) and project definition (estimate inclusiveness). In fact, a common issue is not having enough data at the pilot scale level and premature scale-up, a costly way for examining major process variables.[8] Plant performance correlates with the number of new steps, the percent of heat and mass balances that are based on data, waste handling, and the use of solid feedstocks (McMillan et al. 2011).

Zinoviev et al. (2010) conducted a detailed analyses and found wide ranges of costs estimated for European conditions, primarily, and concluded that better criteria were needed for selecting processes to scale-up. A recent comparison[9] of developers scaling up biofuels and bioproducts processes, including published data technoeconomic data, by Jacobs Consulting for Alberta Innovates (Canada) emphasizes the issues above and further highlights that successful developers have access to versatile, highly instrumented piloting facilities; close access to laboratory facilities…[for] quick turnaround; and are led by multi-disciplinary individuals with process development backgrounds, among others.

More recently, IRENA evaluated transport biofuels costs, based on analyses of more than 15 plants, which are planned to be online within the next few years for lignocellulosic biofuels (IRENA 2013). IRENA also projected the costs of current commercial production (Figure 12.21) and projected 2020 commercial feedstock costs. Figure 12.21 summarizes the analysis results framed with the U.S. range of gasoline and diesel for 2012. IRENA concludes that compared to today's estimated production costs, significant improvement is possible in both the enzymatic hydrolysis and thermochemical lignocellulosic ethanol pathways. Similarly, the thermochemical routes for hydrocarbon diesel fuels could also reduce their costs based on gasification or pyrolysis (IRENA 2013).

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[8] http://www.energy.gov/sites/prod/files/2014/06/f16/d_and_d_workshop_summary_report.pdf

[9] http://www.biofuelsdigest.com/bdigest/2014/10/22/enerkem-albertas-municipal-waste-to-fuels-juggernaut-in-pictures/ and http://www.biofuelsdigest.com/bdigest/2014/10/28/the-8-habits-of-highly-successful-biorefinery-developers-looking-at-albertas-look-at-advanced-biofuels/

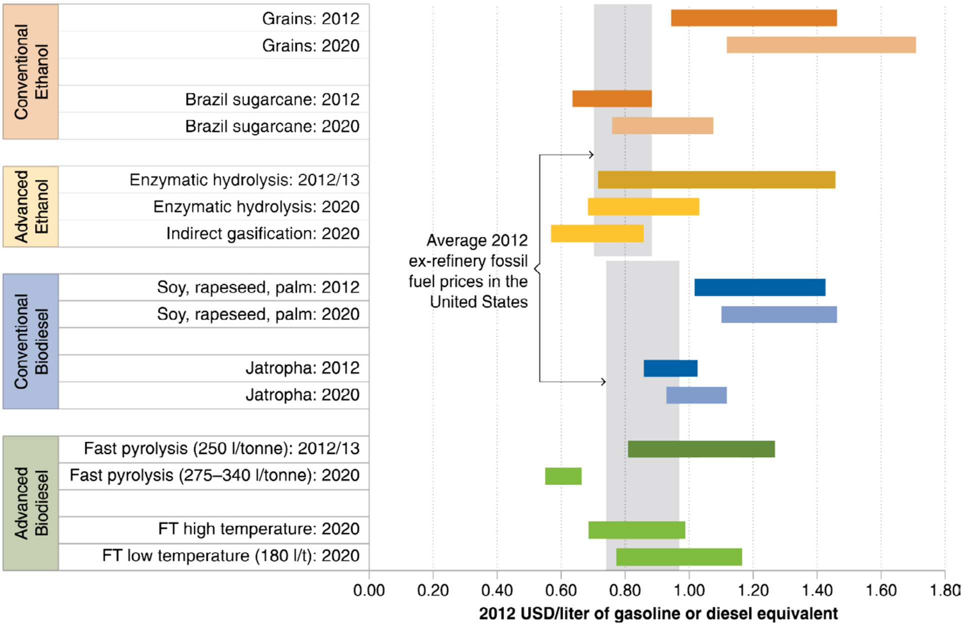

Figure 12.21. Summary of current estimated production costs of biofuels and projected estimates by 2020. A reference is the range of U.S. ex-refinery fossil fuel prices (IRENA 2013) reproduced with permission. Ex-refinery price of a product paid to local refineries is the landed cost of the product. It originates in the import parity price of the product if the same were to be imported.

IRENA expressed a positive outlook conditional to the following:

- “Advanced biofuel deployment accelerates, process stability, reliability and availability could be proven, and production costs could fall to very competitive levels.”
- “Advanced ethanol production costs from biochemical and thermochemical routes could decline by 30-50% if capital costs are reduced to the fully deployed, debottlenecked and upscaled integrated plant designs.”
- “Advanced renewable diesel production costs under the same conditions could fall by 40% to 50% if the capital costs can be reduced to long-run optimized levels.”
- “Fischer-Tropsch synthesis has yet to be deployed commercially using biomass-based feedstocks. However, if deployment can be accelerated and the syngas production from biomass optimized and proven to be reliable, costs in 2020 might be competitive with fossil fuels.”

In addition, there is a need to couple this technical and commercial feasibility to the overall system with sustainability considerations as discussed in sections 12.1.1 and 12.2.1.

12.2.2 Biofuels Utilization in Transport

Each renewable fuel option, whether it is fermentation ethanol or a diesel prepared from vegetable or waste oils, has to fit into a matrix of regulatory requirements that satisfy public safety, and determine the eligibility to be recognized as renewable, per: EU or individual member countries, the U.S. or individual states (California), or other countries. Ethanol and biodiesel, the major biofuels commercialized today, have highlighted the processes by means of which the road transportation sectors can be accessed.

The first requirement is to have a reliable and proven manufacturing process and off-take arrangement. The key to this is that the manufactured fuels meet specifications at the point of delivery to the off-taker. This is done through accepted standards in the U.S. [82] or Europe [83]. Before renewable fuels specifications are accepted into the transportation system, their blends have to satisfy environmental and health criteria with respect to their shipping, as determined by the International Maritime Organization, through certificates for shipping [84].

Storage and end-use consideration also require the fuels and their blends to meet emissions standards. In Europe, these are known variously as Euro 5 or 6 standards and cover the combination of the vehicle, engine, and fuel with respect to the systems emissions of particulate matter (PM), oxides of nitrogen (NO_x), total hydrocarbons (HC), non-methane hydrocarbons (NMHC), and carbon monoxide (CO). In the U.S., the Environmental Protection Agency (EPA) sets standards under Tier 1 and Tier 2, while California has its own standards set by the California Air Resources Board. GHG emissions are also incorporated into the various emissions test programs. We review the use of the two major commercial biofuels to provide common understanding of their history, uses, and limitations. We highlight the use of advanced biofuels that can reach all markets for transport and their commercialization. The first was renewable diesel (hydrotreated vegetable oil—HVO) which reached 10% of the biodiesel market. Several processes for liquid hydrocarbon fuels derived from biomass (see sections 12.2.1.4-7) are producing the whole range of liquid fuels from gasoline, jet A1, diesel, and maritime fuels in various stages of development. The applications and requirements for liquid fuels and networks of stakeholders and systems necessary to use transport fuels are illustrated in Figures 12.22 and 12.23.

12.2.2.1 Ethanol Use Increased

Table 12.4 lists properties of ethanol and gasoline, and common fuel blends used in spark-ignition engines (API 2010; Kasseris 2011; Larsen 2009). In the most common blend, ethanol is an additive to gasoline represented as (E10), as the main fuel, E85 as used in Sweden and in the U.S. (51% to 83%), or the neat wet version (6.5% water by mass) used in Brazil. Mid-level blends properties and references may be found in Stein (2013).

Table 12.4. Comparison of Ethanol and Gasoline Properties and Definitions of Abbreviations (API 2010; Kasseris, 2011; Larsen 2009; Ratcliff et al. 2013; Yanowitz and McCormick 2009).

Property	Gasoline	Ethanol	E10	E85 85%	E100 hydrous
Lower Heat Value (LHV) (MJ/kg)	42-44	27	41	29	25
Mass Density (kg/dm^3)	0.72-0.77	0.79	0.75	0.78	0.81
Heat of Vaporization h_{lhv} (kJ/kg)	310	885	366	836	970
Air/Fuel Stoichiometric Ratio	14.7	9.0	14.1	9.8	8.4
LHV/CO2 Exhaust Emission (MJ/kg)	13.5	14.1	13.6	14.0	14.1
Laminar Flame Velocity @ 1 bar, 20°C (m/s)	0.33	0.41	-	-	-
Research Octane Number (RON)	86-98	110	+7- +3[a]	105-109	111
Motor Octane Number (MON)	80-90	91	+4- +2[a]	90-91	92
Anti Knock Index (AKI) =(RON+MON)/2	87-9[b]	100	+6- +3[a]	97-100	101
Reid Vapor Pressure @ 37.8C (bar)	~ 0.6	0.16	~ 0.7	~ 0.4	~ 0.15

[a] Values of the increment of octane number over that of hydrocarbon gasoline

[b] Regular and Premium unleaded gasolines

12.2.2.1.1 Low and Mid-level Blends Used in More Than Fifty Countries

Fifty or more countries have policies [87] to use low-level blends like E5 or E10 already. Global vehicle manufacturers usually allow a maximum of 10% ethanol blend in their new gasoline vehicles. Low level blends are compatible with the gasoline vehicle fleet, unless the vehicles are older models. Older models can be subjected to corrosion in aluminum fuel lines, exposed Zn/Al/Cu alloys, and swelling of butyl rubber or polyamide 6.6.

From 2010 to 2011, the U.S. EPA granted a partial waiver for E15 use in model year (MY) 2001 and newer light-duty motor vehicles. This waiver included manufacturer requirements like registering the fuel, developing a mitigation plan against misfueling into inappropriate vehicles, and ensuring appropriate blend level delivery; therefore, introduction of E15 started in 2013 [88]. Consequently, vehicles beginning with MY 2012, 2013, and 2014 from General Motors, Ford Motor Co., and Volkswagen, respectively, are compatible with E15, as are certain models of other manufacturers [89].

Currently, more than 75% of ethanol consumption in transportation worldwide is in the form of a low-level blend, limited usually to E10. Mid-level blends (E10<EX<E40) represent approximately 10% of ethanol consumed in transportation worldwide. Ethanol/Gasoline properties are shown in Box 12.4.

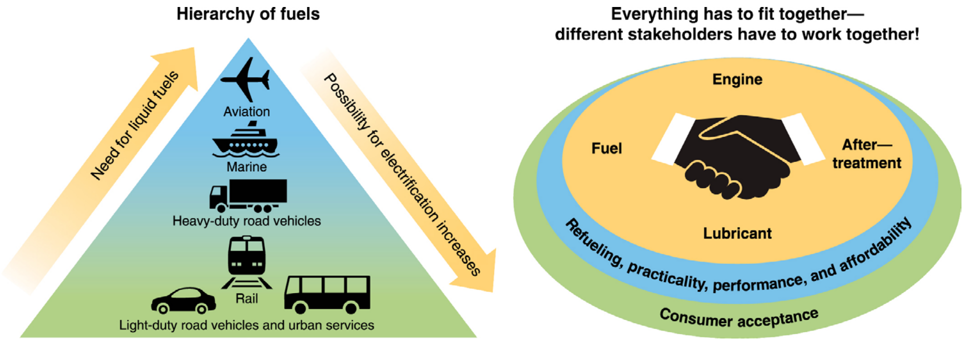

Figure 12.22. Transport fuel applications are shown on the left, showing the ease of introducing electric or hybrid concepts, higher for light duty road vehicles and urban road services. Liquid fuels are needed in the aviation and marine sectors due to the high energy intensity of hydrocarbon fuels. The right figure illustrates the various types of integration of the fuels needed with engines, after treatments to comply with emissions regulations, refueling, and customer acceptance (from Nils-Olof Nylund [85] with permission).

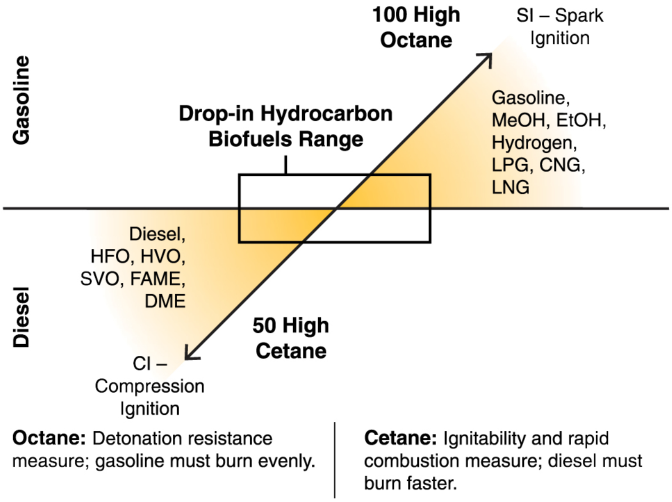

Figure 12.23. Properties of liquid fuels for common types of engines: Left—compression ignition with the corresponding petroleum fuels, diesel and heavy fuel oil (HFO) or oxygenated blends or substitutes from biomass, HVO (hydrotreated vegetable oils), SVO (straight vegetable oils), FAME (fatty acid methyl ester - biodiesel), and DME (dimethyl ether) with SVO causing the most problems in use. Right: Gasoline and blends or alternative fuels such as MeOH (methanol), EtOH (ethanol), Hydrogen, LPG (Liquefied Petroleum Gas), and CNG (Compressed Natural Gas) and LNG (Liquefied Natural Gas). Drop-in biofuels are produced in the range of hydrocarbons for multiple transport applications (adapted from Schramm [86] with permission).

Box 12.4. Ethanol/Gasoline Specifications

- Mixtures of gasoline and anhydrous ethanol are denominated EX, where X represents the volume fraction of ethanol as a percentage. In low-level blends X goes up to 10 or 15, while for mid-level blends X can vary from above 15 up to 50.
- "Splash blended" fuels are a mixture of specified anhydrous ethanol with a commercial gasoline.
- "Match blended" fuels are a mixture of specified anhydrous ethanol with gasoline blendstocks in order to obtain a blend meeting the specifications for finished gasoline.
- To improve the economics of ethanol blending in low-level blends, petroleum refiners have developed hydrocarbon blendstocks (blendstock for oxygenate blending, or BOB). A BOB does not meet the specifications for gasoline until blended with 10% anhydrous ethanol. Typically a BOB will have an Anti-Knock Index (AKI) below the minimum requirement, taking advantage of the relatively high AKI of ethanol. Other properties such as Reid Vapor Pressure (RVP) and the 50 volume percent boiling temperature may also be tailored for ethanol blending. Flex-fuel vehicles (FFVs) can operate on any ethanol level from 0% to 83%. The specification for the fuel known as E85 allows ethanol levels as low as 51%, although this low ethanol level is typically only used during winter months such that the additional gasoline can provide a higher RVP for cold starting. Because FFVs operate on such a wide range of blends they are not optimized to take advantage of the high AKI imparted by the high levels of ethanol.
- Hydrous ethanol, as commercialized in Brazil, contains 5% water on a volume basis and requires less energy for production, but requires some extra care to avoid corrosion on fuel systems components. It has been used in straight ethanol vehicles manufactured from 1979 till 2005 or in flex-fuel vehicles (FFVs) produced since 2003 (Nigro and Swarcz 2010).

In Brazil, gas stations sell a mandated mid-level "matched blend" that contains 18% to 25% of anhydrous ethanol, based on ethanol availability; there are no gasoline pumps. All new vehicles have been developed and emission certified for E22 since the 1980s. Major vehicle manufacturers can build new models compatible with, not only mid-level blends but also, hydrous ethanol, and these have been in production for the Brazilian market for the last 34 years.

“Splash blended” ethanol in the E10 to E30 range increases Reid Vapor Pressure (RVP), which can lead to additional evaporative emissions (API 2010). Blending of about 10% ethanol into a regular gasoline can increase AKI to the level of a premium gasoline. The observed increase in RVP declines to below that of the blending hydrocarbon gasoline at blend levels greater than approximately 40% to 50%. Fuel consumption (L/km) increases about 2.5% for each 10% of blended ethanol, a number just slightly smaller than calculated based on the fuel heating value and density.

The effect of ethanol blends on vehicle emissions depends on the engine and emission control technology to meet regulated emissions levels required in the specific location. Due to the physicochemical properties of ethanol, CO and HC emissions can be reduced. Some studies show no significant effects on NOx emissions in modern cars that have more effective control of air-fuel ratio for blends up to E20 [2]. In older vehicles, there can be increases depending on specific conditions [2]. Life cycle CO2 emissions are addressed in Chapter 10, and they are generally lower.

12.2.2.1.2 Straight Ethanol and Flexible Fuel Vehicles in Brazil, U.S., and Sweden

Brazil produced 5.6 million straight ethanol vehicles from 1979 till 2005 but the program lost credibility after ethanol supply shortages. Brazil started producing flex-fuel vehicles (FFVs) for gasohol and hydrous ethanol in 2003 because of government policies and a clear market pull. In the country’s fourth generation of FFVs, the compression ratio was reaching 13:1, torque and power with ethanol were about 10% higher than with gasohol, and cold start was carried out by pre-heating ethanol, eliminating the need for the auxiliary gasoline fuel tank (Joseph Jr. 2009). More than 20 million FFVs were produced until 2013.

In the U.S., FFVs for gasoline and E85 have been produced since the 1990s, reaching 14 million FFVs in 2013 [90], more than 10% using E85 from about 2,600 retail stations (from 150,000 total outlets).[10] The standard from ASTM International, ASTM D5798, specifies blends containing 51% to 83% ethanol with lower levels ensuring cold starting and driveability during winter months. Overall, the tailpipe pollutant emissions data indicate either no significant change in FFV emissions versus E10 for higher levels of ethanol or some decrease in emissions, with the exception of acetaldehyde (Yanowitz and McCormick 2009). Box 12.5 compares Brazil and U.S. emissions experience with FFVs.

12.2.2.2 Other Alcohols Are Less Volatile but Have Lower Octane Numbers

Isobutanol has a slightly lower octane number than ethanol (106 versus 110 RON, see Table 12.4) but otherwise has several advantageous properties. These include much lower water solubility, and the fact that when blended into gasoline, isobutanol causes

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[10] http://www.eia.gov/todayinenergy/detail.cfm?id=15311&src=email, March 7, 2014

Box 12.5. Emissions and fuel consumption of straight ethanol and flexible-fuel vehicles

- 1979 to 1985: Brazilian hydrous ethanol dedicated vehicles had the same power and performance of similar models running on gasohol, but with 16% lower energy consumption (MJ/km) (Joseph Jr. 2013; Nigro and Swarcz 2010). Model year 1985 ethanol vehicles, without exhaust after-treatment, emitted 30% less CO, 18% less HC, 20% less NO_x and 200% more acetaldehyde (CETESB 2008).
- After the introduction of three-way catalysts and closed-loop control of stoichiometry, the emission changes compared to gasohol were about a 20% reduction for CO, a 30% increase for HC and ethanol, and similar NOx emissions (CETESB 2008). The observed advantage in energy consumption dropped from 16% to 4%, while the ethanol vehicles performance gained compared to gasoline models (Nigro and Swarcz 2010).
- The usual technology applied in FFVs to run on gasoline or a blend of up to 85% ethanol (E85) makes a compromise between gasoline and ethanol, so that the advantageous properties of ethanol are not fully explored to avoid impairing gasoline operation. This is the situation in both Brazil and the U.S. but designs specifically designed for the fuel blend to be used can perform better.
- Brazilian FFVs tested since 2009 in the Vehicular Labeling Program (Inmetro 2012) show 2% higher average energy consumption with ethanol than with gasohol (see also Joseph Jr. 2009).
- U.S. fuel economy data for FFVs (U.S. DOE 2013) shows an average reduction of energy consumption for E85 over hydrocarbon gasoline of about 3% (MJ/km), with large automobiles and SUVs experiencing a slightly larger benefit, while for compact and subcompact cars the fuel energy consumption is about the same for both fuels.
- When Tier 1 FFVs running on E85 are compared to similar non-FFVs running on gasoline with 54% reductions in emissions of NO_x, 27% of NMHCs, and 18% of CO are obtained (Yanowitz and McCormick 2009). Other studies report similar results for NO_x but find no significant change in CO (U.S. Environmental Protection Agency, 2007, 2010). A similar comparison of Tier 2 FFVs running on E85 and similar non-FFVs running on gasoline shows on average, 20% reductions in CO, and no significant effect on NMOGs emissions. NO_x emissions averaged approximately 28% less than comparable non-FFVs (not statistically significant). For both

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» Tier 2 and older cars the results vary widely due to different calibration emphasis during start and cold phase of the test cycle (Haskew 2011).

- Brazilian FFVs are tested with gasohol and hydrous ethanol. Emission differences between these fuels vary depending on the calibration used by the automaker. The effects on NOx are similar to that observed in the U.S. but CO and NMHC are higher in Brazil, due to start up difficulties on ethanol, which require mixture enrichment during the cold phase of the test cycle. Brazilian emission regulations allow subtracting the unburned ethanol from NMHC to avoid gasohol injection during the cold phase cycle. Upcoming regulations will probably incorporate the NMOG concept to limit total VOC and the potential to form ozone (Branco 2013). Several studies have shown lower ozone forming potential for FFVs operating on higher ethanol level blends (Haskew 2011).
- Air toxic emissions when using E85, as presented by U.S. EPA (U.S. Environmental Protection Agency 2010), show a strong increase of aldehydes (~4,000% for acetaldehyde and 100% for formaldehyde) and a significant reduction of 1,3 butadiene (~-70%) and benzene (~-60%). Studies in Brazil have shown aldehydes increases from 200% to 2,000% (ANFAVEA 2013). Considering EPA toxicity equivalence factors (Graner 2013; Hammel-Smith 2002) the differences in 1,3 butadiene and benzene emissions more than compensate for the increased aldehydes and the total air toxic emissions potency is smaller with E85.

RVP [16] to decrease rather than increase as is the case for ethanol up to about E40 blends. This decrease in RVP is potentially a major economic driver for the use of isobutanol by petroleum refiners as it may significantly reduce refining costs for the hydrocarbon portion of the gasoline. The relatively low RON of 96 for 1-butanol makes it less desirable. Longer chain alcohols (pentanols, for example) have even lower octane numbers. Extensive emission testing studies for isobutanol are not available. One study showed no differences for NO_x, CO, and non-methane organic gases (NMOG) in a Tier 2 car. Formaldehyde and acetaldehyde were the largest carbonyl emissions for ethanol blends, while formaldehyde, acetone, and 2-methylpropanal were the largest carbonyl emissions from isobutanol blends (Ratcliff et al. 2013).

12.2.2.3 Biodiesel Is Blended with Diesel, Some Infrastructure and Distribution Issues

Biodiesel is primarily used as a 2% to 20% by volume blend with petroleum diesel. Biodiesel in blends will not separate or partition into water. In most engine and vehicle manufacturers' literature, B5 and lower blends are approved, as long as the biodiesel meets D6751 and/or EN14214, the European biodiesel specification. The ASTM specification for conventional diesel fuel, D975, allows up to 5% biodiesel in conventional diesel fuel. A separate specification, D7467, describes the required property limits for B6 to B20 blends. Blends of B20 or higher are now accepted by most Original Equipment Manufacturers (OEM) [91].

A number of efficiencies could be gained if biodiesel blends could be moved to market in petroleum product pipelines. Both private [92] and a common carrier pipelines have begun routine shipments of B5 [93]. The B5 blends do not degrade during transport; however, the next batch of diesel can be contaminated with low levels of biodiesel. Concerns for broader expansion into most pipelines include jet fuel contamination with FAME in multiproduct pipelines, which could impact the stability of jet fuel [94].

On average, using biodiesel as a blend or in neat form results in substantial reductions in emissions of PM, CO, and HC in engines that are not equipped with catalyst and filter emission control systems (Yanowitz and McCormick 2009). Biodiesel may cause a small increase in emissions of NO_x relative to petroleum diesel, by about 2% for B20 in some cases but not always (Yanowitz and McCormick 2009). Factors that affect NO_x emissions from biodiesel include biodiesel source material, driving cycle and average load, as well as engine and fuel system design and operating strategy. For more modern engines equipped with diesel particle filters, diesel oxidation catalysts, and NOx emission control catalysts there is little if any effect of fuel on tailpipe emissions (Lammert et al. 2012).

Given the broad acceptance of B5 blends by engine OEMs, and the increasing ability to move these blends by pipeline, B5 is close to being considered a drop-in fuel in the U.S. Some additional research is needed on higher blends up to B20. In many markets early biodiesel development has been characterized by product quality issues—emphasizing the importance of national quality standards and their enforcement to increase acceptability.

12.2.2.4 Biomass-Derived Hydrocarbon Fuels Reach a Larger Fraction of the Barrel of Oil

Most of the processes reviewed in Section 12.2.1.5 produce the whole range of hydrocarbons and, therefore, will produce drop-in fuels for road, water, or air transport. See also a recent review of the drop-in fuels research and development by biochemical, thermochemical, and hybrid processing with estimated production costs and companies involved.[11]

12.2.2.4.1 Hydrotreated Vegetable Oils or Renewable Diesel is a Hydrocarbon and Can Come from Many Feedstocks

HVOs are produced commercially by Neste Oil from palm oil and a variety of waste oils (meat, fish, etc.). The diesel product shows encouraging reductions

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[11] “The potential and challenges of drop-in biofuels” IEA Bioenergy Task 39 ISBN: 978-1-910154-07-6 (electronic version) at http://task39.org/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf

of either energy consumption or exhaust gas emissions [95]. In the U.S. several companies are producing commercial quantities of renewable diesel, mostly from wastes [96] and in various phases of development. ENI Spa will start commercial production using the UOP/ENI Ecofining process [97] at its Venice, Italy refinery [98]. Other developers are in start and go phases of production and have tested their products. Bus fleet tests are being conducted with diesel produced from microbial fermentation of sugars [99].

12.2.2.4.2 Developing Bio-Jet Fuels Need a High Density Low Carbon Fuel

For aviation turbines the biofuel has to fit the existing and developing equipment and available distribution infrastructure because this infrastructure is highly regulated and requires a high level of safety and reliability (FAPESP 2013). This pushes solutions toward drop-in fuels, because the increased development costs make non-hydrocarbon alternatives unviable. The aviation industry is pursuing this alternative source of high density carbon fuels vigorously as other power sources concepts would require a new infrastructure and new equipment [100].

A special effort coordinated by ASTM has set the standards: D4054 [101] and the alternative jet fuels standard D7566 [102] with Annexes (A) for the specific biofuels pathways tested sufficiently to meet the requirements for a drop-in alternative jet fuel. This step is necessary to perform the continued assessment of these biojet fuels in commercial flights for their performance in various dimensions (infrastructure, emissions, impact on noise, etc.) until technical confidence is obtained. In parallel, producers refine processes and reduce production costs to enable their commercial adoption. Figure 12.23 presents major process routes being considered for drop-in aviation biofuels until mid-2014. Significant national, regional, and global level efforts are ongoing (International Air Travel Association 2013).

The biomass gasification and catalytic FT upgrading pathway to synthetic paraffin kerosene (SPK – FT A1) received the first approval, because it is substantially identical to the commercial product from South Africa based on coal gasification using this pathway, approved over 10 years ago [103]. Next, the more commercially available HEFA were approved for blends up to 50%. Since HEFA-A2 ASTM certification in 2011, the industry reports (International Air Travel Association 2013) that 18 airlines collectively performed over 1,500 commercial passenger flights with blends of up to 50% biojet fuel from used cooking oil, jatropha, camelina, and algae (6/2012-12/2013). So far, biojet fuel could be blended with conventional fuel; no aircraft modifications were required; and an improvement in the engine in fuel efficiency on the biojet mix was observed in some cases (International Air Travel Association 2013). A six-month commercial flight use study did not show adverse effects in the engines. Multiple partnerships of airlines, airports, aircraft manufacturers, governments, biomass and biofuel producers and suppliers, and sustainability certification groups are leading these efforts (International Air Travel Association 2013). The microbial pathway to farnesene, hydrogenated to farnasane (DSCH A3) was approved in 2014 for up to 10% blend [104]. Other processes undergoing approval for commercial flights are in preparation by technical committees of ASTM [105]. Biojet products from routes not yet approved have produced sufficient fuels to start testing properties on the way to preliminary and then commercial flights (International Air Travel Association 2011, 2012, 2013).

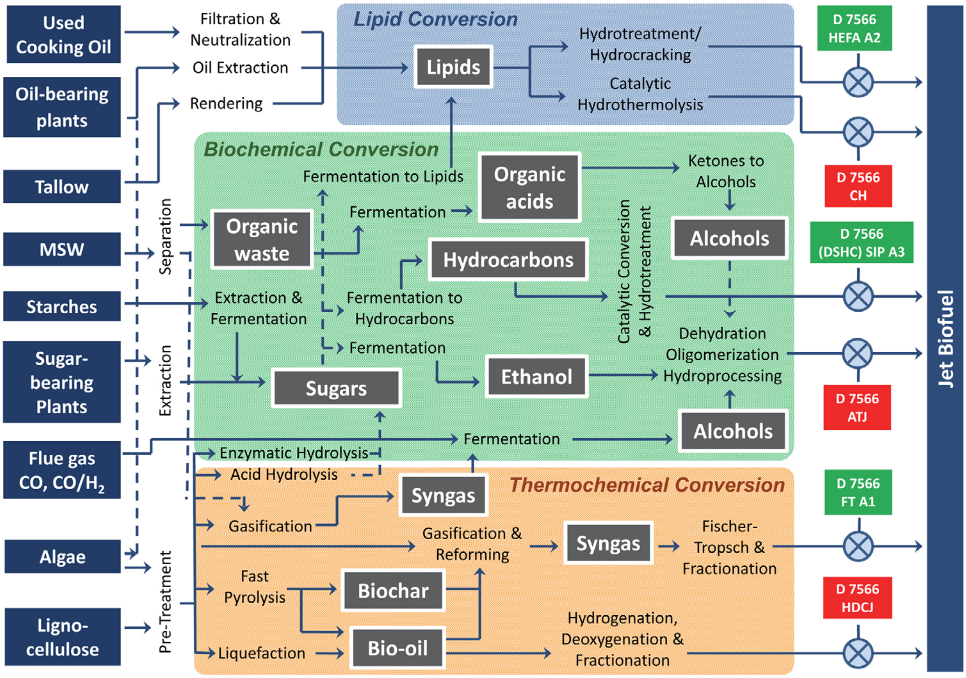

Figure 12.24. Examples of identified pathways for producing biojet fuels and status of ASTM certification (red developing and green approved). HEFA; Alcohol to Jet, ATJ; Direct Sugars to Hydrocarbons, DSHC (approved to 10% as Synthesized Iso-Paraffin, SIP); Hydrotreated Depolymerized Cellulosic to Jet (pyrolysis), HDCJ; Catalytic Hydrothermolysis, CH; Catalytic Conversion of Sugars, CSHC. Modified from references (Schuchardt et al. 2014; FAPESP 2013) with permission.

12.3 Conclusions

- Current commercial biofuels production using annual crops has improved its performance in conversion processes, in feedstock production, and delivery, and in use of the biofuel while decreasing environmental impacts in general. Continuous improvement in performance is forecast. The overall limitation is global availability of feedstocks.

- Hydrotreated vegetable oils or renewable diesel, are hydrocarbon fuels made from plant oils, or waste oils, greases, or animal fats in commercial processes common in the petroleum refineries developed and deployed in the past five years, reaching 10% of the biodiesel market. These are hydrocarbons, compatible with petroleum fuels infrastructure, and of high consumer acceptance. Continuous improvement in performance is forecast including costs, principally as waste streams as logistics of supply development improves.
- Portfolios of conversion technologies using lignocellulosic biomass have emerged along multiple pathways. Many are reaching industrial scales, at a slower pace than anticipated by governments or by the private sector. Developers and their partners had to set up a complex set of value chains: from biomass production, delivery to the conversion facility for biofuel manufacture, fuel distribution, and use, to product acceptance. More work is needed to bring the cost of these technologies down and to integrate the elements of the value chain, including assessments of environmental and overall system sustainability.
- Conversion pathways that optimized the fully integrated process at pilot- and small-demonstration scales benefitted from learning the interdependencies among individual process steps and were able to capitalize on multiple thousands of hours of operating experience required. They avoided pitfalls of performing integration research at large industrial scale, which decreases financial viability of involved companies and partnerships.
- The use of indicators for evaluating conversion processes will benefit from including multiple environmental, materials efficiency, energy, and economic factors to analyze their interdependencies and guide process development toward commercialization.
- Multiple pathways are undergoing development based on transformation of key intermediates from lignocellulosic biomass such as sugars and lignin from a variety of pretreatments, synthesis gas from various types of gasifers, oils from pyrolysis processes, and biogas from anaerobic digestion. Upgrading of these intermediates to final biofuels and coproducts has expanded significantly with biological, biochemical, chemical, catalytic, and thermal processing. These advances are increasing the scope of biorefineries to encompass the majority of petroleum-derived products and expand the portfolio of chemicals and materials from renewable resources.
- Densified biomass such as pellets are facilitating conversion of wood, wood wastes, and agricultural residues into storable materials for larger scale application in power generation and cogeneration, and traded globally. Similarly, such materials could increase the scale of biofuels production from sustainably sourced biomass and wastes.
- Large-scale plant sizes can fit specific country context and available local resources. Developed with sustainable economic, environmental, and resource

efficiency goals, they may provide options that could deliver for rapid GHG emission reductions. Well-designed systems alone or in conjunction with CO_2 capture and storage represent options with risks and uncertainties which can be reduced with further RD&D and integrated testing, verification, and monitoring to assess their potential for climate change mitigation.

- A variety of small-scale processes for gaseous biofuels production with anaerobic digestion are already being used for heating, cooking, and power generation with many successes. Small systems for liquid fuels scaling-down commercial plants are starting and are challenged to achieve reliable supply chains and stable operations. Pyrolysis to bio-oils replacing heating oil for institutional applications is ongoing. Modular integrated systems for liquid transport fuels and biochar and pyrolysis technology provide opportunities to recover degraded soils and improve land productivity for agriculture. Modular systems costs can be reduced with advanced manufacturing concepts. Advances in manufacturing small-scale plants with automation and controls could enable deployment and cost reduction of a variety of processes and products including biofuels.
- Partnerships: Governments in the U.S., the EU and member countries, Brazil, and many other countries, are collectively fostering multiple private sector activities and public-private partnerships. These global partnerships decrease risks in developing a bioeconomy, by taking advantage of existing capital assets and knowledge, and building on each other's developments.

Box 12.6. Examples of Significant Outcomes at Industrial Scales

- Portfolios of biotechnology products, isobutanol, microbial hydrocarbons, and heterotrophic algae-catalyzed fermentation move toward commercialization. Demonstration and pilot-scale production is generating products for subsequent testing as fuels, lubricants, commodity chemicals, and others. Operations are not continuous or at capacity. Two facilities are in grain ethanol plants in the U.S. and one facility is in a sugar mill in Brazil.
- Portfolios of waste biomass gasification products upgraded through commercial Fischer-Tropsch catalytic or industrial scale syngas fermentation are underway for aviation biofuels and ethanol, respectively (U.K., U.S.).
- Feedstock supply development for reliable delivery of agricultural residues and feedstocks took four to six years to set up for each of the three first-of-a-kind commercial conversion plants in the U.S. Each has about 100 million L of ethanol production annual capacity, with two starting operations in 2014 and the third in commissioning.

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- Two ethanol biorefineries are operating industrial-scale facilities at reduced capacity, planned at 30-50 million L/yr, while de-bottlenecking the integrated processes, to achieve sustained operation. These are biochemical ethanol from agricultural residues in Italy and gasification-fermentation ethanol from green wastes in the U.S. The Italian facility process has been scaled up in Northeastern Brazil at the same size as the U.S. commercial operations and is producing ethanol and power.

Multidisciplinary Scientific Breakthroughs and Engineering Advances Fostered

- Industrial biotechnology progress in lignocellulosic feedstocks was synergistic with improvements in commercial starch processes.
- The dry mill corn refining industry matured in the U.S. and is the major ethanol producer with co-products animal feed, corn fiber corn oil for biodiesel, and others, with an ethanol carbon intensity nearly halving between 1990 and 2010, and improved environmental profile.
- Manufacturing of ethanol production facilities matured with the rapid capacity expansion; currently more ethanol is being made from cellulosic corn fiber.
- Resource use efficiency improved significantly in the sugarcane biorefineries with power generation, essential in the Brazilian context during dry periods of low hydroelectricity production.
- Forest products biorefineries diversified into biofuels from coproduct oil streams to biodiesel and renewable diesel, in partnership with oil companies.
- Oil industry leadership is systematically developing, testing, and commercializing biofuels for road, aviation, and chemical coproducts. Renewable diesel commercial production reached 10% of biodiesel production in about five years.
- A new application market is being assessed—aviation biofuels. Two families of hydrocarbon biojet fuels passed stringent standards certification allowing 50% blends to be flown commercially; a fermentation product farnesane was approved at 10% level for jet fuel commercial flights. Through 2013, 1,500 commercial passenger flights from 18 airlines were flown. Additional families of biojet fuel products are being tested and proceeding with the certification process. Tests so far indicate complete infrastructure and aircrafts compatibility.

12.4 Recommendations for Research, Capacity Building, and Policy Making

Long-term goals are to improve efficiency, decrease environmental impact, and enhance the economic viability of advanced biofuel processes by addressing key areas (examples):

- Investment in advanced biosciences research—genomics, molecular biology, and genetics—for major platforms—sugar, syngas, methane, and algae and cyanobacteria for fuels, including hydrogen, and chemicals;

Table 12.5. Developing Sustainable Technologies. Reduce costs while improving environmental characteristics, improving materials, and energy use.

Technology	Key R&D Issues
Cellulosic ethanol, other alcohols, or hydrocarbons	Improvements in microorganisms and enzymes Use of C-5 sugars for fermentation or upgrading to value added coproducts Use lignin as energy and fractions as source of value added coproducts
Biomass to liquids gasoline/diesel/jet fuel and other biorefinery products	Catalyst robustness and longevity Cost reduction in clean up Design and engineering of flexible gasification biorefinery systems
Pyrolysis oil	Upgrading to fungible biofuel Stable bio-oils Biochar
Hydrotreated vegetable oils	Feedstock flexible processes Couple process with renewable hydrogen generation
Other biomass-based gasoline/diesel/jet fuel	Reliable and robust conversion process in pilot and demonstration plants
Algae and cyanobacteria integrated systems	Improvements of organisms for production of fuels, chemicals, and high value products Integrated systems development
Anaerobic digestion	Advances in metagenomics Integrated systems development

- Development of efficient catalysts and microreactor technologies and more efficient separation technologies based on membranes and other technologies;
- Understanding the potential value of every single stream of organic matter—a no waste philosophy;
- Assist decision-makers, designers, and stakeholders in developing more sustainable processes, through understanding the interdependencies in the areas of environment, efficiency (material), energy, and economics, by using the tools for sustainable process development; and
- Address the integrated system—from biomass production, conversion, and use of all products for the specific sites where these technologies will be applied.

Capacity building recommendations

Invest in Knowledge Mobilization programs directed at the diverse networks that support biomass, bioenergy, and biofuels implementation to:

- Facilitate public understanding of the options and impacts;
- Enhance the capability of local governments in economic development based on biomass;
- Provide training for the diverse workforce required; and
- Improve awareness of environment, safety, and health implications across the entire supply chain.

Enhance collaboration between countries and industries to share lessons learned in the many different circumstances in Brazil, the U.S., Nordic countries, and other countries to integrate biofuels production schemes with:

1. the specific economic and agricultural context of the location/country;
2. specific infrastructure of current fuel product distribution and use;
3. vehicle (jet planes, etc.) manufacturing facilities, distribution, and use;
4. customs and culture; and
5. regulations surrounding production and use, and their enforcement.

Policy recommendations

IRENA concluded that the enhancement and acceleration of current public policies would support and advance the positive outlook of emerging cost data within the next few years. Advanced biofuels could become cost competitive with fossil fuels by 2020, assuming some of the technology pathways now being explored will prove to be reliable at commercial scales (IRENA 2013).

Continued co-support of biofuels production and efficiency improvements could further multiple public policy goals in a cost effective manner. Public policies have driven efficiency improvements in many countries, in which biofuels merits should be recognized. Historically, the emphasis for development of new passenger cars addressed almost equally fuel efficiency and performance.

The suitability of biofuels for specific countries should be evaluated against other bioenergy and biorefinery options in order to achieve social, environmental, and economic goals while maintaining the ecosystems and their services. This evaluation should be part of an integrated land use and rural development strategy.

Develop better criteria for selections of processes for scale-up as portfolios of technologies for lignocellulosic conversion are expanding to decrease the technical and commercialization risk.

Facilitate increased availability of site-specific spatial and temporal sustainability assessments data from actual implementation of projects to facilitate dissemination of best practices and growth of the bioeconomy.

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Notes:

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[4] See the hyperlinked presentations of the companies involved in making many of these products in http://www.biofuelsdigest.com/bdigest/2014/05/20/no-shortcuts-to-the-top-a-digest-special-report-on-scale-up-in-industrial-biotechnology/ and http://www.biofuelsdigest.com/bdigest/2013/12/11/heard-on-the-floor-at-bio-pac-rim-sapphire-energy-philipps-66-monsanto-novozymes-braskem-and-genomatica-unveil-key-tie-ups/.

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[55] See: http://ec.europa.eu/energy/renewables/biofuels/flight_path_en.htm: The EU shared and voluntary commitment by its members to support and promote the production, storage and distribution of sustainably produced drop-in biofuels for use in aviation is the “Biofuels Flight path.” It also targets establishing appropriate financial mechanisms to support the construction of industrial “first of a kind” advanced biofuel production plants. See also http://ec.europa.eu/energy/renewables/biofuels/doc/20130911_a_performing_biofuels_supply_chain.pdf .

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[72] See http://www.coolplanet.com/sites/default/files/docs/Cool_Planets_Cool_Terra_Biochar_Receives_International_Biochar_Initiative.pdf; http://www.coolplanet.com/newsroom/first-10-million-gallon-refinery, February 26, 2014; See http://www.biofuelsdigest.com/bdigest/2013/09/25/concord-energy-invests-in-cool-planet-and-announces-asian-jv/.

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[79] See: http://www.ieabioenergy.com/ .

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[81] See: http://www.biofuelstp.eu/srasdd/SRA_2010_update_web.pdf; http://setis.ec.europa.eu/publications/jrc-setis-reports/set-plan-financial-instruments-report; http://ec.europa.eu/energy/publications/doc/2010_setplan_brochure.pdf .

[82] See ASTM International, ASTM D4806-13a Standard specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark- Ignition Engine Fuel.

[83] See European Committee for Standardization EN 14214: Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications .

[84] For ethanol and biodiesel: MARPOL Annex II for shipping dangerous chemicals in bulk; MARPOL Annex I petroleum products see http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx .

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[103] See the detailed 10+years road to certification for the South African product based on coal gasification, which is commercially available at http://www.sasol.com/sites/default/files/presentations/downloads/The_synthetic_jet_fuel_journey_WPC_PMorgan_Sasol_1323236837470.pdf; see also http://www.crcao.com/reports/recentstudies2008/AV-2-04a/AV-2-04a - Comparison of SSJF - CRC Final.pdf .

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chapter 13

Agriculture and Forestry Integration

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Highlights

- Integrated agricultural and forest systems have provisioned societies for millennia.
- Integration can occur in space (agroforestry) or time (perennial rotations).
- Recycling mass and energy among components can increase system efficiency.
- Diverse, integrated systems require investments in human and financial capital.
- Sustainable implementation requires effective governance at local to global scales.

Summary

Integration of agriculture and forestry can increase production, enhance ecosystem services, and reduce development pressure on unmanaged ecosystems. Several systems have been developed that demonstrate complementary plantings of woody species, perennial and annual grasses and food crops can intensify production for greater yields, while more efficiently utilizing water and nutrients. These systems can incorporate spatial diversity through strategic placement of perennial bioenergy crops across the landscape, as well as temporal diversity through crop rotations that include annual and perennial energy crops coupled with food or fiber production. Expanding markets for bioenergy products and co-products can facilitate rural development and form a platform for both socio-economic and ecological benefits.

13.1 Introduction

Agricultural and forest landscapes have long provided humans with food, fiber and energy as well as a range of other ecosystem services. In developing regions, about one third of traditional biomass energy is supplied from forests, with two thirds from other sources including crop residues, livestock manures, and especially “Trees Outside Forests”, i.e. trees interspersed in agricultural cropland and grasslands (FAO 1997). In sheer volume these systems consume more biomass for energy than for pulp and paper or lumber. The FAO (2010a) estimates that more than half of global wood removal is consumed as woodfuels, much of which is for subsistence use or informal trade. As a percentage of total energy consumption, developing countries use more renewable energy than developed countries, mainly due to the vast amounts bioenergy derived from forests and agriculture. While these traditional bioenergy systems sometimes result in ecological disruption and deforestation, many are illustrative of the multi-functional landscapes that are today viewed as harbingers of sustainability (Wiggering et al. 2003; Jordan and Warner 2010).

Several studies have shown there is considerable potential for increasing bioenergy production even further, to meet a substantial fraction of future energy needs (Smeets and Faaij 2007; Somerville et al. 2010). Bioenergy development potentially offers poor countries many advantages, ranging from energy security to poverty reduction, infrastructure development and economic growth (FAO 2010a, Cushion et al. 2010). Yet there are also concerns about food security, especially in regions with widespread poverty, unstable governments, and fragile agricultural systems, and these challenges are likely to be exacerbated with accelerating climate change (Brown and Funk 2008). Effects on the environment are also variable, depending on feedstock type, location, and both prior and future management. While perennial biofuel feedstocks can improve soil quality and biodiversity, reduce greenhouse gas emissions and enhance water quality, some industrial models of modern biofuel production can negatively impact ecosystem services through intensive fertilizer and chemical use, grassland conversion and deforestation (Raghu et al. 2011; Gao et al. 2011; Pacheco et al. 2012).

This chapter examines the forestry-agriculture-biofuel nexus from both production and consumption perspectives. It looks at the interdependencies and complementarity of resource management policies that govern these sectors, and ways to enhance the synergies between the food, bioenergy and biomaterials industries. Special attention is given to strategies that can make agriculture and forestry more sustainable using biofuel production systems. Of particular interest are co-production of timber, food and bioenergy in integrated landscapes (land sharing), ecological intensification to increase production and minimize the need for indirect land use change (land sparing), and efficient value chains that optimize use of by-products, co-products and recycling (industrial ecology). These complementary management approaches include strategies for integration on both spatial and temporal scales, with bioenergy production placed on the most appropriate places on the landscape, and/or integrated in crop rotations with food and fiber production. The focus is on the principles and practices needed to design and implement sustainable bioenergy systems.

13.2 Forestry/Agriculture Interface

Since the dawn of agriculture humans have been converting forestland to cropland, to the extent that today many forest ecosystems are at risk. In this context it is not surprising that large-scale expansion of bioenergy, with increased demand for agricultural and forest biomass, is seen as a major threat. FAO estimated the world's total forest area[1] in 2010 at just over 4 billion hectares, which corresponds to an average of 0.6 ha per capita (FAO 2012). Between 2000 and 2010, around 13 million hectares of forestland were converted to other uses or lost through natural causes each year, down from roughly 16 million hectares per year in the 1990s. While the overall rate is slowing, the distribution is highly variable. Between 2000 and 2010 South America suffered the largest average net loss of about 4.0 million ha annually, followed by Africa with 3.4 million ha, then Oceania with 0.7 million ha. In Asia there is still a high rate of loss in many countries in South and Southeast Asia, but the region as a whole gained some 2.2 million ha annually between 2000 and 2010 mainly due to large scale tree planting in China, a reversal from the net forest cover loss of nearly 0.6 million ha annually in the 1990's (FAO 2010d). Reforestation, afforestation and natural expansion of forests are reducing the net loss of forest area significantly at the global level. By 2010, planted forests and reforestation made up an estimated 7 percent of the total forest area, totaling 264 million hectares (FAO 2012).

Over millennia, forests played a significant role in food security and have been regarded as safety nets for subsistence farmers. Nevertheless, many researchers and policy analysts have observed that conversion to agriculture, both for commercial and subsistence ends, is the primary driver of forestland clearing. This permanent conversion to agricultural land use has dramatically different effects than traditional shifting cultivation. According to Mertz (2009), and others, shifting cultivation by subsistence farmers 1) enables greater carbon sequestration than other forms of land use, 2) enhances biodiversity, and 3) is crucial for *in-situ* conservation of crop genetic resources. Conventional agriculture based on annual grain crops drives all three of these sustainability metrics in the opposite direction, yet is encouraged in many countries by land tenure policies, public investments in transportation hubs and centralized market infrastructure, and eligibility rules for agricultural subsidies.

In this context, the growing demand for food, fuel and fiber associated with global population growth, rising incomes and changing diets continues to drive deforestation (Kastner et al. 2012). Gibbs et al. (2010) estimated that during the period from 1980 to 2000, over 80% of new cropland in the tropics was converted from forests, 55% from primary forests and another 28% from secondary forests. While forest protection policies and especially increasing afforestation and reforestation have slowed the rate of decline, the conversion of natural ecosystems to cropland and other uses still causes major losses of biodiversity, water quality and quantity, terrestrial carbon storage, and other critical ecosystem services.

The forestry-agriculture nexus is clearly demonstrated by contrasting models of food, animal feed, fiber and fuel production and consumption. In many parts of the world traditional systems provide all of these products (and others) simultaneously. However,

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[1] Forests are defined as "Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use". (FAO 2010c).

the dramatic surge in industrial monoculture approaches has introduced imbalances in land use systems, especially in tropical regions. This environmental change is often coupled with rapid social change and controversy driven by unstable land tenure and inequitable government policies and practices.

Growing demand for biofuel feedstocks tends to add to existing pressures on tropical forests, although these pressures vary across regions (Pacheco et al 2012). Expansion of first generation biofuel crops has been reported to have negative impacts on forests and food security due to direct and indirect land use changes (Fisher et al. 2009; Havlik et al. 2011). The indirect effects can be thought of as any losses of forest or savannah required to replace the pasture or cropland directly converted to bioenergy production. These indirect impacts are difficult to measure, and are estimated by models and statistical approaches that use varying assumptions about system boundaries, soil carbon and greenhouse gas implications, demand elasticity and economic equilibrium for food and other commodities (Fargione et al. 2008; Searchinger et al. 2008; Gao et al. 2011). These assumptions can result in substantially different estimates of the impact of biofuel development on deforestation, as illustrated by studies attempting to quantify these effects for the Brazilian Amazon (Lapola et al. 2010; Arima et al. 2011). Despite this uncertainty, there is broad agreement that large-scale conversion of food cropland or natural forests to biofuel production should be treated with caution.

There are a variety of negative social impacts of uncontrolled agricultural expansion into forests associated with biofuel production. Medium- and large-scale plantations for bioenergy and other uses stimulate concentration of land ownership, which may displace local people and threaten their livelihoods (Pacheco 2012). There is a clear need for transparent and equitable governance policies associated with investments in bioenergy feedstock production at the agriculture – forest interface, coupled with effective law enforcement and implementation of social and environmental safeguards and regulations. Compliance must be reinforced by consistent forest and agricultural policies at the local, national and international levels, with buy-in from the full range of stakeholders, especially the private sector.

13.3 New Paradigms in Ecological Land Management

Although the recent history of biofuel development has reinforced perceptions of conflict between food, energy, and other ecosystem services, synergistic interactions are also possible. From the perspective of food security and sustainable landscape management, FAO (2008) stated that “biofuel expansion may represent not only additional stress but also opportunities that affect all four dimensions of food security – availability, access, stability and utilization”. Just as diversity in natural ecosystems can increase resilience, a broader portfolio of products and markets can improve ecological performance but also encourage infrastructure development, improve income stability, and strengthen rural communities.

The evolving paradigm in sustainable natural resources management, often referred to as ecological land management, calls for recognizing the economic, environmental and social interdependencies of these resources, then exploring integrated and complimentary management systems. Cushion et al. (2010) recommended the evaluation of trade-offs related to poverty, equity and the environment when developing a bioenergy system. Included among these trade-offs are the opportunity costs of forgone options, which in land use include prospects of alternative trajectories of development, but also of maintaining natural ecosystems for wildlife, biodiversity and other ecosystem services (Fischer et al. 2008). Several emerging approaches to ecological land management illustrate ways that bioenergy crops can increase complementarities and synergies.

13.3.1 High Productivity Polyculture Systems

Natural forests and grasslands in both tropical and temperate regions represent productive ecosystems with diverse plant and animal communities that efficiently utilize water, nutrients, and light. However, these natural ecosystems are rarely compatible with industrial planting and harvesting technologies, and are often replaced with monocultures of woody or herbaceous species that with inputs of fertilizer and pesticides may produce higher yields. This sort of land use change constitutes both an immediate threat to biodiversity and a long-term one to the productivity of the landscape (FAO 2008).

Recent research has demonstrated that managed polycultures of bioenergy crops can reproduce much of the diversity, resilience, and nutrient use efficiency of natural ecosystems while still achieving reasonable yields. Such systems include artificial or successional prairies that can include grasses, forbs and legumes playing different ecological roles (Tilman et al. 2006; Gelfand et al. 2013), polycultures of tree plantations (Erskine et al. 2006), and interplanting of perennials with high yielding annuals or trees (Manatt 2013) (see Figures 13.1 and 13.2). Diversity of species and even varieties can more efficiently recycle nutrients and capture water and light, provide refuge for beneficial insects, and limit the reproduction and damage from pests and disease (Gurr et al. 2003).

The diversity of polycultures is also likely to improve the resilience of agricultural systems, minimizing yield losses from weather extremes including flooding and drought. These ecological and agronomic benefits can translate into human benefits as well, with both polyculture systems and perennial crops considered important strategies within the framework of ‘climate-smart agriculture’.

The goals of climate-smart agriculture, “to simultaneously improve food security and rural livelihoods, facilitate climate change adaptation and provide GHG mitigation

Figure 13.1. Integration of food and energy crops can be spatial (left) or temporal (right), in either case increasing ecosystem services and biodiversity relative to annual monocultures (center). Photos courtesy of ICRAF (left), Lynn Betts (center) and anonymous (right) of the USDA Natural Resources Conservation Service.

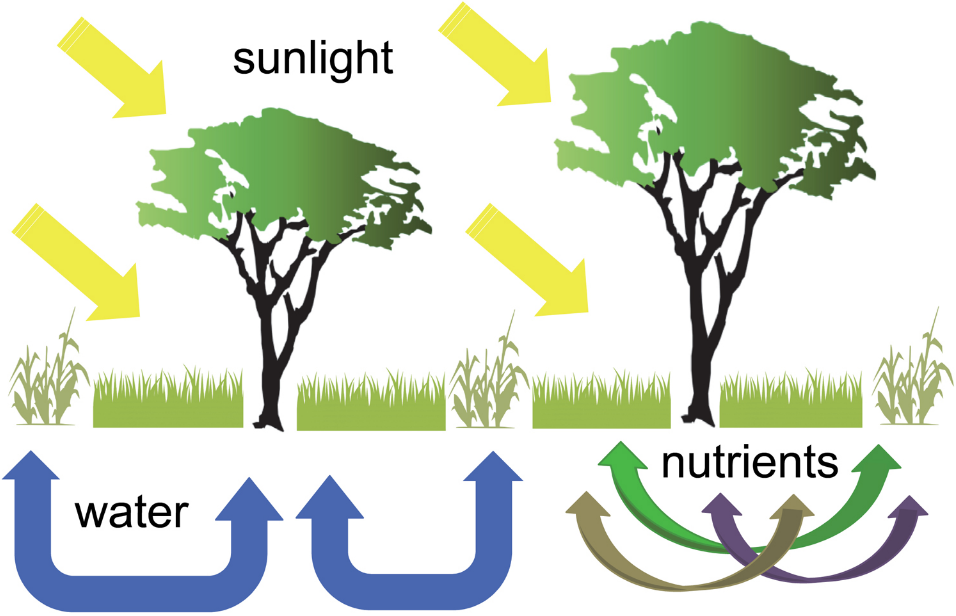

Figure 13.2. The ecological structure and biodiversity of polyculture plantings allows more efficient utilization of sunlight, nutrients and water, as well as pest and disease management.

benefits" (FAO 2010b), provide a platform for new linkages between climate science and more resilient and sustainable agricultural systems. However, "integrated landscape management" provides an alternative and complementary organizing framework for policy development and implementing new strategies for agricultural development and conservation communities (Scherr et al. 2012). Biomass production systems, because of the diverse options for perennials and polycultures, have considerable potential to be major components of both integrated landscape management and climate-smart agriculture.

13.3.2 High Productivity Monoculture Systems

Although polyculture systems are likely to maximize ecosystem services for the reasons previously described, in many cases highly productive monocultures are able to maximize biomass yield and economic returns. While monocultures are by definition less diverse than polycultures, integration of energy crops with food crops can significantly increase the diversity of agricultural landscapes in both space and time (see Figure 13.1). Many of the highest yielding energy crops are perennials, including sugarcane, miscanthus, switchgrass and short rotation woody crops like poplar and shrub willow. Perennials are often planted for their ecosystem benefits, which include reducing erosion, increasing soil organic matter and nutrient retention, thus enhancing soil health and water quality (Smith et al. 2013, Mitchell et al. 2010). On steep slopes, as streamside buffers, and on droughty or poorly drained soils, perennial energy crops can provide energy yield from parts of the landscape where soils are fragile and annual food crops are at greater risk of crop failure. Additional detail about the production practices and ecosystem benefits of these perennial energy crops are provided elsewhere in this book (see especially Chapters 10, 16, and 18, this volume).

Strategic placement of energy crops can occur in time as well as in space. With the increase of mechanization reducing demand for winter feed grains on many farms, winter fallow is common in many temperate cropping systems. In the US these winter crops could increase bioenergy feedstock potential by at least 10% with no new land requirements, while also enhancing soil and water quality (Feyereisen et al. 2013, Manatt et al. 2013). Although winter double crops may require additional inputs including fertilizer, harvested nutrients from these crops can be recycled from biorefinery byproducts as fertilizer (Heggenstaller et al. 2008). Traditional breeding programs for summer annuals have often assumed that longer growing seasons had no opportunity cost, even though the increases in yield from extended seasons can be relatively small. Yet for winter crops, even two weeks of additional growing season can increase yields by 15 to 30% (Feyereisen et al. 2013). Integrated, multi-species breeding programs are needed that exploit the potential synergies of nutrient use and water uptake efficiency for coupled summer and winter annuals to maximize the productivity of the crop rotation system.

Box 13.1. Integrating energy crops requires sustainable management strategies

"Bioenergy crops are often classified (and subsequently regulated) according to species that have been evaluated as environmentally beneficial or detrimental, but in practice, management decisions rather than species per se can determine the overall environmental impact of a bioenergy production system. Prior land use, harvesting techniques, harvest timing, and fertilization are among the key management considerations that can swing the greenhouse gas balance of bioenergy from positive to negative or the reverse…

The international debate about the benefits of biofuels is not likely to be resolved with a generalized view of bioenergy impact assessment because management approaches vary regionally. A diversified assessment approach is needed to account for many management practices that can swing the overall impact of bioenergy crop production from negative to positive or vice versa. The management swing potential is a key part of the sustainability puzzle, but is underrepresented in the policy debates that will decide the future role of bioenergy in mitigating climate change" (Davis et al. 2013)

13.3.3 The Green Economy

The Green Economy as related to bioenergy is a term that captures many aspects of sustainable development and innovation (Chapter 6, this volume). While "green" is often considered a catch-all term for a range of sustainability issues, from a forestry/agriculture perspective there are specific opportunities for national and global economies to shift to products that are based on photosynthesis, especially increasing use of feedstocks from sustainably managed farms, forests, and other cellulosic biomass resources.

In order to fully realize the potential of forestry and agriculture in the "Green Economy", two types of policy reforms are needed. First, there is a need for effective incentives for improved management and new investments in sustainable feedstock production. And second, because of the large inertia and sunk investment in traditional and often exploitative approaches, governments and markets must create disincentives to unsustainable practices. Positive incentive programs are already developed for certification of sustainable forest management with respect to lumber, paper, and other materials, and for sustainable agricultural systems with respect to food. The Roundtable on Sustainable Biofuels (2013) is one of several such programs that are now being developed for bioenergy systems. In most countries such market-based programs are voluntary and there are no formal disincentives to prevent unsustainable practices, although government subsidies are sometimes withheld.

Incorporating bioenergy into these emerging green economy programs offers tremendous potential to harness the power of the marketplace. However, the metrics for these programs vary quite widely. Bioenergy feedstock assessments focus primarily on greenhouse gas emissions, energy, and land use change (van Dam et al. 2010) while food and timber assessments focus more on chemical toxicity, soil fertility and ecosystem protection (Cashore 2002, Raynolds 2004). More comprehensive sustainability assessments can include a wider range of environmental as well as economic and social indicators, and there is some effort to develop standard, quantifiable sets to facilitate consistency and communication (Dale et al. 2013; Efroymson et al. 2013). Integration and optimization of these global and local environmental and socio-economic criteria will require considerable research and policy analysis to optimize and harmonize these programs equitably (Raynolds 2004; McBride et al. 2011; van Noordwijk et al. 2012).

There is a considerable potential for increasing the use of forest and agricultural residues as bioenergy feedstocks. Land productivity can be defined as the efficiency by which a particular crop and management system uses sunlight and other inputs to provision various human needs, and systems that utilize multiple co-products, byproducts and wastes can increase that efficiency and productivity. Co-products and byproducts can be differentiated by their quality and efficiency (see Figure 13.3), creating a hierarchical cascade of value. Processing facilities can be developed that use biomass for more than

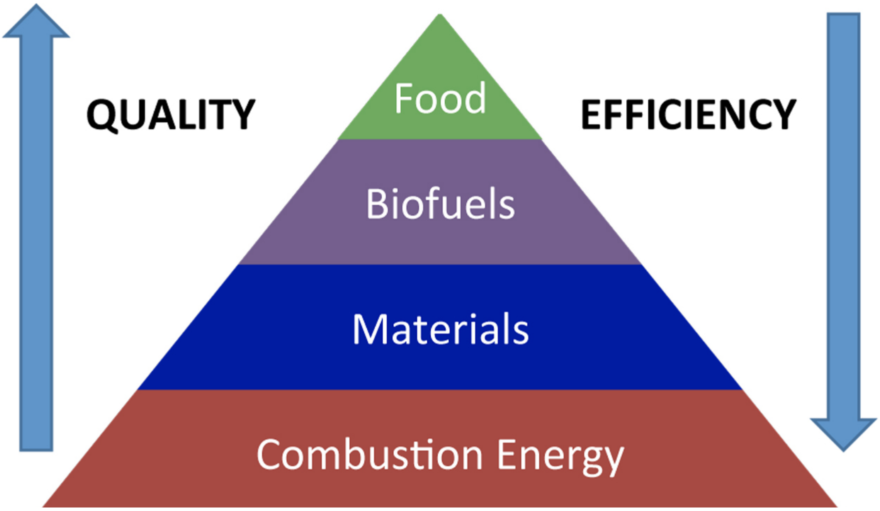

Figure 13.3. The quality (or value) of agricultural and forest products is often inversely proportional to the efficiency (or yield) of the crop. Integrating bioenergy creates opportunities to increase overall system value and efficiency.

one purpose, with biomass as a feedstock providing industrial power for fuel, chemicals and materials (Wang et al. 2007). Some valuable co-products can be separated at the front end of processing, and used for chemicals and materials, while residues can be separated later in the process. Cushion et al. (2010) concluded that co-firing already renders some timber processing and bioenergy operations energy self-sufficient, while ethanol refineries powered by sugarcane bagasse in Brazil even export electricity to the grid (Jofsetz and Silva 2012). The huge quantities of waste products from saw- and paper-milling operations have significant potential for power generation that is not fully utilized, especially in developing countries. Most of the initial cellulosic biorefineries are sourcing crop residues and wood waste as both fuel feedstocks and a source of industrial power (USEPA 2013).

In fully integrated systems, it is important for wastes and byproducts to move in both directions – agricultural and forest residues as industrial feedstocks, but also biorefinery residues and byproducts as agricultural inputs (see Figure 13.4). First generation biorefineries have done this effectively, producing high value animal feeds from both ethanol (distillers dry grains and solubles) and biodiesel (soymeal and canola meal) operations. These recycling strategies improve not only environmental performance, but economic performance as well, with animal feed coproducts providing from 16% to over 50% of first generation biorefinery income (Taheripour et al. 2010). Second generation biorefineries can expand these byproduct recycling strategies to include new kinds of animal feed (Dale et al. 2010; Bals and Dale 2012) and fertilizers as well (Anex et al. 2007).

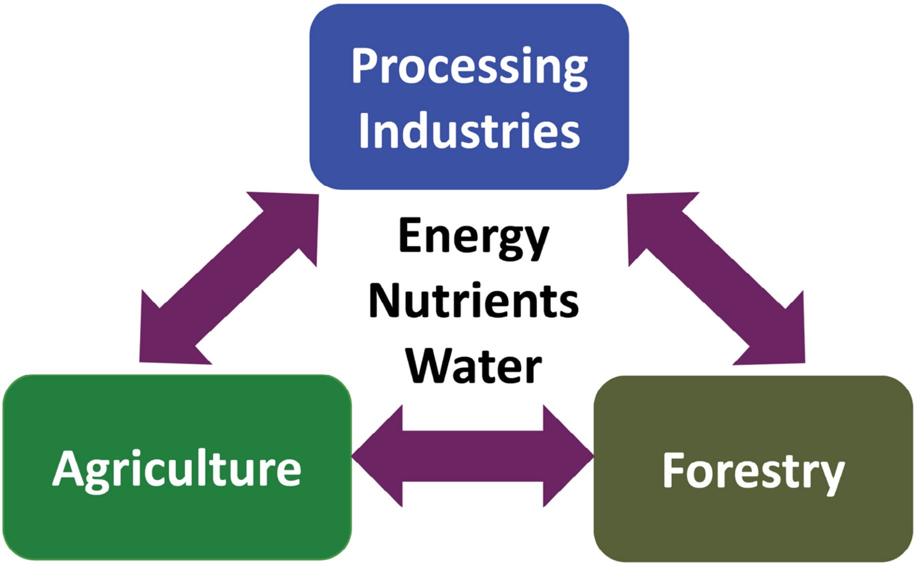

Figure 13.4. Integration of agriculture and forest systems with processing industries increases the opportunities for positive feedback loops that reuse and recycle mass and energy flows and improve system performance.

13.4 Integrated Landscape and Bioenergy System Design

Previous sections of this chapter have outlined several opportunities for integration of bioenergy feedstock production with agricultural and forest landscapes as well as industrial food and energy systems. There is a clear need to not just integrate but also optimize these value chains at each step: on-farm, at distributed preprocessing locations, and at centralized biopower and biorefinery facilities. The benefits of these integrated systems should be evaluated for economic and environmental benefits as well as risks and resilience, and trade-offs should be made explicit for business and policy decisions.

While integrated system design and evaluation is a complex challenge, a powerful suite of planning and analysis tools are available to facilitate this process. These include spatially explicit databases and models (Natavi et al. 2013; Leonard and Duffy 2013) and life cycle assessment tools for both production and conversion (Camargo et al. 2013; Wang 2001). Together, these tools can create a knowledge system that can inform decision makers about their choices and the options available to address these decisions (Herrick et al., 2006; Reid et al. 2010). But a critical remaining challenge is to develop effective mechanisms by which such integrated decisions can be coordinated and implemented. There are serious disparities in scale between land tenure, parcel sizes and conversion technologies, which vary in different localities, as well as different incentives for owners and managers of land, supply chain, conversion and distribution businesses. Aggregating individual incentives for collective benefits will require a realignment of policy and economic incentives with social criteria to encourage integrated and equitable business models.

The discussions related to policy frameworks for climate change, forestry, agriculture and bio-energy have been splintered over several international and national forums in the last few years. One of the initiatives that has potential to integrate policies governing landscape management systems is REDD+[2]. Although it was originally conceived as a market approach to reduce deforestation and forest degradation and the greenhouse gas emissions associated with that land use change, it has come to be used for broader forest preservation purposes. The assumption behind REDD+ is that compensating countries for the returns from converting forest land, i.e. paying the opportunity costs of land conversion would deter them from deforestation. However, several researchers have challenged this assumption. For example, Gregersen et al. (2010) have shown that it might be difficult to estimate opportunity costs correctly in some regions where deforestation is high and market systems are not functioning well. Furthermore, opportunity cost may be an inadequate incentive to reduce deforestation in regions where illegal logging and

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[2] REDD+ is "Reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries". http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf

corruption are common, transparency and accountability are weak, land tenure rights are not clear, and/or technical and financial capacities are inadequate.

More recently, agriculture broke into the REDD+ international arena, perhaps driven by close connections among climate change, forestry and agriculture as well as the enormous amounts of donor funds promised or made available to various developing countries. While coupling climate mitigation programs with food production is fraught with potential obstacles (Kissenger 2011), REDD+ strategies could be used to create incentives to produce biofuels on degraded landscapes while protecting and enhancing food production on priority sites.

While REDD+ is driven by governmental policy, its implementation includes market-based systems to encourage integrated multi-criteria optimization, similar to established and emerging certification processes for sustainable forestry (Cashore 2002) and biofuel production (van Dam et al. 2010, Roundtable of Sustainable Biofuels 2013). These processes can encourage decision makers to take a more holistic view of the bioenergy systems and discover the synergies that often result from an integrated management perspective.

13.5 Integrated Natural Forests, Planted Forests, Agroforestry, and Restored and Artificial Prairie Systems as Sources of Biomass - Potentials and Challenges

With the depletion of natural forests in many countries, there is a growing interest in forest tree planting for multiple objectives including bioenergy uses such as fuelwood and biofuel feedstocks. While converting diverse natural forests to monoculture forest plantations has many negative attributes as described in section 13.2, there are other land use options to consider. Increasingly, nations are using public investment and public-private partnerships to reclaim degraded landscapes and marginal land with managed forests and perennial grasslands. These reclamation efforts may be motivated by environmental or energy security concerns, but are enabled by increasing agricultural productivity, more stable agricultural trade, and improving food security (Lele et al. 2012). Framing these reclamation efforts as multifunctional landscapes offers considerable opportunity to enhance agriculture – forest integration.

Planted forests have, and will continue to play an increasingly significant role in supplying raw forest products, including biofuels. Public and private investment in forest plantations is growing at a fast rate around the world, but mostly in the tropics and sub-tropics where growing conditions are favorable and management costs are reasonable. Some of the tree plantations are dedicated for bioenergy as a primary product, while the majority of plantations are managed to reduce the pressure on natural forests by producing a variety of wood and other forest products. More recently, some planted forests have been established for the sequestration and storage of carbon but the rate of establishment fluctuates depending on the carbon market (IPCC 2014).

The areas of degraded and deforested land worldwide are huge with the available estimates ranging from 1 to 2 billion hectares depending on the source of information (The Global Forest and Landscape Restoration Partnership 2013). Based on the economic, environmental and social parameters of project feasibility, large areas could be transformed into resilient, multifunctional assets that would contribute to local and national economies, sequester significant amounts of carbon and safeguard biodiversity. Analysis by Schoneveld (2010) has shown that there is sufficient marginal and degraded land available for cultivating bioenergy crops in developing countries.

The local socio-economic impacts of biofuel feedstock development are extremely variable (Pacheco et al. 2012). In some cases, feedstock plantations accrue benefits for job and income generation, and for boosting incomes of small-scale farmers engaged in production. In others, plantation development may threaten the livelihoods of native populations as well as reduce opportunities to restore landscapes, especially where insecure tenure rights tend to prevail.

As a complement to extensive forest plantations, partnerships between private sector corporations and small farmers have often proved to be beneficial. Such outgrower schemes have also been common for some time in agriculture, with business networks that aggregate small lots of grain or other commodities into larger lots that can attract market attention. Short rotation woody crops offer one option for intensive, high yield and somewhat scale-neutral production by individuals landholders (Volk et al. 2006). Innovative business models will be necessary to support and reward smallholder production in bioenergy supply chains, especially for the large biorefineries needed to achieve economies of scale in production of biofuels.

Small wood-lots, shelterbelts, farm windbreaks and other woody perennials constitute a valuable component within farming systems that have been both a traditional land-use and a livelihood option developed by subsistence farmers. Agroforestry systems are quite diverse and range from fruit and other treecrops in home gardens, subsistence livestock and pastoral systems, alley intercropping of trees with herbaceous row crops, and biomass plantations. While there are trade-offs associated with conversion of natural forests to agroforestry systems, under certain circumstances these systems may represent an appropriate solution to the dual and often conflicting challenges of socio-economic development and environmental protection (Steffan-Dewenter et al. 2007). In many other cases, introduction of agroforestry approaches to agricultural systems or degraded lands can enhance productivity and conserve natural ecosystems. Agroforestry systems already cover roughly half of the land associated with agriculture. Estimates indicate that out of the total global farm land area of over one billion ha, about 430 million ha have tree cover greater than 10%; of which 160 million ha have more than 50% tree cover (Dawson et al. 2012). This landscape already represents a huge resource of timber and non-timber products and services ranging from solid wood to food, fodder, rubber and other chemical products, fuel-wood, wind and water erosion control and carbon sequestration. When properly planned and sustainably managed in agroforestry systems, much of this resource could provide a significant bioenergy raw material.

An important consideration in all these systems is effective management of land use transitions. The challenge is to achieve successful establishment of a productive biomass system while minimizing the carbon footprint associated with land use change. This is particularly problematic for land that is in forests or established perennials, where trees and grasses have already accumulated carbon in their above ground biomass as well as in the soil. In such circumstances convention land clearing and establishment strategies for biofuel production can create a carbon debt that requires decades to repay (Fargione et al. 2008). Alternative establishment strategies, such as using mowing and harvesting to transition old-field succession into bioenergy systems without disturbing the soil, can result in highly productive artificial prairies and agroforestry systems. Such strategies can reduce the life-cycle greenhouse gas footprint significantly relative to conventional approaches to establishing perennial monocultures of grasses or trees (Gelfand et al. 2013).

Landscape restoration, including through tree planting and prairie reconstruction, is a nature-based solution – going beyond conventional approaches and cutting across sectors, and has gained considerable attention lately. Multifunctional mosaics of tree-lots and cropland developed as an approach to landscape restoration schemes support the livelihoods of smallholders in addition to other economic, environmental social goods and services. Bioenergy markets can thus provide additional incentives for positive social and ecological change for the restoration of degraded landscapes.

13.6 Conclusions and Policy Recommendations

Integrated food/forest/energy systems, i.e. growing energy crops and food or fiber crops in synergy, can be accomplished with either spatial approaches (strategic placement on the landscape) or temporal approaches (crop rotations and succession plantings). These strategies can produce substantial amounts of energy and reduce soil erosion, provide wind protection and contribute to climate mitigation, which in the long run will improve the yield and quality of food and fiber crops. Integration can also occur at a system level, with residue recovery, nutrient and energy recycling and waste reduction addressing sustainability challenges of our conventional food and energy systems.

Harmonizing forestry and agriculture policies is fundamental for the implementation of integrated approaches to sustainable production and supply of bioenergy. This chapter shows the interrelationships and interdependencies of policies governing the three sectors. Beyond that, it demonstrates that the development of bioenergy production schemes within forestry and agriculture systems presents the developers and policymakers with economic, social and environmental opportunities and challenges. Land-use changes associated with integrated food, fodder, fiber and/or fuel production systems are likely to be significant, and can enhance or detract from ecosystem services depending on design, implementation and management.

Regulations that ensure the sustainability of biofuel-specific agriculture and forestry practices have not yet been developed in many countries. The necessary legal and institutional frameworks are also lacking, particularly those related to land tenure and customary land rights.

As we look toward the future, it is clear that global policy frameworks should more explicitly address bioenergy production and provide appropriate incentives for sustainable integration with food and timber production. Such policies must have the flexibility to adapt to local social and biophysical circumstances, yet also drive management practices that achieve global greenhouse gas reduction goals. As this chapter has demonstrated, there are many strategies that can be used to achieve that integration, providing large quantities of fuel while enhancing ecosystem services and addressing socioeconomic needs. Central to all of these strategies are embedded concepts of multifunctional landscapes, integrated landscape design, and resilience in the face of changes yet to come.

13.7 Recommendations

Given the potential changes in land use identified in this chapter and other reports and the impact bioenergy may have on natural forests and agricultural lands, land-use planning should be on the national development agendas before embarking on large-scale bioenergy production systems. Successful implementation of such plans will require clear sustainability metrics and monitoring programs, stable land tenure, and effective local and national governance.

In drawing national and regional integrated forestry, agriculture and bioenergy policies it is imperative to address the underlying causes of land use conversion and unsustainable resource development. Issues to be included in such multi-sector policies include full valuation of forest goods and services, opportunity costs of forestland conversion and alternative cropping systems, governance and law enforcement, institutional capacities, and safeguarding land tenure and other rights of local communities.

Another venue to strengthen cross-sector forestry and agriculture policies and aligning implementation pertaining to bioenergy is to incorporate recent initiatives such as REDD+ programs, Green Economy and Climate-Smart Agriculture into national development strategies.

Tree plantations and agroforestry systems which incorporate biofuel production could be profitable for both domestic use and as out-growers for industrial enterprises, but require that land tenure, access rights and sustainability requirements are all treated unambiguously in both law and in practice.

Integrated forestry, agriculture and bioenergy policies should be based on detailed land suitability and availability assessments (Schoneveld 2010). Furthermore, land availability for biofuel expansion based on agro-ecological zoning would avoid undue competition for land.

Intergovernmental agreements and conventions on climate change, biodiversity and desertification among others, address agriculture, forestry and bioenergy directly and indirectly, but generally consider these as independent rather than integrated sectors. Therefore, internationally negotiated and ratified instruments are needed that systematically address integrated forestry/agriculture/bioenergy interactions.

13.8 The Much Needed Science

A wealth of anecdotal and site-specific scientific evidence demonstrates that diverse agricultural and forest systems, and especially coupled systems that include herbaceous and woody species, can be highly productive in meeting human needs. But a far smaller number of cases or research reports document this productivity through quantitative, independent assessments across multiple systems. As a result, the mechanisms and magnitude of the productivity of diverse, integrated systems relative to uniform monocultures remain contested. Fundamental research on ecological principles, along with systems research on specific mixtures and integration strategies in different socio-ecological contexts, is needed to quantify the costs, advantages, and tradeoffs of integration. These studies should be done with a common set of metrics, so that valid comparison to other studies in other regions is possible, and eventually so that a meta-analysis of the results can be made. Dale et al. (2013) offer a good starting point for such a common set of metrics.

While quantitative and comparable systems and sustainability studies are needed for integrated crop and forest systems in general, this need is particularly strong where bioenergy is concerned. Bioenergy feedstocks and processes offer opportunities to greatly increase the internal energy and nutrient recycling in such systems through residue use, nutrient recovery, and increased water use efficiency. The tools of industrial ecology can provide insight into these opportunities as well as challenges, by expanding the system boundaries beyond individual fields and farms to communities and processing facilities.

Finally, there is a tremendous need for social science research into the preconditions, processes, and governance required for these integrated systems to grow and thrive. Challenges are often not technical, but relate to educational resources, social and cultural norms, private and public financing, infrastructure, markets, policy and governance. The sustainability transitions literature (Hinrichs 2014) offers important insights into these processes and the challenges of getting on and staying on a trajectory toward sustainable food, energy, and landscapes.

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chapter 14

Case Studies

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Highlights

Around the world, there are both successful and unsuccessful bioenergy project deployment cases. It is important to collect information about the most important cases and analyze them. Driving forces including local conditions, technology adaptations and public policies are key issues to be investigated.

A country's tradition in cultivating selected feedstocks and technologies available for bioenergy production are important factors for increasing the potential for success, as illustrated by sugarcane ethanol in Brazil and Thailand as well as cassava ethanol in Thailand. On the negative side, jatropha was a disappointment in several projects and did not deliver the expected performance.

Adequate public policies as well as smart and sustained government support for bioenergy are mandatory for the success of bioenergy programs. Investors need a medium term view of business risks to feel confident enough to invest in these long-term endeavors.

Africa has a huge potential in terms of land and water resources availability, but to date this potential has failed to materialize in a manner that will benefit the local communities. The causes need to be identified, studied, and compared with successful cases.

Biogas has a large potential to provide significant amounts of sustainable bioenergy, but its contribution to the global energy supply is insignificant. A comparison of three countries of similar economic and technology levels has shown that different conditions can lead to success in one and to failure in the other two.

Agriculture and forestry residues are perhaps the most obvious feedstocks for cellulosic biofuels. However, their positive impacts on soil, water, and air resources mean that only a portion of these materials can be harvested sustainably. Fortunately, several tools are already available to help determine the fraction to be left in the fields.

Woody biomass, including forestry residues, in the form of wood chips and wood pellets is used to generate both heat and power in Scandinavia. In some countries, these are becoming one of the most important energy sources and in others they have already been used for decades.

Municipal solid waste (MSW) is another bioenergy feedstock that is in short supply in northern Europe where it is used as fuel in large district heating systems. Some plants are retrofitted to also use woody biomass feedstock.

Summary

Production and use of bioenergy have significantly increased in the past few years, motivated by the global need to reduce GHG emissions, ensure energy security, and strengthen rural economies. The main issues related to bioenergy are addressed in Chapters 3-21 of this volume. This Chapter presents several success and failure cases that took place in the bioenergy expansion path in several regions of the world, under different feedstocks, technologies, policies, and contexts. The number of cases that deserve to be analyzed is very large and choices had to be made taking into consideration the lessons learned in the process, the comparison of the same bioenergy alternative in different contexts that resulted in success or failure under different policies, the scale of the projects, and the potential for replication of the case in other regions of the world. The present size of the bioenergy programs and replicability potential of the experience have given a larger room to sugarcane ethanol in Brazil and Thailand (in this case using also cassava as feedstock), surplus power generation in sugar/ethanol mills in Brazil and Mauritius, biogas in Germany in contrast with California and the United Kingdom. The importance of using residues to take advantage of their wide availability, low cost, and low environmental impact is demonstrated in Scandinavia, through the efficient use of municipal solid waste for

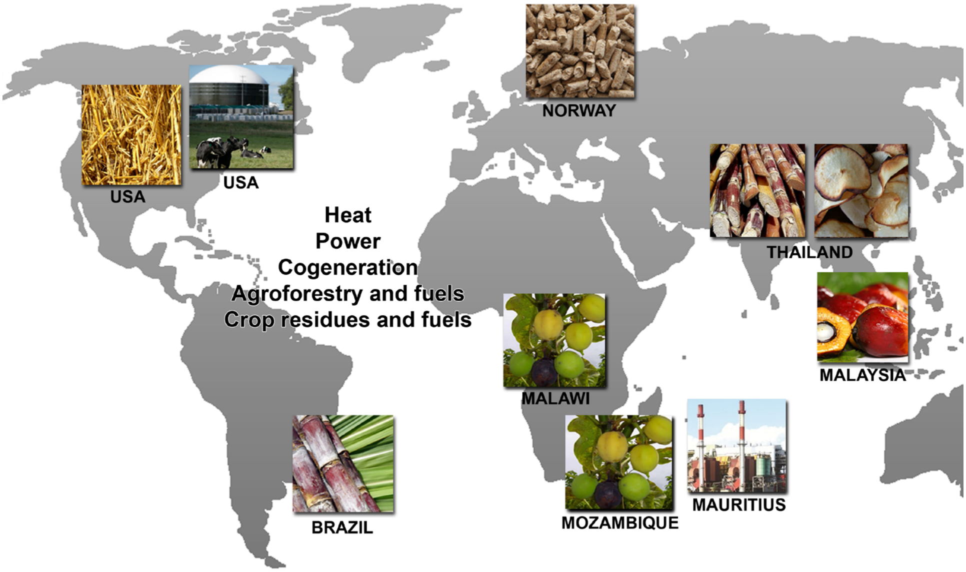

Figure 14.1. The potential of feedstocks for bioenergy production is spread worldwide and needs to be assessed and evaluated for the best alternatives. It is important to learn from available lessons to identify strengths and bottlenecks of each alternative, bearing in mind that local conditions and public policies play a significant role in the success and failure of apparently similar cases.

heat and power by combining with other biofuels, and the economic analysis of the impacts on the use of palm oil production residues. The limitations for a sustainable collection of agricultural residues, such as corn stover, is shown in the work developed in the USA where a model was created to define the minimum amounts of residues that need to stay in the field for soil protection and fertility preservation; this methodology can be adapted to other agricultural residues in other regions, but it will require field experiments and better analysis of the local conditions. The surprising failure of most *Jatropha curcas* biodiesel projects in Africa is commented based on the experiences underway in Mozambique and Malawi in different scales and production models (large and small scales, respectively).

We discuss problems and successes of each case. It is apparent that public policies play a very important role in the final outcome of the bioenergy projects, for instance in the cases of power generation from sugarcane residues in Mauritius and Brazil, biogas in three apparently similar countries and sugarcane ethanol in Brazil and Thailand.

14.1 Introduction

Worldwide, the use and production of bioenergy is growing very fast, driven mostly by concerns about global warming and energy security, and more recently by the enhancement of rural development. As a result, in 2012, ethanol and biodiesel, the main transport biofuels, reached production volumes of 83 and 23 billion liters, respectively, representing approximately 3% of the global transportation fuel requirement. Similarly, in 2011, the production of wood pellets increased to 22 million metric tons (REN21 2013), or some 350 PJ. At the same time, there are controversies concerning alleged negative impacts on food availability and prices as well as questionable statements regarding reduced greenhouse gas (GHG) emissions, due to the emissions resulting from the so called indirect land use change (iLUC).

Ethanol production is highly concentrated in the USA and Brazil, representing around 87% of the total world production. The sugarcane case in Brazil may be widely replicable around the world, since sugarcane is cultivated in more than 100 countries with similar yields, but the success of corn ethanol in the USA will be more difficult to replicate because average corn yields in the world are slightly over one third those in the USA, making the economics highly difficult to replicate sustainably. Also, the GHG abatement potential of corn ethanol, according to the US Environmental Protection Agency (EPA 2010), is very low on average and does not meet the threshold value requirements of the US Renewable Fuel Standards (to qualify as an advanced biofuel) nor those of the EU Renewable Fuel Directive (to be counted towards the Directive mandated values). Besides these two successful cases, there are a few other ones, including sugarcane ethanol in Colombia, Thailand, Guatemala, and Malawi as well as biodiesel in Europe, Argentina, Colombia, USA, and Brazil. On the other hand, bioenergy production failures are abundant, such as the biodiesel from jatropha in many locations worldwide.

Wastes and residues are highly recommended feedstocks for bioenergy production since they can be a source of pollution if not treated or used otherwise. They are generally cheap, available everywhere, and have low GHG emissions in the production chain (normally accounted for in the main product). There are several success stories worldwide including millions of small biogas facilities built in China and India, but it is difficult to assess the long-term results of these large-scale experiences. The use of forestry and wood mill residues to produce solid fuels (pellets, briquettes or in natura) to displace fossil fuels in household and industry heat or power generation (direct or in co-firing) is also growing and indicative of a trend toward becoming a major biofuel.

The strength of driving forces and existence of adequate legal and policy framework are normally the major reasons for success or failure, as illustrated in this chapter. Technology availability and use are also important factors, and although adequate technologies are normally available for feedstock production and processing phases, the question is how to ensure they will be used, especially considering the conservative nature of farmers in developing countries and their reluctance to give up traditional practices. This raises the question of scale, which is very important for the economics, notably in the processing phases, but there are some small-scale projects that have succeeded. However, those projects are highly dependent on planning for local conditions such as land tenure, agriculture production, and deployment capabilities. A combination of small/medium feedstock producers with large-scale processors can be made to work properly without much sophistication, as shown with sugarcane in Thailand, India, South Africa and other countries, but adequate technology must be made available and used by the feedstock producers.

This chapter summarizes lessons learned on several of the problems listed above and takes advantage of the authors' knowledge of the projects. The case studies presented are only examples and not a comprehensive survey. Chapters 8 and 12, this volume, present other interesting cases of bioenergy production and use, thus supplementing the information in this Chapter.

14.2 Key Findings

14.2.1 The Brazilian Experience with Sugarcane Ethanol

Brazil ranks second in global ethanol production (USA is first) but is the primary sugarcane (*Saccharum officinarum* L.) and sugarcane ethanol producer. A brief summary on ethanol in Brazil is presented in Chapter 8, this volume, and in this chapter, only some key issues are described aiming at providing information about the ups and downs of the ethanol trajectory in displacing gasoline toward reaching a market competitiveness without subsidies through technology improvements, as well as adequately balanced conditions between cane producers and millers, and reduced demand for chemical fertilizers via waste use and better use of the land with crop rotation between cane cycles.

The Role of Private Sector in Technology Development and Transfer

The main drivers for recent ethanol production policies include: substitution for imported oil (1975); employment and reduction of local air pollution (1980s); mitigation of GHG emissions (1990s), and demand for electricity (2000s). Accordingly, support for R&D (Macedo and Nogueira 2010) came from different agencies, and always with strong participation of the private sector. Private stakeholders (cane producers, distillery owners, equipment manufacturers, input suppliers, engineering companies and automakers) and government institutions (funding agencies, research institutions) have all contributed to technology development/implementation.

From 1980 to 1990, the primary advances included new cane varieties, milling and fermentation improvements, stillage recycling, biological controls and agricultural equipment (Macedo and Nogueira 2010); since 1990, harvest mechanization, logistics, industrial automation, and flex fuel cars have been the primary improvements. Developments contributing to these advances include transgenic varieties, precision agriculture, electricity production from biomass wastes, second generation ethanol (2G) and new co-products. Table 14.1 summarizes the key results of technology improvements.

Table 14.1. Overall results, from 1970 to 2010(1).

	Productivity t cane / ha	**TRS in cane kg TRS/t cane** (3)	**Industrial Conversion %**	**Ethanol t TRS/ha**	**Cost R$/L ethanol** (2)
1970	49	87	82	3.5	3.0
2010	85	145	87	10.7	1.0

(1) Data from CTC and UNICA (Brazilian Sugarcane Industry Association), presented in (CTC 2013a)
(2) Constant R$, basis Jan 2011
(3) TRS: Total Recoverable Sugars

Implementation of Self Benchmarking Programs

The rapid growth of ethanol production in different regions and with different constraints called for well planned and reliable data acquisition and diffusion, to support technology development and implementation. Benchmarking programs for cane production and processing started after 1991 at the Sugarcane Technology Center (CTC) (CTC 2013b). This system has now 180 mills, and its database includes hundreds of parameters. A varietal census, covering 6.5 million ha of cane and 300 mills, completes the system indicating the commercial use of sugarcane varieties in the different cane producing areas in Brazil. Data acquisition is on line and analytical procedures are established by the CTC (CTC 2007). There are also checks for consistency with results published monthly / yearly, for the associated mills (regional and global averages, time evolution, dispersion). These programs have been very important for technology development/ diffusion throughout the country.

The Cane Payment System

Brazil has approximately 70 thousand independent cane producers and 440 processing industries. The sugarcane industry has specific conditions (high transportation/production cost; need for fast processing after harvest) that lead to a strong interdependency among cane producers and the processing industry; worldwide, different local policies and market organizations are used for price formation models.

After a period during which prices were set by the Government, the private sector in São Paulo established the most successful price formation model in Brazilian agriculture in 1998: a council (Consecana) of cane producers and sugar millers who developed the concept that actual revenues be distributed among the two sectors according to respective costs and cane quality (Machado Neto et al. 2011).

The Consecana model in São Paulo includes 19,400 suppliers producing 130 million t cane (UNICA 2013). Rules, operations and evolution can be consulted (CONSECANA 2006). Similar models are extended to most producing regions.

Recycling Vinasse through Fertigation

Environmental legislation during the last 30 years has determined site specific application guidelines for vinasse (m^3/ha), eliminating soil/water contamination (CETESB 2007) and regulating vinasse storage and distribution (impermeable tanks and channels; in some cases, pipelines). Engineering solutions starting in 1978 (Elia Neto 2007; Souza 2005) led to efficient recycling of stillage (K as fertilizer and water); and also included filter cake and boiler ashes. Vinasse became an important, cost-effective nutrient source, potentially providing 2.45 kg/t in K_2O savings (Donzelli 2005). However, two decades of developments on stillage bio-digestion, including commercial systems and stillage drying for mineral fertilizer formulations, still lack proven economic results.

Use of Idle Land between Harvest and Planting of New Cane

Sugarcane is planted once and harvested after 12 to 18 months of growth depending on when the crop is planted. After the first harvest, the cane re-grows as a ratoon crop that, on average under Brazilian conditions, can be harvested four more times, before the cycle is terminated and the cane replanted. With the 18-month cane growth period, there are a few months between the last harvest and the planting of the new cycle. During this period, it is normal to rotate with nitrogen fixing or other crops such as soybean [Glycine max (L.) Merr.], dry beans [Phaseolus vulgaris], peanuts (*Arachis hypogaea*), sunflower (*Helianthus annuus*) and hemp (*Crotalaria juncea*) (Penariol and Segato 2007). In the Center-South region of Brazil, planting of rotation crops takes place from September to December and harvesting is from January to March. The green material is incorporated in the soil to increase organic matter and nitrogen contents. This procedure has shown significant increases in yields and economic gains from the sale of crop products (soybeans, beans, peanuts, sunflower seeds) and from renting the land to independent growers (Alleoni and Beauclair 1995; Dinardo-Miranda and Gil 2005).

Present Problems

The Brazilian sugarcane sector was growing at a rate of approximately 10% per year between 2001 and 2008 (UNICA 2012a), but during the 2008 financial crisis, the sector found itself highly indebted and unable to obtain money from the banks to finance operational costs. Consequently, mills had to cut expenses. They did so by reducing the application of fertilizers and herbicides, postponing sugarcane field renewals, and laying off personnel. These actions had an immediate and lasting impact on cane yield and quality. Furthermore, the fast increase in mechanized harvest to comply with regulations phasing out cane burning, as well as weather problems in 2009 to 2011 (excess rain in 2009, drought in 2010 and frost and cane flowering in 2011), and poor agriculture management (use of low quality seeds in planting – old cane with diseases and pests) also affected the crops (Sanguino 2013). The compound outcome was a reduction of cane yield from the 20 year historical average of 84 t of cane/ha to 69 t of cane/ha in the 2011/2012 season (UNICA 2012b). Other production costs, such as the price of renting land, chemical inputs and labor, however, sharply increased mainly because of higher oil prices and shortage of qualified labor (UNICA 2012a).

Fortunately, the sector identified the problems associated with past actions and contexts, and started correcting them by accelerating cane field renewal, taking precaution to plant better quality seeds, and reducing the negative impacts of mechanization (soil compaction and ratoon damage). The government also helped by making money available to finance the cane planting activities. With this, the yield is slowly increasing, reaching 72 ton/ha in 2012 and 78 ton/ha in 2013, in the Center-South region (CONAB 2014). On the political side, the situation remains unresolved since the central issue is the government's policy to maintain gasoline price for the domestic market below the international prices, thus reducing competitiveness of ethanol at filling stations.

Conclusions: Brazil has a long history of bioenergy production. Public/Private sector cooperation was essential for identifying problems associated with past actions and for developing effective strategies to correct them. A benchmark system based on well planned and reliable data acquisition and diffusion is crucial for supporting biofuels technology development and transfer. Recycling residues decreased the demand for chemical fertilizer and the planting of crops in rotation with sugarcane at the end of the five harvest cycle added economic viability to sugarcane ethanol. Finally, a payment system based on cane quality and fair division of profits between growers and millers is the reason behind the socioeconomic sustainability of the system.

14.2.2 Surplus Power Generation in Sugar/Ethanol Mills: Cases in Brazil and Mauritius

Surplus power generation is becoming a trend in several sugarcane producing countries, especially in Brazil, India, Mauritius, and Reunion. However, the Brazilian and Mauritian experiences differ in realization of the potential, including what makes these cases worth exploring.

Bioelectricity from Sugarcane in Brazil: Evolution and Current Situation

Currently, hydroelectricity and natural gas are Brazil's primary sources of electricity, accounting for almost 80% of installed capacity (Figure 14.2). Bagasse and straw from sugarcane are in third place, representing 7% of Brazil's installed electric energy matrix (ANEEL 2014).

Bagasse and straw are the main sources of biomass for bioelectricity, accounting for 81.5% of Brazil's biomass-based installed capacity in 2013. The sugarcane sector with its 9,156 MW, in addition to being self-sufficient in steam and electricity for manufacturing sugar and ethanol, has been able to generate surpluses of bioelectricity to the grid since the middle 1980s.

In 2012, bioelectricity from sugarcane was responsible for almost 3% of the total consumption of electricity in Brazil. However, there is a potential to reach 18% by 2020/21 (EPE 2013). Nevertheless, the sugarcane and bioelectricity sectors need long-term policies to stimulate investment.

One of the main barriers to cogeneration projects is connection to the National Grid. In Brazil, the connection cost has to be paid in full by the bioelectricity supplier and, in some cases, it represents 30% of the total project investment. In order to reach the potential, the country needs to establish a free or co-shared cost policy for building the bioelectricity transmission system (Souza 2013).

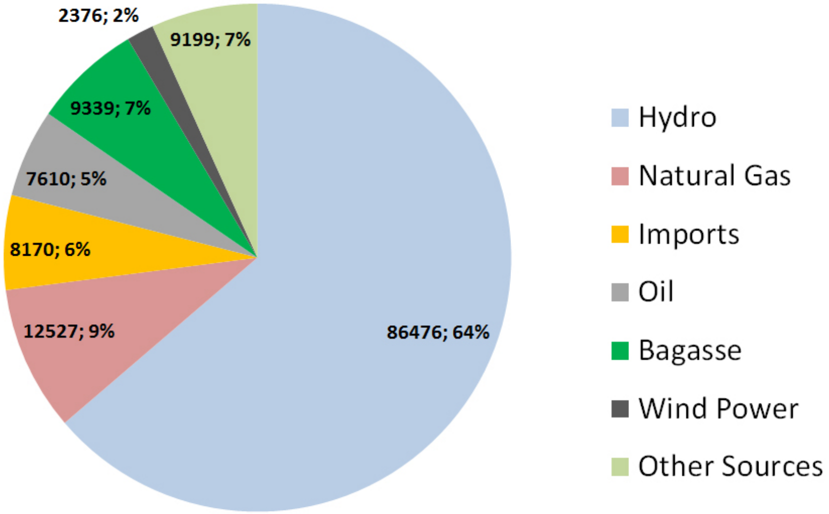

Figure 14.2. Brazil installed capacity by source, March 2014 (MW). Source: ANEEL (2014).

According to Souza (2012), another significant barrier is the commercialization in regulated auctions, promoted by the federal government.

For example, on March 15, 2004, the Law n. 10,848 (New Model of Electric Sector), which specifically focuses on altering the trading environment, was passed. Its main focus is the creation of two distinct energy trading environments in which a generator can act: (1) an environment for contracting energy aimed at distribution companies, called RCE – Regulated Contracting Environment, and operating from energy auctions as the pool for contracting; and (2) a market with more flexible commercialization rules, for producers, free consumers, and energy commercialization enterprises, called FCE - Free Contracting Environment (Souza 2012).

Under RCE, distribution companies purchase electric energy for their markets through public auctions regulated by ANEEL (National Energy Agency - in charge of regulating the sector) and operated by the Electric Energy Commercialization Chamber (CCEE), under the procedures of the Ministry of Mines and Energy (MME) (Souza 2012).

The energy needs, estimated by distribution companies for a horizon of five years, are analyzed by the MME. This represents the demand to be contracted through auctions, characterized as reserved auctions of purchase. On the supply side, there are companies with existing mills and those aiming to build new mills, even if they still do not have concession contracts or authorization to do so. These auctions are called “Auctions of Purchase New Energy and Existing Energy”. According to the new electric sector model, new energy auctions should take place five, three and one year before the effective supply of electric energy to contracting distributors. Therefore, these auctions are called A-5, A-3 and A-1 (regular auctions), while other non-regular auctions are for reserve energy and alternative sources (Souza 2012).

The use of reverse auctions to improve the renewables industry is frequent in Latin American countries, mostly in Brazil, Chile, Peru, Colombia, and Panama (Maurer and Barroso 2011). In Brazil, these auctions are the primary long-term method for selling bioelectricity.

In the Brazilian power sector, reverse auctions have resulted in significantly lower prices, which represents one aspect of success for the consumer (Table 14.2), but this situation has resulted in contracting fewer types or sources of generation and limiting contracts to those whose structural and situational aspects are favored (wind power in particular). Despite the appeal of low tariffs, achieved through competitive auctions, in the long run, this policy should be adjusted to avoid restrictions on development of other renewable sources and their associated industries (Souza 2013).

The generic auctions in the Regulated Environment, without discrimination of the location of enterprises or type of power generation, has limited the ability of the Federal Government to compose the energy matrix according to the needs and potential of each region and source of generation, bringing costs and more losses in power transmission and adding possible variables of uncertainty into the management of energy supply (Souza 2012).

Table 14.2. Price and volume of bioelectricity contracted in regulated contracting environment, 2005-2013 (US$/MWh).

Auction date	Contracted energy (MWh/year)	Current price (US$/MWh)*
Dec-05	849,720	76.44
Jun-06	508,080	81.86
Oct-06	534,360	82.96
Jun-07	1,007,400	81.76
Aug-08	4,756,680	85.81
Sep-08	306,600	79.58
Jul-09**	87,600	76.24
Nov-09	8,760	41.79
Aug-10	1,669,656	71.37
Dec-10	8,760	53.58
Aug-11	713,064	48.04
Dec-11	183,960	45.78
Aug-13	1,170,336	56.65
Total	11,804,976	

Source: Souza (2013).* US dollar exchange rate of August 31, 2013. ** Since 2009, wind power is presenting significant competitiveness in the reverse auctions leading to a decrease in the average prices

Regulated auctions should take the potential of each source or region into account. For sugarcane biomass, the potential is mainly in the Center-South region of Brazil, which also happens to be the number-one energy consuming region in the country. It would be an encouragement if the Brazilian government changed its strategy of contracting power via “generic” auctions that blend sources which are unmatched even by the intrinsic qualities of each one (Souza 2011). Furthermore, it’s necessary to refine the pricing model of regulated auctions to incorporate the positive and negative impacts (externalities) not only of biomass but of other sources as well, which would certainly promote the development of bioelectricity in the Brazilian electric matrix.

Bio Electricity from Sugarcane in Mauritius: Progress and Prospects

Mauritius was the first country to export electricity from a sugar factory to the grid when in 1957, the St. Antoine Sugar Factory in the North exported some 0.28 GWh to the Central Electricity Board (CEB). This was the beginning of a fantastic opportunity for the industry. Since then, the amount of electricity cogenerated by sugar factories from bagasse has been in constant progression. In this evolution there are three distinct phases, namely:

Intermittent, when electricity was exported to the grid from 17 out of 21 sugar factories as available surplus electricity after meeting sugarcane processing requirements.

Continuous, when with the acquisition of appropriate equipment and elementary energy saving devices in 1977, a given amount of electricity to be supplied to the grid was agreed upon. For example, the Medine Sugar Factory in the West with an installed capacity of 10 MW, guaranteed to supply 6 MW to the grid.

Firm, when in 1982 with the acquisition of medium pressure boilers of 44 bars and 475^{o}C steam, the FUEL factory in the East supplied electricity throughout the year, from bagasse during the crop period and from coal during the inter-crop period.

The establishment of the Independent Power Producers (IPP) and the construction of bagasse-fired power plants not necessarily linked to sugar factories in the form of independent power companies further consolidated this firm approach. A significant step forward was the development of the Centrale Thermique de Belle Vue (CTBV) in the North of Mauritius with two high pressure boilers of 82 bars, with steam at 525^{o}C, and an installed capacity of 2 x 35 MW. In 2007, the Centrale Thermique de Savannah (CTSAV) in the South (now Omnicane Energy Operations Limited, La Baraque) was established with an installed capacity of 2 x 45 MW using two high pressure boilers with steam temperature similar to those at CTBV.

The success behind cogeneration of electricity from bagasse in Mauritius and selling to the grid is a result of a continuous and sustained Competitiveness Improvement Program initiated in 1985. The program comprises five phases as detailed below. The Sugar Sector Action Plan (1985), the Sugar Industry Efficiency Act (1988), the Bagasse Energy Development Programme (1991), the Blueprint on Centralization of Sugar Factories (1997), and the Multi-Annual Adaptation Strategy Plan (2006) are of particular importance. These programs which were supported by law, allowed the industry to enhance its competitiveness by increasing its revenues from diversification of its purely sugar activities. The power purchase agreements between the IPPs and the CEB were instrumental to the success of large-scale electricity production from bagasse during the cropping season and coal during the inter-crop period. In 2012, bagasse supplied 16% of the electricity needs of Mauritius.

In 2002 the share of electricity from bagasse amounted to 340 out of 2484 GWh produced in Mauritius, i.e. 13.7%. The growth of this source of electricity is shown in Figure 14.3,. It shows that there was a major growth of the coal share due to its successful combination with bagasse to generate electricity year round.

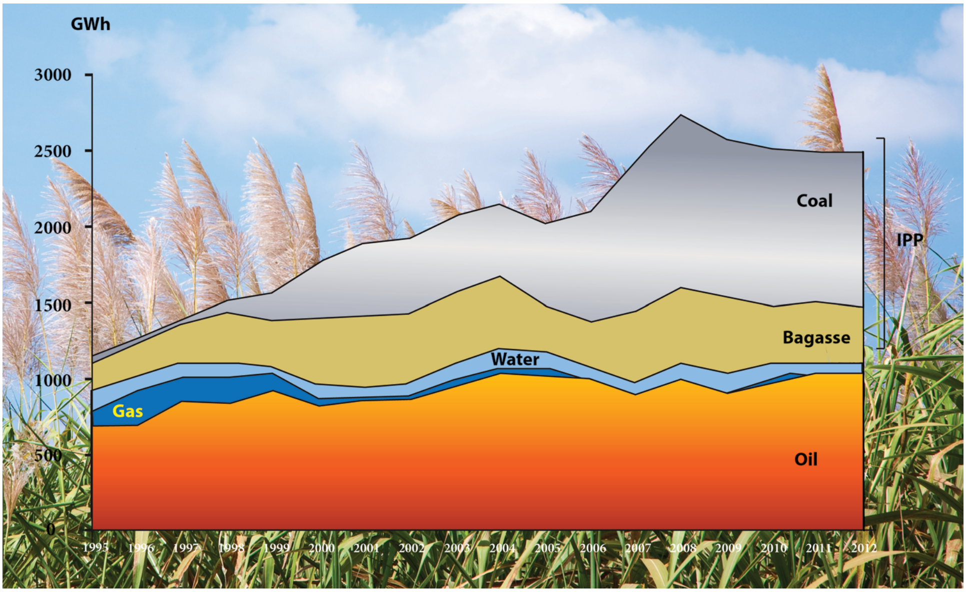

Figure 14.3. Electricity production by source in Mauritius.

At the end of 2013, the centralization process was finally completed with the closure of the sugar mill at Beau Champ in the east of the island, leaving only four factories in operation in Mauritius (one in each geographical section of the island) and with all the bagasse used in high pressure boilers, such as in CTBV and CTSAV, some 550 GWh will be produced from a sugarcane output of approximately 4 M tons. More details are provided by Deepchand (2008) and Kong Win Chang et al. (2001).

National Competitiveness Improvement Programs in Mauritius:

1985	Sugar Sector Action Plan – Restructuration, Modernization Bagasse Energy Policy evoked – Tax free revenue, Export duty rebate on bagasse saving and capital allowance on bagasse energy investment
1988	Sugar Industry Efficiency Act – System of performance linked export duty rebate to improve efficiency in farms, mills and power plants. Tax incentives to produce special sugar, save energy and optimize use of bagasse
1991	Bagasse Energy Development Program – Modernization, technology development, pricing policies such as tax rebate on electricity produced from bagasse and refund of export duty for the installation of energy efficient equipment
1997	Blue Print on Centralization – Facilitate closure of small inefficient factories, linking closure with optimal energy use from bagasse, while offering the right compensation package to leaving employees
2006	Multi-Annual Adaptation Strategy Plan – Drastic restructuration from 11 mills to 4 efficient ones, right-sizing of labor, intense modernization, construction of power plants, distillery and refineries coupled with aggressive marketing

Conclusions: The Brazilian story in surplus power generation had all the ingredients to be successful due to the sector's expansion and building new and large scale mills with high pressure boilers; however the present rules of power contracting at auctions and the lack of government action to solve the high cost of connection problems is jeopardizing the opportunity to develop the huge potential available. The success behind cogeneration of electricity from bagasse in Mauritius and selling to the grid is the result of continuous and sustained Competitiveness Improvement Programs initiated in 1985 with full support from the government and private sector. The track record of Mauritius in terms of bioelectricity production is laudable. However, with the decrease of the area under sugarcane plantation the participation of bagasse in the national energy mix tends to decrease. To maintain or increase the bioelectricity production, the sugarcane sector is looking into the recovery of sugarcane straw (normally called trash), the use of high fiber cane to increase bagasse yield and, ultimately, introducing the biomass gasification/ combined cycle (BIG/CC) technology in the mills to replace the conventional steam cycle.

14.2.3 The African Experience

Despite extensive interest in biofuels, to date there has been very limited production of biofuels in Africa with Malawi being the notable exception because their ethanol has been blended with petroleum since 1982 (Batidizirai and Johnson 2012). At the global level, the total contribution of biofuels from Africa is trivial (IEA 2011), this despite the continent's vast areas of land that are climatically suited for biofuel feedstock production (Smeets et al. 2007; Watson 2010). A large number of African countries have recently developed biofuel policies that envision a contribution of biofuels to the national energy mix (Mitchell 2011). This is seen as being beneficial as a large proportion of foreign exchange is spent on petroleum imports, and in addition the biofuel can contribute to rural upliftment (Diaz-Chavez 2010 and 2013). Biodiesel from *Jatropha curcas* is where there has been the largest investment in biofuels, with GEXSI (2008) estimating over 94 projects and 119 000 hectares being allocated to jatropha in 2008. However, Locke and Henley (2013) found that only 3.6, 12.9 and 3.2 percent of authorized land was actually planted to a biodiesel feedstock (prominently as jatropha) in Mozambique, Zambia and Tanzania, respectively. Several studies reported large-scale collapse of both small- and large-scale jatropha projects (Gasparatos et al. 2012, Locke and Henley 2013; von Maltitz et al. 2012), and none have been found to document extensive oil production from any project or country. This outcome was despite the many jatropha projects established in the mid 2000s. Extensive interest has also been shown for sugarcane based biofuels, but progress to date has been slow, and many proposed projects have stalled in their implementation. Ethiopia, Sierra Leone, Zambia, Zimbabwe and Mozambique are all currently developing plans for ethanol production (Batidizirai and Johnson 2012).

Therefore, Africa's rich history of successes and failures in the implementation of bioenergy projects deserve to be told and discussed. Two interesting examples are included here promoting the same feedstock (jatropha), but with different production models.

Jatropha Projects in Southern Africa

Southern Africa was identified by many investors as an ideal location for jatropha based biofuel development. At least 52 projects were initiated in the region (GEXSI 2008), but most failed and have been abandoned by their investors (Gasparatos et al. 2012). There are multiple reasons, but jatropha's low yields and higher maintenance costs compared to investors' expectations were a major factor.

Jatropha was promoted for its tolerance to dryland conditions and potential ability to grow on wasteland. However, experience has shown these early assumptions were flawed. More recent data suggests that although the tree will grow in low rainfall areas, good yields will require an annual precipitation of over 800 mm. However, the tree also responds poorly to waterlogged soils (Trabucco et al. 2010) so rainfall distribution is also important.

As a result, investors tended to plant jatropha on good soils rather than on wastelands. Furthermore, management costs for jatropha were also found to be relatively high, with seed picking and dehusking in particular being very labor intensive (von Maltitz and Setzkorn 2012). Despite these limitations, a few projects continue to expand and their developers are cautiously optimistic regarding long term successes (von Maltitz et al. 2014). Two projects with contrasting management models were visited in March 2013: one large-scale plantation project in Mozambique and a small-scale hedgerow based project in Malawi (von Maltitz 2014; von Maltitz et al. 2014). Key features of these two projects are summarized in Table 14.3. Despite the fundamental differences in management models of these two projects, both show signs of potential long-term success. Clearly, jatropha is not the high value, low input crop that had initially attracted investors (Gasparatos et al. 2012). However, where expectations are more modest and input costs are low, there seems to be a potential for long-term economic success. In both projects, economics are based on yields of three tons per hectare or less. The plantation type project would seem well suited to areas of relative land abundance, whilst the hedgerow project is better suited to areas with a high farm density. The intense poverty in both areas is another reason why a relatively low valued crop may succeed. Though the two projects use very different production pathways, both, if successful, can have significant positive impact on fuel security in both countries. Long-term success is, however, not guaranteed. A lot will depend on jatropha's ability to actually deliver even the more modest yield on which these projects are based. Something that only time will tell. Also, the financial viability of the projects under real world management is still unknown.

Table 14.3. A comparison of two jatropha projects, the Malawi BERL project and the Mozambique Niqel project. (based on von Maltitz 2014; von Maltitz et al. 2014).

	BERL Malawi	**Niqel Mozambique**
Project type	Small growers planting jatropha as hedgerows. Trees managed by the farmer's household	Large-scale commercial block plantation. Trees managed by paid labor
Project extent	90 field extension staff employed to train and establish over 6 million trees with 30,000 smallholders. BERL ceased extension of planting activities in 2013. Now waiting for the 6 million trees to mature	2,000 ha planted of a proposed 5,500 ha at Grudja. 250 permanent staff plus casual labor for harvesting
Current demography and smallholder farming practices	High population density. Wall to wall permanent small farms of 0.1 to 2.5 ha (1.7 mean). All farmers grow maize, with a wide mix of other crops. Mean income from agricultural sales US$ 38, with most households having 4.1 ± 2.7 (SD) months of food shortage per year	Low population density. Less permanent farms with slash and burn opening of new fields. Only 11.5 % of total land under cropland, the rest woodland. Farms range from 0.5 to 14 ha (3.97 mean), with households reporting a median income from agricultural sales of US$83. Most households having 5.9 ± 4.5 (SD) months of food shortage per year
Role of investor	Providing extension support, purchaser of seeds and oil extraction	Growing trees, harvesting and extracting oil
Processing	BEREL has an oil extraction plant based in Lilongwe. Seeds are purchased from farmers by BERL then transported to Lilongwe for extraction. BERL will sell as pure plant oil. First season oil extracted, but not yet sold	Niqel intends to extract oil at the plantation, extraction plant due to be installed in 2014. Niqel will sell as pure plant oil At the time of the study, no oil yet extracted
Proposed destination of final product	Oil to be directly blended into national diesel fuel to a maximum of 9%. To date this has not happened due to policy delays around the acceptance of the standard	Oil to be exported to Maputo – will probably undergo transestification for blending. Niqel aims to produce 25% of total Mozambique bio diesel needed to achieve 3% blend with diesel
Harvest, yield to date and hoped for yield.	2012/13 first harvest (Jan to Mar) yield ranges hugely, median 0.07 kg/tree, but with 5 farmers reporting over 0.4 kg/tree. BEREL target is 1.5 kg/tree per year at maturity which is equivalent to 1.9 t/ha (at 1250 trees/ha)	2012/13 first formal harvest. Yield increased from 0.16 t/ha in the first year to 0.4 t/ha from two year old trees. Target is 3 t/ha at maturity

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	BERL Malawi	Niqel Mozambique
Proportion of farm land converted to jatropha	A 500 tree jatropha hedge takes up 7% of the average farm at present. This might increase slightly as trees grow	Approximately 6% of the total village's area is converted to jatropha, reducing the potential land area per farmer from an estimated 27 ha to 25 ha. This is far more than the average 4ha used per farmer, and nearly all farmers said they had sufficient land
Impact on food security	At present seems minimal though some cropland land is lost to jatropha trees and there is possible competitive interaction between trees and crops	The plantation does not limit land for home food production Plantation policy limits labor to one family member per household, and respondents say they can maintain their crop production
Impacts on woodlands and woodland products	No or minimal impact	Will be 5500 ha of woodland lost, however, given the ratio of woodland to households the impact of this loss will be minimal in terms of the provisioning services it provides
Infrastructure benefits	BERL has established an oil pressing plant in Lilongwe	Niqel has established 200km of all-weather road. This allows community members from surrounding villages to access the tar road during the wet season – something they could not do in the past. They are also building a new primary school and have created small dams for community water provision

Conclusions: Africa has seen several failures and a few successes in the implementation of biofuel projects. The two projects presented here show some interesting lessons to be learned: Jatropha has demonstrated to be a risky feedstock and not as successful as anticipated because of erroneous initial assumptions regarding crop growth, development and yield potential. It is important to follow and evaluate the installation and operation of such projects to identify the main causes of failure and success and the results properly disseminated, since there is a very broad worldwide interest in this crop.

14.2.4 The Asia Experience

Asia is showing a fast growth in energy demand and bioenergy may or may not play an important role depending on results of the first bioenergy projects and the corresponding experiences and lessons learned. Thailand as the fourth largest sugarcane producer and second largest cassava producer in the World, has launched its ethanol program based on these two feedstocks and is proceeding successfully creating a production system that can be used as reference by other Asian countries with similar conditions. The growing production of oil palm, especially in Malaysia and Indonesia, for food, chemicals and biodiesel is creating a vast source of residual biomass that can be used to generate modern forms of energy such as electricity and second generation biofuels. As is the normal case in the use of residues for bioenergy, there is a question of logistics to recover, transport, store and process the feedstock and also the decision of the scale to be used in the processing. Malaysia is used here as an example of how the whole value chain of palm oil can be optimized by appropriately using the residues for energy products, in an adequate scale.

Thailand's Experience in Bioethanol Promotion

In 2012, bioethanol production in Thailand reached half a billion liters (Figure 14.4), thanks to a strengthened legal and policy framework over the past decade. A major driver is the desire to make biofuels a significant substitute to imported petroleum in the transport sector (Silalertruska and Gheewala 2010; Bell et al. 2011), which accounts for 36% of Thailand's total energy use. Other factors include the potential to reduce GHG emissions (Table 14.4) as well as the expected social benefits of biofuels, such as rural employment (Gheewala, 2012; Silalertruska et al. 2012) (Table 14.5).

The impetus for biofuels promotion began in 2000 when ethanol was designated a commercial fuel, plants to produce fuel ethanol were legalized, and a National Ethanol Committee was set up (Morgera et al. 2009; Jenvanitpanjakul and Tabmanie 2008). The initial goal, set in 2003, was 1 ML/d (million liter per day) consumption by 2006, which was later increased to 2.4 ML/d by 2011. The present target in the Alternative Energy Development Plan is 9 ML/d by 2021 (DEDE 2012a).

Fuel specifications were announced, first for E10 gasohol with 10% ethanol blended with unleaded gasoline octane 91 (or ULG91) and unleaded gasoline octane 95 (or ULG95), in 2006, then for E20 and E85 (based on unleaded gasoline octane 95 or ULG95) in 2008. Ethanol blending is not mandatory, but ULG91 was phased out in January 2013, leaving ULG95 as the sole unblended gasoline. The main incentive for ethanol producers and consumers is price: excise tax is currently being exempted from the ethanol component of gasohol and lower contribution rates to the Oil Fund from gasohol sales. Incentive packages to stimulate investment into the ethanol industry are also in place. In addition, excise tax rates are lower for cars with engines compatible with E20 or higher blends (Morgera et al. 2009).

Thai ethanol is produced mainly from molasses (62%) and cassava (38%). Because of the farmers-millers profit sharing requirement under the Cane and Sugar Act, millers are implicitly discouraged from producing cane juice-ethanol and adopting the more efficient, integrated production models practiced in Brazil. Compared to molasses-ethanol, the cost of cassava-ethanol is more expensive and more vulnerable to feedstock cost fluctuations (Morgera et al. 2009; Damen 2010). The problem of surplus ethanol production has partly been solved since pulling ULG91 off the market, with production surging to 2.3 ML/d on average in the first half of 2013 (DEDE 2013). Since the liberalization of export regulations, ethanol export has reached 170 ML in 2012 (Sikhom 2012). The planned reduction of excise tax rate for flexible fuel vehicles (FFVs) in 2016 will further raise demand for ethanol (Wongtareua 2013).

Fortunately, competition for land and water resulting from increased crop production can be avoided by improving sugarcane and cassava yields and by installing irrigation systems where feasible (Morgera et al. 2009; Damen 2010); adequate policies will be required.

Greenhouse gas (GHG) emissions reduction resulting from the substitution of gasoline by ethanol is estimated to be substantial (Table 14.4) especially in the case of sugarcane as feedstock.

Table 14.4. Life cycle GHG performance of bioethanol from molasses and cassava in Thailand (Source: Gheewala 2012).

Feedstock	Estimated GHG emissions ($kgCO_2eq$/liter biofuel)	Net avoided GHG emissions compared to gasoline****
Molasses*	0.68	64%
Cassava/dried chip**	0.96	49%
Sugarcane juice***	0.5	72%

* Average of three ethanol plants, Allocation Factor (AF) of sugar:molasses = 4:1

**Average values from various studies; plants that use biomass as fuel may emit only 0.77 $kgCO_2eq$/liter (TEI 2007)

*** Sugarcane in Brazil

**** Estimation based on energy content of ethanol = 21.2 MJ/L, and of gasoline = 31.4 MJ/L

Another important issue related to biofuels production, especially in developing countries such as Thailand, is the jobs created by the whole value chain in terms of direct and indirect employment. The benefits in this area from the Thai ethanol program were simulated for 2022 using the target of 9 ml/d in that year and are summarized in Table 14.5.

Table 14.5. Projections of employment caused by ethanol target of 9 ml/d in year 2022 (Source: Silalertruksa et al. 2012).

Feedstock	Employment coefficients for high yield assumption (person-years per million liters of ethanol)			Employment caused by ethanol target in 2020 (person-years)
	Direct	Indirect	Total	Range of 4 scenarios*
Molasses	10	46	56	35k – 70k
Cassava	36	40	76	180k – 277k
Sugarcane	47	32	79	23k – 35k
Total				238k – 382k

* The scenarios depend on factors such as assumptions on crop production yield, agricultural practices, mechanization, etc.; figures rounded off from the reference

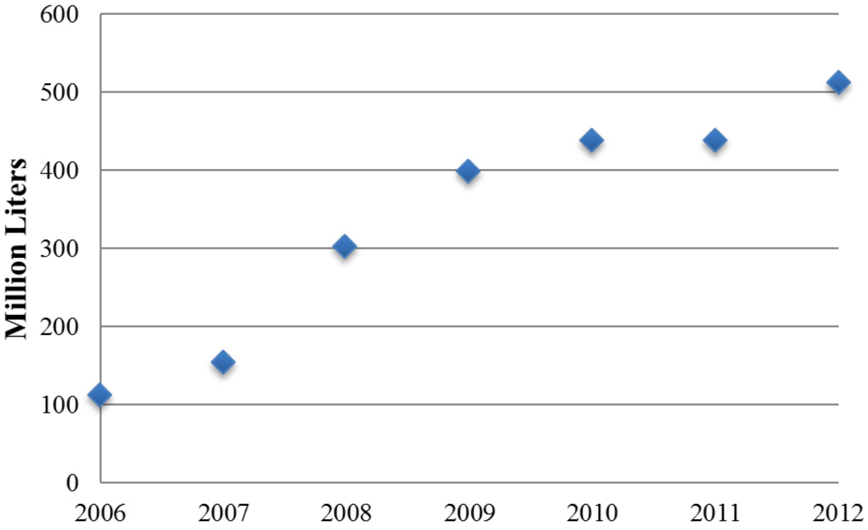

Figure 14.4. Ethanol production trend in Thailand. (Source: DEDE Energy Situation Reports, 2013, 2012b, and 2011).

Conclusions: Introduced in 2000, ethanol production in Thailand has now developed into a relatively mature industry, thanks to a strong legal and policy framework that includes blending standards and mandates, and favorable price mechanisms. The market for ethanol, produced mainly from molasses and cassava thus far, can expand considerably with incentives for flex fuel vehicles (FFVs). Ethanol supply can also grow with crop yield improvements and conducive framework conditions for cane juice-ethanol production. However for the latter it will be necessary to introduce relevant modifications in the cane payment system to create conditions to implement the joint production of ethanol and sugar model used in Brazil.

Palm in Malaysia: Combined Effects of Scale on Biomass Logistics and Conversion Costs

The vegetable oil sector (palm, soy, sunflower, and others) is producing roughly 300 million tons per year of oils, primarily for food and consumer products, but hardly for biofuels (1-2% of total volume). It is not expected that much more oils will be used for biofuels given the other demands. But oil producing plants like oil palm produce one order of magnitude more lignocellulosic residues – for instance in the case of oil palm, these are the fronds (leaves), trunks, empty fruit bunches, and the liquid wastewater effluent of the oil mill, that are today mostly wasted. This excess biomass could provide a substantial feedstock for renewable biobased chemicals, fuels and energy. Using them also considerably reduces the emissions of the sector. To use excess biomass, technologies such as fermentation, Fischer-Tropsch and other may be employed.

Biorefineries for the conversion of biomass into one or several products are often conceptualized as large, integrated facilities that benefit from economies of scale and/or cover the demand for a large market. Bioethanol, power, and sugar/starch from sugarcane in Brazil or corn in the USA or France give clear examples of large-scale operations. As the (relative) capital cost increases with the complexity of biomass processing technology, the optimum scale is larger when economies of scale have larger impacts (Searcy and Flynn 2009). For instance, Wright and Brown (2007) report optimum scales that increase depending on the complexity of the conversion process, e.g. pyrolysis bio-oil has an optimum at a biomass annual processing capacity of 1.08 million tons versus cellulosic bioethanol at 4.57 and FT (Fischer-Tropsch) diesel at 7.69 million tons.

However, as economies of scale for conversion and logistics have opposing effects on production cost, the optimum will be based on both factors. For cases of seemingly abundant biomass availability, especially in Asia such as palm biomass in Malaysia (Palmeros et al. 2013) and Indonesia and specific biomass uses in other situations such as bioenergy in India (Pantaleo and Shah 2013), the scalability of biomass conversion chain is substantially limited by economics and technology for transportation as well as market structure. An often overlooked effect in logistical costs is tortuosity, which is a measure for the degree of development of local infrastructures versus a simplified straight-line model. Tortuosity can be about 1.2 for developed agriculture regions where roads are laid out in rectangular grids or as great as 3.0 for less developed regions. Tortuosity leads to a proportional increase in logistical costs (ranging from 20% to 200% from developed to less developed situations). In practice, average transportation costs are further impacted by seasonal influence on softness of soils, degree of actual coverage with biomass, the non-circular nature of actual plantations, remoteness etc. In those case studies, the biomass supply and value chains including operational and investment models have to be re-designed.

Palmeros et al. (2013) provide a detailed case study for oil palm biomass use in Malaysia, which is an example that demonstrates the general case. Palm biomass (residues) is currently generated at mills as a result of oil extraction from fresh fruit bunches (FFB), namely empty fruit bunch (EFB), fibers, and shells. Additionally, oil palm fronds (OPF) and trunks (OPT) become available at the plantations, and the case is to use both streams. A simplified (approximate) biorefinery model as well as a more detailed plant design have been considered in two cases, namely (1) biomass derived from milling operations (M), and (2) biomass derived from plantation and milling operations (M+P). The scale effect is introduced by centralized processing of M or M+P biomass to fermentable sugars of *n* mills, benchmarked against current technology and economic numbers. Generation of heat and power, and treatment of wastewater from the biomass conversion and other palm oil mill operations, are taken into account to calculate Total Production Cost (TPC in $/metric ton) in the below figure 14.5 (*n* ranges from 1-20). TPC decreases in both cases with increased production scale (effect of relative CAPEX-reduction), and then increases due to the logistical costs. Increased learning effects in production technology (Van den Wall Bake et al. 2009) will even lower conversion costs and push the minimum to (single) mill integrated processing.

Further profitability analyses for palm biorefineries were performed at two different scales of central biomass processing, derived from three and ten mills and plantation as 15 year

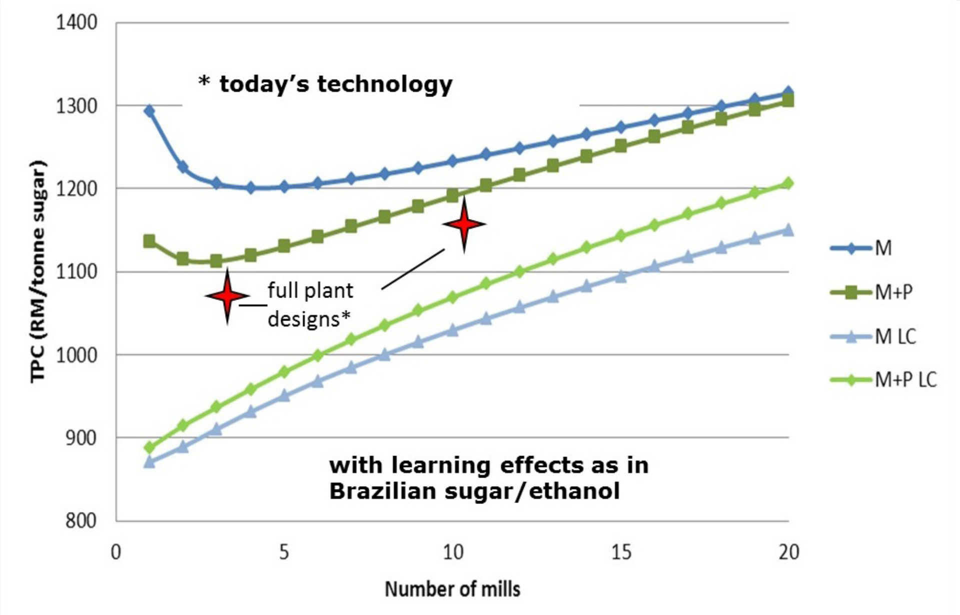

Figure 14.5. Impacts of the mill scale on the Total Production Costs (TPC) of lignocellulosic palm biomass to sugars (Palmeros et al. 2013).

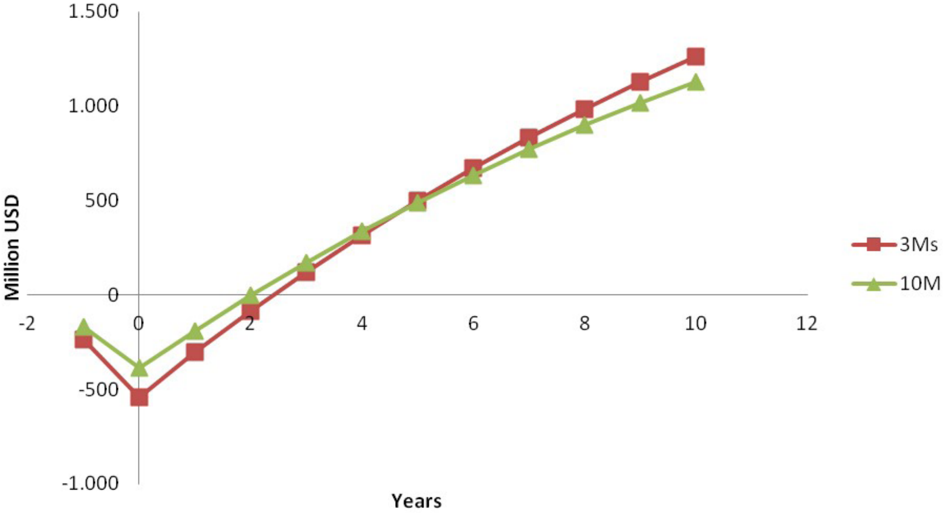

Figure 14.6. Cumulative and discounted cash flows of a single biorefinery compared with multiple biorefinery alternatives (Palmeros et al. 2013).

projects, Evaluation was done in terms of NPV (Net Present Value), with actual operation starting in year 3 after the start of the project. The two situations were scaled to the same feedstock processing capacity, i.e. a single biorefinery processing biomass from 10 mills and plantations (10M) versus a larger number (10/3) of biorefineries processing the same amount of feedstock (3Ms). The cumulative discounted cash flows are presented in Figure 14.6. The economies of scale have a positive impact on the payback time for the investment. As a result, the payback time of the 10M case is shorter than for the multiple mill 3Ms case. However, due to the differences in total production cost (Figure 14.6), multiple smaller biorefineries are more profitable than a single biorefinery processing the same amount of feedstock over the whole project lifetime.

Conclusion: The experience with this case study directs towards small scale, single-mill-integrated processing of biomass, for palm and comparable cases with high logistic costs. This is in opposition to the current tendency in (increasing scale) technology development. One important conclusion is that the case of optimum scale is highly dependent on the local conditions and contexts. Developing regions such as Southern Africa, Southeast Asia and others may have similar situations as the Malaysia oil palm biomass case.

14.2.5 Biofuels from Agricultural Residues: Assessing Sustainability in the USA Case

The production of bioenergy in developed countries often encounters different problems than in tropical countries because of geographic diversity and well-developed industries for multiple feedstock sources (Braun et al. 2010). The use of wastes, on the other hand, can benefit from a better organized collection and transport infrastructure and good technology available for conversion (Brick 2011). Furthermore, because of regulations regarding waste handling and disposal, using those materials for bioenergy production can reduce waste handling costs and thus improve the economic competitiveness of using wastes as bioenergy feedstock. The developed countries also have several functional technologies for recovering agriculture residues and substantial knowledge regarding the impact of harvesting them so that the real potential for using agricultural residues as bioenergy feedstock can be rigorously assessed. This knowledge is also extremely important for developing countries as it defines a scientific basis framework for sustainable recovery of agricultural residues taking into consideration not only the economic issues, but also the agricultural impacts of the residues in terms of soil protection against erosion and soil organic matter (SOM) stock; this system needs only to be adapted to the local conditions in developing countries to determine the optimal conditions for agricultural residues harvesting.

The anticipated 2014 launch of three full-scale corn stover to ethanol conversion facilities is a strong U.S. market signal that sustainable feedstock supplies must increase dramatically to supply 242 million Mg yr^{-1} for each facility producing biofuel at 252 L Mg^{-1} (Congress US 2007; Humbird et al. 2011; Schroeder 2011). To achieve that

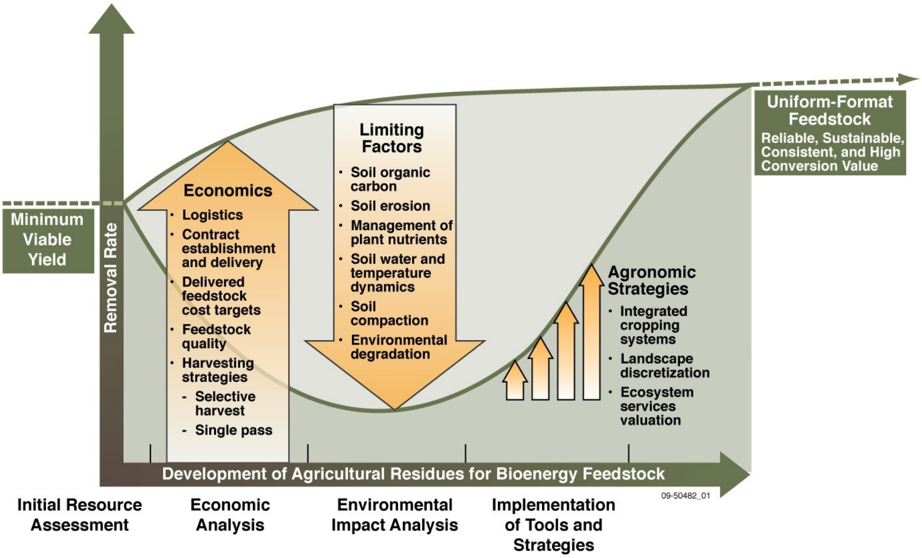

Figure 14.7. An illustration of competing economic drivers and environmental sustainability forces that must be balanced to achieve sustainable cellulosic feedstock supplies to support the transition from fossil to renewable fuels (With permission from Wilhelm et al. 2010).

goal without degrading soil quality (Andrews 2006; Reijnders 2006; Wilhelm et al. 2004; Wilhelm et al. 2007; Wilhelm et al. 2010), improved agronomic practices are needed. The conceptual framework guiding development of those practices (Figure 14.7) illustrates how economic drivers focused on feedstock supply and limiting environmental factors must be balanced (Wilhelm et al. 2010). The environmental factors were addressed by requiring soil erosion to be kept at or below the annual tolerable (T) rate of soil loss as defined by USDA-Natural Resources Conservation Service (NRCS), and by using the Soil Management Assessment Framework (SMAF) (Andrews et al. 2004; Karlen et al. 2011a; Karlen et al. 2011b) to monitor SOM and other soil quality indicators (Andrews et al. 2004; Karlen et al. 2011a, Karlen et al. 2011b).

Initially, extensive literature reviews were used to determine the amount of surface residues required to not only protect against wind and water erosion but also sustain SOM because of its effect on aggregation, soil structure, water entry and retention, nutrient cycling, and biological food webs. This provided general U.S. Corn Belt guidelines showing that an average of 5.25 or 7.90 Mg ha^{-1} of corn stover should be left in the field to sustain SOM for continuous maize (*Zea mays* L.) or maize-soybean [*Glycine max* (L.) Merr.] rotations. Assuming a 1:1 dry grain to dry stover ratio, these guidelines mean that continuous maize fields yielding 8.5 Mg ha^{-1} (160 bu ac^{-1}) of grain could sustainably provide an average of 3.25 Mg ha^{-1} (1.25 ton ac^{-1}) of stover.

Since 2008, coordinated, multi-location field trials have added 239 site-years of data from 36 replicated field experiments, to help make the general guidelines more site specific. Those studies had grain yields ranging from 5.0 to 12.0 Mg ha^{-1} and showed N, P, and K removal was increased by 24, 2.7, and 31 kg ha^{-1}, respectively, with moderate (3.9 Mg ha^{-1}) stover harvest or 47, 5.5, and 62 kg ha^{-1}, respectively, with high (7.2 Mg ha^{-1}) stover harvest. The field studies also quantified removal effects on SOM, microbial communities, trace gases, economics, and other factors (Karlen and Johnson 2014).

Simultaneously, an integrated data management and modeling framework, identified as the Landscape Environment Assessment Framework (LEAF) (www.inl.gov/LEAF) was developed and verified using the literature guidelines and field data. LEAF was designed to perform feedstock availability assessments and explore alternate agronomic strategies for increasing feedstock supply without compromising soil, water, or air resources. The framework (Muth et al. 2013) integrates the Revised Universal Soil Loss Equation 2 (RUSLE2) (USDA 2013a), Wind Erosion Prediction System (WEPS) (USDA 2013b), Soil Conditioning Index (SCI) (USDA 2013c), and DAYCENT model (Parton et al. 1998). Each model runs in an optimized manner with inputs and outputs seamlessly linked through the LEAF framework to produce landscape plans (Brick 2011) that if implemented could supply feedstock and protect soil resources.

To date, four key products have been delivered: 1) a revised national assessment for the Billion Ton Study Update (USDOE 2011), 2) a sub-field assessment framework used to characterize effects of surface topography, soil characteristics, and grain yield on sustainable residue removal, 3) an analytical assessment and toolset for designing precision agricultural residue removal equipment, and 4) multiple deployments of decision support tools being used across the public and private sectors. In summary, the strategy for developing sustainable feedstock supplies in the U.S. has been to develop trans-disciplinary teams of field researchers, computer modeling engineers, and private industry partners. Together they have made progress that could not have been achieved independently by any of these groups.

Conclusions: Sustainable biomass feedstock supplies must increase dramatically to develop viable biofuels industries. Public-private partnerships are evolving to provide the crucial data needed to support these endeavors by balancing economic drivers from the industry perspective with natural resource and social concerns of those supplying feedstock materials. Rigorous field data and simulation modeling are both crucial and easy to use tools to make this simulation a very important component in the process.

14.2.6 Comparison of Biogas Production in Germany, California and the United Kingdom

An examination of biogas case studies reveals the importance of consistent leadership and adaptive policy support for the adoption of renewable energy. Biogas production can be implemented in very low technology, small-scale systems or in very high technology, large-scale systems. The gas has a variety of end-uses including direct combustion for heat and cooking, electricity generation, or as transportation fuel (Abbassi et al. 2012).

Despite these advantages, biogas contributes very little to current bioenergy portfolios of most nations. The reticence to adopt biogas technologies is not technical; factors such as cost, public acceptance, knowledge and expertise, environmental policy and energy security seem to drive striking differences.

The status of biogas in Germany, California, and the U.K., three regions with similar per capita GDP and energy use, is informative (Table 14.6). All three regions began implementing agricultural biogas in the 1970s. Today, Germany has over 7,500 medium- to large-scale plants, more than three times the rest of the EU combined and nearly 40 times more than in the U.S. Germany's success can be largely traced to a steady drip of adaptive policy supports starting in 1991 (Figure 14.8) (deGraaf and Fendler 2010). Despite similar biogas potentials, California and the U.K. trail

Table 14.6. Biogas in Germany, California, and the U.K.

	Germany	**California**	**U.K.**
Per capita GDP ($USD)	41,514	47,482	38,514
Per capita energy use (kWh)	7,081	6,721	5,516
Per capita fossil natural gas consumption (m^3)	918	1,695	1,249
Dairy Cows (million)	4.2	1.8	1.8
Biogas facilities*	7,589	11**	106
Biogas Electricity capacity* (MW)	3,179	3	88
Current Feedstocks	85% Dedicated energy crops, 15% manure and other waste	90% Manure, 10% food waste	50% Food waste, 50% manure
Primary Driver	Energy Security	Environmental Impact – Water	Environmental Impact - GHGs
Secondary Drivers	Farmer Support	Environmental Impact- GHGs	Landfill Limitations
Biogas Potential (billion m^3)*	20	18	5-18
Percentage of Fossil Natural Gas Use	21%	28%	23%

* not including wastewater treatment facilities

** The U.S. has 201 agricultural biogas generating facilities in total

Source: World Bank (2014a, 2014b), IEA (2014), EIA (2014a, 2014b), California Energy Commission (2014), European Commission Farm Accountancy Data Network (2013)

Germany with a little more than 1% of its capacity. Recent E.U. Directives, a desire to limit landfill, and a steady decline in offshore natural gas production have spurred the U.K. to start investing in biogas, establishing a feed-in tariff and other incentives (Biogas UK 2013). The combination of initial policy supports, economies of scale, conversion efficiencies, and farm economics resulted in large-scale systems, many of which used maize for feedstock. While this provided farm support, it nudged up against an unacceptable feed for fuel scenario. As economics for large-scale systems improved, it was possible for policymakers to implement incentives for heat capture, use of wastes and small-scale systems and thus allow for a more desirable path for biogas.

California, on the other hand, has struggled with sporadic programs and inconsistent regulations (Sanchez 2013). Unlike Germany, which has a feed-in tariff based on the retail electricity rate, California's feed-in is determined by the wholesale rate, which is very low and variable. Whereas Germany has enabled upgrading and connections to natural gas pipelines, California biogas producers are hampered by high connection costs and variable acceptance criteria. Cheap new sources of domestic natural gas, financial constraints, and incentivized on-farm use over grid injection have not helped. While the California Energy Commission had assisted on-farm biogas installations in the past, changes in NOx emissions standards forced many to shut down, leaving farmers reluctant to reinvest (Zhang, 2007). As a result, less than 1% of the state's 1600 dairies recover biogas from their herds. Finally, a preference for composting over anaerobic digestion in many communities has discouraged biogas from food waste. Thus, rather than grow, the number of biogas facilities in California fell by half between 2008 and 2012 (Sanchez 2013).

Biogas is also important as a clean-burning energy source for rural communities lacking access to conventional energy distribution. In the BRIC nations, China and India have embraced biogas, while Brazil and Russia have not. China has over 50,000 medium- to large-scale digesters and over 40 million household digesters. India has over 4 million household digesters and several large-scale projects. In both cases, government was critical in adopting biogas, lowering financial barriers and promoting usage. In Brazil, with clean, centralized hydroelectricity, and Russia, with large supplies of natural gas, there has been little incentive to invest in biogas. Brazil has 22 biogas facilities. While there are plans to build biogas plants in Paraná, Brazil (Osava 2013) and the Belgorod region of Russia (BD Agrorenewables 2012), the projects face tough economics without clear policy supports. In 2012, the Brazilian Energy Agency (ANEEL) called for strategic R&D projects related to biogas to support the 2010 National Solid Waste Law aimed at reducing landfill and encourage projects dealing with agricultural waste and wastewater.

International development programs play an equally important leadership role for developing nations (Table 14.7). The programs provide investment capital, organizational capability, knowledge and expertise, which are all essential for adoption of new bioenergy options. For example, early programs for households digesters in China (1970s to early 1990s) often failed because of poor installation and lack of local expertise in care and maintenance. When systems became more widespread and local knowledge grew, success and adoption rates increased. Non-profit agencies can fill some of this need, as demonstrated by the Netherlands Development Group -SNV (2012). They work with local governments to train masons and maintenance operators to build and repair local biogas system for cooking and heating using household and farm waste.

Table 14.7. Biogas plants installed in Africa and Asia by non-profit group (SNV), in cooperation with the World Wildlife Fund, the Asian Development Bank and the World Bank. (Netherland Development Group SNV 2012).

Country	**Program Start Date**	**Number of Digesters***
Nepal	1992	268,418
Vietnam	2003	140,698
Bangladesh	2006	23,611
Cambodia	2006	17,450
Lao PDR	2006	2,715
Rwanda	2007	2,171
Ethiopia	2008	3,232
Tanzania	2008	3,334
Pakistan	2009	2,097
Indonesia	2009	5,572
Uganda	2009	2,325
Kenya	2009	4,917
Burkina Faso	2009	1,117
Cameroon	2009	111
Benin	2010	42
Senegal	2010	334
Bhutan	2011	155
Total		**487,359**

*as of June 2012

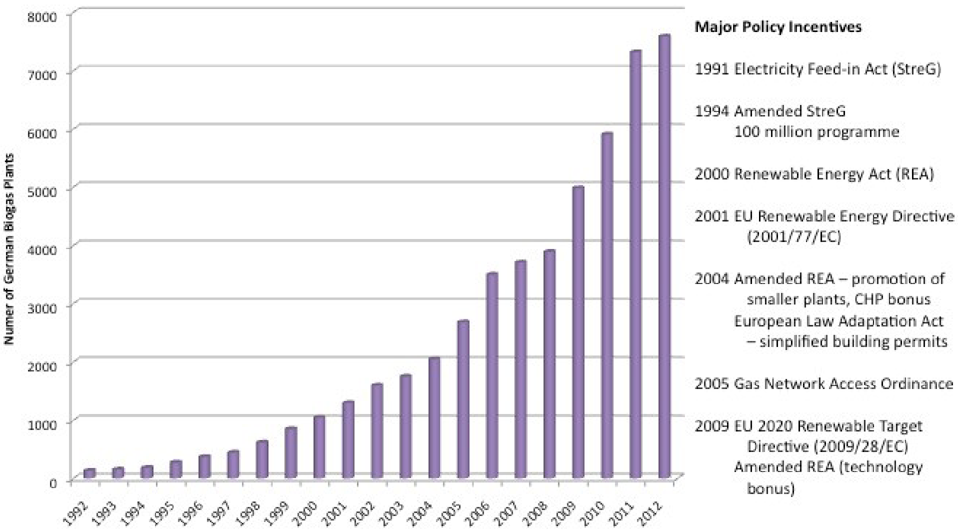

Figure 14.8. Adoption of biogas in Germany with major policy incentives (deGraaf and Fendler 2010; German Biogas Association 2013).

Conclusions: Biogas contributes very little to current bioenergy portfolios of most nations even though it has many well-defined advantages. Barriers to adoption are socioeconomical rather than technical, including factors such as public acceptance, knowledge and expertise, energy and environmental policy, energy access and security as well as financial considerations. Successful programs share consistent and adaptable leadership, whether at the local, regional or national level.

14.2.7 Wood Pellets and Municipal Solid Waste Power in Scandinavia

In population dense communities of Scandinavia, district heating systems have been introduced to provide heat and hot water to office buildings, schools, apartment buildings, etc. Hot water is distributed from a central thermal energy station. The fuel used in many plants can be municipal solid waste (MSW), wood pellets or wood chips.

MSW can only be used in larger plants since the waste, due to hygienic requirements, cannot be stored and must be combusted immediately upon arrival at the plant. In small plants the heat demand during summer is so low that it would be impossible to run a plant without storing the waste during hot periods. Therefore, these plants run on woody biomass or bio-oil.

The demand for MSW in the Nordic countries is now so large that there is not enough MSW available in the local markets. To cover the demand, MSW is imported from other parts of Europe. Some of these plants are or will be retrofitted to run multifuel.

The use of bioenergy has increased steadily in Scandinavia and has reached about 20% of the total energy supply in Sweden (see Figure 14.9). Most of the bioenergy comes from forests.

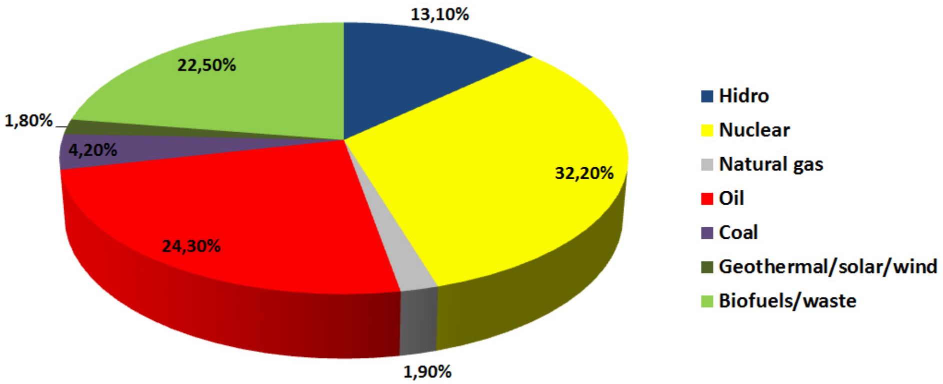

Figure 14.9. Total Primary Energy Supply (TPES) in Sweden in 2012 (Source: IEA 2014). Notes:1. Sweden TPES in 2012= 50 162 ktoe (thousand tons of oil equivalent);2. Shares of TPES excludes electricity trade;3. In this Figure, peat and oil shale are aggregated with coal, when relevant.

Figure 14.10. Akershus energy park in Norway.

One of the most modern utilities is the Akershus energy park in Norway (Figure 14.10). The plant provides heat to some 10,000 persons and local institutions. It opened in 2011. It was considered to run this plant on MSW, but the summer demand for heat is too low. Instead it runs on wood chips, bio-oil and gas from the local landfill.

The plant has 2 furnaces that use chipped wood, mainly from local suppliers. Each furnace has a power of 8 MW and the heat in the flue gas is recovered by condensing the water vapor, thus making each furnace effectively 10 MW. There are cleaning systems for the flue gas and the ash is collected from the bottom of the combustion chamber. These 2 furnaces are essentially used for base load and they are not operated during summer months when the demand is low.

There is a 1.5 MW gas burner that burns the gas that is piped down from the landfill. However, this gas has a low caloric value and the methane and CO content is rather low.

Finally, the plant is equipped with some 10,000 m^2 of solar thermal collector panels, providing 7 MW additional capacity. In combination with a water accumulation tank, this heat can be stored for later use.

Conclusions: MSW is an attractive fuel for energy production and the demand is increasing in Nordic countries to the point that the demand exceeds the offer, requiring the use of supplemental fuels such as wood chips and pellets. Wood pellets and wood chips are already increasingly being used directly for heat generation in Scandinavia and other northern European countries. The heat is distributed as hot water through pipes that connect to major office and apartment buildings in dense areas. In Sweden, bioenergy including waste covers about 20% of the primary energy supply. Demand for sustainable supplies of wood pellets is currently ahead of that for biofuels in many countries.

14.3 Overall Conclusions

Even for apparently similar situations, the implementation of bioenergy in several countries has resulted in different problems and production models that are strongly influenced by the local context and supporting policies. This is the case for ethanol production in Brazil and Thailand where technology developments and management practices evolved slowly in the former, to make it the largest sugarcane ethanol producer in the world, while they served as starting point for the latter, adapting them to local conditions. Strong and adequate policies were key factors for success in both cases. The use of jatropha as a feedstock for biodiesel production has failed in several projects, but it is shown that the production model (scale, land tenure, interfaces with the local community, etc.) can be adapted to local conditions to increase the chances of success.

An important by-product of sugarcane ethanol production is surplus electricity to be sold to the national grid or to large consumers directly. The cases of Brazil and Mauritius have shown that government support and wise policies make the difference in determining the role that this option plays in the national power generation matrix of each country; the potential is far from being reached in Brazil and is fully exploited in Mauritius.

The use of wastes and residues has an enormous potential for bioenergy generation, but has failed to become a significant source. The case studies show some of the reasons why and also point out that adaptive policies as well as the combination of different fuels in an integrated manner can help achieve success. While most people believe that agricultural residues can be freely collected and used, detailed studies in the USA have demonstrated that there are optimal recovery strategies that depend on the local conditions; these findings should be used more broadly in other countries in order to develop successful strategies for the use of agricultural residues. The case of scale of the processing plants and the existing logistics for transport can play a significant role in determining the best model for implementing the projects.

Last, but not least, the lessons that can be learned from these very different cases are that proper government policies are essential to increase the chances of success of bioenergy programs and projects, and the local conditions and context (technology level, driving forces, public support) should be carefully evaluated in the development of these policies. There is no single solution that fits all cases.

14.4 Recommendations

The multiple causes for success and failure in the deployment of bioenergy projects need to be evaluated and the data organized in a manner that can be used to guide selection of the most viable alternatives, and to help develop public policies that will support implementation of bioenergy programs. These data must be made widely available and disseminated in order to take advantage of the lessons learned.

It is important to identify issues that are strongly dependent on local conditions and treat them adequately. Land and water availability, agriculture technology levels, and needs for improvement in land tenure, infrastructure and energy systems at both regional- and country-scales are all crucial.

The impact of project scale on economics and social indicators need to be better understood and the tradeoffs optimized.

All alternative strategies to promote bioenergy should be identified and extensively evaluated to determine short, medium and long term effects. Direct subsidies, mandates, soft loans, R&D support, infrastructure building and capacity building are some of the alternatives that can have different impacts and effectiveness under different conditions.

Build policies that incorporate clear, consistent, and cohesive targets and standards for bioenergy production.

14.5 The Much Needed Science

After producing high yields of feedstocks, they must be processed efficiently. Most processing technologies for first generation (1G) biofuels are fully mature, but there is still room for improvement, especially in the energy balance.

The full use of feedstocks must be sought to make sure the primary energy content of the material is converted to useful products. Here second generation technologies can be a great help when integrated with the first generation plant.

Understanding the dynamics of land use change (LUC), both direct and indirect, is very important for the assessment of several key impacts on the biofuel sustainability. There is no consensus on the methodology to be used and there is a critical shortage of reliable, reasonably disaggregated data in time and space. Both of these difficulties must be overcome.

Impacts of agroforestry residues on the soil resources, pest populations and disease dynamics must be better understood.

Second generation biofuels are very important alternatives, but they need to reach economic viability to start to participate in the biofuels pool. Technologies need further improvements.

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chapter 15

Social Considerations

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Highlights

- There are clear synergies and trade-offs to be established between bioenergy production and socio-economic development at different geographical scales.
- Policy instruments have been put in place in several countries to effect these synergies, but they still need to be linked to wider objectives relating to food production, education and land use planning.
- The success of bioenergy production at all levels will require taking into account the requirements of the different stages of the feedstock production along with the benefits to be obtained at small scale or the community level.
- International programs need to adopt an integrated approach for the use of renewables in general, and of bioenergy, in particular.

Summary

This chapter reviews some of the key issues that relate to the social impacts of bioenergy supply chains at local, national and international levels, with a particular focus on food production and the implications for natural resources management. The review shows that data is available only for some topics and on some regions, and how, although some point to negative aspects in this relatively new sector, there also is positive data that demonstrates that bioenergy can contribute to social and economic improvements at local and national levels, given appropriate considerations and measures. The chapter introduces some of the main social issues discussed in the literature as well as providing background information on global policy framework. This is followed by a consideration of social benefits of bioenergy production, such as job creation, provision of training and skills development. Additional social and environmental impacts that result from the use of land, water and other natural resources for bioenergy production are then examined in relation to gender, food production, poverty reduction and land tenure. The final section discusses public perception of bioenergy production and the usefulness of public reporting of corporate sustainability.

15.1 Introduction

Bioenergy can make a valuable contribution to meeting energy security, economic and social development goals, as well as addressing climate change and other environmental issues (Morese 2012). Among these issues are environmental and social aspects, including the area of land required to produce biomass raw material and the impacts on local communities and the environment (Woods and Diaz-Chavez 2007). The social impacts of different bioenergy supply chains depend on scale, location, duration of crop production (e.g. annual, perennial crops), and on the form of bioenergy provision e.g. heat, electricity or mobility. It is probably for bioenergy where more tradeoffs and integrated systems with social issues can be perceived (Figure 15.1).

Although biofuel[1] production has grown in recent years, only a few countries dominate production worldwide (Ecofys 2012). Several efforts to guarantee sustainable production have been introduced, ranging from policy regulations to voluntary standards and international frameworks such as the Global Bioenergy Partnership (GBEP). However, there is still a lack of reliable data on socio-economic impacts of biomass production and conversion, and also on the use of biomass for bioproducts that takes environmental aspects into consideration (Global-Bio-Pact 2013).

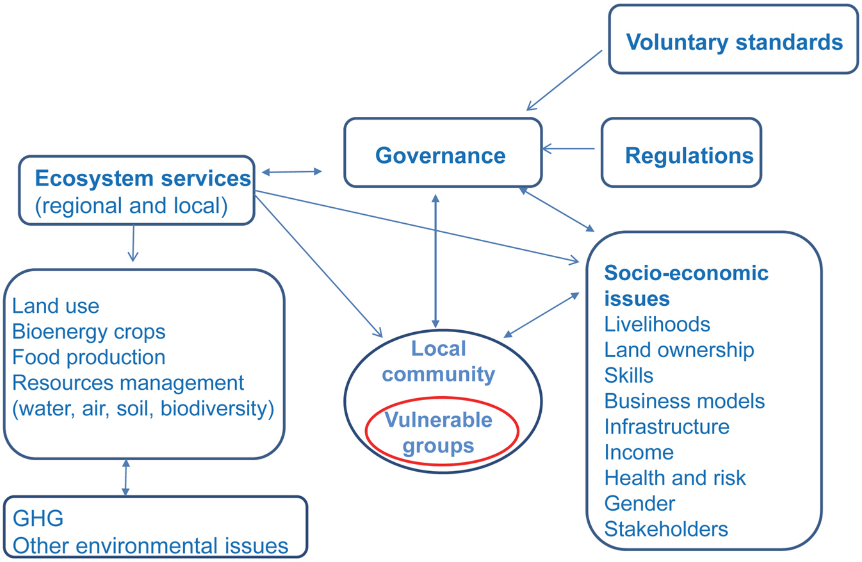

Figure 15.1. Tradeoffs and synergies of bioenergy and social issues.

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[1] Define 'biofuels' as bioenergy products destined for use in the transport sector, particularly as liquid fuels

Most of the social impacts that have been investigated are found in developing countries, where claims about improving local livelihoods and reduction of poverty have not always been substantiated. Across Africa, in particular, the main issues of concern include land tenure, impacts on water availability and quality, large-scale production (Cotula and Leonard 2010), and food security (FAO 2008; Diaz-Chavez et al. 2010). Nevertheless, opportunities exist for biofuel production to make an important contribution to improve local conditions, through employment creation, business models that generate value and provide new infrastructure for local communities (e.g. outgrower schemes, joint ventures) (Sagar and Kartha 2007; Vermeulen and Cotula 2010), voluntary contributions to social services and infrastructure through private investment. Brazil, for instance, provides a positive example, where large-scale production predominates, yet some 70,000 independent sugarcane growers, along with producers associations and agriculture cooperatives are involved in the production chain. Sugarcane production by independent suppliers accounts for about 40% of the total sugarcane national production. In the Centre South region in Brazil, over 85% of sugarcane growers farm on less than 50 hectares of land. The profile of the sugarcane suppliers can be found in Table 15.1.

The topic of societal perception of biofuels has, in turn, been reviewed in a number of projects e.g. BEST, Global-Bio-Pact, and also by some authors (e.g. Fallot et al. 2011; Michalopoulos et al. 2011). Research on Corporate Sustainability Reporting has also

Table 15.1. Profile of independent suppliers and rural partners, 2012-2013 harvest seasons, Center South region, Brazil.

Quantity of sugarcane produced	Number of sugarcane suppliers	Proportion of the total Number of suppliers	Average farm size (ha)	Overall production (thousand tons)	Proportion of total production
≤ 1,000 tons	8,297	42.8%	8	4,647	3.5%
1,001–6,000 tons	7,902	40.8%	46	25,451	19.3%
6,001–12,000 tons	1,580	8.2%	151	16,720	12.7%
12,001–25,000 tons	941	4.9%	308	20,255	15.4%
25,001–50,000 tons	394	2.0%	638	17,580	13.3%
50,001–100,000 tons	161	0.8%	1,236	13,902	10.5%
> 100,000 tons	105	0.5%	4,533	33,249	25.2%
Total	19,380	100.0%	97	131,808	100.0%

Source: ORPLANA 2014

examined the topic, and an increasing number of companies offer a review through the Global Reporting Initiative (GRI 2013). Still, much more reporting and reviewing is required for a better understanding of the societal impacts of bioenergy production, its social role and its impacts on communities.

The literature on bioenergy feedstocks production and their use has increased in the last few years. For instance, German et al. (2011) and Baka (2013) report on research conducted in Africa and Asia, whereas Solomon and Bailis (2014), Schaffer et al. (2011), and Borras et al. (2011) report on research in Latin America. Bailey et al. (2011) and Selfa (2010) - in turn, report on research in the US. Nevertheless, little is yet available in the way of hard data about aspects such as water use and air emissions. Soft data is still even more difficult to obtain due to its qualitative nature and lack of agreement on measurement, for instance, public values and perception about bioenergy production.

15.2 Review of Legal Frameworks and Social Considerations in Bioenergy Production around the World

Existing legal and regulatory frameworks for bioenergy production range from mandatory targets to more advanced frameworks which include sustainability criteria which are in place in five key world regions (the EU, North America, Latin America, Africa and Asia). Their objectives also vary greatly, from a focus on climate change concerns to energy security (reducing imports of fossil fuels) and local rural development. One such policy framework is the EU Renewable Energy Directive (2009/28/EC), which aims to increase the share of renewables to 20% by 2020. Uniquely amongst these regional policy frameworks, the Directive includes mandatory environmental sustainability criteria for liquid biofuels (i.e. on land use and GHG emission reduction), whilst social criteria, although not mandatory, requires reporting. Nevertheless, on June 13th 2014, the Energy Council of the EU agreed on the draft directive on indirect land-use change (iLUC) amending the fuel quality (98/70/EC) and renewable energy (2009/28/EC) directives. The agreement acknowledges and addresses the iLUC phenomenon and indicates mitigation of indirect land-use change emissions through a threshold of 7 % of the final consumption of energy in transport in 2020 for conventional biofuels to count towards the renewable energy directive target. At the same time it encourages the transition to advanced biofuels (EN 2014). This will still need to be approved by the EU Parliament at a later stage. It is important to note that this only applies to biofuels, as solid biomass does not have sustainability requirements at EU level.

In the USA, the Renewable Fuel Standard and the California Low Carbon Fuel Standard are the two main laws incentivizing blending of biofuels into the transportation fuel supply chain. Only those renewable fuels seeking to qualify for the mandate are regulated by the Renewable Fuel Standard 2 (RFS2 2013). The RFS sets minimum GHG thresholds for renewable fuels although the impacts on food prices remain controversial and contested (Baffes and Dennis, 2013; Kim and Dale, 2011; Oladosu et al. 2011). Nevertheless, the RFS does allow for EPA to adjust the mandate if there are effects on food prices (EISA 2007). Additionally, the USA has the Biomass Crop Assistance Program of the US Farm Bill that requires the participation of landowners and provides incentives for the establishment of new bioenergy feedstocks. The BCAP, which provides payments for the growing, harvest, and transportation and usage of non-food bioenergy crops, will receive $25M in funding for each fiscal year through 2018. The Program is also intended to assist with some of the feedstock supply challenges facing the cellulosic biofuels industry (FSA 2011).

The situation in Africa is very different as traditional fuelwood, along with other agricultural and forestry residues are the main bioenergy sources. Only a few African countries have consumption targets for liquid biofuels (Jumbe and Mkondiwa 2013) and current production and consumption are not yet significant. Several countries have been producing biofuels for energy security reasons (Deenanath et al. 2012), including South Africa, Malawi, Mauritius, Zimbabwe and Kenya (although the last two have stopped production). Mauritius, for instance, has well formulated and consistent government policies and incentives to stimulate production of both ethanol and power from sugarcane bagasse (Mapako et al. 2012). Although Watson and Diaz-Chavez (2011) reported on the potential for production and crops, large-scale production still remains at early stages (Ecofys 2012). Therefore, the main challenge for most African countries is to move away from traditional bioenergy towards modern bioenergy in order to contribute to sustainable development (IRENA 2011).

In Africa, regional strategies have been developed, such as the 2012 Regional Bioenergy Strategy, put forward by the Economic Community of West African States (ECOWAS) with the support of the GBEP. It seeks to enable investments that help address energy poverty without compromising food security and environment, through the creation of added value in employment, food and energy security (GBEP 2012). Another initiative is the Renewable Energy Strategy and Action Plan (RESAP) for the Southern Africa Development Community (SADC) finalized in 2012. The mid-term review of the SADC Renewable Energy Support Programs concluded that RESAP required improvement to make it implementable (Camco, 2012). At the continent level, the New Partnership For Africa's Development's (NEPAD) 'Strategy for Sustainable Bioenergy Development in Africa' is being developed within the NEPAD / Comprehensive Africa Agriculture Development Program (CAADP) / Program for Infrastructure Development in Africa (PIDA) frameworks and principles, for 'rural transformation'.

Local energy security impacts in some African countries, such as Tanzania, Kenya, Mozambique and Uganda, are likely to be strongly influenced by the recent discoveries of gas and oil reserves. Tanzania's Energy and Minerals minister captured the hopes placed in the new hydrocarbon discoveries thus: "*Tanzanians have been farming since independence, but remain poor. We want the gas economy to benefit all Tanzanians*"

(Reuters 2013). It remains to be seen what impacts will result from policies targeting the export of bioenergy, as the focus shifts to include these newly found options.

In Asia, the major bioenergy players are China, India, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam (IEA Bioenergy 2009; BP 2009). Most already have bioenergy policies, mandates and regulations in place. Their main focus is to reduce dependence on fossil fuels. Yet, the social and political character of bioenergy development remains unclear with key policies currently enacted in Asia primarily regulating social aspects of food security and land tenure (Bush, 2008). The Biofuels Act implemented by the Philippines Department of Labor and Employment is meant to secure some social guarantees, such as promoting livelihood opportunities, employment, and social security coverage for workers, at the same time as making recommendations for plans, policies and programs that will enhance the positive social impacts of the National Biofuels Programs (NBB) (FAO 2009). India's policy on biofuels (National Biofuels Policy 2008) foresees the implementation of a series of financial instruments that will enable farmers to access loans and economic incentives for the whole bioenergy supply chain (FAO, 2009).

In Latin America, the Economic Commission for Latin America and the Carribean (ECLAC) (Dufey and Stange 2011) reported on policies and regulations showing that while many countries do not have a dedicated bioenergy policy, several do have mandatory targets to reduce imports of fossil fuels and develop their agricultural sector. Several countries in this region already produce biofuels for national use as well as for export, including Brazil, Argentina, Guatemala, and Colombia. Brazil has, since 1975, enhanced the bioenergy sector by reducing foreign energy sources, but this strategy has tenuous links with its social policies. More recently, though, Brazil has improved on social issues related to bioenergy production, adapting labor legislation for the agricultural sector (Sallum 2007; Moraes and Pessini 2004; Moraes 2011b). In the state of São Paulo, employer associations and labor unions have been strong and highly active in negotiating wages for sugarcane workers (Moraes 2011a). Additionally, although the Brazilian labor legislation is rather rigid, it can still accommodate flexibility through the collective agreements on wages and working hours, as long as they do not violate the thresholds contained in the legislation (Consolidação das Leis do Trabalho – CLT) (Sallum 2007). A more intensive program was created in 2004 for small-scale agriculture for biodiesel production (the Social Fuel Seal), which was not as successful as anticipated, as it proved difficult to reconcile the provision of markets for small holder production and increase production of biodiesel to 15% from soybean (large-scale) and animal fats (FAO 2009).

On the topic of sustainability standards for bioenergy production, Dam et al. (2010), Diaz-Chavez (2011), Morese (2012), Dale et al. (2013) and Endres (2012), among others, have provided in-depth reviews of several voluntary standards and frameworks that include social criteria (see Chapter 19, this volume). It is worth noting that international Conventions, such as the International Labor Organization and the work carried out by different NGOs have played a role in taking account of social issues in the bioenergy sector.

15.3 Land, Water and Natural Resources

The multi-functionality of land use has increasingly been challenged by global environmental change (Winter and Lobley 2009). In particular, there is growing pressure on farmers and land managers to act as “carbon stewards” and adapt land management to minimize carbon losses, maximize carbon storage and provide substitutes for fossil fuels (Smith and Maltby 2003).

The bionergy sector integrates different environmental components, such as, for instance, land, water, forestry, soil and biodiversity that also impact on social aspects such as health and welfare. In particular, the literature debates issues around the role of the sector on feedstock depletion (particularly forestry), water depletion and pollution (Diaz-Chavez 2011). An alternative strategy put forward for better resource management is that of integrated land use, which aims to strike a balance between economic, social and environmental objectives (DeFries et al. 2004). Bioenergy systems also provide an example of integrated systems as they cover different aspects of linking environment, socio-economic and land use alternatives.

The Ecosystem Services approach has also emerged recently as an alternative for helping establish synergies between environmental and social issues. In their review, Rettenmaier et al. (2012) noted that this approach could help reduce the trade-offs between bioenergy production and ecosystem functions. In addition, the Global-Bio-Pact project (2013) has advanced a number of indicators to monitor the impacts of bioenergy production on ecosystem services (Diaz-Chavez et al. 2012). These included impacts on biodiversity and its use for local communities (e.g. fishing, hunting, collecting, other), water use (availability and quality) and other recreational uses of the landscape.

Bioenergy production may engender a number of effects on water resources, on demand and on quality, which all depend on where the bioenergy infrastructure is located and how it is managed, leading to either water quality deterioration or improvement, and they are observable also along the supply chain, from production to transformation (Clancy 2013; Diaz-Chavez 2011). The EU has examined the option of setting up mandatory criteria for monitoring the impacts of bioenergy production on water, air and soil, where changes in local management practices might be a more effective option given differences in local conditions for feedstock production (Ecofys 2013). Further, Clancy (2013) suggests that it is possible to grow biofuels crops without damaging associated ecosystem services if institutions support is in place to help to plan and monitor agricultural development (see Chapter 19, this volume). This shows that the critical challenge is the complexity of developing integrated land management frameworks that can reconcile food and bioenergy production with ecosystem service delivery.

15.4 Employment, Rural Opportunities and Livelihood Impacts

The literature on social issues in the bioenergy sector has produced estimates of job creation that vary according to region and other factors in the supply chain. IRENA (2011) estimated that in 2010 the world's gross employment in the biofuel sector was over 3.5 million in biofuel for transport and renewable energy for transport, with an estimated 1.5 million in first generation biofuels. Commercial 2nd generation plants in operation are not yet numerous except for the Beta Renewables Ltd plant in Crescentino, Italy (Novozymes 2013), therefore estimated jobs in the lignocellulosic fuels are still limited to few thousands (see BIOCORE 2013a). In turn, the Global Renewable Fuels Association (Urbanchuk 2012) estimated that global ethanol and biodiesel production supported nearly 1.4 million jobs in all sectors of the global economy in 2010, with 221,183 jobs estimated in the EU alone. The IRENA report (2011) noted that the majority of jobs (direct and indirect) in this supply chain are currently located in a few major economies i.e. China, Brazil, Germany, India and USA majority in rural areas for production of feedstock (Ecofys 2012).

Ecofys (2012) reported that in the USA half a million jobs were created (virtually doubling since 2008), whereas in 2010, Brazil employed around one million people in the biofuel sector (Azevedo 2010). Urbanchuk (2014) reported a total of 386,780 jobs in the ethanol industry in 2013 (86,503 direct jobs, 87,164 indirect jobs, and 213,113 induced jobs to satisfy direct and indirect needs). Together, these two countries produce 88% of the world's ethanol production (Azevedo 2010). In Europe, over 150,000 jobs are thought to have been created recently as a result of biofuel production (EurObservER 2011; Ecofys 2012).

The biogreen economy (biorefineries) also presents an opportunity for job creation and rural development in different parts of the supply chain beyond feedstock production, such as pressing, collecting, transporting and storing (BIOCORE 2013a; Diaz-Chavez 2013). The BIOCORE (2013a) project, for instance, reported that feedstock production for biorefineries may contribute to the creation of indirect jobs. In Europe, case studies have indicated the actual expected contribution of the sector in terms of employment. In the in Beauce region in France, one company expected to create around 115 jobs in its biorefinery plant, whereas estimates for a similar plant in Hungary ranged from 250 direct jobs (some highly-skilled), to up to 3,000 indirect jobs (e.g. farmers and suppliers). Also, the last few years have seen an increase in the manufacturing side (biochemical) in Europe, which is expected to continue to grow as a result of incentives for green technology, particularly in pharmaceuticals and chemicals (Diaz-Chavez 2013).

A number of studies in Brazil have demonstrated the positive socio-economic impacts of the sugarcane industry for biofuel production in the state of São Paulo. Chagas et al. (2011) analyzed the effects of the increased sugarcane production on municipal revenues. They showed that the value of agricultural production of sugarcane is greater per hectare than for most crops, thus accruing a greater value of agricultural income to the municipality in terms of tax income. Assato and Moraes (2011) also noted that jobs generated by the expansion of the sugarcane industry and related sectors have played a key role in reducing rural migration. Similarly, Satolo and Bacchi (2013) assessed the effects of the sugarcane sector expansion over municipal per capita GDP, noting that the GDP for one municipality and that of its satellite neighbors grew from 24% in 2000 to 55% in 2010.

Martinelli et al. (2011) have, in turn, compared the following development indices: the Human Development Index (HDI), São Paulo´s Social Responsibility Index (SRI), and the Rio de Janeiro Municipal Development Index. (MDI), in the municipalities predominantly based on cattle and mixed cattle against sugarcane, sugarcane with processing mills, or non-rural activities. The three indices for cattle municipalities were significantly lower than those for all the other categories compared to the municipalities with both sugarcane and processing mills, and higher than non-rural municipalities. Sugarcane's integration with processing activities has had a multiplier effect. Further, Hofmann (2006) analyzed the effects of the increased ethanol production and the poverty reduction in Brazil. A lack of food security in Brazil, as elsewhere, is strongly associated with poverty and so it is expected that, increased level of employment and income that follows the expansion of the sugarcane agribusiness will help combat food insecurity, whilst also compensating the negative effects of eventual food prices increases. Other authors have also noted the improvement on indicators, such as education, employment (quality and quantity), as well as wages in other producing states (Balsadi and Borin 2006; Moraes 2007; Oliveira 2009; Moraes 2011a; Moraes 2011b; Gerber Machado and Walter 2011; Neves and Castro 2013).

15.5 Skills and Training

The levels of job creation and job quality in the bioenergy production are likely to vary greatly, depending on whether they are needed in more intensive agricultural or forestry production or in the industrial and processing sectors, and in service delivery. These differences are also accentuated depending on location, with more intensification being observed in developing countries at the agricultural level, than at the industrial level in the more developed economies. Clear exceptions here are Brazil, as well as Argentina, that balance production with shipping requirements so as to spread along the value chain (Ecofys 2012).

Environmental legislation in Brazil that phases out the burning of sugarcane, has led to continuing mechanization of harvesting and loss of jobs. The private sector has provided training and qualifying programs for manual cutters through the *Renovacão* project. The project is a partnership between UNICA, the Federation of Rural Workers in São Paulo State (Feraesp), the Solidaridade Foundation and supply-chain companies: Syngenta, John Deere and Case IH, with support from the Inter-American Development Bank (IADB). The Project provides specialized training for approximately 3,000 workers per year in six of the major sugarcane producing areas in São Paulo (Sugarcaneorg 2014).

In developing countries where bioenergy represents an important resource, specific training needs have yet to be fully addressed. The importance given by stakeholders to training and skills development is lost to the processing stages, as producers place greater importance on maximizing productivity. On an average Indonesian oil palm plantation, only about 3% of the workers are classified as skilled, the remainder 97% is unskilled (FAO, unpublished). If bioenergy is to be made sustainable, it is fundamental that good practices and training are adopted throughout the chain, from the feedstock production upwards.

On the issue of skilling the workforce in bioenergy production, FAO has, through its BEFSCI project, compiled a set of environmental practices that producers should adopt to minimize their negative environmental impacts, whilst also increasing the potential of such practices for climate change (FAO 2012a). These practices can help improve the efficiency and sustainability in the use of land, water and agricultural inputs, thus reducing the potential competition with food production. FAO stresses the importance of training provision at all levels of the supply chain which incorporates an integrated approach to sustainable bioenergy. Furthermore, the GBEP's set of 24 sustainability indicators for bioenergy has an indicator (number 12 under the social pillar) that relates to the creation of skilled/unskilled jobs in the bioenergy sector (FAO 2011).

Recently, the BIOCORE EU FP7 funded project, canvassed the views of stakeholders in the EU and India to assess skills and capacity in the green economy sector, particularly with reference to biorefineries. The exercise showed that stakeholders disagree on the topic. While some considered that the requisite skills are already in place for feedstock production, others noted the discrepancies that exist in the industrial sector as a result of the importance of the chemistry and oil sectors. One prevalent view is a need for further development in skills for jobs in the biorefinery (BIOCORE 2013).

15.6 Poverty, Health and Food Production

These topics have been looked at under the context of rural development and access to energy. They have been researched in Africa, Asia and Latin America. Africa has the world's highest incidence of rural poverty, with over 80% of the rural population living under $2 per day (IFAD 2011), and bioenergy production has been held out as one way to help reduce it. A study on Mozambique (Arndt et al. 2011) indicates the role of poverty reduction in the African context is strongly influenced by production technologies and associated institutional arrangements. 'Outgrower' models of bioenergy production were found to be more pro-poor in that they provided more jobs to unskilled labor, compared to large-scale, centralized approaches. Raising agricultural productivity and human capacity among the poor and vulnerable are seen as vital for facilitating the poverty reduction role of bioenergy production.

The role of energy on poverty reduction especially at local level has also been considered by different authors and initiatives (UNDP 2004; Clancy 2013; RSB 2010; Diaz-Chavez 2010). Although not considered explicitly under the Millennium Development Goals (MDG), the United Nations recognizes that access to energy affects aspects of sustainability from developing agriculture to health care and education (UNDP 2004). The proposed Sustainable Development Goals to follow after 2015 when the MDGs program is finalized have not yet been decided. Nevertheless, it is crucial to explicitly include energy services. This has been the focus of the initiative “Sustainable Energy for All” (SEFA) launched by the UN which has outlined three overarching aims as follows: universal access to modern energy, double the share of renewable energy in the global energy mix, and double the rate of improvement of energy efficiency by 2030. SEFA recommended improving data and definitions for bio-energy and sustainability over the next five years (SEFA 2013).

According to Conway (2012), around three billion people in the world rely on solid fuels for cooking, whose consumption produces a number of very negative health impacts. Burning them inside households causes respiratory illnesses and nearly 1.6 million deaths per year, mainly women and children (WHO 2006). Therefore the improvement and dissemination of improved cooking stoves continues to be one of the main global objectives in terms of health and solid biomass use. The Global Alliance for Clean Cookstoves aims to foster the adoption of clean cookstoves and fuels in 100 million households by 2020 (GACC 2013). Other initiatives in Mozambique such as the Cleanstar Ethanol Cookstove program and the Cooking Fuel Project aim to facilitate a transition away from inefficient conventional biomass stoves by disseminating up to 30,000 clean burning and highly efficient cooking stoves to households in and across its peri-urban areas (UNFCCC 2013).

The debates around the food/and fuel problem and how to address this key issue continue to rage (Diaz-Chavez 2010; Fischer et al. 2009). Bioenergy production raises both positive and negative issues in each of the four dimensions of food security: availability, access, stability and utilization (CWFS 2013). Avoiding the use of food crops or the careful integration of bioenergy production on land suitable for growing food have been advocated as important ways of addressing the food versus fuel debate. Lynd and Woods (2011), for instance, have argued that the production of bioenergy from non-food crops on under-used and marginal land can have numerous positive impacts, particularly through the introduction of technologies useful for food production, local job creation, enhanced energy self-sufficiency, improved food security and economic status that reduces conflict. It has also been suggested that proposed bioenergy projects in Africa must provide concrete improvements to local food security (Lynd and Woods 2011).

The GBEP also recognizes that there is a complex, multi-faceted relationship between bioenergy and food security.

Investing in and improving agricultural systems and, particularly, in infrastructure, could lead to increased production of food fodder and fiber. It would also help reduce waste whilst making more efficient use of residues as feedstock for bioenergy production. In combination, these measures would contribute to improved household welfare and, ultimately, rural development (FAO 2011). A case in point is that of the Bioenergy and Food Security (BEFS) projects, which FAO has implemented and which demonstrate that biofuel production from cassava in Tanzania can have positive impacts on household food security (FAO 2010).

Other issues to consider are nutrition and health improvement through agriculture. There is a need to target women of childbearing age and children during the first 1000 days of life. As Martorell et al. (2010) and Hoddinott et al. (2008) showed, improved nutrition during the first 2-3 years had long-term positive effects on education and also working capacity. Improving the nutrition of women of reproductive age and infants during the first 1000 days of life is key for overall improved health. Importantly too, indigenous foods can enhance food and nutrition security. Wild foods are important sources of nutrition in periods of food and income shortages (Kengni et al. 2004). Indigenous crops are easy to grow, have medicinal properties and are well adapted to local climate (Anwar et al. 2007; Fahey, 2005). Intercropping with bioenergy crops has been suggested as a way by which agriculture may help improve local conditions.

15.7 Land Rights, Gender and Vulnerable Groups

In developing countries, land rights are linked to livelihoods and development. Land rights refer not just to ownership but also to access to, use of, possession and occupation of land, and security of use and tenure. Dispossession of land, limits on access to land and lack of formal, documented rights to land threatens the livelihoods of farmers, peasants and fisherfolk. Many authors (Sjaastad and Bromley 1997; Adams et al. 1999) agree that a lack of secure land rights impinge on development efforts. Changes in land use and land ownership have not always been accompanied by appropriate reforms in policies (Kagwanja 2006). This has been identified as one of the main social problems, particularly in South Africa related to biofuel production (Schoneveld 2010). Yet, a review by Hamelinck (2013) of the Land Matrix database (2013) concluded that only 0.5% of total 38.3 Mha land deals worldwide are related to biofuels production (Table 15.2).

Few developing countries address issues related to land tenure disputes in their policy framework. Brazilian Law No. 11.952, 2009, for instance, grants tenure rights to individuals occupying land in the Amazon states and restricts the occupation of public land to Brazilian citizens engaged in agricultural operations who are not owners of another rural estate in the country and who effectively possessed the area prior to 1st December 2004 (FAO 2009). But this law explicitly excludes lands that have been traditionally occupied by indigenous peoples or that are found within nature reserves. India, through its National Biofuels Policy Act requires that consultations

Table 15.2. Analysis of land deals from the ILC Land Matrix (Mha) (Hamelinck 2013).

Assessed 25.8 Mha out of 38.3 Mha	**For biofuels**		**Not for biofuels**	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Confirmed 9.0 Mha	0.53	4.9	4.1	8.5
Land grab	0	1.3	1.8	3.1
Strong concerns	0	0.16	0.22	0.38
Generic concerns	0.07	0.89	0.59	1.4
Small concerns	0	0.77	0.31	1.1
No concerns	0.45	1.8	1.1	2.5

No deals were found in 16.8 Mha

The minimum area allocated to biofuels is based on those crops that are being uniquely developed for biofuels (jatropha and a few others). The maximum area allocated to biofuels is the area for all switch crops (for both food and fuel production)

Strong concerns: land deal was not carried out correctly/local context gives rise to extreme caution

Generic concerns: Concerns related to similar activities in region, not specific to the site/ Concerns related to the holding company, not specific to the site

Small concerns: Concerns roughly less than 1% of the total acreage

be undertaken with local communities (through Gram Panchayats/Gram Sabhas which are local self-governments at the village or small town level in India) when new bioenergy plantations are planned.

FAO (2012b) produced voluntary guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the context of the National Food Security program. Some countries adopted the global guidelines on tenure of land, forests, and fisheries to safeguard the rights of their people. The guidelines address:

- Recognition and protection of legitimate tenure rights, even under informal systems
- Best practices for registration and transfer of tenure rights
- Making sure that tenure administrative systems are accessible and affordable
- Managing expropriations and restitution of land to people who were forcibly evicted in the past
- Rights of indigenous communities
- Ensuring that investment in agricultural lands occurs responsibly and transparently
- Mechanisms for resolving disputes over tenure rights
- Dealing with the expansion of cities into rural areas

Other measures to help address land rights problems, including accessible local land rights registration processes, have been advanced by various authors (Benjaminsen et al. 2009; Toulmin 2009; Kagwanja 2006). Supporting local institutions that undertake forms of land registration has shown to be effective in many places (Tousling 2009), and collective action represents one way for local communities to create and control their land rights (Meinzen-Dick et al. 2002; Meinzen-Dick and Pradhan 2002; Mwangi 2006; McAuslan 2006). For example, collective registration of community lands can be a powerful tool for protecting local land rights vis-à-vis incoming investors (Cotula et al. 2009). Voluntary guidelines (VGs) for the responsible governance of land tenure (Seufert 2013) help formalize customary tenure rights by strengthening women's land and resource rights and the tenure rights of indigenous people.

A common issue about indigenous tenure is that land rights insecurity leads to suboptimal investment incentives (Sjaastad and Bromley 1997), particularly where land rights are complex (Goldstein and Udry 2008; Sjaastad and Cousins 2009), so educating communities, and particularly women about their own land rights, is crucial. This is because of the significant role women play in agriculture (Migot-Adholla et al. 1991), and because land rights existing in various forms in developing countries have consistently discriminated against women (Carpano 2011; Gomez and Tran 2012; Whitehead and Tsikata 2003).

The Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN), under the project "Women Accessing Re-Aligned Markets" (WARM) in Malawi and Mozambique has used the "Theatre for Policy Advocacy" (TPA) as an education tool. This participatory theatre encourages improvisation and allows for community participation. It was used to achieve the overall project goal of strengthening the capacity of women farmers to influence agriculture policy development issues. In Mozambique, one critical issue raised by women farmers during these dialogues was the challenge of "*direito de uso e aproveitamento da terra"* (DUAT), where the state granted land rights. This is a very effective tool for highlighting land right issues and getting communities to share possible solutions with policy makers (FANRPAN 2012).

Scoones et al. (2013) propose that a new phase of land grab research is needed where new concepts, methods and criteria are incorporated to implement better "systems for sampling, recording and updating information" (page 481).

15.8 Societal Perception, Corporate Sustainability Reporting and Monitoring

Over the last decade, as climate change started to be systematically tackled in international negotiations and national policies, bioenergy became part of the mitigation options being considered for the energy and transport sectors. Although the media has focused on food insecurity, land grabbing and deforestation as trade-offs of Bioenergy production (Delshad et al. 2010), general public knowledge on bioenergy is still quite limited (Fallot et al. 2011), even in major producing countries, such as Brazil (Gerber Machado et al. 2011b) or Indonesia (Wright 2011) although more literature exists. In this context, NGOs and the media have played an important role, both in informing the public (if only partially) and in framing the debate, although several misconceptions have emerged (e.g. fuel quality issues at the combustion stage, in Germany and Costa Rica); whilst other opportunities have been detected e.g. poverty alleviation in Tanzania and Mali, agro-industrial innovation in Argentina.

Corporate Sustainability Reporting (CSR) has helped improve the image of the sector and promoted sustainable production. Since 2005, the Brazilian sugarcane sector has increased its efforts towards CSR. With an interest in exports, greater public scrutiny and encouraged by the agreement on sugar quotas against the EU, which was arbitrated by WTO, the sugarcane producers association UNICA (the Brazilian Sugarcane Industry Association), agreed to the application of EU-RED derived sustainability indicators for sugarcane ethanol destined to EU markets. Sugarcane mills faced with public pressure, regulations and certification schemes, have thus started to step up or introduce CSR and/or adopted the voluntary certification scheme ‘Better Sugarcane Initiative’ (Bonsucro), which is a multistakeholder initiative (MSI).

Originally the focus on the sugarcane sector was on social factors, as one mill representative stated: “*We conducted a survey with 50 journalists on the most critical sustainability issues in the sector and there was almost no concern for environmental impacts. Social issues, especially labor rights, were their main concern…”* (Olényi 2014).

To improve the sector’s image and alleviate political pressure, improvements and communication became crucial. Later, demands from the EU and USA for alternative energy options put environmental concerns higher on the agenda. Mill owners support the sustainability concept and reporting, claiming it had a strong impact on their business, providing vision and a benchmark. They aim to engage the whole chain and be transparent with regular reporting on improvements (Olényi 2014).

Research into the real benefits of the CSR and MSI initiatives on this sector will still need to be conducted considering international guidelines such as the Global Reporting Initiative. Moreover, it is essential to develop monitoring and evaluation systems that permit an accurate and fair assessment of the performance of different initiatives and their impact on social conditions as well as the impact of standards and regulation, which also guide effective measurement and reporting.

15.9 Conclusions and Recommendations

This chapter presented an overview of the state of social aspects of bioenergy production in relation to a number of topics. This review is not exhaustive but demonstrates the synergies and trade-offs that bioenergy production presents for socio-economic development at different geographical scales. Nevertheless, the data for assessing social aspects is still limited. Although literature has increased, this limitation is either because the focus of the discussion has been centered on some regions, such as Sub-Saharan Africa and Brazil or because the access and development of data is constrained by, for instance, economic factors. This data will also need to be extended to agroforestry and forestry social implications. Chapter 19 in this volume also includes a discussion on the need for data.

Policy instruments specific to biofuels have been put in place in several countries, but they still need to be linked to wider country-level objectives on food production, education and land use planning. This is the case of Brazil and the land use planning for bioenergy crops. The success of bioenergy production at all levels will still need to take account of the different production scales of the feedstocks and the benefits at small scale, or community level. Furthermore, an integrated approach (considering all pillars of sustainability) for the deployment of renewables in general and bioenergy in particular, will need to be integrated in future national and international efforts, such as the Sustainable Energy for All and the Global Bioenergy Partnership frameworks, amongst other initiatives.

Finally, it is essential to develop monitoring and evaluation systems, or use existing ones, to evaluate the progress towards sustainability on social and environmental issues. The collection of data should be carried out according to carefully selected indicators, which are used to measure the evolution of different aspects of environmental or socio-economic contexts. This will entail a larger effort that needs to involve producers, local governments and international organizations.

15.10 The Much Needed Science

Socio-economic data for assessing the social dimension in the bioenergy context is still limited. This limitation is either because discussion has centered on some regions, such as Sub-Saharan Africa and Brazil, or because access and production of data is constrained by, for instance, economic factors. Also, data collection needs to be extended to cover the social implications of bioenergy production through agroforestry and forestry, and adequate measuring tools for such social (soft) data need to be agreed upon.

It is essential to develop monitoring and evaluation systems, or use existing ones, to evaluate the progress towards sustainability on social and environmental issues. The collection of data should be carried out according to carefully selected indicators, which are used to measure the evolution of different aspects of environmental or socio-economic contexts. This will entail a larger effort that needs to involve producers, local governments and international organizations.

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chapter 16

Biofuel Impacts on Biodiversity and Ecosystem Services

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Highlights

- Biodiversity resources are unevenly distributed across the globe. As a consequence of the asymmetrical geographic distribution of species, any consideration of the impacts of biofuels on biodiversity is likely to be biome, site and context specific. Land transformation is the most serious threat to biodiversity, and the rapid expansion of biofuels crops, most especially sugarcane and palm oil in the tropics, is currently the most serious of these concerns. Thus effects of biofuel feedstock production on biodiversity and ecosystem services are context specific, and location-specific management of biofuel feedstock production systems should be implemented to maintain biodiversity and ecosystem services.
- Few positive influences on biodiversity and ecosystem services result from biofuels development. Such positive outcomes are of limited spatial and taxonomic scale. Biofuels-mediated improvements can occur when already degraded lands are rehabilitated with non-native feedstocks, but such changes in habitat structure and ecosystem function support few and mostly common species of native flora and fauna. Even the limited evidence of perennial grass crops favoring certain bird species indicates the requirement of special management regimes.
- Trade-offs between biofuels and environmental resources are inevitable. The mitigation of climate change via reducing GHG emissions through a transition to low carbon energy systems such as selected biofuels offers a logical trade-off, as long as the design of expanded biofuel production avoids areas of special biodiversity concerns or embeds new production areas within a sustainable matrix of natural and transformed ecosystems.
- Available land resources exceed the projected needs for biodiversity conservation in terms of both the Convention on Biological Diversity target of Protected Area system expansion to 17% of the global terrestrial area and biofuels expansion to several fold current production levels.
- Sustainable biofuels and biodiversity management requires cross-sectoral integrated planning and regular monitoring of selected, cost effective and policy relevant indicators. Cost effective, landscape-level biodiversity indicators are in development but await application over most of the developing world.

Summary

As with all land transformation activities, effects on biodiversity and ecosystem services of producing feedstocks for biofuel are highly variable and context specific. Advances toward more sustainable biofuel production benefit from a system's perspective, recognizing spatial heterogeneity and scale, landscape-design principles, and addressing the influences of context, such as the particular products and their distribution, policy background, stakeholder values, location, temporal influences, and baseline conditions. Deploying biofuels in a manner to reduce effects on biodiversity and associated ecosystem services can only be done with planning, monitoring, and appropriate governance. The effects of biofuels can be avoided or reduced by conservation of priority biodiversity areas, recognizing the context specific effects of biofuels, and adopting location-specific management of production systems. Developing those management strategies takes time and effort.

16.1 Introduction

Biofuels can provide answers to current global energy and economic crises - both as a sustainable energy source and through promoting economic development, especially in rural areas of developing countries. Dependence on non-renewable fossil fuels as well as environmental concerns related to air pollution and greenhouse gas effects contributing to global warming and climate change have stimulated interests of policy makers and industry to promote bioenergy as part of energy security and climate change mitigation strategies. However, expansion of the feedstock production for biofuels has been controversial due to potential adverse side effects on natural ecosystems and the services they provide (Gasparatos et al. 2011). Ecosystem services are the benefits that humans derive from ecosystems (Mace et al. 2012) and offer a useful way to assess effects associated with biodiversity and energy use and its implications (see Highlights). There is lack of agreement on the degree to which biofuels both provide positive ecosystem services (e.g., fuel, climate regulation) and compromise other ecosystem services (e.g., biodiversity, food) (e.g., SCOPE 2009; Fischer et al. 2009).

Enhancing ecosystem services via biofuels can be achieved by location-specific design of bioenergy systems. If not well planned, the establishment of biofuel crops may result in environmental impacts (e.g., alterations in habitat or biodiversity quality, changes in soil and air quality, changes in water quality and quantity, productivity changes, and local introduction or elimination of species (McBride et al. 2011) as well as changes in social and economic interactions and outcomes (Koh and Ghazoul 2008; Wilcove and Koh 2010; Dale et al. 2013b). Such effects should be evaluated by scientists and policy makers in order to increase positive outcomes and reduce negative impacts of biofuel production. When produced in a sustainable and equitable manner, biofuels can increase energy self-sufficiency and support rural development as well as reduce deforestation (Amigun et al. 2011) and greenhouse gas (GHG) emissions compared to fossil fuels (Muok et al. 2010). The challenge is to identify appropriate management practices and incentives. In addition, environmental monitoring programs should be established across fuel sheds in order to understand environmental effects of biofuel operations and to guide adaptive management.

There are four means by which terrestrial feedstock production can be increased: expansion of land area used to grow biomass, increases in crop yields, use of wastes and residues as feedstocks, and increases in system efficiency. This chapter deals largely with the effects of expansion of the land area planted to biofuel feedstocks, which has the largest impact on biodiversity. The chapter also focuses on proactive solutions that avoid or reduce impacts and enhance benefits. It does not consider feedstock production in aquatic systems (e.g., algal based biofuels) or feedstock and fuel transport, fuel production and end use of the fuel.

16.2 Key Findings

SCOPE's first Rapid Assessment on Biofuels and the Environment (SCOPE 2009) concluded that "environmental consequences of biofuels depend on what crop materials are used, where and how these feedstocks are grown, how the biofuel is produced and used, and how much is produced and used. Effects on the environment are both positive and negative" (Howarth et al. 2009). This 2014 SCOPE assessment concurs with that general statement and offers options whereby the negative effects of biofuel production on biodiversity and ecosystem services can be avoided or reduced and positive effects enhanced by attention to three guiding principles:

- Identification and conservation of priority biodiversity areas are paramount;
- Effects of biofuel feedstock production on biodiversity and ecosystem services are context specific; and,
- Location-specific management of biofuel feedstock production systems should be implemented to maintain biodiversity and ecosystem services.

This chapter considers these guiding principles independently even though they are clearly related (e.g., conservation areas must be established within particular contexts, and both conservation areas and their adjacent lands should be managed appropriately).

16.2.1 Identification and Conservation of Priority Biodiversity Areas are Paramount

Biodiversity is the basis for ecosystem services and the foundation for sustainable development. It plays fundamental roles in maintaining and enhancing the wellbeing of the world's 7 billion people, rich and poor, rural and urban (UNEP 2009). Expansion of any human activities is the most serious threat to biodiversity, and the rapid expansion of biofuel crops raises a serious concern but also can address some problems. The maps in Figure 16.1 depict areas on the Earth of greatest biodiversity concern and where biofuel feedstocks are likely to overlap them.

Preserving biodiversity hotspots is of paramount importance. Conservation is particularly important in the moist tropics, for loss of primary tropical forests is the greatest threat to biodiversity (Gibson et al. 2011). The global network of nearly 133,000 protected areas covers 25.8 million km^2, approximately 12% of the terrestrial surface (Butchart et al. 2010), an order of magnitude larger than the area currently occupied by biofuel crops. Even so, the network of protected areas does not adequately represent biodiversity, areas of cultural importance, or all ecosystems of value. Maintaining the existing protected areas and establishing new ones require systematic and science-based conservation planning (Margules and Pressey 2000) and effective management and governance (Sodhi et al. 2013) to ensure sustainable and persistent matrices of biodiversity corridors and ecosystem service linkages.

16.2.1.1 Effects of Feedstock Production on Biodiversity and Ecosystem Services are Context Specific

The effects of feedstock production on biodiversity are specific to the biome, site conditions and characteristics of the production system. Context considerations include the particular fuel production and distribution system, policies, stakeholders and their values, and baseline soil, water, air, biodiversity and ecosystem conditions (Efroymson et al. 2013). For example, changes in greenhouse gas emissions relate to feedstock type and soil conditions as well as prior and current management practices (e.g., Castanheira and Freire 2013).

There are contexts in which well-designed deployment of biofuels enhances biodiversity and ecosystem services and other systems where biofuels reduce biodiversity and the benefits of ecosystem services. For example, biofuel-mediated improvements occur where degraded lands are rehabilitated with native or non-invasive, non-native feedstocks, and detriments occur where areas of high diversity value are converted to monocultures of a feedstock that eliminates native species or critical habitats. The challenge is to figure out how to deploy biofuels in a way that maintains or enhances biodiversity and ecosystem services. Effective deployment is facilitated by governance systems that support conservation of resources, protection of rare species, and enhancement of ecosystem services.

Environmental effects of biofuels should be considered in relation to energy and land-use practices that occur in the absence of their use. The displacement of fossil fuel use can reduce soil subsidence (Morton et al. 2006) and land-use changes associated with exploration and extraction of fossil fuels (Finer and Orta-Martinez 2010) that impact biodiversity. Furthermore, risk of environmental catastrophes that affect biodiversity is much less for biofuels than for fossil fuels, which involve exploration and extraction in relatively untouched environments such as deep seas and arctic regions (Chilingar and Endres 2005; Parish et al. 2013; Butt et al. 2013).

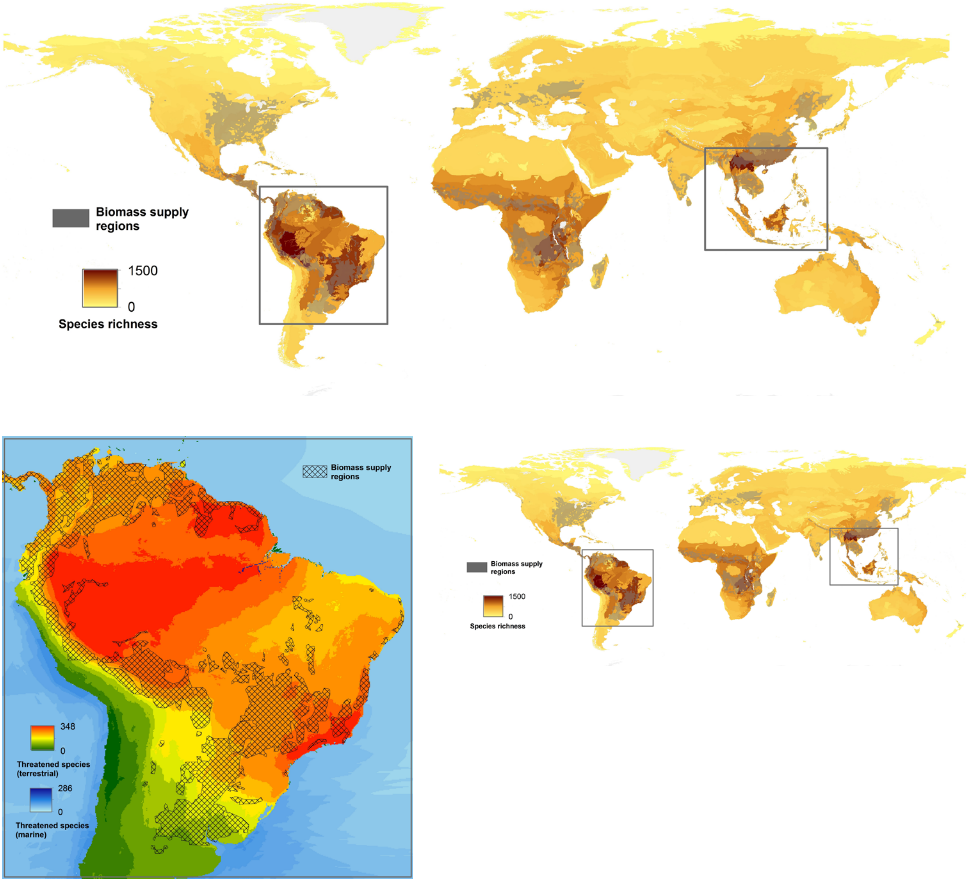

Figure 16.1. Terrestrial species distribution (number of species per ecoregion) compared with distribution of projected biofuel feedstock production areas circa 2030 (from Dale et al. in review). (a) Global area projected for near-term use of biomass resource areas for energy production compared to richness of terrestrial mammals, reptiles, amphibians, marine mammals and birds. Biofuels generated from the land areas shown offer the opportunity to replace 50% of the estimated worldwide demand for liquid transportation fuel by 2030. The species richness data was created by Butt et al. (2013) from the number of different species present in each ecoregion from the World Wildlife Fund's (WWF's) Wildfinder Database (http://worldwildlife.org/pages/wildfinder), WWF Terrestrial Ecoregions of the World (TEOW) polygons, and the 2012 IUCN Red List of Threatened Species datasets (http://www.iucnredlist.org/). The background map depicts point estimate counts of threatened species ranges at the center of each 0.1° grid cell. Details are shown for potential biomass production areas across a portion of (b) South America and (c) Southeast Asia where many threatened terrestrial and marine species may be affected. These same areas might see improvements in biodiversity conditions given proper resource management for sustainable biofuels production.

16.2.1.2 Location-Specific Management of Feedstock Production Systems should be Implemented to Maintain Biodiversity and Ecosystem Services

While the biofuel industry can build on established good practices in forestry, agriculture, transport logistics, and refinery establishment and operation, some aspects of feedstock production and acquisition are unique. For example, collection of agriculture and forest residues as feedstock requires attention to other ecosystem services. Well-managed feedstock production systems should include environmentally sensitive, science-based planning for resource use such as integrated land management, buffers, intercropping, and appropriate application of fertilizers, herbicides and pesticides. Tradeoffs between environmental resources and energy production and use are inevitable and should be considered in developing management plans. For example, a monoculture can sequester carbon and increase biofuel production but might reduce or eliminate indigenous diversity if the feedstock species becomes invasive. Effects of increased energy crop cultivation on biodiversity depend on landscape structure, and impacts can often be tolerated if a minimum level of crop-type heterogeneity is retained (Engel et al. 2012). Adoption of more sustainable agricultural practices entails defining goals for sustainability within the particular context, developing easily measured indicators of sustainability and monitoring them over time, moving toward integrated agricultural systems, and offering incentives or imposing regulations to affect the behavior of land owners (Dale et al. 2013a; Verdade et al. 2014b; see also Chapter 13, this volume).

16.2.2 Biofuel Feedstock Production Interactions with Biodiversity

The choice of feedstock and its location and management is the first step in the biofuel supply system and has great implications for environmental effects. The use of crop, forest and urban wastes does not require any new land area. Residue removal can be done so as to reduce environmental impacts (e.g., Muth et al. 2012), and it supports the benefits of using biofuels to displace fossil fuels.

16.2.2.1 Impacts of Land-Use Change and Production Intensification

The expansion of feedstock production has been based on land-use change (LUC) or management intensification. These changes can occur in relatively undisturbed ecosystems (Fitzherbert et al. 2008), crop or managed forest lands (Scharlemann and Laurance 2008), or degraded lands (Plieninger and Gaertner 2011). Direct loss of biodiversity occurs if there is a concurrent loss of wildlife habitat. Where feedstocks for biofuels are planted in pristine landscapes, biodiversity losses exceed positive impacts of biofuels production on biodiversity. However, benefits to biodiversity can occur where feedstocks are planted on degraded land (see Table 16.1 and Harrison and Berenbaum 2013; Leal et al. 2013; Phalan et al. 2013).

Effects of land changes due to biofuels should be considered in light of the particular context (Principle 2). For example, biofuel-driven expansion of corn planting in the US results in lower landscape diversity, thereby decreasing biocontrol services by reducing the supply of natural enemies to nearby fields (Landis et al. 2008). But those land changes should be interpreted in the context of trends of reduction in farmland area since the 1970s (USDA 2009) - largely due to urbanization, which had a stronger impact on biodiversity than recent land and crop changes due to biofuels. Examples of the effects of biofuel feedstock crops on biodiversity with their relative guiding principle are presented in Table 16. 1 and discussed below. Greater feedstock productivity per area is achieved by intensification of agricultural or forestry practices by second cropping, increased planting density, fertilizer use, or irrigation (Fernando et al. 2010; Prins et al. 2011). It is important to mention in this context that some areas in the world (arid and semi-arid lands) are bound to face water shortage with the expansion of irrigation for food production and bioenergy crops as well. As with any system, misuse or overuse of chemicals can result in contamination of the biota and the physical environment (e.g., Meche et al. 2009; Schiesari and Grillitsch 2011). On the other hand, some perennial crops being used for biofuels feedstocks require less chemical application and enhance soil and water conditions as compared to prior agricultural use (Sarkar et al. 2011).

In some circumstances, particular biofuel crops have a positive impact on biodiversity in relation to prior agricultural land uses (Milder et al. 2008; Parish et al. 2012). For example, perennial grasses used for biomass production can enhance avian species richness and abundance relative to avian diversity of corn fields in the US (Fletcher et al. 2011; Robertson et al. 2012, 2013). The benefits of perennial crops on biodiversity are enhanced when specific management practices are adopted such as avoiding harvest during nesting periods and promoting stream-side buffers (Principle 3) (McLaughlin and Walsh 1998; Tolbert and Wright 1998; Tolbert 1998). Natural biocontrol is higher in perennial grasslands than in annual croplands, increases with the amount of perennial grassland in the surrounding landscape, and is negatively related to insecticide use across the Midwestern United States (Meehan et al. 2012). Hence strategically positioned, perennial bioenergy crops could reduce insect damage and insecticide use on adjacent crops (Meehan et al. 2012).

Effects on biodiversity of the use of forest residues for bioenergy depend on forest harvest operations (Principle 3). Woody residue feedstocks are typically tops of trees that have no other commercial value. It is advisable to avoid coarse woody debris (CWD) (snags and downed logs), which provide sites for breeding, foraging and basking for a variety of organisms (more details in Chapter 13, this volume). Best Management Practices (BMPs) have been developed for woody bioenergy feedstocks in order to protect wildlife (Rupp et al. 2012). These practices suggest maintaining a diversity of age classes and stream-side buffers as well as harvesting at times that avoid nesting.

Table 16.1. Example effects of biofuel feedstock crops on biodiversity with the guiding principle involved in each example. The three guiding principles are (1) Conservation of priority biodiversity areas, (2) Context specificity of effects of feedstocks on biodiversity and ecosystem services, and (3) Need for location-specific management to maintain biodiversity and ecosystem services.

Region	Biofuel feedstock as landscape matrix	Taxonomic group	Process	Principle(s) involved	Ref.
Brazil	Sugarcane	Rodents	Increased abundance in relation to native vegetation	3	Gheler-Costa et al. (2012)
			Decrease of mesopredators and rodents following suspension of pre-harvest fire	3	
		Rodents	Spread of emergent infectious diseases (e.g., Hantavirus and Leptospirosis)	2,3	Verdade et al. (2012, Labruna (2012), Patz et al. (2008)
		Wild canids and felids	Increased abundance in relation to exotic pastures	1,2,3	Dotta and Verdade (2007, 2009)
		Passerine birds	Decreased diversity in relation to degraded exotic pastures	1,2,3	Penteado (2006)
		Birds	Decreased diversity in relation to secondary Atlantic forest	1,2	
	Eucalyptus	Birds	Decreased diversity in relation to secondary Atlantic forest	1,2,3	Millan et al. (2015), Penteado (2006)
		Marsupials	Increase in bird α-diversity in some plantations	2	Prevedello and Vieira (2011)
			Affected dispersion		
USA	Annual crops (i.e., maize and soybean)	Insects (agricultural enemies of food crops)	Decreased abundance in relation to perennial grasslands	1,2	Werling et al. (2011)

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Region	Biofuel feedstock as landscape matrix	Taxonomic group	Process	Principle(s) involved	Ref.
USA	Annual crops (i.e., maize and soybean)	Grassland birds	Decreased habitat availability in relation to perennial grasslands	1,2	Fletcher et al. 2011, Meehan et al. (2010), Robertson et al. (2010, 2012)
	Annual crops (i.e., maize and soybean)	Migratory birds	Decreased habitat availability in relation to perennial grasslands	1,2	Robertson et al. (2013)
	Switchgrass	Migratory birds	Increased habitat and bird abundance (if harvest scheduled to avoid nesting period)	2,3	Tolbert and Wright 1998, Tolbert 1998, Tolbert et al. 1997
	Perennial crops	Fauna	Increased habitat when used as buffers between annual crops and waterways	2,3	McLaughlin and Walsh 1998
UK	Miscanthus	Flora and birds	Decreased diversity in relation to short rotation coppice (SRC) willow or poplar	1,3	Rowe et al. (2009)
SE Asia	Palm oil	Vertebrate species	Decreased diversity	1,2	Danielsen et al. (2009)
		Forest birds	Decreased diversity	1,2	Sodhi et al. (2005)
		Insectivorous birds	Predation on herbivorous insects that attack palm oil plants	2	Koh (2008)
Argentina	Soybean	Raptors	Decreased diversity	2	Carrete et al. (2009)

Sugarcane plantations for ethanol and sugar production cover approximately 8 M ha in Brazil and might expand to 14 M ha by 2016 (UNICA 2008). Expansion is predominantly occurring on degraded exotic pastures in Southeastern Brazil and does have local impacts on water eutrophication and soil pollution (Principle 2) (Verdade et al. 2012). While some claim that subsequent indirect pressures may drive deforestation in the Amazon basin (Lapola et al. 2010) such indirect effects are unlikely in the near future in Brazil. Sugarcane is planted in only 0.4% of the Amazon, for it does not grow well there, and a new Brazilian law prevents sugarcane planting in sensitive areas (Martinelli and Filoso 2008) (supporting Principle 1). However, such land-use systems reinforce inequality in land ownership contributing to rural–urban migration that ultimately fuels haphazard expansion of urban areas (Lapola et al. 2013).

Oil palm crops currently occupy over 13.5 million ha of former extremely diverse moist tropical forest in Southeast Asia (Fitzherbert et al. 2008), mainly (80%) in Indonesia and Malaysia. Palm oil is mostly used for cooking oils and soaps, and some of the oil and production wastes are used for biofuel (Corley 2009). Hence only a portion of its impacts is attributable to biofuels. More than 50% of the recent (1990-2005) palm oil expansion is directly related to deforestation (Koh and Wilcove 2008, Sodhi et al. 2010a). The rate of annual deforestation in Malaysia has been over 22,000 ha per year during the last three decades (Koh and Hoi 2003). Converting forests into palm oil crop is more profitable than preserving it for carbon credits traded in compliance markets (Butler et al. 2009). This trend is supported by the international market (Lenzen et al. 2012) and might result in massive biodiversity loss (Sodhi et al. 2004) especially of forest birds (Sodhi et al. 2005). Palm oil plantations support only 38% of the vertebrate species found in primary forest (and only 23% found in primary forests and plantations) (Danielsen et al. 2009). The Roundtable on Sustainable Palm Oil requires that “high conservation value forest” not be cleared to plant oil palm (www.rspo.org) (Principle 1). If this rule were rigorously implemented, the current rates of biodiversity loss in Southeast Asia would be greatly reduced.

The continuous increase in the supply and demand of cassava in developing countries has accentuated the negative impact cassava production and processing has had on the environment and biodiversity. The replacement of kerosene cooking fuel with ethanol produced from cassava in Nigeria requires the conversion of 400,000 ha of forest into farmland. Also, large volumes of waste streams are generated including toxic cassava effluent and solid wastes containing cyanide (Ohimain 2013). Cassava expansion also contributes to soil erosion, depletion of soil nutrient supply, and loss of biodiversity. Losses can include wild Manihot species, which may be of future importance for the incorporation of favorable characteristics, such as disease tolerance, in cultivated cassava.

16.2.2.2 Invasion of Exotic Species introduced through Biofuel Production Activities

Invasive species are associated with a variety of human activities and have driven many native species to extinction, altered the composition of ecological communities, changed patterns of periodical events, and altered ecosystem processes (Vitousek et al. 1987). Where nonnative plants are used as feedstocks, biofuel production may increase the risks and costs associated with invasive species as a direct consequence of the species and genotypes used to produce biofuels or of invasion of other taxa (Sala et al. 2009). This risk is relevant to both Africa (Blanchard et al. 2011, Witt 2010) and Europe (Genovesi 2010), where biofuel production is based on use of nonnative species. In some cases, however, introduced species used as feedstock provide habitat for native species (e.g., Eucalyptus and sugarcane, according to Dotta and Verdade 2011 and Gheler-Costa et al. 2012). The use of non-native species that have invasive characteristics requires adoption of specific management practices to reduce their potential for spread (Principle 3).

16.2.3 Ecosystem Services and Biofuel Feedstock Production

Ecosystem services as defined and described in the Millennium Ecosystem Assessment (MA 2005) provide a useful conceptual framework for structuring this review of the environmental impacts of biofuels following the trans-disciplinary approach proposed by Gasparatos (2013). Table 16.2 provides example services and effects related to feedstock production for biofuels, which has direct influences on provisioning, regulating and supporting services. In addition to supplying food, crops like corn, wheat, and sugarcane can contribute to biofuel production and enhance soil, water, and air conditions. The potential role of sustainable biofuels in mitigating climate change is still debated (see Chapters 9 and 12, this volume). The unresolved question is how much change is attributable to biofuels versus to other products and as compared to other land or energy uses.

Table 16.2 provides examples of the effects that feedstock production for biofuels can have on different ecosystem services. Effects are context specific and depend on prior uses of the land as well as the degree to which fossil fuel use is offset. Feedstock production practices can enhance or degrade air and water quality, and thereby affect biodiversity, food security, and soil quality.

16.2.4 Mitigating Impacts of Biofuel Production on Biodiversity and Ecosystem Services

There are several measures for avoiding or reducing environmental impacts of biofuel expansion. First, land-use planning with clearly defined agricultural production zoning can limit the expansion of biofuel crops into pristine ecosystems. Spatial planning based on

Table 16.2. Potential interactions with ecosystem services of production of terrestrial feedstock for biofuel (after Gasparatos et al. 2011).

Categories of Ecosystem Services	Service types	Positive and negative effects
Provisioning	Fuel	Biofuels provide around 3% of the world's fuel for transport and have potential for meeting a high proportion of liquid fuel needs in certain countries and regions. (Brazil: 23%, United States: 4%, European Union: 3%). (http://www.iea.org/aboutus/faqs/renewableenergy/)
	Food/ fodder	Most feedstocks used for first generation biofuels are food crops (Gasparatos.et.al, 2011)] An important bi-product of biofuel production is food for animals (Dale et al. 2010a) Integrated systems can improve food production at the local level creating a positive influence on food security (Diaz-Chavez 2011) Biofuel feedstock production replaced 1.6% of the cultivated land globally as of 2007 (Fischer et al. 2009) but provides a reason for retaining land in agriculture in the face of world-wide urban expansion, which has claimed a much larger area of farmland
	Water quantity and quality	Some feedstocks are used to purify wastewater (Börjesson and Berndes 2006) and to restore contaminated aquifers and marginal lands (Gopalakrishnan et al. 2009) When perennial feedstock crops replace annual crops, less fertilizer is used and deep roots reduce runoff (Achten et al. 2008; Gmunder et al. 2010; Dale et al. 2010b, Parish et al. 2012) Palm Oil Mill Effluent (POME) and sugarcane mill effluent are used for oil palm and sugarcane irrigation, respectively Biofuel systems can degrade and exploit water quality and quantity (de Fraiture and Berndes 2009) Where water is limited, the use of irrigation in feedstock production can deplete vulnerable aquifers (Chiu et al. 2009) It can be more water-efficient to use biomass to produce bioelectricity than biofuels (Gerbens-Leenes et al. 2009) Biofuel production can produce effluents with high toxicity and Biological Oxygen Demand (BOD) (Gasparatos et al. 2011) The palm oil industry is a major source of water pollution in Malaysia (Muyibi et al. 2008) POME has high levels of BOD [approximately 2.5–3 tonnes of POME per tonne of palm oil (Wu et al. 2010)] Effluent from sugarcane mills is rich in BOD (12–13 liters of vinasse generated per liter of ethanol) (Martinelli and Filoso 2008)

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Categories of Ecosystem Services	Service types	Positive and negative effects
Provisioning *(cont.)*	Water quantity and quality *(cont.)*	Expansion of feedstock production in previously uncultivated land in Brazil increases use of chemical compounds that can elicit neurotoxic, reprotoxic, carcinogenic, or endocrine-disrupting effects in humans and wildlife (Schiesari and Grillitsch 2011) Both nitrogen and phosphorus reduction can occur where lignocellulosic bioenergy feedstocks are grown that require little fertilizer and can absorb runoffs with their deep perennial rooting systems (Simpson et al. 2008, Almaraz et al. 2009, Parish et al. 2012) Using perennials feedstocks, alternative rotation systems, and sustainable crop production (e.g., no-till farming, reduced use of fertilizer, and riparian buffers) can reduce both nutrient input and the transport of nutrients and sediments to waterways (Dale et al. 2010a, Costello et al. 2009) Woody biomass-to-liquid production (BTL) may locally increase eutrophication and have subtle effects on acidification (Sunde et al. 2011)
Regulating	Soil quality/ Erosion regulation	Jatropha can improve soil quality and control erosion on marginal lands (Achten et al. 2008; Gmunder et al. 2010) Martinelli and Filoso (2008) in (Gasparatos et al. 2011) mention that sugarcane cultivation is a significant driver of soil erosion in Brazil Soybean cultivation for biodiesel in Argentina exhibits greater soil erosion potential and greater negative effect on soil nutrients than switchgrass (van Dam et al. 2009) Smeets et al. (2008) suggest that leaving sugarcane residues on the field reduces erosion Creating bio-energy plantations on degraded land can positively affect soil and biodiversity (Danielsen et al. 2009) Growing switchgrass in the southern United States on land previously in pasture or annual crops reduces soil erosion (Parish et al. 2012) Deep-rooted perennial bioenergy feedstocks in the tropics could enhance soil carbon storage by 0.5 to 1 metric tonne ha-1year-1 on already cleared land (Fisher et al. 1994) Annual exposure of bare soil rich in Al can result in contamination of freshwater fish (Meche et al. 2009) Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions (Liska et al. 2014; see also Chapters 13 and 18, this volume)

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Categories of Ecosystem Services	Service types	Positive and negative effects
Regulating *(cont.)*	Climate regulation	Sustainably produced biofuels substitute for fossil fuels and thereby contribute to mitigating climate change Biofuel systems can emit significant amounts of GHGs during their whole life cycle depending on prior land use (Hess et al. 2009) Oil palm plantations are net carbon sinks and protect the soil if they are established on marginal crop/grassland (Danielsen et al. 2009, Verwer et al. 2008) Danielsen et al. (2009) calculated that depending on the forest clearing method used, it takes 75–93 years for an oil palm plantation to compensate the carbon lost during the conversion of the initial forest and 600 years if that happens on peatland Georgescu et al. (2009) state that biofuel expansion in the US Corn Belt might affect regional climate as a result of conversion of land cover from one crop type to another and the associated changes in energy and moisture balance of the surface
	Air quality	Biofuel feedstock production can release Volatile Organic Compounds (VOCs) and NOx Use of cane for biofuels can reduce burning, which is a major source of particulate matter with aerodynamic diameter and Polycyclic Aromatic Hydrocarbons (PAHs) (Gasparatos et al. 2011) Introduction of biofuels in Brazil has contributed to improvements of air quality in the city of São Paulo (Goldemberg 2008) Air pollution can result from biofuels production (Williams et al. 2009) including anthropogenic emissions of NH_3 (Erisman et al. 2007)
Supporting	Habitat	Open habitats like sugarcane plantations attract species and migratory birds (Acevedo and Restrepo 2008) Changing from annual crops to perennial energy crops on metal polluted soils increased soil invertebrate density (Hedde et al. 2013)

systematic conservation planning principles (Margules and Pressey 2000) can establish networks of sustainable protected areas (Principles 1 and 3). Secondly, wildlife friendly agricultural and forestry practices can be employed (Principle 3) as promoted by the work of FAO (2012) and the Forestry Guild (Forest Guild Biomass Working Group 2010, Forest Guild Pacific Northwest Biomass Working Group 2013, Forest Guild Southeast Biomass Working Group 2012). These approaches complement public policy (Charles et al. 2007, Lovett et al. 2011, Soderberg and Eckberg 2013) and market demands (Di Lucia 2010, Palmujoki 2009). However, both strategies depend on the implementation of a global network of long-term monitoring activities as discussed below.

16.2.4.1 Zoning

Zoning for particular uses could be established in countries that allow such land management systems. Agricultural or forestry zoning for biofeedstock production should be based on edaphic and hydrological limitations (Lal 2008) as well as unsuitable areas (Groom et al. 2007; Joly et al. 2010). Almost all countries identify and have some protection of environmentally sensitive areas; however their level of protection varies greatly. For those countries that allow zoning, the steps are set forth below. For other places, voluntary market-based incentives for appropriate resource management may be effective. Giving value to clean water, clean air, and other ecosystem services encourages their protection (Buyx and Tait 2011). Financial incentives to reduce carbon emissions from deforestation and forest degradation (REDD) provide economic compensation for landowners (Butler et al. 2009; Visseren-Hamakers et al. 2012; Kileen et al. 2011; Chapter 13, this volume). Furthermore, zoning is supported by promoting sustainable development in countries where agricultural and feedstock production are expanding (Martinelli and Filoso 2008).

The first step in zoning is selecting areas needed to protect threatened species and sensitive ecosystems. Then locations for biofuel feedstocks can be identified within the context of other ecosystem services and the needs of society. Expansion of biofuel crops over degraded lands instead of pristine ecosystems and food croplands has advantages for sustainability and food security (Fitzherbert et al. 2008; Henneberg et al. 2009; Koh and Ghazoul 2010, Obidzinski et al. 2012; Plieninger and Gaertner 2011; Ravindranath et al. 2011; Stoms et al. 2012; van Vuurven et al. 2009). The characteristics of degraded lands and their management need to be defined in specific contexts (Li et al. 2010). The zoning system should be complemented by wildlife-friendly management practices, as discussed below.

16.2.4.2 Wildlife Friendly Management Practices

Environmental impacts of agriculture and forestry can be mitigated by either improving or reducing productivity (Green et al. 2005) or selectively using areas most suitable for agriculture or forest production (Dale et al. 2011) (more details in Chapter 13, this volume). The successful implementation of this approach results in concentrated highly productive crop fields or forests and more natural areas maintained for conservation (Koh et al. 2009; Koh and Ghazoul 2010; Buckeridge et al. 2012). Such agroecosystems or forest systems are part of a landscape matrix that includes conservation areas and corridors as well as secondary remnants of native vegetation with conservation value (Wiens et al. 2011; Ranghanatan et al. 2008; Smith et al. 2008; Smith and Gross 2007; Metzger et al. 2010; Koh 2008). Attributing economic values for agroecosystems and forest systems counters pressure for land development [such as is occurring in the southeastern United States (USDA Forest Service 2012)] and thereby maintains or even expands the area in forest and croplands, which provides more ecosystem services than developed areas. Environmental certification can strengthen such strategies. (see Chapter 19, this volume).

Retention of native vegetation within agricultural or forested landscapes (Principle 1) increases both the matrix permeability for specialist species and habitat quality per se thus enhancing landscape β-diversity (Verdade et al. 2014a). Hence, there are local improvements of ecosystem services (Gasparatos et al. 2011, George et al. 2012, Berry and Paterson 2009). Such a strategy builds multifunctionality of agricultural landscapes (Martinelli et al. 2010) including production of domestic species and conservation of wild species (Verdade et al. 2014a).

16.2.4.3 Biodiversity and Environmental Monitoring

Assessment of long-term effects of biofuels production on biodiversity requires a global monitoring network (Tilman et al. 2006; Sodhi et al. 2010a; FAO 2012; Dale and Kline 2013a; Verdade et al. 2014b). Such a program should feed into life-cycle impact assessments (LCA) of biofuel feedstocks and other crops and energy uses (Bare 2011; Markevicius et al. 2010; Reinherdt and von Falkenstein 2011); Weiss et al. 2012). An effective monitoring approach (e.g., Wilbur 1997) builds from use of targeted indicators (e.g., Scharlemann 2008). Environmental indicators of sustainability that should be monitored should reflect soil quality, water quality and quantity, greenhouse gases, biodiversity, air quality, and productivity (McBride et al. 2011). Key socioeconomic indicators include measures of social well-being, energy security, trade, profitability, resource conservation, and social acceptability (Dale and Kline 2013b). Sampling procedures should be systematized to reduce methodological uncertainties (e.g., Gao et al. 2011; Magnusson et al. 2014). Databases generated by sampling sites within the global network should be interoperable in order to connect patterns of diversity with processes (Verdade et al. 2014b). Monitoring and analysis should feed into adaptive management (Lattimore et al. 2009).

16.3 Conclusions

As with all land transformation activities, effects on biodiversity and ecosystem services of producing feedstocks for biofuel are highly variable and context specific. Advances toward more sustainable biofuel production benefit from a system's perspective, recognizing spatial heterogeneity and scale, landscape-design principles, and addressing the influences of context, such as the particular products and their distribution, policy background, stakeholder values, location, temporal influences, and baseline conditions. Good governance, strong institutions, market based voluntary certification, and access to information about appropriate management strategies and tactics all support sustainable resource use and management that can benefit biodiversity. Developing those management strategies takes time and effort. In summary, the negative effects of production of feedstocks for biofuel can be avoided or reduced by conservation of priority biodiversity areas, recognizing the context specific effects of feedstock production, and adopting location-specific management of production systems.

16.4. Recommendations

Agroecological zoning principles and enforcement is of paramount importance to impede the conversion of ecologically significant and sensitive areas for biodiversity and ecosystem services protection into producing feedstocks for biofuel. Good governance and strong institutions are the most critical determinants of sustainable land use, especially in terms of biodiversity. Without good governance, biofuels expansion will lead to environmental and social loss. As a highly sophisticated, innovative and efficient industry, biofuels can be part of the solution, not part of the problem.

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chapter 17

Greenhouse Gas Emissions from Bioenergy

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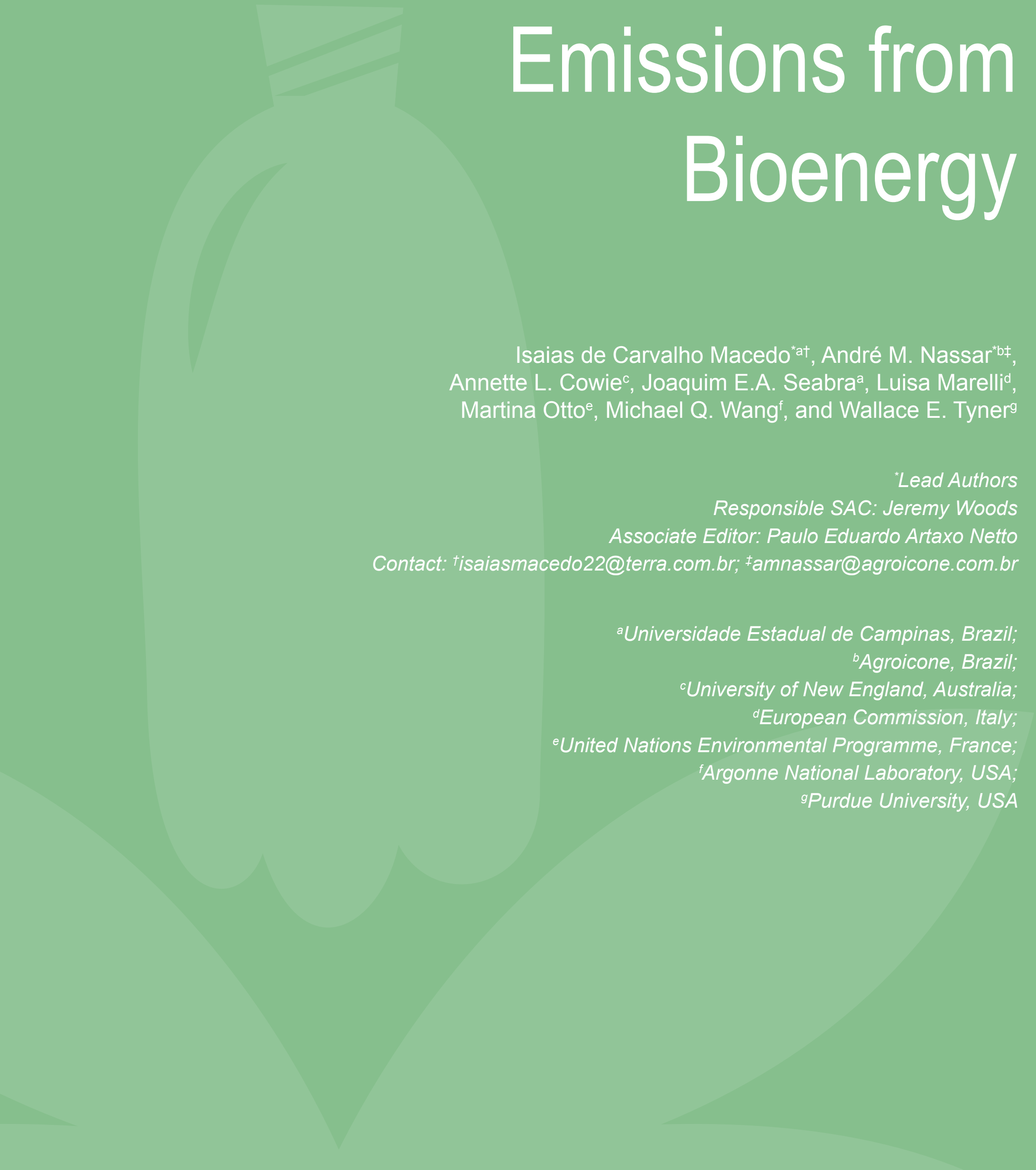

Highlights

- Biofuels in suitable conditions can provide substantial levels of GHG mitigation. Co- and by-product utilization can improve this effect
- Second generation biofuels may show higher GHG mitigation, to be demonstrated in full scale commercial operation
- LUC studies for better biofuels evidence the great improvement potential for the whole agriculture / forestry system
- Further development of GHG LCA methodologies is needed to quantify the influence of timing of emissions and removals, albedo change, and short-lived climate forcing agents. New data will be required in order to apply these methods
- Tools to help provide technical support for public policies have been developed and are being implemented.

Summary

Recent advances in modeling and access to new data have enabled advances in greenhouse gas (GHG) emissions estimation. Current methodological issues (e.g., treatment of indirect land use change (iLUC) and co-products) are presented, as well as current knowledge on climate change impacts other than GHGs (timing of GHG emissions / removals; albedo changes; aerosols emissions). Commercial biofuels in suitable conditions can provide moderate levels of GHG mitigation, and second generation biofuels may show higher GHG mitigation. Ethanol from sugarcane shows the largest "average" net GHG mitigation today; biodiesel (many sources; Europe) provides 30 – 60% mitigation (no LUC considered) compared with diesel; commercial biopower from solid biomass produces emissions typically ranging from 26 to 48 gCO_2e / kWh (systems > 10 MWe), providing substantial net GHG mitigation. There is still considerable uncertainty surrounding the quantification of emissions associated to iLUC but recent studies tend to converge toward the lower level of the range of estimates. At the time of the prior SCOPE report (SCOPE 2009), the magnitude of LUC emissions was felt to be large enough to negate the GHG emission benefits of an otherwise low-emitting biomass-based fuel supply chain. Five years later, this is no longer the case for ethanol crops as illustrated in this document. LUC emissions can be avoided if land demand for biofuels expansion is managed, if yield increase exceeds increase in demand and as

long as deforestation rates are decreasing. Implementation of methods to provide the data needed to support policies and strategic decisions is discussed. Recommendations include continued support i) for technology development, and data acquisition for GHG evaluation; ii) to clarify some GHG emissions issues; iii) to implement methodologies and policies to maximize biofuels GHG emissions benefits such as zoning systems, policies for deforestation control and monitoring; good practices in agriculture; intensification of land use (discussed in Chapter 9, this volume).

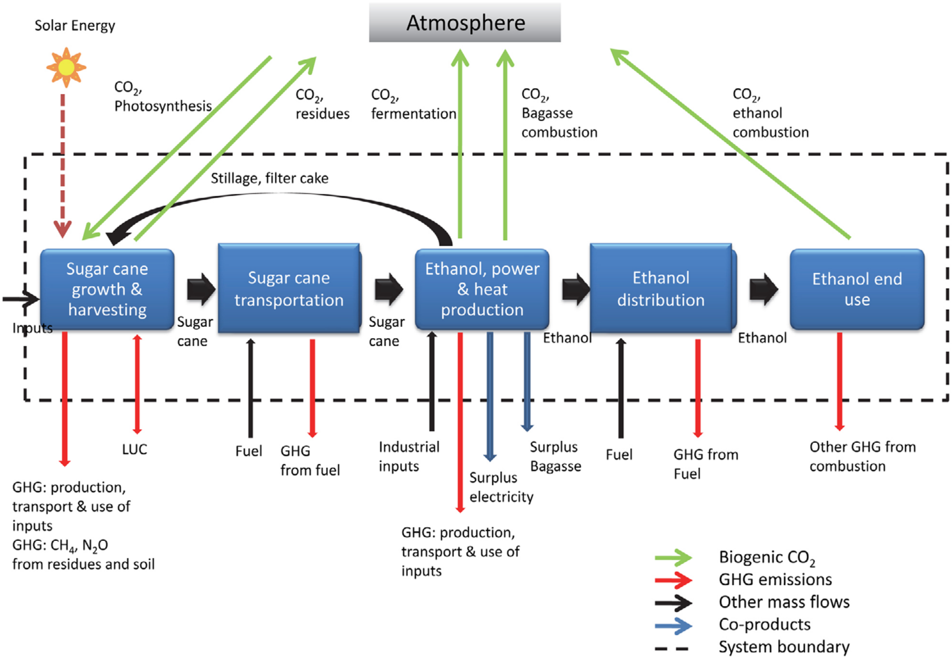

Figure 17.1. Mass flows and life cycle GEE emissions in production of ethanol from sugarcane.

17.1 Introduction

The implementation of efficient bioenergy has been considered essential to reduce and stabilize GHG emission levels in the next decades. The last five years have seen important efforts to improve models and obtain more reliable data on key parameters (e.g., soil carbon stocks and N_2O emission coefficients) (JRC 2010a; Winrock 2009a; Winrock 2009b, FAO/IIASA/ISRIC/ISS-CAS/JRC 2008), both globally and for specific regions (Galdos et al. 2009; Mello et al, 2014), as well as the estimation of unobservable phenomena such as indirect land use changes (JRC 2010b; JRC 2011; Dunn et al. 2013), and to support and help improve the contribution of bioenergy to GHG mitigation, and guide policy decisions.

This Chapter presents the current methodological issues in the Life Cycle Assessment (LCA) of GHG emissions; a summary of the results for the most important commercial biofuels (including solid, liquid and gaseous bioenergy products), and perspectives for the advanced biofuels in development. It also presents the evolution of the models for estimating biofuels-induced direct and indirect land use change (LUC – iLUC) and the data for corresponding emissions assessment; a summary of the current knowledge on climate change impacts other than GHGs (effects due to timing of GHG emissions / removals; albedo changes; aerosols emissions); and recommendations to help improve data acquisition and the delivery of sound assessments of the different uses of biomass for energy to support public policies. This chapter has several cross references to other chapters in this volume, especially chapters 9, 16 and 19.

17.2 Key Findings

17.2.1 Life Cycle Assessments of GHG Emissions from Biofuels

17.2.1.1 LCA Issues in GHG Emissions

LCA is a structured, comprehensive and internationally standardized method for assessing environmental impacts of a product. It quantifies all relevant emissions and resources consumed and the related environmental and health effects and resource depletion (ISO 2006a; ILCD, 2010). The comprehensive scope of LCA is useful to avoid problem shifting among life cycle phases, regions, or environmental problems (Finnveden et al. 2009).

The International Organization for Standardization (ISO) provides two international standards on the general principles and requirements of LCA: ISO 14040:2006 and ISO 14044: 2006. The ISO standards define four phases in a LCA study (ISO 2006a and b): Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation (see Chapter 19, this volume). An important issue regarding the goal and scope definition is the differentiation between attributional (ALCA) and consequential LCA (CLCA), with the former being more widely used for historical and practical reasons. But in the last five years the application of the CLCA modeling technique has boomed also stimulated by the debate on the environmental consequences of the expected expansion of biofuels (Zamagni et al. 2012). Box 17.1 presents the differences between these two modeling approaches.

Box 17.1. Attributional LCA (ALCA) versus Consequential LCA (CLCA)

ALCA and CLCA, from their logic, represent the two fundamentally different situations of modeling the analyzed system (ILCD, 2010). ALCA focuses on the environmentally relevant physical flows to and from a life cycle and its subsystems, to describe the impacts of the average unit of a product, while CLCA describes how environmentally relevant flows will change in response to decisions (Finnveden et al. 2009). In attributional modeling the system is modeled as it is or was (or is forecast to be), whereas CLCA models a hypothetic generic supply-chain prognosticated along market-mechanisms, and potentially including political interactions and consumer behavior changes (ILCD 2010). CLCA first appeared as a discussion in Weidema (1993), which broadly outlined the need to consider market information in life cycle inventory data.

The different focuses of attributional and consequential LCA are reflected in several methodological choices in LCA, for instance, when discussing system boundaries, data collection and allocation (Finnveden et al. 2009). The approach for solving multifunctional processes is one of the most critical issues in LCA. According to the ISO (2006b) hierarchy, wherever possible, allocation should be avoided by process subdivision, or by expanding the product system to include the additional functions related to the co-products for solving multifunctionality (ILCD 2010).

Where allocation cannot be avoided, the ISO standards (ISO 2006b) advise that the “inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects underlying physical relationships between them”. Lastly, (ISO 2006c) “where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them” (e.g., economic value of the products).

LCA considers aspects of environment, human health and resource use, but the challenges posed by climate change have brought special attention to the emissions of GHGs in the life cycle of products. New standards and methods over the last years focused on the assessment of the life cycle GHG emissions and removals (also referred to as carbon footprint) of products. The GHG Protocol Product Standard, PAS 2050:2011 and ISO/TS 14067:2013 are examples of these new standards, while the Roundtable on Sustainable Biomaterials GHG Calculation Methodology (RSB 2011) is an example of a specific method developed in the context of biofuels certification. In general, these standards are founded on the same basic principles set in the ISO LCA standards, with the difference that they address only one impact category (climate change), and provide more specific guidance for some methodological aspects (e.g., how to deal with land use change). Figure 17.1 exemplifies the topics in the evaluation of life cycle GHG emissions for a commercial biofuel.

In the context of biofuels policies, regional regulatory schemes have used different approaches based on the LCA technique to estimate GHG emissions. For example, the impact assessment developed by the U.S. Environmental Protection Agency (EPA) for the Renewable Fuel Standard – RFS2 (EPA 2010) and the analysis performed by the California Air Resources Board (CARB) for the Low Carbon Fuel Standard (CARB 2009) vary greatly between themselves, and also in comparison with the European Commission's Renewable Energy Directive (EU-RED), (EC 2009). Agricultural aspects, allocation procedures and economic modeling approaches for iLUC assessments are the major areas where methodological divergences exist (Khatiwada et al. 2012). In terms of the modeling approach, EU-RED is largely consistent with ALCA methodology, with the exception of the treatment of excess electricity from cogeneration. However, inconsistencies may be created in the future if the European Commission develops a method for indirect effects, a consequential issue (Brander et al. 2009). The EPA assessment is fully based on consequential modeling, while the CARB analysis includes some elements of ALCA.

17.2.1.2 LCA Results of Greenhouse Gas Emissions for Biofuels

Many LCA studies address energy use and greenhouse gas (GHG) emissions of biofuels vs. conventional petroleum fuels. In 1990s and early 2000s, studies addressed energy balance (or energy ratio) of biofuels. Biofuels usually have a positive energy balance (energy ratio greater than one) (e.g., see Wang et al. 2012 for ethanol energy results).

Biofuel GHG LCA results vary considerably among different biofuel types and regions; the GHG benefit of biofuel use depends on the actual fossil fuel displacement and on the life cycle GHG emissions of the displaced fossil fuel. Biofuel LCA GHG results also are affected by LCA methodology, including technology modeling and data availability. The issues include LCA approach, LCA system boundary, treatment of biofuel co-products, modeling of LUC, and how to include technology advancement over time (Menichetti 2008; Gnansounou et al. 2009; Cherubini et al. 2009).

Regional biofuel regulations such as the EU Renewable Fuel Directive (RED), the U.K. Renewable Transport Fuel Obligation (RTFO), the California Low Carbon Fuel Standard (LCFS), and the U.S. EPA Renewable Fuel Standard (RFS) require estimation of life cycle GHG emissions of biofuels. Several LCA models are available for this estimation, including the Argonne National Laboratory GREET model (GREET 2012) and the U. C. Davis Model (Delucchi 2003) in the U.S., the GHGenius model in Canada, and the E3 Database and Biograce (LBSM 2013; BioGrace 2013) in Europe.

LCA databases (e.g., ELCD, Ecoinvent), the UNEP/FAO/UNIDO GEF developed tool (GEF 2013) and commercial LCA software packages (e.g., SimaPro, GaBi, Umberto) can also be used as tools for biofuels LCA.

This section summarizes some LCA GHG results for commercial, relatively large scale biofuels (ethanol from corn and sugarcane, biodiesel from rapeseed and soy, and wood pellets) and the available data on “advanced” biofuels (in development, or in early commercialization stages, see Box 17.2). As mentioned above, the ALCA has been more widely used for historical and practical reasons, while system expansion is the prevailing approach for the treatment of co-products among the studies below. Most of the analyses have employed elements of ALCA and CLCA as the discussion and differentiation between these approaches became more evident in the last years.

17.2.1.2.1 LCA Results for Commercial Liquid Biofuels

Commercially, a number of biofuels are produced worldwide; feedstocks, conversion technologies and volumes are shown in Chapters 10 and 12, this volume. Ethanol comprises the largest biofuel production volume globally. Major sources are U.S. corn ethanol and Brazilian sugarcane ethanol (Chum et al. 2013a), followed by ethanol produced from wheat and sugar beet in Europe (see Chapters 10 and 12, this volume). Process energy used in corn ethanol manufacture per unit produced has been the subject of many LCA studies in the past twenty years (Wang et al. 1999; Farrell et al. 2006; Wang et al. 2007; Kim and Dale 2008; Wang et al. 2011b; Wang et al. 2012; Chum et al. 2013b). Over the past 40 years, U.S. corn yield per hectare increased at an annual rate of 1.7%, while fertilizer inputs per unit of corn harvested declined steadily (Chum et al. 2013b). Corn ethanol plant energy use has been reduced by more than 70% between 1980 and 2011 (Wang et al. 2011b; Mueller et al. 2010). These improvements in combination with process fuel switch (e.g., from coal to natural gas) have contributed to reduced GHG emissions. One-third of corn mass ends up in distillers’ grains and solubles (DGS) used as and animal feed; the method used to allocate impacts between ethanol and DGS affects corn ethanol GHG results considerably (Wang et al. 2011a).

Brazil has also experienced improvements in sugarcane farming and ethanol production (Macedo et al. 2008; Seabra et al. 2011; Wang et al. 2012). Most sugarcane mills have flexibility between sugar and ethanol production. Bagasse (residue) is commonly combusted on site in combined heat and power (CHP) systems providing steam and power for the sugar mill operation and exporting power to the electric grid. Feedstock production is the major GHG emission source, with N_2O emissions and N fertilizer manufacture being important contributors.

The GHG emissions sources breakdown for corn and sugarcane ethanol produced in the U.S. and Brazil are presented in Table 17.1, along with soybean and rapeseed biodiesel (U.S. and EU); LUC effects are not included here (see Chapter 9, this volume); and co-product credits (and approaches to quantify these: displacement or allocation) can have a large influence on the results. The significant contribution from the fuel production stage for corn ethanol is strongly influenced by the process fuel choice (usually fossil), whereas for sugarcane ethanol process fuel is always bagasse. The difference in the source of process fuel is the main factor responsible for the larger GHG emission reductions observed for sugarcane ethanol as compared to corn ethanol. The uncertainties around these estimates are illustrated in Figure 17.2, along with the range for rapeseed biodiesel in Europe. Those ranges were estimated based on datasets from large-scale commercial systems, using internally consistent methodological choices. In general, the overall uncertainties are particularly influenced by the N_2O emissions from the field, as well as by the use of fertilizers and industrial efficiencies.

Table 17.1. Breakdown of GHG emissions per life cycle stage for four commercial biofuels (gCO_2eq/MJ).

	Corn Ethanol[a]	**Sugarcane Ethanol**[a]	**Soybean Biodiesel**[b]	**Rapeseed Biodiesel**[c]
Feedstock Farming	30.8	22.5	34.2	57.5
Fertilizer production	10.1	3.8[d]	Not separated	Not separated
N_2O emissions in field	16.7	6.7[e]	20.1[e]	Not separated
Farming	4.0	12.0[f]	14.1	Not separated
Fuel Production	31.0	2.6	9.6	15.2
Transport and distribution	4.5	1.8	1.9	1.9
Co-product credit	-13.7	-6.4	Not separated	-20.8[g]
Total without credit	66.3	27.7[h]	45.7	74.6
Total with credit	52.6	21.3	16.8[i]	53.8

[a] Wang et al. (2012); Seabra et al. (2011). Displacement method was used to address co-products of bio-ethanol

[b] Pradhan et al. (2012). Allocation method was used to address co-products of biodiesel

[c] Edwards et al. (2013). Displacement method was used to address co-products of biodiesel

[d] Includes other agrochemicals

[e] Includes CO_2 emissions from lime and N_2O emissions from nitrogen fertilizer in field. GHG emissions of lime in field are included in all four studies. In Wang et al. (2012) and Edwards et al. (2013), lime GHG emissions are included in farming emissions. For sugarcane ethanol, it also includes emissions from residues

[f] Includes emissions from trash burning

[g] Includes a GHG credit of 14.6 g/MJ for meal and 6.2 g/MJ for glycerin

[h] Includes tailpipe emissions

[i] Calculated by the mass allocation method that was used by the original authors. The mass shares between soybean meal and soy oil are 81.6% and 18.4%; between biodiesel and glycerin are 89.9% and 10.1%

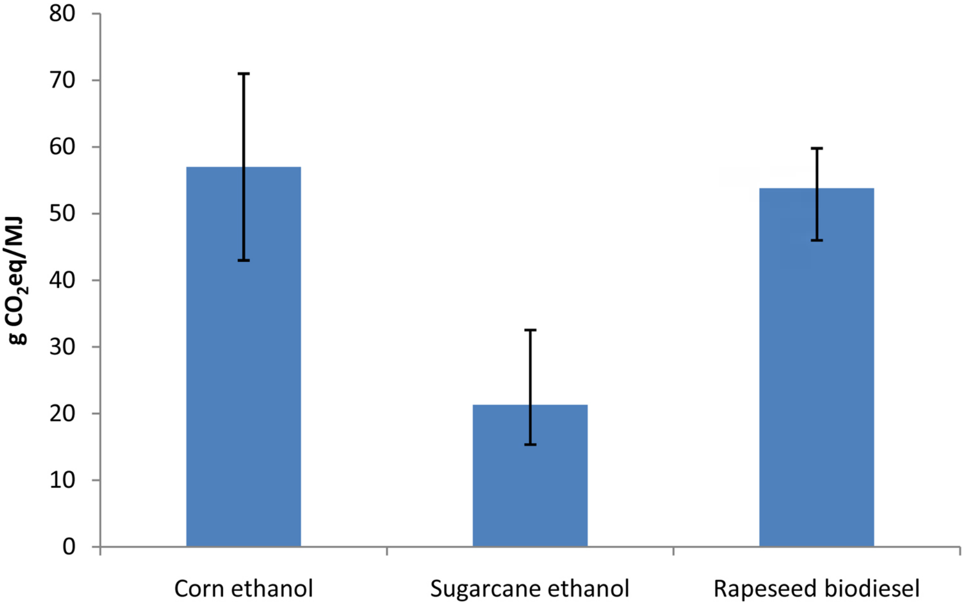

Figure 17.2. Life cycle GHG emissions of commercial biofuels.
For corn and sugarcane ethanol, error bars represent the 10th and 90th percentiles (from Wang et al. 2012 and Seabra et al. 2011); for rapeseed biodiesel, error bars represent maximum and minimum values, when using meal for animal feed and glycerin for chemicals (from Edwards et al. 2013). For base cases, refer to Table 17.1.

Biodiesel (fatty acid methyl esters – FAME) is produced mainly from vegetable oils (rapeseed, soybean, palm and sunflower). Rapeseed oil is the major source in Europe, soybean oil in North and South America, and palm oil in Southeast Asia. GHG emissions from biodiesel production vary depending on feedstock types and fossil energy intensities for feedstock farming and biodiesel production, and results from LCA studies also depend on methodological decisions (e.g., approach to consider co-products and whether LUC effects are considered or not; see section 17.2.2).

Several studies have addressed LCA GHG emissions associated with soybean biodiesel production in the U.S. (Sheehan et al. 1998; Huo et al. 2009; Pradhan et al. 2012). Results by Pradhan et al. represent the up-to-date data on soybean farming and biodiesel production. They use mass-based allocation amongst co-products (meals and glycerin). After allocation (co-products credits) biodiesel production (soybean crushing and transesterification) is the most significant emission source (Table 17.1, column 3), requiring steam, electricity and chemicals. GHG emissions from lime and nitrogen fertilizer are also significant sources. Relative to the GHG emissions of 90 g CO2eq/MJ for petroleum diesel, Pradhan et al.'s results show GHG reduction of 81% for soybean biodiesel in the U.S. when LUC emissions are not considered.

Edwards et al. (2013) assessed biodiesel produced from rapeseed, sunflower and soybean, using the substitution method to consider meal and glycerin co-produced. Rapeseed farming is by far the largest GHG emission source, 68% higher than that of soybean farming in the U.S.. Excluding LUC emissions, Edwards et al. (2013) estimated average GHG emissions of biodiesel at 37-59, 46, 55-60, and 31-63 g CO_2eq/MJ for rapeseed, sunflower, soybean and palm oil, respectively, leading to GHG emission reductions of 33-58%, 48%, 32-38%, 29-65% if displacing petroleum diesel (GHG emission rate of 88.6 g CO_2eq/MJ). The range for each option reflects different uses for meals and glycerin; the low-end value for each option represents the case where glycerin is used in anaerobic digestion, which might be the only option if other glycerin markets become saturated as biodiesel production grows.

Advanced biofuels have not yet reached commercial, large scale production and LCA of GHG emissions are estimates based on projections from different stages of development, technical data, and methodology choices (Box 17.2). Recent results for cellulosic ethanol are shown in Wang et al. (2012); and reviews are presented, among others, in Borrion et al. (2012) and Wiloso et al. (2012). Results from a meta regression analysis based on published data for cellulosic ethanol and BtL (synthetic diesel) emissions are shown in Figure 17.3 (Menten et al. 2013).

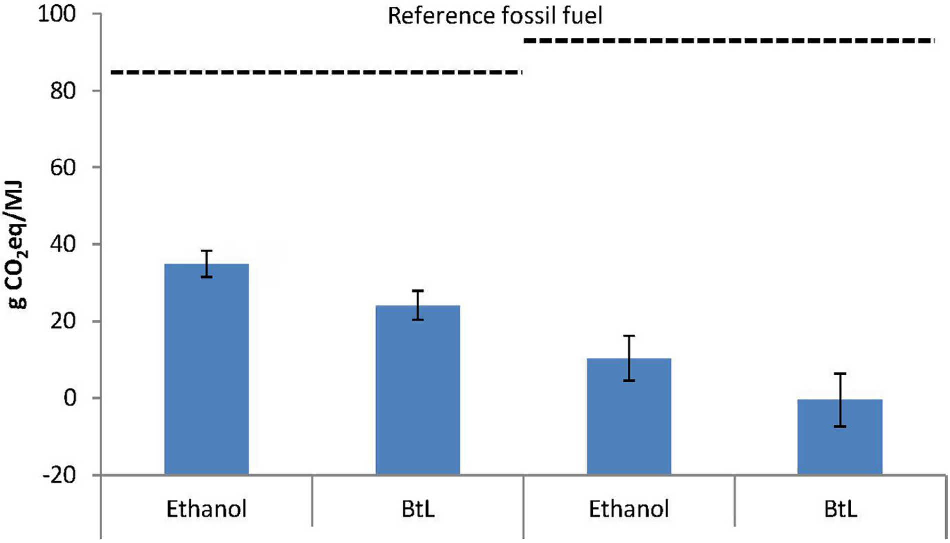

Figure 17.3. Meta-regression analysis based on projected second generation (2G) biofuels literature data for cellulosic ethanol and BtL (diesel) routes (after Menten et al. 2013); see Box 17.2. First two columns for EU results; columns 3 and 4 for North America results. -Data Base: 516 observations (G2) in 47 selected studies, 2003 – 2012; 314 ethanol, 202 synthetic diesel; 51% including LUC (less than 10% including iLUC); 97% using CLCA, 3% ALCA; 53% from EU, 45% from North America. -Vertical bars: 95% confidence interval - Reference fossil fuel emissions: EU (83.8 g CO_2eq/MJ for both gasoline and diesel); U.S. (92.5 g CO_2eq / MJ, average of gasoline and diesel references, for both).

Box 17.2. Estimated LCA results for advanced biofuels

Advanced biofuels here refer to biofuels in development or early commercialization stages; sometimes called “second generation” (G2) biofuels (cellulosic based, thermochemical or biochemical processing) and “third generation” (oils produced by algae). Research and development efforts are helping advance cellulosic biofuels technology and economics. Pilot and commercial scale plants recently began to come online in the U.S., Europe and Brazil. Cellulosic feedstocks with large potentials are crop residues, bagasse in sugar mills, perennial grasses, woody plants, and forest residues. Feedstock supply, including collection, transportation, and storage cause different levels of GHG emissions depending on feedstock type, location and system design. Processes for feedstock pre-treatment and conversion also lead to significant differences in GHG emissions. Cellulosic ethanol plants can use residues such as lignin to generate steam and electricity with CHP; and electricity export to electric grid can help improve plant economics and reduce GHG footprint. Results from Wang et al. (2012) suggest that cellulosic ethanol is projected to have larger GHG emission reductions compared to gasoline than the current commercial biofuels. Since there is no commercial scale production, almost all results come from estimates projected for different processes and feedstocks, at pilot plant (and even laboratory) scale. A meta regression analysis of the literature results on cellulosic ethanol and biomass to synthetic diesel (thermochemical, BtL) processes support these projected higher decreases in GHG emissions (Menten et al. 2013), Figure 17.3; however the systematic difference between North American and European estimates, and ethanol and BtL, remains to be fully explained.

17.2.1.2.2 LCA Results for Solid Biofuels

Commercial solid biomass utilization (e.g., power production and indoor heating using household or district heating systems) has grown significantly in the last decade; estimated consumption of wood pellets in EU alone was 12 million t/year, in 2012 (NREL 2013). In 2011, the EU started evaluating binding EU-wide Standards, including GHG emissions.Table 17.2 shows the results of a recent, comprehensive analysis using data from 387 references; GHG emissions vary according to scale, feedstock and technology.

Table 17.2. LCA GHG emissions (excluding LUC): commercial biopower generation technologies[a].

Feedstock	Development stage	Lifecycle GHG Emissions, gCO_2eq/kWh [c]			
		>10 MWe avg	>10 MWe range	0.01-10 MWe avg	0.01-10 MWe range
		Electrical efficiencyb		Electrical efficiencyb	
		31.5%	27-36%	20%	10-30%
Wood waste and forest residues	Commercial	26	23-30	40	27-80
Agriculture residues	Commercial and developing with respect to logistics collection and preprocessing	48	42-56	75	50-151
Short rotation woody crops	Commercial and developing with respect to crops and logistics	35	31-40	55	37-109
Herbaceous crops	Developing	56	49-64	40	59-173

[a] Courtesy of the Sustainability Information Exchange Database, Ethan Warner, NREL (2013). Data sources and meta-model: Warner et al (2013) including 387 references through June 2011 of which 117 LCAs passed quality and relevance screens in the harmonization process. Efficiency data for biopower systems from Bruckner et al. (2011) and IEA Bioenergy (2010)

[b] Ranges represent electrical efficiency end point values

[c] As references, the fossil fuel combustion GHG emissions in thermo-electric power plants, with their variation due to different technology levels, are: i) coal: 1000 g CO2eq / kWhe; (800 – 1300) g CO_2eq / kWhe; ii) oil: 800 g CO_2eq / kWhe; iii) natural gas: 550 g CO_2eq / kWhe; (400 – 800) g CO_2eq / kWhe (Weisser 2007)

For any form of bioenergy – current or advanced, solid or liquid – the avoidance of GHG emissions on a life cycle basis increases as the efficiency of feedstock production and conversion improves, and as the penetration of renewables increases in the overall energy matrix. With respect to the latter point, consider for example a biofuel pathway with process energy provided by unfermented residues, as it is the current case for sugarcane ethanol and is anticipated for most cellulosic biofuels. Such pathway has greater than zero life cycle GHG emissions today in good part because of the fossil energy used in the ancillary processes involved in the production cycle: fertilizer manufacture, feedstock cultivation, harvesting and transport, and product distribution. As the energy matrix progresses toward being low-carbon, the emissions associated with these ancillary processes is reduced proportionately and the life cycle GHG emissions will be lower. In Brazil, for instance, the increasing biodiesel blend in diesel (6% volume today) and the increasing substitution of bagasse generated energy for thermo electricity (in the margin) is expected to substantially reduce sugarcane ethanol life cycle GHG emissions.

17.2.2 Land Use Changes and GHG Emissions

LUC has been the most contentious issue in evaluating GHG effects of biofuels. LUCs can lead to a reduction or an increase of C stocks in biomass and soil, thus affecting the net GHG emissions from the bioenergy system. The causes behind LUC are multiple, complex, interlinked, and change over time. This makes quantification of GHG emissions and C sequestration associated with LUC inherently uncertain and studies report widely different results. Bioenergy projects may also indirectly reduce LUC pressures, such as when the ethanol co-product DGS displaces soy as animal feed, reducing the direct LUC (dLUC) pressure associated with increasing soy demand.

Especially the inclusion of iLUC adds greatly to the uncertainty in quantifications of LUC effects. Because agricultural markets are integrated and supply response to shocks in demand can take place in various producing regions, LUC estimates have to be calculated globally. LUC estimates, therefore, can only be determined using global models, which are highly uncertain, because the available models are based on unobservable and unverifiable parameters and are dependent on assumed policy, economic contexts, and exogenous inputs. Models results, therefore, can only be verifiable if all conditions are also met in the reality.

For conceptual reasons, it is important to distinguish between dLUC and iLUC. Direct LUC accounts for changes in land used associated with the direct expansion of biofuel feedstock production, such as the displacement of food or fiber crops, pastures and commercial forests or the conversion of natural ecosystems. Indirect LUC comprises induced effects of biofuel feedstock expansion promoting land use changes elsewhere than where the expansion has taken place. For example, natural ecosystems can be displaced elsewhere in order to re-establish market equilibrium compensating for the losses in food/fiber production caused by the bioenergy project.

Bioenergy emissions associated to LUC are measured through three steps: dLUC and iLUC are accounted in area amount through global models; dLUC in area amount is translated into total emissions and total emissions are converted to an *iLUC factor* dividing it by bioenergy production. Emissions are estimated for the direct displacement caused by the biofuel crop and the direct displacement caused by another land use but as a result of the bioenergy crop expansion.

Although dLUC and iLUC are conceptually different, models capture both effects together. An *iLUC factor*, therefore, is a result of a combination between dLUC and iLUC. Differently than iLUC, dLUC patterns can theoretically be established through satellite images or secondary data and used as evidences for calibrating models. When measured in projections, however, both are determined by models scenarios. iLUC not being empirically observable, the estimation of an *iLUC factor* depends on assumptions of cause-effect relations that will attribute responsibility of land conversion to individual agricultural land uses.

Most of the attempts to quantify LUC and associated GHG emissions have used general or partial equilibrium models of varying scope concerning geography and spatial resolution, sectors covered and detail in their characterization (Keeney and Hertel 2009; Kretschmer and Peterson 2010; Lapola et al. 2010; Taheripour et al. 2011; Laborde 2011; Khanna and Crago 2012; Havlik et al. 2013). Alternative approaches include statistical analyses (Barona et al. 2010; Arima et al. 2011) and quantifications based on pre-defined causal-effect chains, where specific LUC patterns are assigned to specific biofuels/feedstocks grown on specified land types (Tipper and Brander 2009; Bauen et al. 2010; Fritsche et al. 2010; Kim and Dale 2009; Moreira et al. 2012). A stylized way of grouping modeling approaches for assessing LUC is to divide them in four families (Wicke et al. 2014), namely, computable general equilibrium models (CGE), partial equilibrium models (PE), bottom-up analysis and integrated assessment models (IAM).

Net GHG emissions associated with LUC are obtained by combining the LUC quantification outcome with data on GHG emissions associated with the specific types of LUC that are obtained. Equilibrium models with detailed biofuel features, incorporation of animal feeds, and revision of economic parameters (price elasticities of crop yields and demand) have been developed in the last years. Databases and models to quantify GHG emissions associated with LUC are continuously improved (Dunn et al. 2013; JRC 2010b; JRC 2011). Yet, limitations in methodology and data make quantification of iLUC emissions and identification of causal mechanisms behind iLUC highly contentious issues (Gao et al. 2011; Mathews and Tan 2009; Nassar et al. 2011; Prins et al. 2010). Equilibrium models, unless explicitly represented in scenarios, are not capable of capturing certain long-term changes, particularly considering innovation and paradigm shifts within agriculture systems. One strong example is the double crops systems that are still not represented in CGE models.

Nevertheless, considering the global nature of iLUC effects, global models, both general and partial, are up to now the most suitable methodology available for quantifying land use effects. The main weakness of the models, besides the methodological issues already mentioned, is that they are not friendly for policy makers and they give responses to specific conditions rather than generalized situations as expected by governments and legislators. Therefore, in general, policy makers are not confident in using their results for policy decisions.

17.2.2.1 Models Results: iLUC Factors

Estimated LUC emissions are usually presented in two formats: iLUC factors, i.e., CO_2e per unit of energy output, and area amount, i.e., hectares per unit of energy output. The majority of the studies present results in iLUC factors but due to the additional uncertainty that is added in the simulations related to the methodology used to translate area amount changes into emissions, some studies only present results in area amount (Taheripour and Tyner 2013; Elobeid et al. 2011).

Available model-based studies have found changes in land use as a result of biofuels feedstocks expansion, therefore resulting in positive iLUC factors. A comprehensive sample of iLUC factors results is presented in Table 17.3, which was inspired by and is an update of Figure 1 in Wicke et al. (2012). There are two main underlying reasons for models to estimate positive net LUC: they are not calibrated to allow productivity increase to compensate higher demand for biofuels and they assume that any expansion in production will require additional conversion of native vegetation land.

Table 17.3 shows results from a selection of studies of ethanol from corn, sugarcane and sugarbeet and biodiesel from palm, rape and soy. Results show that uncertainties are high and strongly associated to the methodology used. Although not described in Table 17.3, differences are also associated to scenario assumptions, as presented in ranges of some studies.

The more recent iLUC factors for corn and sugarcane ethanol have found much lower figures than reported in the initially published studies. iLUC factors for biodiesel crops are considerably higher and subjected to higher uncertainty levels than ethanol crops. Several reasons justify those findings: lower energy production rates per producing area, evidences of direct displacement of native vegetation by oil crops, no accounting for co-products and vegetable oil substitution patterns in economic models.

Collaboration, including model comparison and data and information exchange can result in less divergence of quantification outcomes from different research groups when similar cases are modeled. However, modeling outcomes are not valid beyond the specific conditions for which the model is calibrated. Since LUC depends on many factors that can develop in different directions, it should not be expected that methodology development and improved empirical databases will bring convergence towards narrow LUC-GHG ranges that are valid for the full range of possible future conditions.

Concerning LUC GHG emissions associated with cellulosic ethanol, Dunn et al. (2013) report low values. However, the outcome is sensitive to assumptions about whether ethanol is produced from organic waste and residues or from cultivated feedstocks and – if so – the LUC effects of expanding cellulosic feedstock cultivation.

At the time of the prior SCOPE report (SCOPE 2009), the magnitude of iLUC was felt to be large enough to negate the GHG emission benefits of an otherwise low-emitting biomass-based fuel supply chain. Five years later, this is no longer the case for ethanol crops as illustrated in Table 17.3. This change is a result of the reduction in the estimated magnitude of iLUC-induced emissions over time. Current trends relevant to iLUC observable in most parts of the world include ongoing improvements in the efficiency of feedstock production and conversion processes, decreased rates of deforestation, and more stringent regulation of agricultural practices. Each of these trends will reduce the magnitude of iLUC calculated using current models. Thus there appears to be a strong basis for expecting continuing reduction in the importance of iLUC-induced emissions in the future. Nevertheless, planning the expansion of biofuels with the objective to concentrate direct and indirect effects on less carbon rich soils continues to be very relevant.

Table 17.3. Summary of iLUC factors.

	Corn	Sugarcane	Sugar beet	Palm oil	Rape oil	Soy oil	Methodology
Searchinger et al. 2008	104.0	111.0	n.a.	n.a.	n.a.	n.a.	FAPRI
CARB 2009	30.0	46.0	n.a.	n.a.	n.a.	62.0	GTAP
EPA 2010	26.3	4.1	n.a.	n.a.	n.a.	43.0	FAPRI w/ Brazilian model, FASOM
Hertel et al. 2010	27.0	n.a.	n.a.	n.a.	n.a.	n.a.	GTAP
E4Tech 2010	n.a.	8.0-27.0	n.a.	8.0-80.0	15.0-35.0	9.0-67.0	Causal-descriptive approach
Tyner et al. 2010	15.2-19.7	n.a.	n.a.	n.a.	n.a.	n.a.	GTAP
Al-Riffai et al. 2010	n.a.	17.8-18.9	16.1-65.5	44.6-50.1	50.6-53.7	67.0-75.4	MIRAGE
Laborde 2011	10.0	13.0-17.0	4.0-7.0	54.0-55.0	54.0-55.0	56.0-57.0	MIRAGE
Marelli et al. 2011	13.9-14.4	7.7-20.3	3.7-6.5	36.4-50.6	51.6-56.6	51.5-55.7	MIRAGE and JRC emissions model
Moreira et al. 2012	n.a.	7.6	n.a.	n.a.	n.a.	n.a.	Causal-descriptive approach
GREET1_2013	9.2	n.a.	n.a.	n.a.	n.a.	n.a.	GREET
CARB 2014	23.2	26.5	n.a.	n.a.	n.a.	30.2	GTAP
Laborde 2014	13.0	16.0	7.0	63.0	56.0	72.0	MIRAGE and JRC emissions models
Elliott et al. 2014	5.9	n.a.	n.a.	n.a.	n.a.	n.a.	PEEL
Harfuch et al. 2014	n.a.	13.9	n.a.	n.a.	n.a.	n.a.	BLUM

17.2.2.2 Biofuels iLUC

iLUC comes about via market mediated responses to added commodity demands. As an example, the U.S. government policy of supporting corn ethanol causes an increase in demand for corn to produce ethanol; this induces several changes in the market (market mediated changes). First, the additional demand, everything else staying the same, will cause the price of corn to increase; this causes additional production of corn and corn substitutes anywhere in the world. It can also cause a reduction in corn consumption in response to the higher price. The added production of corn can come, first, from crop switching: more corn is produced, and less of some other crops is produced. In this case, the total cropland area might not change; there is just a reallocation of land towards more corn. The second change that can occur is that more land is needed for crops; and land can be converted from pasture or forest to cropland. This conversion can occur anywhere in the world.

The next question is how to determine how much land might be converted, where the conversion would occur, and to what extent it could be forest or pasture. These are complicated issues. One approach has been to use a global computable general equilibrium model, the Global Trade Analysis Project (GTAP) that has been adopted for handling biofuels and land use change (Hertel 1997; Hertel et al. 2009; Hertel and Tyner 2013; Hertel et al. 2010). As a general equilibrium model, all sectors and factors of production (land, labor, and capital) are represented in the model for each region. In simple terms, everything is related to everything else. For example, an increase in the price of corn not only affects corn markets, but can also affect other agricultural crops, inputs to corn production like machinery and labor, land rent, etc. GTAP has up to 113 regions and 57 commodity groups. However, it is normally run with aggregations that collapse the regions to around 18 and likewise for sectors. The sectorial and regional aggregations can be tailored to the specific problem being addressed.

The added demand for corn for ethanol is called a shock on the system. This shock can cause changes in any sector or region. The model, like most general equilibrium models, uses nests of production and consumption possibilities that govern how the shocks play out in the model. There are elasticities of substitution for different commodity groups that determine the extent of substitution possible. For biofuels, on the demand side, biofuels first substitute with petroleum products. Then this combination substitutes with other energy products and the combination of energy products finally substitutes with non-energy products. A similar structure is used on the supply side. Key parameters in GTAP help determine how the biofuel demand shock plays out:

- A yield price elasticity, which determines the extent to which crop yield increases over the medium term due to an increase in crop price.
- A whole set of land transformation elasticities that help determine the extent of forest and pasture conversion in each region (Taheripour and Tyner 2013).

- Parameters regarding the expected productivity of natural land converted to crops, estimated using a Terrestrial Ecosystems Model (Taheripour et al. 2012).
- The livestock sector in GTAP accounts for biofuel byproducts (Taheripour et al. 2011; Taheripour et al. 2010).

The important output is land use change. To the extent that land is converted from pasture or forest to annual crops such as corn, there is a loss of stored carbon and possibly also foregone future C sequestration, depending on characteristics and future fate of the land had it not been converted to feedstock cultivation. Models parameters, however, when empirically calculated, are calibrated based on historical trends or expert opinion. All models predicting pasture conversion to crops also have forest conversion as output. Such a result would not necessarily occur if pasture yield response was able to compensate the higher land demand for crops.

17.2.2.3 Translating Land Use Changes into GHG Emissions

Increased demand of bioenergy is likely to cause both direct and indirect land use change. Converting land cover types with high biomass and soil carbon stocks (e.g. forests) into cropland usually results in an immediate loss of carbon store in above and belowground biomass (vegetation), and a more gradual decline of carbon in the soil organic matter (SOM).

The carbon released from biomass is emitted to the atmosphere as CO_2, while other non-CO_2 gases will be emitted under particular circumstances (i.e. if biomass burning is involved in land clearing). SOM contains both nitrogen and carbon and a decline of SOM releases both CO_2 and N_2O.

Land use change may also cause an increase in soil carbon stock over the existing level (e.g. through changes in crop management) or in biomass (e.g. if grassland is replaced by permanent woody crops or sugarcane).

In the case of direct land use change, the calculation of GHG emissions is usually implemented using simplified methods based on default emissions factors for soil and biomass carbon stocks. Although straightforward, this method is subjected to debate given that it may not capture local variations accurately.

The first aspect of the GHG impact, for correct estimate of size and location of emissions, is the characteristic of the land that would be converted to evaluate how much carbon would be released as a result. Therefore, global maps of soil organic carbon levels under different land uses are needed in order to estimate the effects of changes in soil carbon associated with scenarios of change in cropping systems under demand for biofuels. Furthermore, N_2O emissions due to the mineralization of nitrogen accompanying soil carbon stock decrease must be considered, together with CO_2 emissions which result from change in above and belowground biomass carbon stocks, due to changes in cropland area.

Precise rules for the calculation of land carbon stocks changes due to land conversion for biofuel production are established in EU legislation, following the Tier 1 approach described (IPCC 2006). It is based on the definition of default values of carbon stocks for a set of soil, land cover and climate conditions. The default carbon stocks are modified according to changes in land use, management practices and inputs, which form a management system. Explicit data on cropland categories and a breakdown on crop types (e.g. perennial or annual) are also included in the methodology (EC 2010; JRC 2010a).

However, quantifying the indirect effects of bioenergy policies is a complex exercise that requires a combination of energy, agro-economic, global land use and emission modeling approaches.

Agro-economic models provide estimates of the total change in crop area for a given increase of biofuel demand and of how much extra crop would be produced in different countries or world regions as a result of biofuels policies. Some models also predict the area of land converted from pasture, forest, or natural land into cropland within each region, but in most cases they do not specify where in the economic regions the extra-production will take place. To calculate carbon stock changes resulting from land conversion, economic models must be combined with biophysical or other land use models. One crucial issue is to identify those areas within a certain economic region where the expansion of biofuels production is most likely to occur, and how the additional (marginal) cropland required in different bioenergy policy scenarios can be spatially distributed (see Chapter 9, this volume). Since GHG emissions from land use change vary depending on soil, climate, management factors, status of converted land etc., the level of spatial disaggregation used is important to capture the pattern of agricultural expansion and related GHG emissions within an economic region.

One relevant example of geographically explicit “biophysical” models is the AEZ-EF model, which was developed to be applied to the GTAP economic model (Plevin et al. 2011). With AEZ-EF, average values for carbon stocks are calculated and aggregated to the same combination of 19 regions and 18 Agro-ecological Zones (AEZ) used in the GTAP–BIO-ADV economic model (Tyner et al. 2010). No specific criteria for land allocation were applied to compute weighted average, which means that land selection is random and that carbon stocks are assumed to vary little across the landscape.

However, applying generic regional emissions factors cannot capture the differences in terms of GHG emitted between two crops with different soil or climatic needs expanding in two distinct areas of a same country. Spatially explicit models capable to calculate the emissions at grid cell level are more suitable for this purpose; results can be aggregated to the economical regions of interest afterwards (which also may facilitate the comparison between models which do not use the same economic regions). These models are more sophisticated, but certainly also data-challenging.

An example of “spatially resolved” models is the CSAM (Cropland Spatial Allocation Model) developed by the JRC (JRC 2010b; JRC 2011). It allows for the computation of

GHG emissions and CO_2 removals due to changes in soil organic matter, and above- and below-ground biomass carbon stocks. Such a method can potentially be applied to the outcome of any economic model; easing comparison of iLUC emissions estimated from different models (CSAM accepts results of AGLINK-COSIMO, FAPRI-CARD, GTAP and IFPRI-MIRAGE).

17.2.2.4 Options for Mitigating iLUC from a Policy Making Perspective

Indirect LUC derived GHG emissions are associated to the indirect conversion of carbon rich areas as a consequence of bioenergy production expansion. There is a growing consensus that policies stimulating biofuels adoption should also encompass options for mitigating iLUC (Wicke et al. 2012).

The first option for mitigating iLUC is, therefore, reducing deforestation through national policies, monitoring systems, environmental zoning and landscape management. National policies for deforestation control, however, are out of the scope of any renewable energy policy, which challenges policy makers, especially the ones from supplying regions. Deforestation is showing consistent decreasing rates in some regions in the world, indicating that iLUC have a great potential to also decrease over time. Increasing the amount of bioenergy produced per unit of land is the second mitigation option. Increasing crop yields is one alternative but more limited than using the residual biomass for producing lignocellulosic ethanol. In some crops the use of the biomass combined with the ethanol produced from sugar or starch can strongly increase productivity leading to potential positive impacts in iLUC reduction.

Making land more productive is a third option. Yields gaps are still high in agricultural systems of regions with very low yields compared to big agricultural producers such as the U.S., Canada, Brazil, Argentina, and some European countries. Increasing double crop and crop-livestock integration systems can also increase agricultural production with no impacts on additional demand for land. Nevertheless, the large potential for increasing land productivity is in pasture systems (see Chapter 9, this volume). Some regions are facing strong pasture intensification processes helping reduce deforestation and natural vegetation land conversion.

Developing crops suitable for marginal, degraded or erratic precipitation lands is the fourth option. Large amounts of marginal land are occupied with degraded pastures with low potential to increase cattle productivity. Either for some regions in the world or for tackling specific regional conditions, growing bioenergy crops in marginal lands can be a viable option for mitigating iLUC (see Chapter 18, this volume). The use of such lands can be one way of mitigating iLUC and can in some instances result in C sequestration into soil and biomass. Even when they are available it might be more favorable to cultivate the better soils. This depends on economic and policy context where the feedstock cultivation expands.

17.2.3. Bioenergy Systems, Timing of GHG Emissions and Removals, and non-GHG Climate Change Effects

Bioenergy is effectively carbon neutral, as long as there is no decline in the average carbon stock in the areas supplying the biomass, except for emissions from biomass production, transport and processing. However, the timing of CO_2 sequestration and emissions influences the warming impact over a given time period. In long rotation forestry, carbon is sequestered by the growing stand for many decades before harvest takes place; emissions occur when biomass is used for bioenergy. Emissions are delayed when biomass is stored as forest products, before the final use for bioenergy.

In single forest stands when biomass is extracted for bioenergy an initial increase in net GHG emissions is found unless the biomass use displaces very emissions-intensive fossil carbon sources. However, stand level quantification is not sufficient for determining how the deployment of forest based bioenergy influences climate; the induced effect on the carbon stock across the whole forest landscape must be considered.

Bioenergy demand may induce changes in forest management regimes, changing rates and timing of carbon sequestration and/or release. Re-establishing a stand through planting instead of relying on natural regeneration, or skipping pre-commercial thinning to produce a larger bioenergy harvest in later thinning, result in increased sequestration at least during the time preceding the thinning. Conversely, the use of felling residues for bioenergy expedites carbon releases that would occur as residues decay. Changes in forest management to enhance biomass production may lead to gains in forest carbon stocks in some circumstances.

If bioenergy demand leads to forest management and harvesting regimes that increase the forest carbon stock across the whole forest landscape, the GHG mitigation is enhanced. If the forest carbon stock is reduced, there may be a delay until the savings from avoided fossil fuel emissions lead to a net reduction in atmospheric CO_2 (e.g. Walker et al. 2010, McKechnie et al. 2011, Hudiburg et al. 2011); and the temporary increase in atmospheric CO_2 will cause increased global warming. Also, in some situations the forest carbon stock may increase, but at a slower rate compared to the absence of harvesting for bioenergy; bioenergy is in this case associated with foregone carbon sequestration, to be taken into account when evaluating the net GHG effect. In assessing foregone sequestration it should be recognized that sequestration rate slows as forests approach maturity (Cowie et al. 2013).

Several authors have proposed metrics to account for the timing of GHG emissions and removals, to be incorporated in LCA (Brandão et al. 2012). Levasseur et al. (2010) developed the “dynamic LCA” approach, which quantifies the radiative forcing resulting from an emission during a finite assessment period, and assigns a reduced impact if emissions are delayed within this period. Applying a similar approach to bioenergy, Cherubini and others have proposed (Cherubini et al. 2011) and demonstrated (e.g. Guest et al. 2013) a method that quantifies the radiative forcing over the assessment period due to combined effects of a pulse emission followed by regrowth. They define a modified characterization factor "GWP_{bio}" that reflects this temporal profile of radiative forcing in comparison with a pulse emission of fossil CO_2, and varies with rotation length of the forest system. Cherubini et al. (2013) assessed bioenergy systems based on global temperature potential (GTP), which is more directly related to surface temperature change than GWP, and demonstrated that GTP indicates greater positive contribution from long rotation forest systems than GWP does.

Berndes et al. (2010) proposed "GHG emissions space" as a complementary concept to encourage consideration of longer-term temperature targets. Focusing on the accumulated emissions up to a given year (which is relevant for CO_2 in relation to temperature targets), society may decide to invest a portion of the emission space allowed within the GHG target on the establishment of renewable energy systems. For equilibrium temperature targets (e.g. 2 degrees), the exact timing of CO_2 emissions and removals is not important; but if systematic changes in carbon stocks occur, they need to be considered. Cowie et al. (2013) argue that some level of - possibly temporary - carbon stock reductions due to bioenergy expansion can be viewed as an investment in establishing the renewable system.

Besides the impact on fluxes of GHGs, bioenergy systems can affect climate through additional forcing processes, including direct impact on albedo (e.g. Georgescu et al. 2011; Loarie et al. 2011). Harvest of forests in high latitudes or altitudes with snow cover can increase albedo, reducing global warming (Bright et al. 2013). In some circumstances this effect is substantial, even counteracting negative impacts of a reduction in forest carbon stock (Bright et al. 2011). Similarly, changes in albedo and evapotranspiration due to conversion of crop and pasture land to sugarcane in the Brazilian Cerrado are found to have a localized cooling effect, adding to the climate mitigation benefit of biofuels (Loarie et al. 2011). In contrast, where evergreen biomass crops are planted into high-albedo landscapes (snow covered or arid) this can decrease the albedo (Schwaiger and Bird, 2010). Cherubini et al. (2012) included the temporal imbalance in CO_2 emissions and removals and change in albedo for a range of biomass sources, concluding that they can be important in case-specific assessments. Bioenergy systems may also influence climate through emissions of aerosols, or black carbon, in different ways (Box 17.3).

17.2.4. Funding Innovation: Data Needed to Support Policies and Strategic Decisions

Harnessing innovation capacity and investments of the private sector requires policy frameworks that provide long-term investor security and that set investments on a sustainable trajectory. Policy frameworks must be based on integrated planning on the national policy and individual project levels, considering different end uses of biomass within the planetary boundaries, and their GHG emissions mitigation. Data are required both for developing and evaluating these frameworks. Challenges related to land use and water require particular attention (see Box 17.4; UNEP GEO-5 2012; Chapter 18, this volume).

Box 17.3. Advanced bioenergy systems may reduce emissions of black carbon and aerosols

Black carbon emitted through incomplete combustion of biomass is a short-lived but powerful climate forcing agent: it absorbs radiation, influences cloud formation, and when deposited on snow and ice it reduces albedo (Forster et al. 2007). The net effect is complex and site dependent; so there is high uncertainty over the absolute estimates of the impact of black carbon. Organic carbon particles released through biomass combustion scatter radiation, offsetting global warming caused by black carbon (Forster et al. 2007). Increased use of bioenergy in developed countries may increase emissions of black carbon and organic carbon; but replacing traditional fuel wood uses in developing countries with improved biomass cook stoves and advanced bioenergy technologies is critical to reducing black carbon emissions (UNEP 2011).

Land use Mapping and Agro-Environmental Zoning have been successfully used by a number of countries to formulate policies and designate production areas, with the aim of addressing cumulative effects of projects on land and water, and curbing direct and indirect effects of land use change.

UNEP has identified variables that should be considered for a bioenergy mapping methodology (UNEP 2010); they include agro-climatic variables (e.g., water balance and edaphic variables), environmental screening of sensitive areas, screening of other land use (e.g., cultural, medicinal and food production), and infrastructure / logistics. The level of detail in terms of scale and accuracy of data for each variable is important for planners to consider; often there is a tradeoff between availability and cost of data. For example, often only annual rainfall data are available, whereas at least seasonal variations would be needed, complemented by measurements of impacts on the watershed level. In many developing countries data availability is a concern, and institutional strengthening is needed to improve the capacities to gather and analyze data.

The Global Bioenergy Partnership (GBEP 2011) agreed on 24 sustainability indicators to provide a framework for collecting data. The indicators are value neutral, “do not feature directions, thresholds or limits and do not constitute a standard, nor are they legally binding. Measured over time, these indicators will show progress towards or away from a nationally-defined sustainable development path” (GBEP 2011), and inform any corrective measures. For example, the four components of the indicator ‘Land use’ (Box 17.4) allow an evaluation of the role bioenergy plays in land use and LUC, and the LUC implications of different bioenergy feedstocks. With the “measurement of the share of land used for bioenergy feedstock that has been subject to some land suitability assessment, it will indicate how bioenergy expansion is part of official land use planning” (GBEP 2011). The indicator on Water use and efficiency (Box 17.4) "gives information about the extent of water demand from the bioenergy sector and how it compares to water availability and other competing uses" (GBEP 2011) in a given watershed. Analyzed in combination with projections of future changes in water demand (population growth, climate change, consumption patterns), it can inform an outlook on longer-term sustainability of national bioenergy plans. It also "provides a tool to monitor current water use efficiency and compare it with best practice data, so as to optimize the use of water resources for bioenergy production" (GBEP 2011).

The testing of indicators in a number of countries has confirmed the usefulness of the framework for policy decisions and for stakeholder engagement including representatives of different Ministries, industry and civil society, and is leading to a more integrated approach to planning, beyond bioenergy development. Yet, it also pointed to some challenges: insufficient data availability, suitability and quality; need for a simplified methodology; different country contexts requiring adaptation of indicators.

Box 17.4. Land Use Resources, Soil Quality and Water Use Indicators (GBEP 2011)

Land Use Indicators

- Total area of land for bioenergy feedstock production, and as compared to total national surface

- Agricultural land and managed forest area

- Percentages of bioenergy from: yield increases, residues, wastes, degraded or contaminated land

- Net annual rates of conversion between land-use types caused directly by bioenergy feedstock production, including the following: arable land and permanent crops, permanent meadows and pastures, and managed forests; natural forests and grasslands (including savannah, excluding natural permanent meadows and pastures), peat lands, and wetlands.

Water Use and Efficiency Indicators

- Water withdrawn from nationally-determined watershed(s) for the production and processing of bioenergy feedstocks, expressed as the percentage of total actual renewable water resources (TARWR) and as the percentage of total annual water withdrawals (TAWW), disaggregated into renewable and non-renewable water sources;

- Volume of water withdrawn from nationally determined watershed(s) used for the production and processing of bioenergy feedstocks per unit of useful bioenergy output, disaggregated into renewable and non-renewable water sources.

At project level, FAO/UNEP/UNIDO developed a Screening Tool (GEF 2013) related to ten sustainability criteria, with three levels of quantitative and qualitative thresholds to evaluate risks of biofuels projects. As an example, for GHG emissions a calculator provides pre-calculated GHG balances for 74 biofuels settings (no LUC related emissions included); the settings can be adapted and the calculator can accept user-defined input data. The tool is useful for assessing project proposals. The data to be used in the screening process are clearly established; project developers determine the areas to be used (avoiding conversion of carbon-rich ecosystems) and the final use of co-products.

Also applicable at the project level, the Organization for Standardization (ISO) is developing a standard to define sustainability criteria for bioenergy intended for reporting by the individual economic operator.

Improving local data collection is key for determining impacts. Improved global land-use mapping/ GIS data are necessary to track land use and help address cumulative effects. Support activities are needed at national, regional and global level to strengthen data availability. Governments and ministries in developing countries will require support in collecting comprehensive and current data, which can inform decision making for biofuel projects.

17.3 Conclusions

- Technological development for commercial (first generation) biofuels has improved biomass production and conversion in the last 30 years, as well as the use of by-products and co-products with important gains in GHG mitigation; improvements are expected to continue in the next years. Ethanol from sugarcane shows the largest “average” net LCA GHG mitigation (including LUC) today. Biodiesel (rapeseed, sunflower, soybean and palm oil; Europe) provides 30 – 60% mitigation (no LUC considered). Commercial biopower generation with solid biomass (wood and agricultural residues, short rotation woody crops) GHG emissions range from 26 to 48 (averages) g CO_2e / kWhe (systems > 10 MWe), providing substantial net GHG mitigation from fossil fuel thermo-electric plants (1000 g CO_2e / kWhe for coal, 800 g CO_2e / kWhe for oil, or 550 g CO_2e / kWhe for natural gas).
- With the proper matching of technology and local conditions, and applying sustainability screening, biofuels can make important contributions to reduce LCA GHG emissions globally.
- Advanced (second generation) bioenergy technologies (cellulosic ethanol, and synthetic diesel from BtL thermochemical technologies) have shown (although still at development stage) the possibility to reach larger net GHG mitigation than the commercial liquid biofuels today, with BtL technologies better than cellulosic ethanol (averages); again, sustainability screening must be applied.

- In the last five years, a deeper understanding of the LCA issues in the evaluation of GHG net emissions from biofuels led to improved models and the search for better data (carbon stocks, iLUC, co-products treatment, N_2O emissions), significantly changing some earlier results (e.g., iLUC estimates). The complexity involving different feedstocks, regions, soils, local land use contexts, and conversion processes requires more data and still better analyses to provide sound support for policies.
- LUC emissions were formerly thought to be sufficiently large to change an otherwise low-emitting fuel supply chain into one offering no benefit relative to the status quo. Recent studies, however, indicate that iLUC factors are decreasing for ethanol crops indicating that bioenergy is capable of reducing emissions.
- iLUC estimates can only be determined using global models; the available models are based on unobservable and unverifiable parameters and are dependent on assumed policy, economic contexts, and exogenous inputs. Models results, therefore, can only be verifiable if real markets meet all conditions.
- Options for mitigating iLUC are: reducing deforestation and native land conversion rates, increasing the amount of bioenergy produced per unit of land using residual biomass, making land more productive through double cropping, crop-livestock integration and pasture intensification, and developing crops suitable for marginal, degraded or erratic precipitation lands.
- It is reasonable to expect increasing GHG emission reductions calculated on an LCA basis, and a reduction of LUC emissions over time resulting from continuing trends of increased efficiency of feedstock production and conversion, increased penetration of renewables into the energy matrix, decreasing rates of deforestation, and increasing regulation of land use and land clearing.
- Accounting for the timing of GHG emissions and removals may be important in forest based biomass systems (long rotation times).
- In specific conditions, the change in albedo resulting from LUC (for biomass production), and the aerosol and black carbon emissions from the biomass conversion systems, can have a significant influence on global warming, and they should therefore be considered.
- Acceptable biofuels are those that lead to significant GHG emissions mitigation, while minimizing other environmental and social impacts. To support public policies (planning and monitoring), tools have been developed for use at national (GBEP 2011) and at project level (GEF 2013; ISO 2013); improving data collection is key for determining impacts.

17.4 Recommendations

The experience with commercial biofuels development, the successful results (aiming at GHG emissions mitigation), the great improvements in co- and by-product utilization, and the potential for advanced biofuels indicate the paths to follow towards more efficient and sustainable biofuels. Technical challenges include methodological difficulties in evaluating GHG emissions, and the need for reliable data. Institutional challenges include support for implementing adequate policies. To address the needs, we recommend:

- Support programs to improve local data for soil conditions, SOM stock changes, and N_2O emissions; and to improve the knowledge of the impacts on climate of timing of GHG emissions and removals, and of biomass production / conversion (processes that affect albedo and aerosols).
- Continued efforts towards harmonization in outstanding GHG quantification issues (by-products, co-products and residues treatment; iLUC consideration and interpretation).
- Actions are needed both at national policy and at project levels to enhance GHG benefits from biofuels. The main points are: establishing of specific zoning systems to manage LUC emissions; policies for deforestation control and monitoring; implementation of good practices in agriculture and forestry; programs for increasing land productivity (see Chapter 9, this volume). New governance structures supported by technical understanding and effective monitoring may be needed. Bioenergy could lead the development of such structures, with benefits that would spill over the whole (much larger) land use sector, including agriculture and forestry.

17.5 The Much Needed Science

- New technologies for advanced biofuels production;
- Search for a higher level of (scientific) consensus on the treatment of net emissions for co-products and by-products;
- N_2O emissions data in bioenergy systems;
- Local data on SOM change with LUC;
- Search for a higher level of (scientific) consensus on the iLUC evaluation;
- Global land use data and monitoring system (including agriculture, silviculture, and pastures); see Chapter 16, this volume.

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chapter 18

Soils and Water

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Highlights

- Bioenergy systems can have positive impacts on water and soil resources when feedstocks and conversion technologies are matched to local conditions and planning includes holistic landscape-level assessment.
- Landscape-level optimization of bioenergy, especially perennial and woody systems, can reduce soil erosion, improve water quality, allow nutrient recycling, and promote carbon sequestration in soils.
- Like other agricultural, silvicultural and industrial systems, bioenergy can cause negative impacts, which should be minimized through appropriate planning and use of Best Management Practices.
- Policies addressing environmental impacts of bioenergy should be informed by assessments specific for the location, rather than relying on average/generic data and broad brush footprint and efficiency metrics.

Summary

Bioenergy production can have positive or negative impacts on soil and water. To best understand these impacts, the effects of bioenergy systems on water and soil resources should be assessed as part of an integrated analysis considering environmental, social and economic dimensions. Bioenergy production systems that are strategically integrated in the landscape to address soil and water problems should be promoted where their establishment does not cause other negative impacts that outweigh these benefits (Figure 18.1). While standardized metrics, such as footprints and water- and nutrient-use efficiencies are convenient and intuitive, they can be insufficient to achieving sustainable production and environmental security at relevant spatial and temporal scales. Rather, comprehensive ecosystem impact analysis should be conducted. Sustainability standards and certification schemes should use metrics that are consistent with other agricultural and silvicultural activities and sustainability goals at the local, regional, and global level.

Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is possible and essential. Bioenergy crops offer

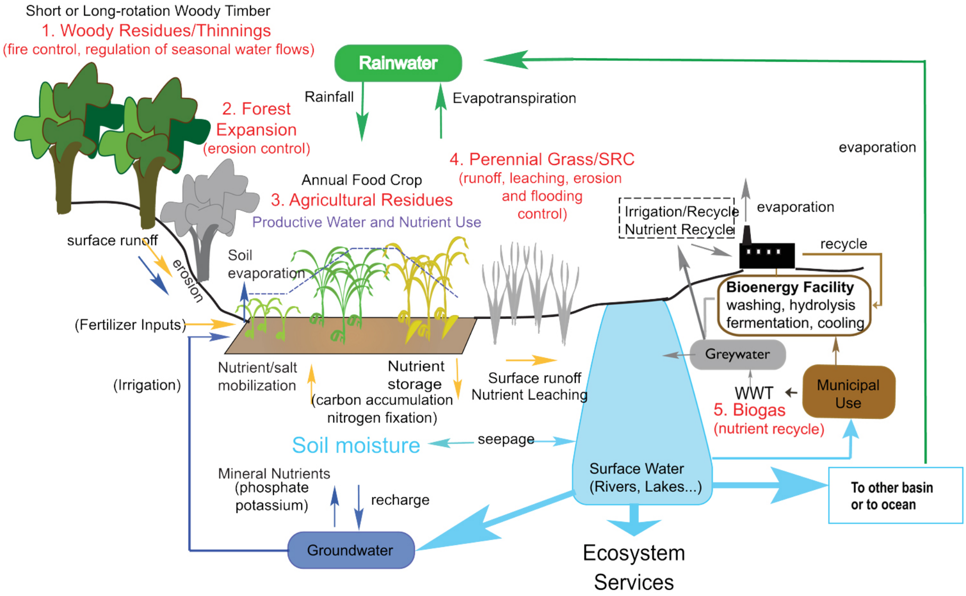

Figure 18.1. Bioenergy, Soils and Water – There are many opportunities to implement or improve bioenergy production to address long-term sustainable use of water and soil resources. For example, in cases where erosion and water/nutrient flows are excessive, such as sloping land (2) and riparian zones (4), woody and perennial bioenergy crops may provide relief. In lands already under productive forest (1), agricultural (3), or urban use (5), the use of harvest residues may be appropriate. As in all land use, inputs such as fertilizers and irrigation should be used judiciously. The inter-related impacts of bioenergy systems on water and soil must be examined in an integrated assessment with consideration of other human activities and ecosystem service requirements.

good opportunities for nutrient recycling, and in some cases, can increase soil organic matter, which improves soil quality and may also mitigate carbon dioxide (CO_2) emissions. However, excessive removal of plant material from the field or forest may jeopardize soil and water quality, causing economic and environmental losses. The need to retain some portion of crop or forest residues is site-specific and regional data are important to guide practices. Higher output in crop and forest production, enabled by active management and the use of inputs such as fertilizers and irrigation, can spare land and enable more efficient resource allocation. However, possible negative impacts on water availability and water and soil quality should be assessed and minimized. If there is a risk for serious impacts on local livelihoods and food security and environmental flows, irrigation of energy crops may need to be avoided, even in instances where it represents the most productive use of available water in terms of output or income per unit water. Caution, periodic evaluation, and appropriate water pricing and allocation systems can help avoid unwanted effects in water-stressed regions. In most cases, bioenergy solutions can be found that contribute to energy and climate security and which are compatible with local and regional constraints. As in other agricultural activities, the adoption of Best Management Practices (BMPs) is important in bioenergy feedstock production because it tends to minimize risks of excessive input use.

18.1 Introduction

Bioenergy systems can affect the state of water and soils in both positive and negative ways. The outcome depends on: (i) the nature of the feedstock production systems; (ii) their location in the landscape; (iii) what types of land cover/use are replaced; (iv) the location of the biomass conversion facilities; (v) whether - and if so how - the biomass conversion facilities integrate with other societal activities, such as waste management, industrial activities, energy supplies other than bioenergy, and the land using sectors, and (vi) the quantity and quality of local water supplies.

This chapter describes the soil and water consequences of bioenergy systems and discusses how novel and emerging bioenergy systems may present challenges as well as opportunities concerning soil and water. Soil and water effects depend critically on how previous management has influenced the state of soil and water and whether bioenergy implementation induces *changes* in management of land and water resources (and in management of energy and material flows in general). For this reason, special attention is paid to how an expanding bioenergy sector - that changes in character over time due to evolving governance and innovation - may affect the state of soils and water. There has been a surge in research studying environmental impacts since the previous SCOPE reports (de Fraiture and Berndes 2009). New knowledge – which has moved beyond speculation to hard data – is highlighted, but general quantitative impact factors such as efficiencies and footprints are not specified in the discussion since these numbers may provide a false sense of surety regarding impacts and they often bear little relevance to impacts within any particular region or implementation strategy (Berndes 2002; Efroymson et al. 2013; Jewitt and Kunz 2011) (see section 18.1.2).

18.1.1 Interconnectivity of Water and Soil

Water and soil are inextricably linked (Table 18.1, Figure 18.2), providing the basic chemical requirements for plant life on earth (Neary et al. 2009). The use of such resources, for bioenergy or any other human purpose, must be viewed in the context of total ecosystem services and through the lens of long-term sustainability. In a world where close to one-third of the Earth's land surface is used for agriculture production - which is also responsible for about 70% of global freshwater use (Aquastat 2012) – bioenergy development might present considerable challenges, from the perspective of soil and water quantity as well as quality. At the same time, bioenergy systems present new opportunities to improve land and water productivity and help address soil and water impacts of current land use.

Table 18.1. Interdependencies of water and soil resources.

	Soil Tilth	Soil Organic Matter	Mineral Nutrient Availability	Water Holding Capacity	Erosion
Water Runoff	▲	🟢	🟢	●	■
Precipitation Interception					🟦
Downstream Water Availability	🔵	🟢		🔵	
Soil moisture	●	🟢	🟩	🔵	
Evaporative Losses	▲	🟢	■	🟦	
Surface Water Turbidity		🟢	🟢		●
Eutrophication		🟢	●		🔵
Groundwater Recharge	🔵	🟢		🔵	

Key: ● Soil effect on water ■ water effect on soil ▲ mutual effect

Black = direct physical effect, Green = effect mediated through the crop specific attributes such as root or canopy structure, Blue = effect is both physical and plant-mediated

18.1.2 Metrics

The use of metrics that concern only one or a few aspects (e.g., footprints, water and nutrient use efficiency (Box 18.1) in lieu of comprehensive ecosystem impact analysis has become common in discussions about bioenergy. However, such metrics, while convenient and intuitive, should not be used in isolation since they can be misleading and irrelevant to assessing sustainability of production and environmental security (Yeh et al. 2011). For example, a system can have ten-times the water use efficiency (WUE) as another system while using twice the water. Even so, neither the absolute water use nor the WUE is sufficient to decide if either system is appropriate for a given site. Rather, a full understanding of the land cover-soil-atmosphere feedbacks on the hydrologic cycle in the context of all human uses and ecosystem functions, as well as the consequences for other resources including information about social and economic costs and benefits at that site is required. Assessing these effects among resource users requires agreement on metrics, methodology, and ethical values, including social, economic, and environmental sustainability criteria and acceptable limits to change in resource availability and quality, which requires transparency and stakeholder input as well as an appropriate baseline against which any impacts can be assessed (Chapter 19, this volume). Also, allocation of water impacts in multiproduct landscapes such as the production of both food/feed and energy needs to be standardized (Chapter 13, this volume).

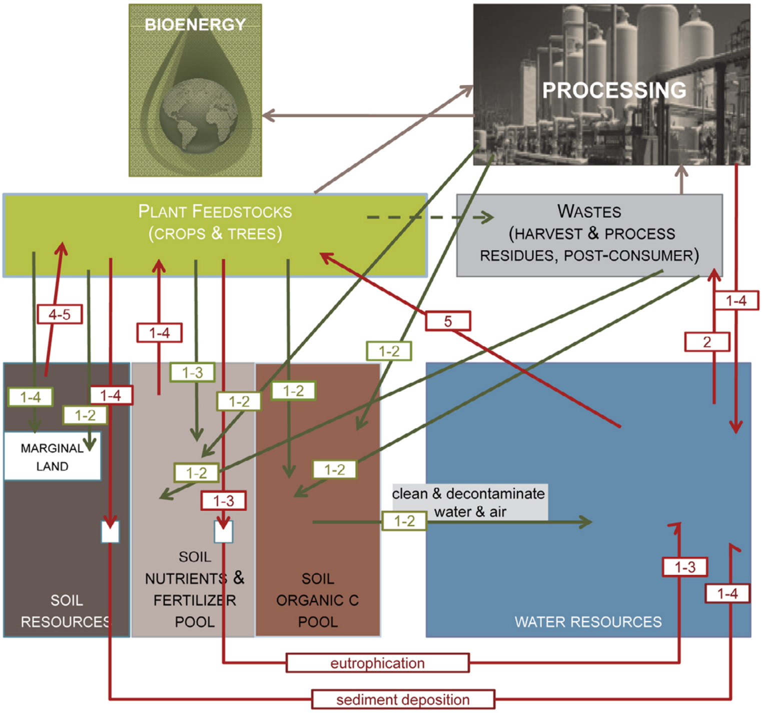

Figure 18.2. Water and Soil Impact Matrix – Diagram of the complex soil-water-feedstock interactions for bioenergy production. Red arrows indicate resources expenditure for feedstock production or negative impact. Green arrows represent mitigating activities or positive impact. Boxed numbers are the estimated size of the impact in a 1-5 scale and illustrate the possible range of impact. Proper management of bioenergy production should focus on increasing the beneficial and reducing the negative impacts so that the balance is positive. **Resource expenditures**: soil, water, and nutrients are needed for cultivation of bioenergy biomass; water is also spent for feedstock processing. **Negative impacts**: contamination/eutrophication from waste disposal; erosion, sediment deposition and nutrient leaching that affect soil and water quality from land cover change and field cultivation and maintenance. **Positive impacts**: Carbon and nutrient recycling and soil protection from perennials, plant residues, and wastes (both from feedstock and processing) returned to or maintained in the field; organic matter improvement to soil quality and provision of environmental services such as water and air cleaning and decontamination.

The water intensities (or water footprints) of biofuels reported in the literature vary by orders of magnitude (Figure 18.3). Though widely adopted, the methodology for such reporting is not standardized, not validated by measurement, and marginally useful for determining ecosystem impact. Some footprints include rainwater inputs, theoretical transpiration losses from plant growth, and in some cases theoretical use of irrigation water. Some include additional water volume as a proxy for water quality impacts. Water use is not consistently allocated when multiple products arise from a particular feedstock.

However, the recently completed ISO water footprint standard (ISO 14046) is intended to improve consistency in quantifying water footprints.

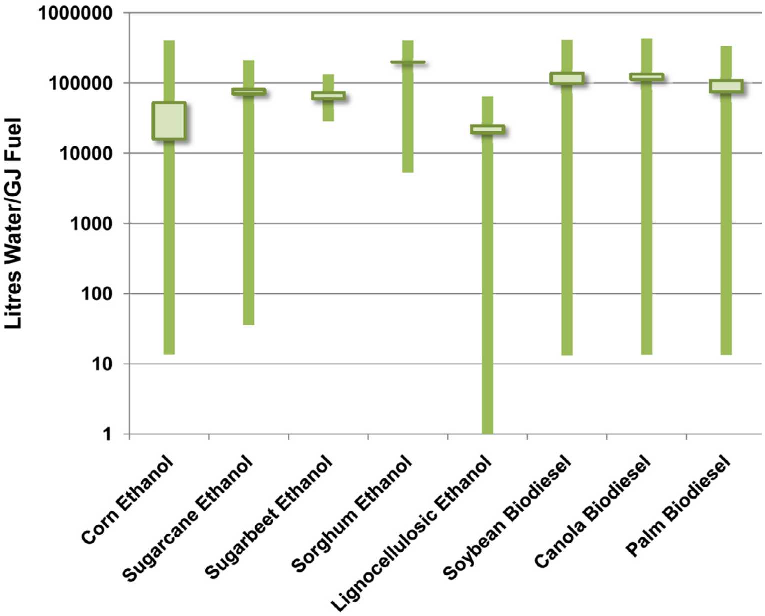

Figure 18.3. Water intensity indicators are not sufficient to guide decisions but must be complemented with other metrics and evaluation frameworks. (Solid bars indicate the range of values reported in literature. Boxes represent the difference in the median and mean values. The range for lignocellulosic ethanol includes thermochemical and biological conversion pathways.) Sources: Gerbens-Leenes et al. 2009; Fingerman et al. 2010; 2011; US National Research Council 2008; Bhardwaj et al. 2010; deFraiture et al. 2008; Scown et al. 2011; Schornagel et al. 2012; Wu et al. 2009; Kaenchan and Gheewala 2013; Gerbens-Leenes et al. 2008; Dominguez-Faus, et al. 2009; Rio Carrillo and Frei 2009; Gerbens-Leenes and Hoekstra 2012; Chiu and Wu 2012.

Box 18.1. Definitions of Terms (Sources: Hoekstra et al. 2011; Baligar et al. 2001; Baldock and Nicoll 2008; Neary 2013)

Best Management Practices (BMPs): These activities constitute a system of recommended actions. In bioenergy production these can relate to resource stewardship, biomass cultivation and harvest, and waste disposal. The rationale for BMP usage is multifaceted. Some of the reasons include (1) State and National environmental regulations, (2) Agency regulations and goals, (3) Private land management objectives, (4) Land manager desires to seek certification for marketing purposes, (5) Corporate/individual commitment to sustainability goals, (6) Recognition of the productivity benefits of BMPs, (7) Desire to integrate multiple ecosystem services into resource management, (8) Cultural and religious legacy, (9) Personal conservation heritage, and (10) Desires to emulate successful examples of good natural resources management.

Nutrient Use: The mass of nutrient amendment (fertilizer added) or the amount required for optimal yield. Thus, the use is dependent on the concentration of available nutrients in the soil, which is highly variable. The nutrients most commonly limiting plant growth are nitrogen, phosphorous, potassium and sulfur.

Nutrient Use Efficiency (NUE): Similar to WUE, the term NUE is a commonly used abbreviation for yield per unit nutrient input. In agriculture this is usually related to the input of fertilizer, whereas in scientific literature the NUE is often expressed as fresh weight or product yield per content of nutrient in the plant. NUE depends on the ability to efficiently take up the nutrient from the soil, but also on transport, storage, mobilization, usage within the plant, and even on the environment. Improvement of NUE is an essential pre-requisite for expansion of crop production into marginal lands with low nutrient availability.

Soil Organic Matter/Soil Organic Carbon (SOM/SOC): Soil organic matter (SOM) is plant and animal material humified or in the process of decay. This material contains many elements including soil organic carbon (SOC). Deposition and lifetime of SOM and SOC varies by climate, plant type, by soil and water conditions, microbial population, and management activities including fertilization, tilling, drainage, etc.

Water Footprint: An indicator of freshwater use that looks at both direct and indirect water use and can include groundwater, surface water, rainwater, and traded water embedded in products (virtual water) as well as proxies for water quality and other ecological impacts. Footprints are usually expressed in the same units as efficiencies. How footprints are calculated is highly variable.

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Water Use: The volume of water required by an activity such as growing a feedstock or converting that feedstock to a useful energy carrier. Water use is discussed in terms of water withdrawal (the volume of freshwater abstraction from surface or groundwater) and water consumption (the volume of freshwater used and then evaporated, transpired, incorporated into a product, or moved to another watershed).

Water Use Efficiency (WUE): The volume of water used in relation to a specified parameter, commonly water use per unit of product or, water use per unit gross/net revenue. For bioenergy this is typically liters of water per liters of biofuel produced or liters of water per MWh electricity, etc. WUE can be improved through management by eliminating excess water applications and minimizing water losses or through plant selection, taking advantage of varying physiological adaptations that maximize growth and minimize water loss. Improvements of the biomass conversion process can improve the WUE by reducing process water requirements and/or improving the biomass conversion efficiency.

18.1.3 The Need for Local and Regional Integrated Assessments

Integrated impact assessment frameworks are evolving to recognize the interconnectivity of water, soil, and biodiversity into a systematic view with integrated metrics (Donnelly et al. 2010; Fernando et al. 2010; Hooper 2003). Such frameworks allow replacement of disjointed field- or facility-based productivity analysis with decision-making at the landscape level, which is required for long-term sustainability. Improved data collection and modeling capability now allow high resolution of local impacts and assessment of the differing sensitivities and tolerance of individual regional niches to human activities such as biomass cultivation and removal and the various processes of energy generation. However, the requirements to conduct and implement such assessments still present technical and sociopolitical challenges. Integrated assessments require fairly detailed landscape-level baseline data and an adequate understanding of the mechanistic linkages among regional environmental processes and regional activities including other human and non-human use.

18.2 Water Impacts of Modern Bioenergy

Reporting of water requirements for bioenergy is widely variable (Figure 18.3). While some estimates include only active human use such as irrigation water and water used in biofuel conversion processes, others include rain-fed evapotranspiration, which is a natural ecosystem process that is influenced by human land use. While, water limitations may reduce bioenergy opportunities in some regions, there are many opportunities for bioenergy to advance both socioeconomic objectives and sustainable landscape planning (Figure 18.1).

18.2.1 Water Impacts Current and Novel feedstocks (see also Chapter 10, this volume)

18.2.1.1 Annual Bioenergy Crops

The cultivation of conventional annual crops as bioenergy feedstocks affects soil and water resources in the same way as when such crops are cultivated for food and feed. Water withdrawals and the effects of fertilizers, pesticides and other chemicals applied to croplands on surface and ground water must be carefully managed to avoid human health impacts and damage to ecosystems (Sutton et al. 2012). Worldwide, 20% of agricultural cropland is equipped with irrigation (FAOstat 2010), of which bioenergy crops represent less than 1%. As in other agricultural and forestry activities, the adoption of BMPs is crucial to minimizing the risk of water impacts and promoting sustainable resource use in the cultivation of bioenergy crops (see Box 18.1 and Section 18.5). Assessing BMPs and their effectiveness further requires defining appropriate water quality expectations, determining what site conditions limit BMP effectiveness, and determining specific watershed metrics and appropriate spatial and temporal scales for assessment (Ice 2011).

18.2.1.2 Perennial and Semi-Perennial Crops

Because of their extensive root systems, long-term soil cover and protection, and reduced need for tillage and weed suppression, semi-perennial crops such as sugarcane, perennial grasses such as switchgrass, Miscanthus and elephant grass (Morais et al. 2009; Dale et al. 2011) (Chapter 10, this volume), and trees grown in rotations ranging from just a few years up to several decades (both coppice and single-stem plantations) tend to have lower water quality impacts than conventional crops (Dimitriou et al. 2011). While many perennial crops considered for bioenergy have relatively high WUE, their total water requirements can also be relatively large. Such crops are ideally suited to areas with high water availability, with caution to preserve ecological water flows (Parish et al. 2012). For example, Van Loocke et al. (2010) report that Miscanthus could replace 50% of corn acreage in most areas of the Midwest US without affecting the hydrologic cycle, but that in drier regions Miscanthus should be limited to 25% of the area. Additionally, it has been suggested that the use of perennial grasses may increase seasonal evapotranspiration (ET) compared to maize due to the access of these grasses to deeper soil moisture (Hickman et al. 2010). This increase in ET would lead to higher humidity, lower surface temperature, higher precipitation and cloud cover with lower solar radiation. In turn, soil moisture would increase, affecting soil metabolism and finally carbon sequestration. The same trend was observed for sugarcane in parts of the Central Brazil savannas (Loarie et al. 2011) and Southeast Brazil (Cabral et al. 2012).

18.2.1.3 Forest Biomass in Long Rotation

Forest biomass for bioenergy is typically obtained from a forest estate managed for multiple purposes, including production of pulp and saw logs, and provision of other ecosystem services such as water purification and regulation of water flows in watersheds. Forest bioenergy systems are judged compatible with maintaining high-quality water supplies in forested catchments, as long as BMPs that are designed for environment and resource protection and include nutrient management principles are followed (Mead and Smith 2012; Neary 2013; Shepard 2006). While short-term water impacts, including increased sediment, nitrates, phosphates, and cations can occur, there is no evidence of long-term adverse impacts in forest catchments subject to normal management operations (Neary and Koestner 2012). However, more research is needed to guide BMPs concerning stump extraction and forest fertilization (de Jong et al. 2014). Quantitative water flows in a specific forest stand are naturally affected if the stand is subject to operations involving significant felling and biomass extraction. But since a forest estate typically is a mosaic of stands of different ages, where only a small share of all stands are harvested in a particular year, water flow regimes on the larger landscape level typically are not affected significantly by stand level operations. Exceptions occur where forests are replaced with other land covers as discussed in section 18.4.

18.2.1.4 Organic Waste and Residues

Energy recovery from secondary and tertiary waste biomass (e.g. municipal waste, food processing waste, manures, and wastewater with high organic content) has the potential to improve water quality in communities all over the world by reducing landfill leachate and providing incentives to avoid direct discharge of waste into water bodies. However, utilization of this resource remains inefficient. For example, even with zero landfill policies and a Waste Framework Directive, the EU-28 countries recovered energy from only about 6% of its non-recyclable municipal waste in 2010 (EuroStat 2014). Currently, use of primary waste biomass (e.g. harvest residues, forest thinnings and slash) for energy is limited. By increasing the use of these materials, bioenergy output can increase without requiring more land and water. However, site-specific conditions (e.g., soil, climate topography) and competing uses (e.g., animal feed and bedding) need to be considered (see section 18.4.2.1).

18.2.1.5 Algae

The water impacts of algal propagation vary widely by technology and environmental conditions, with water use ranging from 3 to 3,650 L L^{-1} of biodiesel or advanced biofuel produced (Wigmosta et al. 2011; US NRC 2012). Freshwater is needed to replace water losses from open ponds, even when halophilic organisms are used. While the volumes in photobioreactors are relatively small, cooling requirements, usually met by freshwater, are large. Algae do provide an opportunity to recover nutrients from wastewater for lipid-based biofuel production, which may be advantageous in some locations (Pittman et al. 2011).

18.2.2 Water Impacts of Conversion Technologies (see also Chapter 12, this volume)

In general, water impacts of biomass electricity remain similar to fossil fuel pathways, with large water withdrawals but low consumptive use ranging from 0-1800 L MWh^{-1} (Fthenakis and Kim 2011). Cooling water, which may contain some salts, is returned at higher temperature to the basin, with variable ecological impact. Water requirements for biofuel processing continue to improve. Water use per metric ton of feedstock has decreased dramatically for both corn and sugarcane ethanol. For instance, the water use of ethanol-sugar mills in Southeast Brazil decreased from 15 m^3 per metric ton of sugarcane prior to 2008 to approximately 1-3 m^3 per metric ton in 2008 (Martinelli et al. 2013). However, in water stressed regions new or expanded facilities may still not be approved due to the associated water demand (Martinelli et al. 2013). While, untreated effluent can cause eutrophication and acidification of waterways, process water offers an opportunity to recover and recycle nutrients (see section 18.5.3.1). Biofuel facilities with zero liquid discharge, such as Pacific Ethanol in Madera, California, have been operating in the U.S. since 2006 and continue to expand worldwide. The most recent example is the BioChemtex/Beta Renewables lignocellulosic ethanol plant in Crescentino, Italy. Technological improvements in water recovery and recycling have progressed to the point that some facilities are able to use municipal wastewater and some have achieved closed loop recycle (Figure 18.4).

Figure 18.4. The Tharaldson Ethanol plant in North Dakota uses municipal wastewater and returns about 25% of the volume at drinking water quality to the city of Fargo (www.tharaldsonethanol.com).

18.3 Soil Impacts of Modern Bioenergy

18.3.1 Soil Impacts of Current and Novel Feedstocks

The soil organic carbon (SOC) pool to 1 m depth holds more carbon than the atmosphere and the biotic pool combined (Lal 2008). The changes in soil carbon at any site reflect the balance between organic matter inputs, and mineralization rate. Considering the large size of the SOC pool, fluctuations in this balance over large areas can have a significant impact on atmospheric CO_2. Land conversion to agriculture often leads to SOC losses, especially when annual crops are cultivated (Nafziger and Dunker 2011; Perrin et al. 2014). Mechanization of agriculture has accelerated SOC losses in croplands, whereas development of carbon-sequestering practices over the past decades may have limited SOC loss from arable soils (Eglin et al. 2010).

Bioenergy systems vary widely in their potential to affect soil properties including soil tilth, SOM including SOC, soil water holding capacity, risk of erosion, and mineral nutrient content (Figure 18.1). The outcome will, to a significant degree, be determined by the existing and previous land use where the bioenergy systems become established. Matching appropriate feedstocks and management practices to soil requirements offers many opportunities to improve soil conditions and avoid negative impacts (See also Chapters 9 and 10, this volume). Biomass production for bioenergy should apply management practices that minimize negative impact on soils and - where possible - promotes positive outcomes (Cowie et al. 2006). Box 18.2 summarizes key points relating bioenergy feedstock production and soil carbon discussed in this chapter (See also chapters 5 and 9, this volume).

Box 18.2. Bioenergy feedstock and soil carbon

General trend of soil carbon stock	
Decrease	**Increase**
Replace forest and other natural ecosystems with crops	Grow perennial or semi perennial crops on degraded land including degraded pastureland
Replace perennial or semi perennial crops with annual crops	Return plant residues and organic wastes to soil (organic fertilization)
Crop and forest residues removed or burned	Preserve plant residues by avoiding burning
Intense soil mechanical disturbance (i.e. plowing, sub soiling, uprooting forest stumps, etc.)	No till or minimum till
Biomass production systems or managements that increase soil erosion	Amending soil with biochar (economic feasibility to be established)

18.3.1.1 Annual Bioenergy Crops

Annual crops provide farmers with flexibility in land use decisions and immediate income. However, annual systems can be demanding of soil resources. SOM is a fundamental soil quality indicator and affects ecosystem services such as nutrient retention, degradation of pollutants, water infiltration and cleaning, invertebrate biodiversity, etc. (Lal 2009a; Lal et al. 2007). In annual crops used for bioenergy such as maize and rapeseed, frequent cultivation and removal of biomass can lead to low SOM, nutrient loss, and poor soil physical characteristics not to mention emission of greenhouse gases (Blanco-Canqui and Lal, 2009). In addition, nutrient depletion caused by inadequate fertilization and residue removal can jeopardize long-term productivity of soils (Snyder et al. 2009). Use of BMPs (section 18.3.2) can obviate these negative effects.

18.3.1.2 Perennial and Semi-Perennial Crops

Perennial and semi-perennial systems (i.e. crops with multi-year rotations) offer several benefits to soil. In parts of the USA, soil loss could be reduced by 60% if switchgrass is grown for bioenergy instead of corn (Khanal et al. 2013). While some nutrient loss can occur during the establishment phase, bioenergy crops including sugarcane (Galdos et al. 2009) and Miscanthus (Anderson-Texeira et al. 2013) have been shown to accumulate SOM/SOC in many soil types under BMPs (Figure 18.5). In general, perennial systems have lower nutrient requirements than annual crops. Crops that undergo seasonal senescence such as Miscanthus can relocate nutrients to root structures and soil, reducing loss during harvest of above-ground material (Cadoux et al. 2012). Like grasses, short rotation woody crops such as willow and poplar can improve SOC when compared to tilled annual crops (Dimitriou et al. 2011). The ability of some perennial feedstocks to tolerate higher levels of metals and salts may present soil remediation opportunities (see section 18.3.3).

18.3.1.3 Forest Biomass in Long Rotation

Long-rotation forests offer clear benefits to biodiversity and soils. The large and permanent root systems of trees can take up nutrients deep in the soil profile, thus reducing leaching losses and accumulating carbon (Maquere et al. 2008; Woodbury et al. 2007). Forestry operations for fiber and bioenergy can affect SOC and cycling of nutrients such as nitrogen through soil movement and alterations in flow routes. Forest harvesting and the subsequent site preparation for forest regeneration (including soil scarification, trashline burning and road construction) are major disturbances. Logging machinery may cause soil compaction and the removal of nutrients at harvest can be negative from a nutrition and acidification perspective, but can result in reduced N loading of ecosystems in areas subject to high N loading via atmospheric deposition (de Jong et al. 2014). Nutrient losses can be compensated by fertilization and ash recirculation (Saarsalmi et al. 2012). Also the use of herbicides and other chemicals associated with intra-rotation silvicultural operations can have transient impacts on water quality and other ecosystem parameters (Neary et al. 1993, Neary 2002).

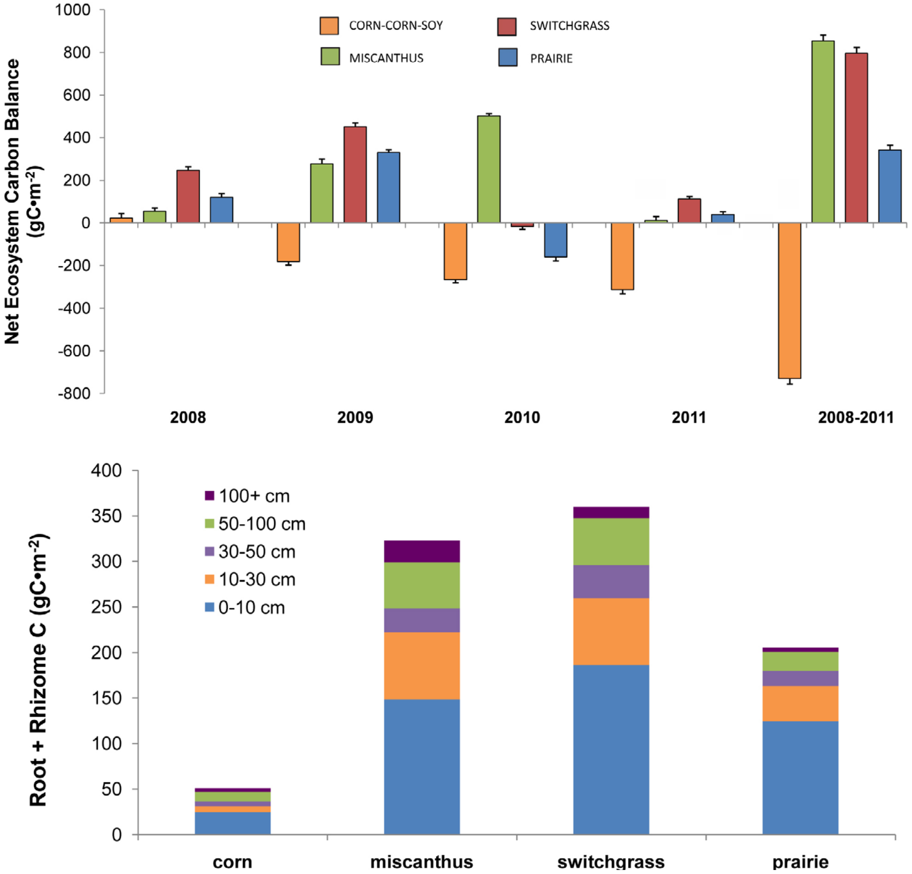

Figure 18.5. Perennial bioenergy crops can accumulate soil carbon – Primarily mediated through changes in below-ground plant matter (bottom), surface litter, and soil respiration, perennial systems tend to have higher net ecosystem carbon balance (top) compared to annually tilled crops such as corn and soy. Soil organic matter losses are reduced in no-till annual systems. Source: Anderson-Texeira et al. 2013.

18.3.1.4 Waste Biomass

The use of waste biomass for energy affects soils primarily through diversion of the biomass from its normal disposal route. The use of municipal waste for energy allows for destruction of toxic organic compounds and recovery of toxic metals such as cadmium, arsenic, and lead that can contaminate soils. In addition, some nutrients required for biomass production are recoverable (see section 18.5.3.2). Agricultural residues normally left in the field contribute to nutrient cycling, erosion prevention, and turnover of soil organic matter. If these residues are increasingly removed from fields and used for energy, this can cause soil impacts (see section 18.4.2.1). The extraction of branches and tops from silvicultural operations and from final felling implies additional carbon and nutrient export with possible consequences for soil status and tree growth (Helmisaari et al. 2011). However, growth reduction can be a temporary consequence of reduced N availability (Egnell 2011) and can be compensated for through earlier stand establishment, better conditions for site preparation and planting operations, and fertilization. Research and practical experience gained so far indicate that stump extraction can reduce the cost of site preparation for replanting (Saarinen 2006) and reduce damage from insects and root rot fungus (Berch et al. 2012; Cleary et al. 2013; Zabowski et al. 2008). While stump removal may not affect forest productivity in the short term, it can lead to negative effects including reduced forest SOC and nutrient stocks, increased soil erosion and soil compaction (De Jong et al. 2014; Persson 2013; Walmsley and Godbold, 2010).

18.3.2 Phytoremediation and Recovery of Marginal Soils

Bioenergy feedstock systems can be designed, sited and managed to provide specific environmental services, such as when plantations are established as vegetation filters for the treatment of nutrient-bearing water (e.g. pre- treated wastewater from households and runoff from farmlands (Börjesson and Berndes 2006; Dimitriou et al. 2011) (Figure 18.6). Studies with sugarcane indicate some benefit from irrigation with sewage effluent, although evaluations are still needed to assess long-term impact (Leal et al. 2010; Leal et al. 2011). Some species, such as willow, that accumulate heavy metals can remove cadmium and zinc from cropland soils (see, e.g., Berndes et al. 2004; Dimitriou et al. 2011), while others, such as Spartina, can be grown on arsenic contaminated soils (Mateos-Naranjo et al. 2012). The use of such marginal lands provides an important economic potential. For example, saline soils could support as much as 50 EJ of biomass for energy (Wicke et al. 2011).

18.4 Anticipating Changes Associated with Expansion of Bioenergy Production

18.4.1 Effects of Land Cover Change

Perhaps the most controversial aspect of bioenergy expansion involves the potential for changes in vegetative land cover or land use change (Lapola et al. 2010) (Chapters 5 and 9, this volume). The trend through much of human development has been to convert forests and perennial landscapes to annual cropping systems (Chapters 4 and 9, this volume), which has often caused negative impacts on water and soil resources. Changing annual systems back to perennial systems and forests affects water and soil resources, usually - but not always - in a positive way. For example, downstream water availability may decrease; see Figure 18.7 and further discussion below.

Figure 18.6. Willow to the rescue - combining bioenergy with waste treatment.
Willow is commercially grown in Sweden to produce wood chips for heat and power production. Willow coppice plantations with drip or sprinkler irrigation systems have been established adjacent to a range of wastewater treatment plants to facilitate alternative wastewater treatment and recirculation of N and P. Different types of nutrient-rich wastewaters, such as municipal wastewater, landfill leachate and log-yard runoff, have been treated in such willow vegetation filters. Willow producers benefit from increased yields and reduced fertilizer cost thanks to the irrigation water input. The Enköping municipal wastewater plant, shown in the photo below, installed 75 ha of willows used as vegetation filters to treat municipal wastewater. The wastewater is stored in lined ponds during the cold season. Between May and September, the stored water is mixed with conventionally treated wastewater and used to irrigate the adjacent willow plantation using drip pipes laid in double rows so that harvesting will not be obstructed. The willow plantation receives about 250 mm yr^{-1} of irrigation water containing some 200 kg ha^{-1} nitrogen and 10 kg ha^{-1} phosphorous. Monitored low nitrogen losses indicate that the system is capable of capturing the added nitrogen at improved costs over conventional N treatment. The wood chips are used in the local district heating plant, which in turn recycles boiler ash back to the willow plantation. Source: Börjesson and Berndes (2006) Photo credit: Per Aronsson, Swedish University of Agricultural Sciences, Sweden.

18.4.1.1 Effects of Land Cover Change on Water

Land cover change can cause changes in the partitioning of precipitation between runoff, drainage, evaporation and plant transpiration (Figure 18.8). Gordon et al. (2005) found that deforestation is as large a driving force of changes in the hydrological cycle as irrigation. Studies have also found that afforestation with tree plantations can decrease streamflow and regulate seasonal water release (See section 18.6). King et al. (2013) combined projections of the global distribution of relative water availability in the coming decades, obtained from 16 global circulation models, with data on the water-use efficiency of tree- and grass-based bioenergy systems and found that relative water availability will be one of the most important climatic changes to consider in the design of bioenergy systems. For example, an analysis of 504 annual catchment observations revealed that afforestation

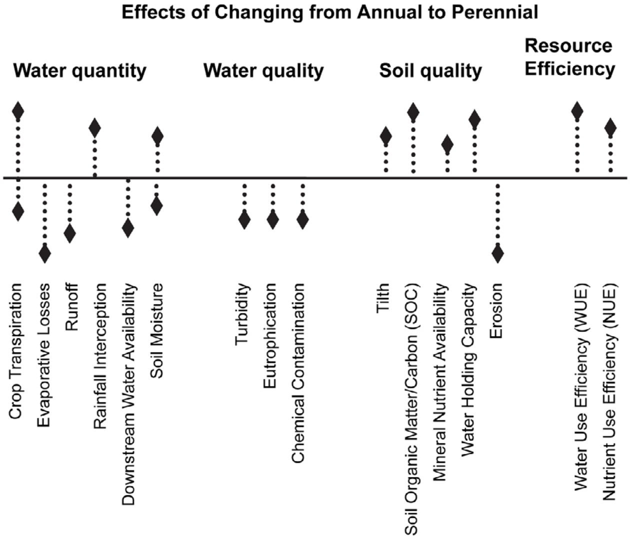

Figure 18.7. Land cover change affects soils and water in a multitude of ways. For example, changing from an annual to a perennial crop has a range of effects that depend on which plants are being changed and how management changes.

commonly resulted in reduced streamflow. Averaged over all plantation ages, afforestation of grasslands, shrublands or croplands reduced streamflow by almost 40%. For 10- to 20-year-old plantations, average losses were about 50% of streamflow (Jackson et al. 2005). Similarly, Zomer et al. (2006) report that large areas deemed suitable for afforestation - especially grasslands and land used for subsistence agriculture in drier areas, notably semi-arid tropics - would exhibit increased ET and/or decreased runoff, if planted with trees. A third example, Vanloocke et al. (2010) evaluated scenarios of miscanthus production on the simulated Midwest US hydrologic cycle and found that on an annual basis miscanthus uses more water than the ecosystems it will likely replace.

Bioenergy implementation involving irrigation can bring further changes in field-level water availability, ET rates and downstream water flows. The direction and size of the changes depends on location, prior land cover and use, and on what specific changes are made (Sterling et al. 2013). For example, replacing natural vegetation (forest or savannah) with pasture or annual crops, including sugarcane, in Brazil decreases local ET (Cabral et al. 2012). In contrast, annual ET of sugarcane is higher than pasture and other annual crops (Figure 18.9). Thus, sugarcane expansion into existing crop and pasture land increases ET in rain-fed areas (Cabral et al. 2012; da Silva et al. 2013), which may have a local cooling effect (Loarie et al. 2011) but can also reduce downstream water availability. Sugarcane ET is similar to the annual ET found in savannah regions, where most expansion is occurring in Brazil.

ET increases and reduced runoff can cause or intensify water shortages in some regions but can have positive effects in other regions. For instance, earlier conversion of native vegetation to agriculture land in parts of Australia resulted in rising water tables due to reduced ET. As a consequence, salt moved into the surface soils and reduced their suitability for agriculture (Anderies 2005). Tree plantations can, in such situations, intercept water that moves through the soils and in this way help reduce groundwater recharge and soil salinization (Bartle et al. 2007, Harper et al. 2013; Pannell et al. 2004). Afforestation can also have other positive impacts on water flows;

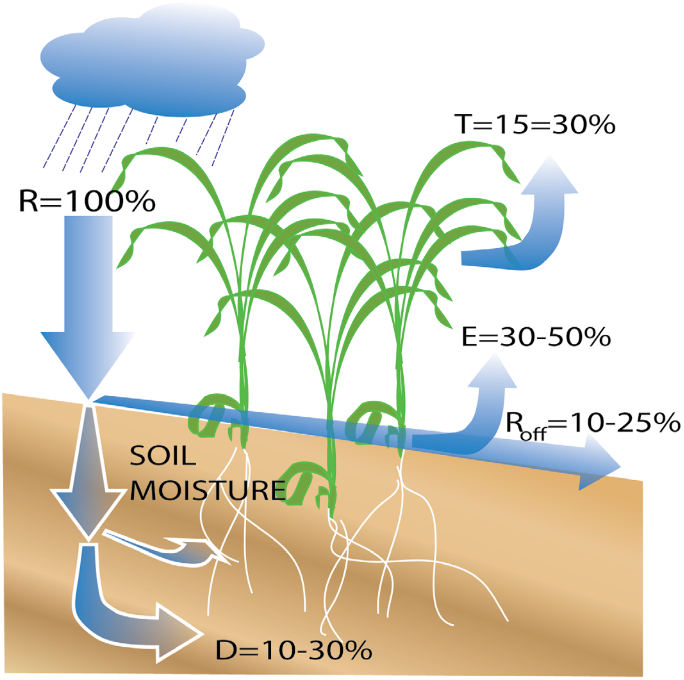

Figure 18.8. More biomass can be cultivated without using more water.
Rainfall (R) is partitioned by vegetative land cover. The water that is lost from the field due to runoff (R_{off}) and drainage (D) is potentially available further downstream, unless it is lost as evaporation (E) elsewhere in the landscape. Transpiration (T) by the cultivated plants represents the productive use of water. The percentages shown correspond to conditions in the semi-arid tropics in Sub-Saharan Africa (Rockström et al. 1999). E is often larger than T during the early part of the growing season for annual crops and may comprise 30-60 percent of seasonal ET, sometimes even more. Sparsely cropped farming systems in regions characterized by high evaporative demand can have very large water losses through E. If E losses can be reduced and a larger part of the rainfall can be channeled to plant T, productivity and biomass production can increase without necessarily increasing the pressure on freshwater resources. However, if total ET increases this can have consequences for both groundwater recharge and available surface water. The ET can increase both as a consequence of measures to enhance the yields of presently cultivated crops, or as a consequence of changes in land use such as when high-yielding biomass plantations are established on lands with sparse vegetation, e.g., degraded pastures. However, ET increases can in some situations be beneficial (Section 18.4.1.1). Source: Berndes (2008).

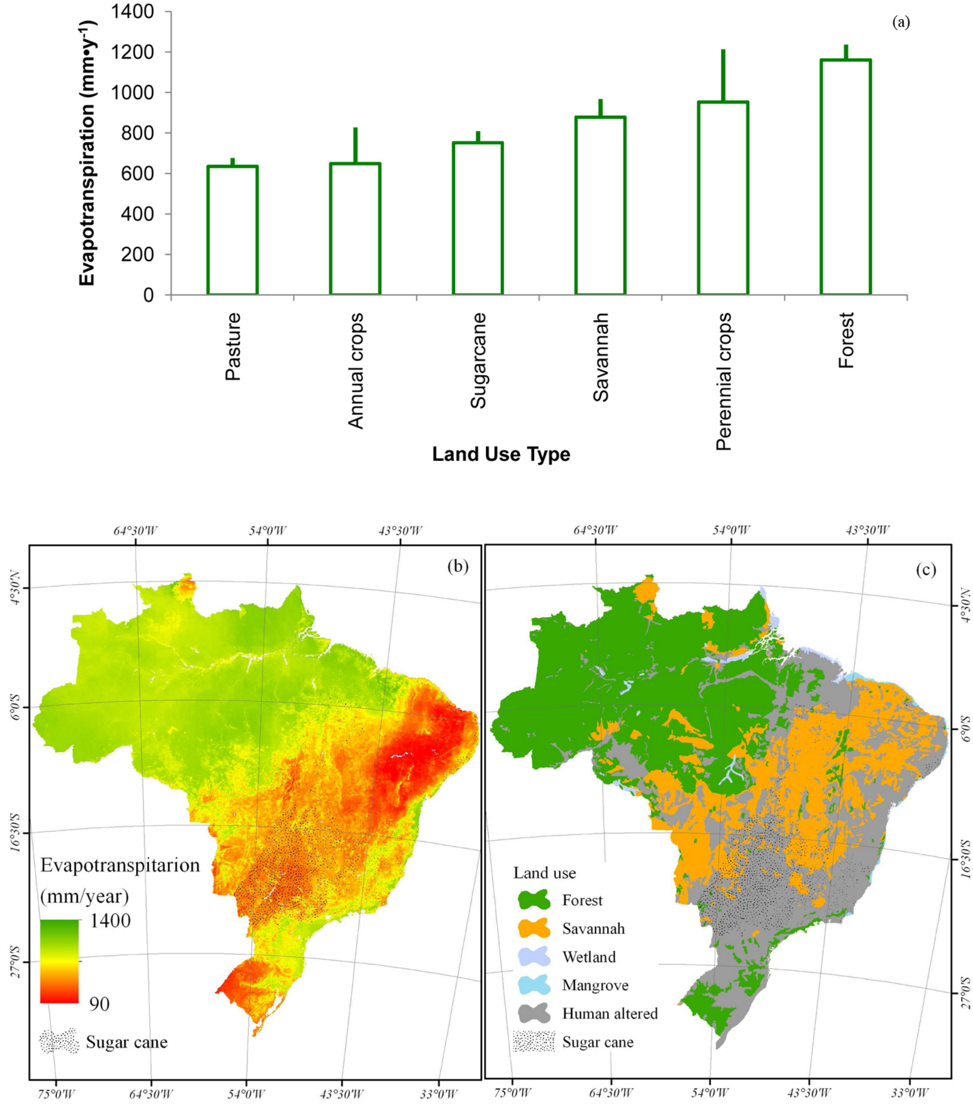

Figure 18.9. Landcover effects on evapotranspiration in Brazil. (a) Total ET (mm.year^{-1}) of monthly values for 2012 (b) for main land use types in Brazil (c), derived from a GIS integrated analysis of a 1 km time series of monthly MODIS ET product using land use (EMBRAPA Satellite Monitoring 2012; IBGE 2012) and vegetation maps (MMA 2005) to integrate over space. MODIS ET data were obtained from the Global Evapotranspiration Project - MOD16- (Mu et al. 2007; http://www.ntsg.umt.edu/project/mod16). The MOD16 algorithm is based on the logic of the Penman-Monteith equation which uses daily meteorological reanalysis data and 8-day remotely sensed vegetation property dynamics from MODIS as inputs.

in humid areas and steep slopes, tree cover can decrease runoff, erosion, and even floods, by increasing infiltration of rainfall and its retention in the soil. For example, Garg et al. (2011) modeled the hydrologic consequences of planting Jatropha on wastelands in India and found several desirable effects: more precipitation was channeled to productive plant transpiration and groundwater recharge and less was lost as soil evaporation. Also, soil erosion was reduced and downstream water conditions were improved resulting from that more stable runoff.

18.4.1.2 Effects of Land Cover Change on Soils

Changing vegetation types and management practices can alter soil physical and chemical properties, which can impact soil microbial systems, nutrient availability, SOM, and water holding capacity and, consequentially, plant growth. Understanding impacts on changes in SOM, especially SOC, are important if bioenergy is to contribute to low-carbon energy solutions to addressing climate change. Shifting from annual tilled crops to soil-covering perennial plants on sloping land with erodible soils can reduce flooding (Zuazo and Pleguezuelo 2008), soil erosion and degradation (Khanal et al. 2013; Maetens et al. 2012) and increase SOC (Anderson-Teixeira et al. 2013; Mello et al. 2014; Watanabe and Ortega 2014) (See also Chapters 10 and 16, this volume). However, the outcome of other land uses changes is site- and use-specific and dependent on physical and historical factors, as well as the time frame for evaluation. For example, replacement of tropical peatland forest with oil palm incurs a carbon debt ranging from 54 to 115 Mg CO_2eq ha^{-1} yr^{-1}, varying by site and also by the accounting time frame (Page et al. 2011). In contrast, SOC under oil palm may equal or exceed native forests over time in some locations (Frazão et al. 2013).

18.4.2 Effects of Changes in Residue Management and Irrigation Use and Practice

18.4.2.1 Effects of Changes in Residue Management

It is likely that socioeconomic pressures on resources for bioenergy will drive a shift to multifunctional landscapes. In many scenarios increased bioenergy demand will trigger new approaches to residue management. Most plant residues presently left on the field from corn and other cereal grains may become economically viable feedstocks for heat and power, biomethane, or cellulosic biofuel production (Tyndall et al. 2011; Muth et al. 2013).

For example, the usual practice of burning sugarcane to facilitate harvest is being replaced in many countries by mechanical harvest thus preserving the straw in the field. The amounts of plant material that remains after stem harvest are huge – on the range of 8 to 20 Mg ha^{-1} of dry material (Leal et al. 2013). The benefits of straw for nutrient cycling, soil conservation, yield increase, and carbon sequestration in soil are well documented (Carvalho et al. 2013; Figueiredo and La Scala Jr. 2011; Galdos et al. 2009; Robertson and Thorburn 2007). Soil nutrients removed with the plant material can be replenished with synthetic fertilizers, but maintenance of SOM depends on regular supply of plant residues (Trivelin et al. 2013; Lal 2009b). The tradeoff between more bioenergy per unit land area and the need to maintain soil quality is the subject of intense debate (Cantarella et al. 2013; Franco et al. 2013; Gollany et al. 2011; Hassuani et al. 2005; Karlen et al. 2011; Lal, 2009b; Tarkalson et al. 2011). In many systems some or all of the residues must be left behind (English et al. 2013; Blanco-Canqui and Lal 2009; Huggins et al. 2011). For example, while palm residues have been proposed for expanded bioenergy production (see Chapter 16, this volume), the importance of these residues in nutrient recycling may limit that activity (Moradi et al. 2012; Bakar et al. 2011). With site-specific information, collecting plant residue can be sustainable in many situations (Hassuani et al. 2005; Muth et al. 2013). The threshold limits for residue removal depend on soil type, slope and climate.

In silvicultural activities, studies report wide ranges concerning how much forest residues can be extracted without causing negative impacts (e.g., Dymond et al. 2010; Gronowska et al. 2009; Lamers et al. 2013). This reflects varying biotic and abiotic conditions over landscapes and considerations of more aspects than soil and water effects, e.g., biodiversity. In addition, differences in forest industry infrastructure associated with forest resources and varying economic realities will cause extraction rates to vary over space and time.

18.4.2.2 Effects of Changes in Irrigation Use and Practice

The growth of bioenergy feedstocks is an economic activity that occurs in the context of agricultural and silvicultural production, which in some areas includes irrigation. There is no inherent need for bioenergy feedstocks to use irrigation. However, the availability of water in many regions will limit bioenergy potential. For example, one modeling study found that the global biomass potential varied from 130 to 270 EJ yr^{-1} in 2050, depending on land availability and extent of irrigation (Beringer et al. 2011).

Unsustainable use of water can occur in any agricultural or silvicultural endeavor, but societal preferences and technological changes also shape the land use and intensification outcomes. Economic modeling (Popp et al. 2011) supports the intuitive hypothesis that, under climate change, bioenergy could increase irrigation in some regions. Although past evidence may indicate that these effects could be less than anticipated (Figure 18.10). Supplementary irrigation in rain fed areas can significantly increase biomass yield (Rockström et al. 2010) with little additional water use. There is large scope for improving WUE in both rain-fed and irrigated production (Figure 18.8) and water not suitable for food production can be used in bioenergy feedstock production (Figure 18.6). Use of drought-tolerant plants, plants adapted to regional seasonal water constraints, and proper management of water transfers and groundwater recharge can mitigate water stress impacts. Water withdrawals for irrigation (both quantity and timing) should be carefully considered in context of watershed needs, vulnerability, and resiliency, regardless of whether the irrigation supports food, biomaterials or bioenergy feedstock production.

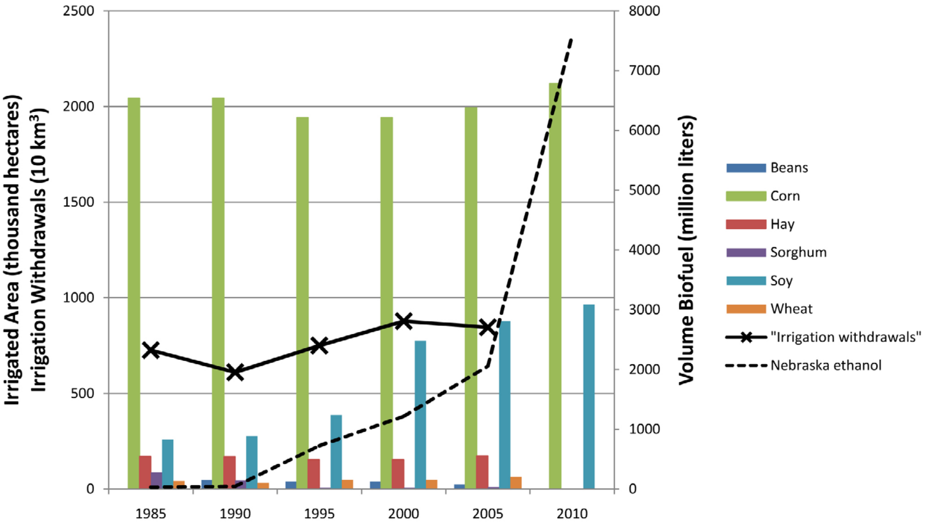

Figure 18.10. Will bioenergy drive increased water use?
The answer is most likely yes, but perhaps not as much as is feared, and this will vary by location. The state of Nebraska in the US Midwest has the highest share of irrigated land (15% of the US total) and is the second largest ethanol producing state. With construction of 25 biorefineries, corn ethanol production in the state skyrocketed from 32,176 m^3 yr^{-1} (8.5 million gal yr^{-1}) in 1985 to 8.328 million m^3 (2.25 billion gal yr^{-1}) in 2012. Although the total area of irrigated land has increased in the past five years, irrigated corn has fluctuated around 20.242 million ha (50 million acres) since 1979 and the percentage of corn land that is irrigated has decreased. The trend in water withdrawals is less clear. Overall water withdrawals increased from 9 billion m^3 in 1985 to 10.4 billion m^3 in 2005 (water withdrawals peaked at 11.5 billion m^3 in 1980). While some interpret the data below as fluctuating around 10 billion m^3, others contend that water use did increase, reversing a previous downward trend. A confounding factor is that this period coincided with a near tripling of irrigated soy acreage for food and feed production (Nebraska has no biodiesel production). More refined data are required to assess the true impact of corn ethanol expansion. Data from USDA 2013; RFA 2012; AFDC 2012.

18.5 Minimizing Impact of Bioenergy Production

18.5.1 Selecting Appropriate Bioenergy Systems for Ecosystems

The promotion of bioenergy offers considerable opportunities for the agriculture and forestry sectors, which can find new markets for their products, diversify land use, and also make economic use of biomass flows previously considered to be waste (Chapters

11 and 13, this volume). For instance, several major wood producing countries are seeking alternative markets as the demand for pulpwood has declined. In agriculture, perennial grasses and woody plants can be grown in sensitive locations where cultivation of conventional food crops causes soil, water and other impacts (Chapters 9 and 10, this volume). Strategic placement of such plants can reduce eutrophication (Dosskey et al. 2008), and improve soil structure, which in turn increases water infiltration, permeability, and water-holding capacity (Table 18.1).

Perennial biomass crops (Chapter 10, this volume) can also make better use of rain falling outside the growing season for conventional food/feed crops, and some plants can use water not suitable for conventional crop production, such as saline water and pre-treated municipal wastewater. Hardy and drought tolerant plants with traits suitable as bioenergy feedstock are considered for cultivation in areas where conventional food and feed crops are difficult to cultivate. While over-optimistic expectations about “wonder crops” have caused a number of projects to fail, there is still scope for optimizing the use of land with varying suitability based on cultivating a wider set of plants. Successful implementation requires both investments in the development of suitable plant varieties and implementation of BMPs in forestry and agriculture (Chapter 10, this volume). Development of integrated systems for optimal use of soil and water resources requires consideration of local/regional socio-technical structures as well as ecosystem properties.

18.5.2 Landscape-Level Planning and Mixed Systems

Landscape-level planning is an important tool for balancing social and economic resource use with environmental objectives including conservation of water and soil resources (Dale et al. 2011; Harper et al. 2013; Frank et al. 2014) and biodiversity (Bourke et al. 2013; Dale et al. 2010; Dwivedi et al. 2011; Foster et al. 2011). Mixed plant systems such as crop-pasture rotation or crop-pasture-forest integration are options for small farmers to combine the production of food and plants for bioenergy (Herrero et al. 2010) (Chapters 3 and 4, this volume). Mixed systems help to overcome problems of economic returns of long cycle crops, price fluctuations and allow the combination of production of food, bioenergy and plants for other purposes (Chapter 6, this volume). Management of bioenergy production systems can be adjusted to achieve substantially greater social and environmental benefits, in terms of soil impacts and greenhouse gas balance, such as through crop selection, timing of harvest, residue management practices (Dale et al. 2013; Davis et al. 2013; Herrero et al. 2010; Pereira et al. 2012; Vilela et al. 2011; Smith et al. 2013) (Chapter 5, this volume).

18.5.3 Evolution in Best Management Practices

Appropriate agronomic practices such as minimum tillage or no-till can overcome many soil effects of biomass removal by maintaining soil cover and decreasing mechanical soil disturbance (Govaerts et al. 2009). In some systems such as sugarcane, no-till can result in increased SOC, higher water storage, decreased losses of soil, water and agrochemicals, decreased fertilizer need because of better soil conservation, and lower fuel consumption by field operations (Boddey et al. 2010; de Moraes Sá et al. 2013). No-till with mulch preservation is especially important in tropical regions. In other systems, such as no-till in continuous corn in temperate regions, some biomass removal may be necessary to provide sufficient soil warmth for germination (Gentry et al. 2013). Presently, in Brazil over 30 M ha are managed under no-till as part of a sustained effort to improve agricultural practice in the past decades (Bernoux et al. 2006; Pereira et al. 2012). While no-till is less important in perennial or semi-perennial crops than annual crops, increased SOC has been reported when soil plowing is skipped and sugarcane is planted with no-till (Bordonal et al. 2012; Galdos et al. 2010; Segnini et al. 2013). In forest systems, applying BMPs may mean setting limits on the amounts, timing, and methods of biomass extraction and nutrient management in forests (Helmisaari and Kaarakka 2013; Lamers et al. 2013). For instance, extraction of branches, tops and stumps needs to be adapted to local soil and watershed conditions to limit impacts. In all systems, optimized nutrient management is essential to long-term sustainable soil health. Of course, BMPs must be tailored to the local site in the context of a landscape perspective (Figure 18.11) (see also section 18.5.2.1).

18.5.4 Using Wastes in Bioenergy Systems to Improve Water and Soil Quality, Close the Nutrient Cycle, and Recover Energy

18.5.4.1 Fertirrigation

Fertirrigation using wastewater (Chapters 12 and 14, this volume) can provide soil moisture and nutrients for biomass growth, while simultaneously providing a solution to wastewater disposal. One example of such practice is the use of vinasse (Figure 18.12), a by-product of ethanol fermentation, with a high biological oxygen demand (175,000 mg L^{-1}), containing around 3-6 g L^{-1} of organic carbon and 2 g L^{-1} potassium as well as other nutrients (Mutton et al. 2010). About 10 to 13 L of vinasse are produced for each L of ethanol, around 300 billion L yr^{-1} from sugarcane in Brazil alone. If vinasse accidentally reaches water bodies, it can be a pollutant, creating algal blooms and anoxic zones (Martinelli et al. 2013). Similarly, if applied in excessive amounts to agricultural soils it can increase salinity and cause nutrient leaching, with potential to affect ground water quality (Magalhães et al. 2012). However, vinasse can also act as a fertilizer, recycling potassium and other nutrients, and adding organic matter to the soil. In Brazil, practically all vinasse is returned to the fields, reducing the need of synthetic fertilizers in sugarcane (Cantarella and Rossetto 2012). Current legislation in São Paulo State regulates the disposition of vinasse to the soil in order to avoid soil salinization and nutrient overload (Magalhães et al. 2012) (See also chapter 5, this volume). Direct discharges of vinasse to water bodies are not allowed in Brazil (Magalhães et al. 2012), although accidental discharges have occurred and can affect water quality in areas where sugar mills are located (Martinelli et al. 2013).

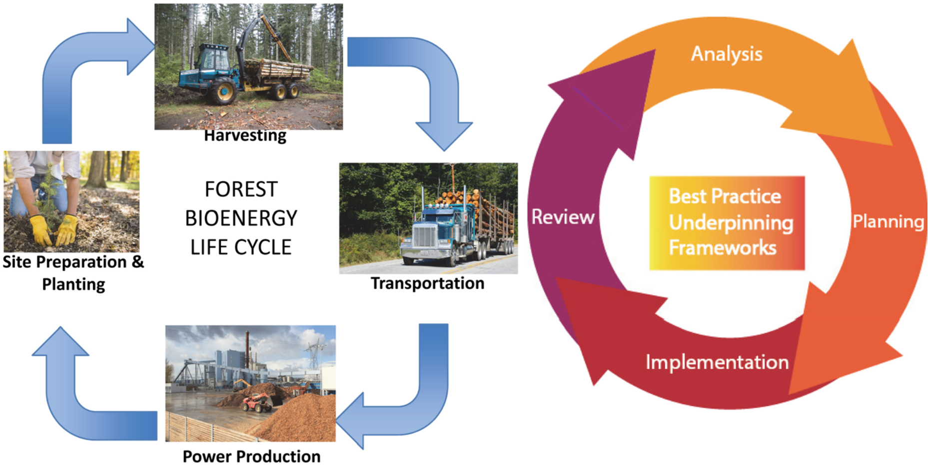

Figure 18.11. The use of BMPs enables forest feedstock production for bioenergy programs as a sustainable part of land management and renewable energy production. The development and application of BMPs to the life cycle of bioenergy is not a static process, but one that relies on a continual cycle of analysis, planning, implementation and monitoring, and review (Neary and Koestner 2012). Although some countries have "national standards", the complex matrix of forest ecosystems, climates, soils and topography, crop establishment and tending systems, and harvesting systems requires on-going assessment, monitoring, and refinement to craft BMPs to best suit local conditions. The use of BMPs is widespread in developed countries and it varies from mandatory to voluntary (Neary et al. 2011). For example, in many countries, BMPs are already incorporated in "Codes of Forest Practice" that guide forest managers through the complete bioenergy life cycle. BMPs have been developed and implemented in many agricultural countries to deal with water quality problems. Research and development studies play a key part in the refinement and communication of improved BMPs and are also crucial in validating the effectiveness of BMPs. This is especially important where local environmental conditions or operational standards are unique.

The recycling of vinasse and other industrial residues is generally managed using appropriate pipelines, channels and roads that cross several fields, an infrastructure investment that is facilitated by the vertically integrated structure of the sugar/ethanol industry in Brazil. Depending on the feedstock-industrial structure of specific ethanol industries in different countries, the recycling of vinasse may be more difficult or costly. Alternative options include anaerobic digestion to yield methane, concentrating vinasse to facilitate long-distance transport for disposal, and reduction in vinasse production. For instance, in Brazil it was demonstrated that by increasing the alcohol content of the sugarcane extract during the fermentation process, the volume of vinasse could be decreased by 50% (Martinelli et al. 2013). Biomethane production and vinasse concentration are not currently common in the sugarcane industry.

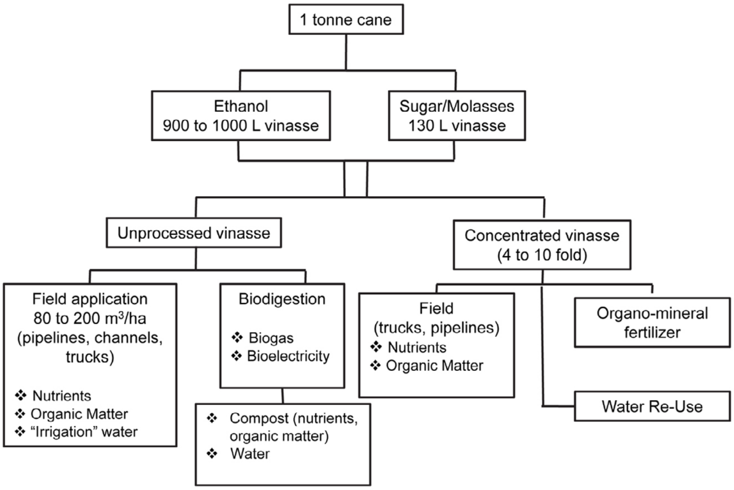

Figure 18.12. Possible modes of nutrient recovery from vinasse in Brazil.

Presently, most ethanol stillage, or vinasse, in Brazil is applied to the fields as produced, i.e., without concentration. Usual rates vary from 80 to 200 m^3 ha^{-1}. In addition to the nutrients, such vinasse load represents 8 to 20 mm of water added, an irrigation input usually applied in the dry months. The disposition of vinasse to the soil is regulated to protect surface waters from eutrophication. Stillage represents an opportunity for biomethane generation as well.

18.5.4.2 Municipal Solid Waste and Wastewater Digestion (Biogas)

Municipal wastes have the potential to generate sizeable amounts of bioenergy (Kalogo et al. 2007; Shi et al. 2009) and, at the same time, reduce landfill and its associated negative impacts. Anaerobic digestion (AD) of organic components in municipal solid waste (e.g. food waste, yard trimmings), manures, residues from food, feed, and biofuel processing, and wastewater can generate biomethane. This process reduces waste volume, controls GHG emissions, and provides a means to remove unwanted contaminants and recycle nutrients (Chapters 12, this volume). AD is one of the few technologies that can effectively handle wet biomass and is adaptable from small scale to large scale (Chapters 12 and 14, this volume). Recovery of nutrients through the process is variable. Phosphorous and potassium can be recovered at rates ranging from 76-99% (Yilmazel and Demirer 2011). Removal of phosphate as struvite ($MgNH_4PO_4{\bullet}6H_2O$) facilitates simultaneous recovery of soluble nitrogen and magnesium. Nitrogen recovery is variable but innovative ion exchange and membrane technologies could allow substantial (>90%) recovery (Mehta et al. 2014). Because nutrients are in organic form, which can be accessed by plants slowly over time, soils treated with digester residues tend to have less nutrient leaching while promoting plant growth (Walsh et al. 2012).

18.5.4.3 Ash and Biochar

Thermochemical conversions of biomass produce chars and ash, which contain mineral nutrients and variable amounts of carbon (Chapter 12, this volume). Depending on the biomass source, ash from combustion and gasification may contain unacceptable levels of alkali and heavy metals, which can present leaching hazards and affect soil pH (Vassilev et al. 2013). However, recycling of mineral nutrients from ash has been successful in many forest applications (Omil et al. 2011), and in sugarcane (Magalhães et al. 2012). Biochar is the solid charcoal-like product of pyrolysis that is used as a soil amendment. Many biomass materials can be pyrolyzed, including wood waste, manures, and crop residues. The properties of biochar vary widely depending on the feedstock and pyrolysis conditions. Biochar is highly recalcitrant, stabilizing carbon for decades to centuries (Singh et al. 2012). Furthermore, biochars may substantially reduce nitrous oxide (N_2O) emissions from soil (Singh et al. 2010). However, the magnitude and longevity of these effects are likely to be context-specific (Jones et al. 2012). Biochar benefits to soil properties can include reduced acidity (McCormack et al. 2013), increased nutrient retention, increased water holding capacity (Karhu et al. 2011), and stimulation of beneficial microbes (Lehmann et al. 2011). The chemical, biological and physical interactions between biochars, soil minerals and organic matter are the subject of on-going investigation. Combining pyrolysis with other bioenergy technologies may offer advantages. For example, pyrolyzing the digestate from anaerobic digestion could yield bioenergy products (from bio-oil and/or pyrolysis gas), while producing biochar as a soil amendment that enhances soil fertility, thus increasing biomass production for other bioenergy applications.

18.6 Policy and Governance

Worldwide, there is progress toward consensus on goals for sustainable use of soil and water resources, although differences in governance approaches and concerns for sovereign control of resources continue to interfere with progress at the regulatory level. The move beyond political boundaries to basin-level collaborative governance that is taking place in many regions of the world including the US, EU, China and Brazil is encouraging. There is an absolute requirement for clear and transparent goals and leadership for such activities to be successful (Steinzor and Jones 2013; Gupta et al. 2013). The inclusion of water and soil metrics in voluntary sustainability certification schemes (See Chapter 15, this volume) is a useful step toward mainstream implementation of sustainable water and soil stewardship (Gheewala et al. 2011). However, large deficiencies in governance remain (Chapters 19 and 20, this volume). The most glaring of these is continued weak governance of water withdrawals in stressed regions, insufficient prioritization of water use rights (i.e. antiquated rights provisions), and insufficient water pricing in cash-rich nations (Rogers et al. 2002; Srinivasan et al. 2012). There is also a need for harmonization and integration of water and soil sustainability criteria in many regional and national policies, especially with regards to non-point source emissions, which are typical of biomass production activities (Endres 2013; Moraes et al. 2011) (Chapter 19, this volume). While these issues and the policies they spurn are not specific to bioenergy production (Table 18.2), they will affect sustainability of bioenergy systems.

Table 18.2. Frameworks can be developed for watershed impacts of land cover change – In South Africa afforestation of 1.4 million ha of trees reduced annual runoff by 1417 million m^3 (3.2%) and reduced annual low flows by 101 million m^3 (7.8%) (Scott, 1998). Several policies were enacted to address the issue. The Afforestation Permit System in 1972, followed by the Forest Act of 1984 regulated the area of afforestation and required a rough calculation of effect on flow. The early regulation ignored other water users and did not consider catchment size or low flow (seasonal effects). The National Water Act of 1998 and the implementation of the Stream Flow Reduction Allocations (SFRA) Water Licensing System in 1999 integrated catchment management and established catchment agencies to examine streamflow. The areas were categorized according to three levels of activity (below). The system requires a publically available Strategic Environmental Assessment that considers biophysical, economic, social components including a soil survey, and a preliminary assessment of impacts on allocatable water and on the water resource, subject to environmental and statutory constraints. Under the system, water use licenses extend for 40 years, conditional to periodic review every 5 years.

Category	Description	Restriction
I	Biggest demand with other purposes with higher priority	No more new afforestation
II	Sporadic water shortages with existing priority rights to be protected	New afforestation limited to levels where Mean Annual Runoff (MAR) would not be reduced more than 5% of pre-1972 levels
III	Remainder of catchments	New afforestation limited to where MAR would not be reduced by more than 10% of pre-1972 levels

18.7 Conclusions

Water and soil are inextricably linked. Assessment of positive and negative effects of bioenergy production on soils and water should be part of an integrated analysis considering environmental, social, and economic dimensions. Metrics, such as water footprints, have little informative value unless combined with information about resource availability and competing use at relevant spatial and temporal scales. Soil and water effects depend largely on whether bioenergy implementation induces changes in management of land, water and other resources, and on how the previous management has influenced the state of soil and water.

Forest bioenergy systems following BMPs are judged compatible with maintaining soil quality and high-quality water supplies in forested catchments. Excessive removal of plant material from the field or forest may jeopardize soil and water quality. Extended or intensified cultivation of conventional annual crops as bioenergy feedstock will cause the same impacts as when these crops are cultivated for food. The cultivation of perennial grasses and woody plants commonly causes less impacts. These production systems can – through well-chosen siting, design, management, and system integration – help mitigate soil and water problems associated with current or past land use and improve soil and water use efficiency.

Advances in water recovery and recycling reduce water requirements for conversion processes as well as effluent production. Feedstock production and conversion stages can, in some cases, be integrated to use resources more effectively and support good land and water management. Examples include the recirculation of sludge to willow plantations, vinasse application to sugarcane fields, and possibly, the use of biochar as a soil amendment.

Water withdrawals (both quantity and timing) should be carefully considered in context of watershed needs, vulnerability, and resilience. Water scarcity may limit bioenergy potentials in some regions, but suitable bioenergy cropping systems can take advantage of currently unused water resources such as saline water, pre-treated wastewater, and rain falling outside the growing season for conventional food/feed crops.

Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is possible and essential. Successful implementation requires investments in the development of suitable plant varieties and conversion systems, systems integration to use resources effectively, and implementation of best management practices in forestry and agriculture.

18.8 Recommendations

- The effects of bioenergy systems on water and soil resources must be assessed as part of a comprehensive analysis considering environmental, social, and economic dimensions. Metrics such as footprints and water- and nutrient-use efficiencies are insufficient and can be misleading and irrelevant if used as the sole basis for decisions and policy development to promote sustainable production and environmental security at relevant spatial and temporal scales.
- Bioenergy systems that offer good opportunities to address soil and water problems should be promoted where their establishment does not cause other negative impacts that outweigh these benefits. Examples of such systems include energy and nutrient recovery from waste materials and the strategic integration of suitable feedstock cultivation systems into agriculture landscapes to address soil and water problems. Payments for such additional environmental services might be needed since system costs are sometimes higher than for conventional bioenergy systems.
- Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is possible and essential. The use of irrigation for bioenergy must be subject to a high level of scrutiny. Caution,

periodic evaluation, and appropriate water pricing and allocation systems can help avoid unwanted effects in water-stressed regions.

- Crop and forest intensification, enabled by active management and the use of inputs such as fertilizers and irrigation, can spare land and enable more efficient resource allocation. However, possible negative impacts on water availability and water and soil quality should be assessed and minimized. In most cases, bioenergy solutions can be found that contribute to energy and climate security and which are compatible with local and regional constraints.
- As in other agricultural and silvicultural activities, the adoption of BMPs is important in crop intensification because it tends to minimize risks of excessive input use.

18.9 The Much Needed Science

1. Site-specific and regional data are needed to guide practices regarding use of residual biomass from current agricultural and forest systems to understand where there may be risks associated with excessive removal of plant material from the field or forest which can jeopardize soil and water quality, causing economic and environmental losses.
2. Breeding and selection of plants should favor those species and genotypes tolerant to poor conditions including drought, waterlogging, salt accumulation, etc., in addition to those with high WUE and NUE.
3. Long-term research is needed on soil nutrient and carbon cycles under perennial crop and forest systems, and concerning land use change effects on water and soils.
4. Improved methods should be developed to leverage remote sensing capabilities for monitoring land use and soil and water status.
5. Continued innovation in use of waste materials and in water and nutrient reuse and recycling in bioenergy systems is needed to fulfill the potential contribution of biomass to sustainable energy production.
6. Long-term studies on use of ash and biochar as fertilizers and soil amendments should be supported.
7. In addition to research and data collection, assessment frameworks, including relevant indicators and dissemination tools are required to support the development of strategies for integrating bioenergy systems into existing agriculture and forestry practices. Such strategy development needs broad stakeholder involvement in order to capture synergies and strike a balance between social, economic and environmental objectives. The development and use of relevant indicators is one critical part of this work.

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chapter 19

Sustainability Certification

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Summary

Assuming that achieving environmental and social maintenance and improvement compared to a baseline should be the goal of biofuels policy, certification will require sizeable capacity building to operationalize standards meaningfully. Knowledge gaps—particularly in biodiversity, water quality, shed-level, and carbon assessments are magnified in underdeveloped countries and among smallholder farmers. Bioenergy policy therefore must support all supply-chain actors through scientific, educational and technical assistance. Measurements at the landscape level, informed by field level experience, can perhaps provide the most important gauge of progress toward systemic sustainability, and can be led at the biomass consumer level where know-how and capital is likely greatest. International harmonization of standards should occur only at the most general level to account for regional and local variation and to avoid trade barriers. Policy design must ensure that outcomes match aspirations by channeling information from certification back into adaptive management, which allows for on ramps to continuous improvement of environmental and social conditions. In places where public governance fails to prevent detrimental actions or maintain essential societal services (e.g., food security, land use change, land grabbing, and lack of education, health care, and clean water), policymakers should question the capabilities and effectiveness of bioenergy sustainability certification standing alone. Instead, society should push for policies to deal with these more systemic problems on the ground more directly through improved governance and similar capacity building. Nonetheless, in cases where private sustainability certification is expected to stand in for failed public governance, organizational governance must facilitate participatory processes that foster credible and legitimate sustainability outcomes.

19.1 Introduction

Certification schemes for biomass attempt to satisfy requirements for “sustainability” set by government policies as a result of interest group advocacy. A diversity of competing standards and certification bodies has emerged in recent years in the bioenergy context, both public and private (Scarlat and Dallemand 2011; IEA Bioenergy 2013). Such standards, however, do not necessarily represent an objective measurement that a product or process is indeed sustainable. Instead, standards allow for a comparative process to determine whether one set of actions may be better than another based on criteria set by society through the political process. One of the most critical questions

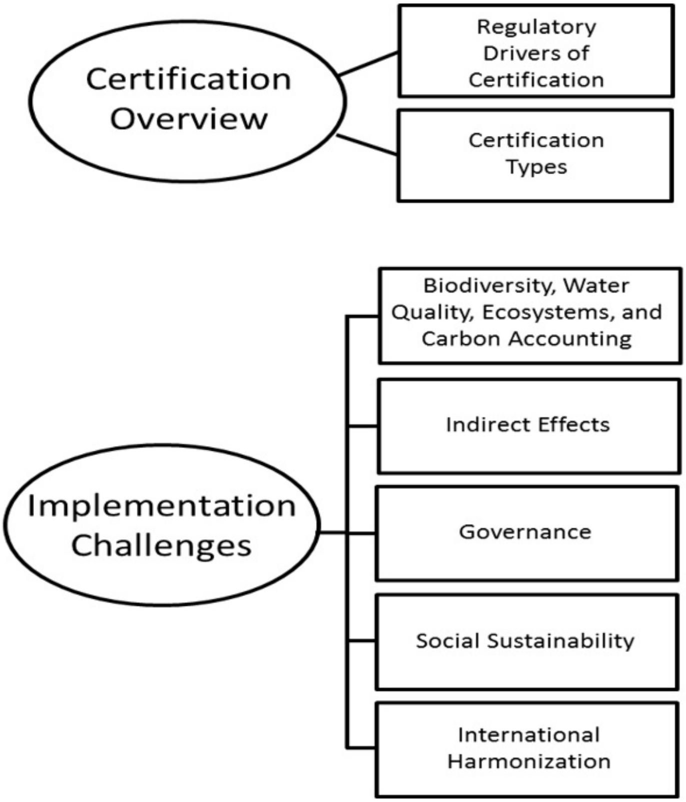

Figure 19.1. Chapter overview.

moving forward in biofuels certification, assuming that achieving environmental and social maintenance and improvement compared to a baseline is the goal of biofuels policy, is how to fortify this process so that standards application can continually improve as a mechanism based on scientifically-verifiable, objective measurements. Where scientific uncertainty exists, or dueling sciences conflict, appropriate governance mechanisms must be in place within standards organizations to make value judgments on risk.

In principle, biomass sustainability standards and certification have potential to support the development of sustainability science in agriculture and forestry. We posit, however, that paper standards and certification standing alone merely abet the increasingly overused and hollow term “sustainability.” Governments, and the third party standards they have come to rely on to implement and verify sustainability attributes, are faced with several difficult capacity challenges ahead to provide verifiable meaning to certification. First and foremost, if standards are to be the most credible measurement of environmental, social and economic performance, they must translate their paper aspirations into frameworks that: (1) assess baseline conditions;

(2) collect data and measurements; and, (3) analyze those results to the baseline at the appropriate landscape level. Even in developed countries, baseline conditions have not been established due to a combination of funding and capacity deficits, and political resistance. Assessment capacity problems across-the-board are magnified in developing and underdeveloped countries, posing serious market access barriers. Further, ecosystem boundaries often do not respect jurisdictional boundaries that govern policy formulation and the application of standards.

Standards organizations working with economic actors, therefore, must discover how to harness public and private capabilities. Where gaps exist, stakeholders must consider whether and how to build the technical capacity that facilitates the most meaningful and cost-effective measurement of sustainability. Policy must create channels to feedback information from third-party sustainability certification into government and research institutions so that decisions can be adjusted if necessary and further tailored to diverse land conditions.

We first lay a foundation for addressing these issues by examining in section 19.2 the public policy drivers for sustainability certification of liquid biofuels in the European Union and the United States, such as the Renewable Energy Directive, Renewable Fuel Standard, and California's Low Carbon Fuel Standard. Types of third-party sustainability certification standards and their common elements are identified. Section 19.3 then identifies particular implementation challenges to sustainability certification such as capacity building and costs, and building necessary and available tools to conduct assessments and analysis. We particularly highlight challenges in the areas of biodiversity and water quality. Further, we consider the efficacy of individual level certification when broader facility certification could be tied to corresponding systemic environmental and social conditions to determine at a broader (and more impactful level) what benefits producers in the aggregate are achieving. We identify hurdles to tying multi-functional landscape design at the individual ownership level into shed-level design.

In section 19.4, we consider whether broader bioenergy policy (versus individual certification) should consider whether, how and where to draw the line between assessment of direct and indirect effects. If the core purpose of bioenergy policies is to facilitate development of the sector, we question the motive of mostly one-sided focus on curtailing possible negative impacts, some very indirectly related to biofuels. Positive impacts, both direct and indirect, on the other hand remain inadequately quantified. For example, while another chapter covers social sustainability (Chapter 15, this volume), we observe that certification systems' measurement of community benefits has been limited generically to jobs created, and whether health care is provided, whether the refinery provides educational opportunities, etc. Certification could assist science in pursuing the almost absent study of the possible direct and indirect environmental and social *benefits* the biomass sector provides. Section 19.5 examines the emerging debate surrounding good governance (i.e., stakeholder involvement, transparency) in forming and implementing standards, and section 6 addresses the issue of international harmonization of standards. Finally, section 8 presents key recommendations for moving forward.

19.2 The Rationale for Sustainability Certification and Baseline Sustainability Principles

19.2.1 Regulatory Motivations For Certification

Examining the underlying regulatory rationale for certification is one way to gauge its efficacy. As bioenergy policies emerged in the mid-2000s, environmental groups pressured governments to ensure that mandates produced environmental and social gains over the business as usual baseline, befitting of the “biofuels” moniker (Endres 2011). Sustainability certification for bioenergy arose in part in response to regulatory requirements such as the 2009 European Union (EU) Renewable Energy Directive (RED) (EC 2009). Article 17 disqualifies liquid biofuels derived from land with high biodiversity value, or from converted high carbon stock lands, and agricultural feedstocks for biofuels should comply with sustainability requirements embedded in the Common Agricultural Policy’s cross-compliance environmental measures covering air, water, soil and biodiversity. The RED also requires biofuels to achieve 35% reductions in greenhouse gas (GHG) emissions compared to fossil fuels, and provides default GHG accounting for various feedstocks in Annex V. The minimum GHG reduction will increase to 50% by 2017, and to 60% for new installations from 2018. The European Commission has recognized 14 voluntary schemes that can check compliance with all or part of the sustainability requirements for biofuels in the RED. Assessment reports of each of these standards for demonstrating compliance with the sustainability criteria have been published on the Commission’s website (EC 2013a).

The United States (US) Renewable Fuel Standard (RFS) (EISA 2007) contains a similar prohibition for sourcing from converted lands, but until recently applied only an aggregate compliance approach to policing the requirement. Accusations of fraud spurred the Environmental Protection Agency (EPA) in 2013 to propose an individual renewable identification number (RIN) documentation that includes a verification of land sourcing (US EPA 2013). Unlike the EU RED, the RFS applies both direct and indirect land use change (iLUC) accounting of GHG emissions for various feedstock pathways, which must achieve various threshold reductions below baseline. California’s Low Carbon Fuel Standard (LCFS) takes a similar approach to GHG accounting, and the Air Resources Board (ARB) is in the process of formulating a sustainability policy that may include some type of verification requirement (ARB 2010). Both the EU RED and US RFS require reporting on the sustainability impacts of the policies. The EU Commission must report every two years to the Council and Parliament on national measures taken to ensure the sustainability criteria in Article 17 and soil, air and water protection, as well as impacts on social sustainability. A first report was published in March 2013 and concluded that "no major impacts are readily apparent and current measures are sufficient. It is necessary to continuously assess and monitor the impacts with a view to implementing corrective measures when needed" (EC 2013c; Ecofys 2012). Similarly, the US EPA must assess the sustainability impacts of the blending mandate every three years. Its first report admits that many baselines for comparison do not exist (US EPA 2011a), and budget pressures may prevent EPA from issuing its second report. Both the EU RED and US RFS have come under legislative pressure over concerns that biofuels mandates increase food prices. More recently, the aviation sectors in Europe and the US have concluded that its biofuels must be sustainably sourced and verified through certification (MASBI 2013). No international agreement has been reached yet on standardized GHG accounting methodologies for aviation, although EU regulation of the sustainability of aviation under the EU Emissions Trading System (ETS) is looming if the International Civil Aviation Organization (ICAO) does not come to an agreement (EC 2013b).

19.2.2 Types of Sustainability Certifications

Even prior to the advent of biofuels certification, sustainability regimes have been developed for a wide range of products, addressing good resource management and responsible entrepreneurship to gain market access, develop a green business profile, obtain price premiums, and to improve supply chain efficiency (IEA Bioenergy 2013). These are generally performance-based schemes aiming to achieve a certain standard (versus *practice-based*), and include a number of principles, criteria and indicators designed to verify compliance. With regard to energy biomass, certification systems have become available for almost all feedstock and products covering parts of, or the complete, supply chain–from production and processing to trade of biomass and biofuels. Some of these systems exist on a national level, and others are internationally recognized and applicable. Due to the fact that these systems have been developed with different interests and priorities (i.e., by governments, NGOs, companies), the scope, approach and complexity vary from scheme to scheme.

19.2.2.1 Forest Certification Systems

The Forest Stewardship Council (FSC) was the first standard to set international principles for sustainable forest management; each region implements the international FSC standards based on local input. Other standards developed later include the international Program for the Endorsement of Forest Certification (PEFC). PEFC acts as an umbrella organization for certification by endorsing national-level regimes. Some 30 certifications have been recognized to date through its multi-stakeholder process, varying in their definitions and approaches to a certain extent but all consistent with PEFC's "sustainability benchmarks." One example of a national-level program recognized by PEFC is the Sustainable Forestry Initiative (SFI), the largest third-party certification in the U.S. sponsored primarily by the forest industry. SFI, like FSC, contains principles related to soils, water, and biodiversity, among others. FSC has been used in the U.S. to certify short-rotation woody biomass (SRWB) for bioenergy, and SFI is considering whether to add a bioenergy-specific module to their certification program that would cover SRWB. No forest certification systems have yet developed carbon accounting modules, likely in part due to disagreements about methodologies. Thus, the challenge moving forward will be for these regimes to address reporting of GHG emissions, and to determine whether and how to incorporate short-rotation woody biomass systems that straddle forestry and agricultural characteristics.

19.2.2.2 Agricultural Certification Systems

Certification, regardless of the crop's end-use, has existed in agricultural systems for decades. Some regimes are more general (e.g., the Sustainable Agriculture Network (SAN), Global Good Agricultural Practices (GAP)), while others, more recently developed are crop-specific (e.g., the RTRS (soy), RSPO (palm oil) and Bonsucro (sugarcane)). In the U.S., the National Organic Program (NOP) has been the primary avenue for organic certification in agriculture, although private third-party systems of various content and verification are continually emerging such as Sustainability in Practice (vineyards), Field to Market (commodities), and the Stewardship Index for Specialty Crops. Similar to forest certification, all of these standards cover environmental, economic and social principles although criteria do differ from scheme to scheme. RTRS, RSPO, and Bonsucro now cover bioenergy and are recognized by the EU RED.

19.2.2.3 Biofuel/Bioliquids Certification Systems

With the advent of the EU RED certification requirement for "bioliquids," certification systems emerged that specialize in biofuels such as ISCC, RSB, REDCert, and 2BSvs. Compared to more general agricultural certification systems, these were required to address carbon emissions because of the EU RED requirement that liquid fuels reduce emissions compared to their petroleum counterparts. A recent trend among some has been to develop into a broader certification. For example, the "Roundtable for Sustainable Biofuels" transformed to "Biomaterials," and ISCC now has an ISCC+ certification to cover all end-uses. Environmental groups prefer some standards over others (e.g., Hammel 2013), as some (e.g., ISCC) are intended to fulfill baseline legal compliance with CAP cross-cutting measures, versus others outcomes beyond merely legal compliance (e.g., RSB).

19.2.2.4 Wood Pellet Certification Systems

Wood pellets make up the primary source of solid biofuels for electricity generation. Although the EU RED currently only requires certification for liquid fuels, the Commission is in the process of considering whether or not to require certification for solid biofuels.

Members States such as the United Kingdom in their Renewables Obligation, require large generators to apply carbon accounting and ensure that biodiversity is not harmed (DECC 2014). Private, chain of custody standards such as the Green Gold Label (GGL) and the Laborelec system developed initially to meet Member State programs and consumer demands for sustainability generally, but also could be used theoretically toward RED qualification depending on what a final directive entails. GGL is the only standard currently approved for certification under the UK's RO (GGL 2014). Currently a consortium of large pellet buyers and their suppliers has formed an initiative called "Sustainable Biomass Partnership" (SBP) to streamline their quality and sustainability requirements to facilitate trade within the sector and potential EU RED requirements. Few states in the U.S. with renewable portfolio standards specifically require certification from a third party, but some (e.g., Massachusetts) disqualify certain sources based on sustainability (e.g., soils, carbon accounting, source) (Endres 2013a).

19.2.2.5 Summary of Environmental and Social Indicators

The basics of biofuels certification have been extensively examined in the literature (IEA 2013; Endres 2013b; Diaz-Chavez et al. 2011a; Junginger et al. 2012; Scarlat and Dallemand 2011; Yeh et al. 2009). Figure 19.2 highlights common environmental indicators in sustainability standards:

Our purpose in this chapter is not to reiterate basic components of each standard; instead, we highlight particular challenges common to each so that standards' effectiveness in maintaining and improving environmental and social conditions is not overestimated, misunderstood, or oversold.

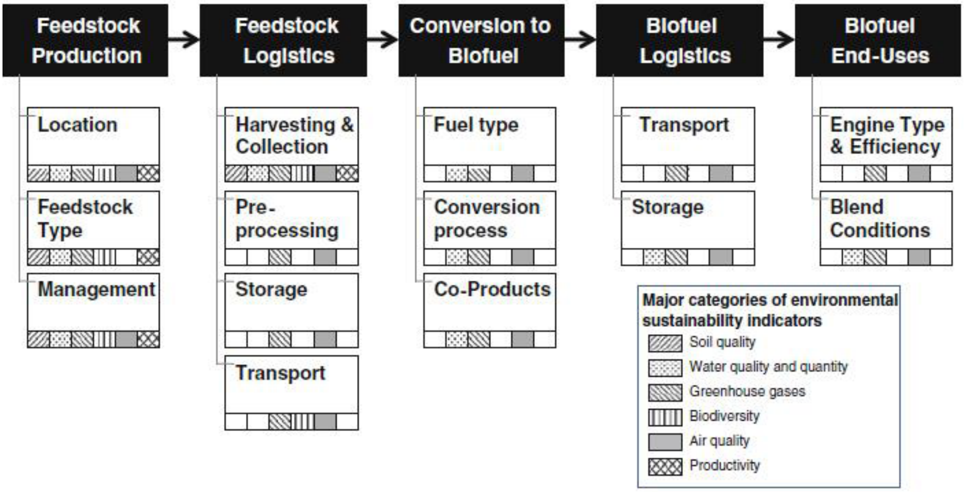

Figure 19.2. Environmental indicators within the biomass-based supply chain (Efroymson et al. 2013).

19.3 Implementation Challenges for Bioenergy Certification Standards

Despite the proliferation of standards as elaborated above, bioenergy policy's application of formal sustainability standards represents a significant expansion and policy shift. While Europe's CAP has contained cross compliance with environmental measures for over a decade, European farmers are not required to formally verify that compliance through certification. Congress has largely exempted farmers in the U.S. from federal air and water pollution requirements, although they must comply with the Endangered Species Act (ESA) and protect highly erodible lands, wetlands, and grasslands (Endres 2013b). Brazilian farmers in theory must comply with environmental licensing requirements and protection of water and biodiversity through the Forest Code, but enforcement has been questionable (Walter et al. 2013). Labor and employment laws in all three continents constitute the primary element of ensuring "social" sustainability, but do not reach broader community concerns such as inclusiveness in business decision-making, or the provision of education and health care that have worked their way into some biofuels certifications. In the forestry context, market-driven, private certification has been applied to many more acres, at least by larger forestry corporations and landholders. Thus, capacity to verify sustainable practices is more evolved and commonly accepted by forestry stakeholders. Experience finds, however, that challenges remain perhaps greater for forestry smallholders than for those in agriculture, because many fewer tools have been developed for them to gauge environmental performance.

Thus, whether such a shift in agricultural and social policy is feasible hinges in no small part on governments' and emerging biofuels sustainability certification organizations' ability to operationalize standards from paper to practice. Research, education, outreach, and support are critical building blocks of agricultural and silvicultural knowledge from both natural and social sciences perspectives. The following brief synopsis draws from case experience in standards development and implementation to exemplify the challenges ahead in the most complex areas of sustainability measurement.

19.3.1 Biodiversity Measurement and Protection

The first obstacle in complying with biodiversity prescriptions is in the terminology of itself. The EU RED and international standards typically extend protections to "high conservation value" (HCV) areas. None of the three regions where biofuels production is most in the spotlight (the U.S., European member states, and Brazil), however, maintain laws that establish common definitions across legislation as to what those areas constitute. Thus, when determining how a biofuels' operator is to comply with HCV protection, standards must determine what habitats and individuals HCVs encompass and what actions should be prescribed to protect them. Determining a baseline definition for HCVs may be necessary, but difficult. For example, the EU protects some grasslands from conversion because of their HCV, but in other countries this type of protection based on an HCV determination may interfere with competing goals of intensification that also has environmental benefits. Second, sustainability standards typically require that biodiversity be protected, which at a baseline requires an assessment of what biodiversity exists on a farmer's property. Experience in developing a U.S. standard through the Council for Sustainable Biomass Production (CSBP) presented many questions on how to assess lands and species subject to protection, and how to develop a set of criteria that certified actors would have to take to protect them. At baseline, actors must comply with the federal ESA; environmental groups, however, insisted that protections also reach those species not protected by the ESA (e.g., rare, or those that should be listed under the ESA but are not). The group determined that the best avenue to do this was for producers to apply Nature Serve (2013) databases where available, in conjunction with consultation with State Fish and Wildlife agencies and their wildlife action plans to fill potential gaps. Field testing revealed that such assessments: (1) can be prohibitively expensive, particularly for aquatic species and in the forest context; (2) require expert consultants to help guide small holders through the process; (3) may be incomplete because not all states have provided complete information to Nature Serve nor completed wildlife action plans, particularly for aquatic species; and, (4) create fear among farmers that assessment will lead to greater regulation beyond what private standards require. Scientific studies have provided frameworks and models to evaluate biomass cropping systems effects on wildlife (e.g., Stoms et al. 2011), but would require translation at the producer and biorefinery level in the application of certification.

Brazil presents another example of significant obstacles facing sustainability standard implementation with regard to biodiversity protection. The Bonsucro standard and other non-certification programs such as Etanol Verde contain language typical of standards requiring biodiversity protection, as well as a general provision that mandates compliance with all existing laws. One of them will be the implementation of the amended Forest Code (2012). The Forest Code amendments may require landowners, both large and small who are not already in compliance with the existing Forest Code, to come into some type of compliance with both Legal Reserve (LR) and Areas of Permanent Protection (APP) requirements. Not only must producers register their lands, but they must also work with the states, using guidance that has not yet been developed, to develop recovery plans. New extension programs for smallholders are still being designed and implemented. Brazilian certifiers must also be able to implement the restrictions implemented by states regarding expansion into sensitive areas as established by the Sugarcane Agro-Ecological Zoning plan (MAPA 2009). How Brazilian states implement the Forest Code is ultimately the key question moving forward, both in preventing a reversal of improvements made prior to the amendments (Metzger et al. 2010), but just as importantly is determining how the amendments can be positively used to better design implementation based on ever-improving scientific knowledge of complicated ecosystem functions.

19.3.2 Water Quality

As demonstrated with biodiversity, sustainability standards typically require producers to assess baseline resource conditions and then take actions to prevent degradation (and continuously improve) that resource. In Brazil, environmental authorities must consider watershed plans when making siting decisions for the Legal Reserve. Thus, government is assuming the lead role in assessing watershed conditions and applying those to land use decisions. This speaks to the question of whether certification organizations are the most appropriate institutions –and the most capable– to take on interpreting ongoing, complex assessments of watersheds in light of certification requirements that producers not contribute to water pollution.

Assessment of water quality conditions poses great obstacles to U.S. producers. States are responsible for assessments, and in many cases have not completed studies of current conditions as required by the Clean Water Act (CWA). Even where assessments exist, it is difficult, if not impossible, for an individual agricultural or forest producer to know his or her contribution to water quality issues because pollution from farmer or silvicultural activities is not regulated like point source dischargers. Under the CWA, states are responsible for non-point source pollution control, and if any programs exist to address such pollution, they are mostly voluntary, except on highly erodible lands, to receive federal payments. As regulation appears to become more stringent under new actions taken by the Obama Administration to clean up hypoxic dead zones in major estuaries, states are only beginning to design more detailed guidance for producers to reduce nutrient pollution. Only if and when states are able to pinpoint discharge thresholds for nutrients will a performance-based standard (e.g., numerical discharge thresholds), which is typically preferred in the standards community, be possible. In the meantime, standards will require farmers to implement less targeted practice-based standards (Diaz-Chavez et al. 2011a). Efforts are underway in the U.S. to fortify existing erosion and soil quality modeling tools with the capability to integrate even grid-level performance, particularly for corn-stover removal, but even those tools must still tie in to water quality models currently being used by the U.S. EPA to calculate maximum nutrient loading thresholds for agriculture.

19.3.3 “Shed” Level Sustainability Assessments

The biodiversity and water quality examples above demonstrate a challenge of emerging importance in the standards community dialogue: individual producer certifications provide little or no indication of whether their actions produce positive effects within a broader water and biodiversity “sheds.” That is, farmers are limited to taking actions within their own property, but ecosystems and watersheds do not neatly fit within individual owner’s boundaries or even within state jurisdictional lines. Thus, standards systems, such as the Biomass Market Access Standard (BMAS) in the U.S. (BMAS 2014), are developing “consumer” level standards that would guide how to collect and aggregate data, and provide methods and recommendations on how to assess that data in relation to identified ecosystem, watershed, and other shed-level goals. Not only would this provide a more meaningful measurement of environmental achievement, but it would also allow for varying levels of performance by individual producers from year to year, or even avoid costly audits each year. Challenges remain, however, including gathering field and even sub-field level data and accompanying costs, complexity of analysis, and defining the system or “shed” boundaries.

Brazil’s implementation of the Forest Code and Agro-Ecological Zoning could provide a leading example of how the government can and should make land use decisions–in this case the placement of reserve lands–based on the laws’ ability to facilitate the designation of ecological corridors and areas of major importance for the conservation of biodiversity. Certification standards such as Bonsucro could incorporate a complimentary requirement that facilities cooperate with and reference efforts to restore lands to Legal Reserve and APPs in a way that achieves broader conservation of biodiversity and water quality improvements. In the U.S., however, the legality of any federal-level policy to achieve landscape level values is questionable due to Constitutionally-vested police powers at the state level and the Supreme Court’s recent tightening of how coercive the federal government can be through funding conditions (Endres 2012). This may inhibit coordinated, landscape level efforts in the U.S. to protect or restore biodiversity when those efforts cross state jurisdictional boundaries.

19.3.4 Forest Carbon Accounting

It is uncertain whether forestry sustainability standards will be required to coalesce around a common methodology for accounting the carbon footprint of forest-based bioenergy.[1] The issues certification regimes face include how to draw system boundaries, baselines, and attribution, among others (NCASI 2013). With regard to timing of emissions–central to the “carbon debt” debate– in the short to medium-term, emissions from forest harvests are higher than for non-biomass systems (id.). However, under longer-term scenarios, forest biomass systems “almost always provide greater GHG mitigation benefits than alternative systems” (NCASI 2013). U.S. federal approaches to accounting vary depending on the underlying obligation. For example, U.S. UNFCCC reporting uses a reference point baseline that measures net emissions occurring over a set period. The US EPA Science Advisory Board for Biogenic Accounting, convened to assist the EPA in setting a methodology for regulation of stationary source emissions, has concluded that the better approach is to evaluate the impact of a policy relative to business-as-usual conditions (US EPA 2011b; NCASI 2013). European-wide policy under the RED has not yet been set, although a leaked proposal setting forth a proposed methodology uses a 20 year span for measuring annualized emissions from carbon stock changes caused by land-use change (EndsEurope 2012). Further, similar uncertainties associated with calculating emissions from indirect land use change (iLUC) precipitated by agricultural

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[1] It should be noted that short-rotation woody biomass, grown as an agricultural crop, does not encounter the difficulties with forest carbon accounting to the extent conventional forestry (e.g., stands of hardwoods grown over decades) would.

biomass production exist for forest carbon accounting for indirect deforestation caused by market price effects from forest land use change.

19.4 Accounting for "Indirect" Effects

Biofuels incentives create increased demand for land to grow biomass crops. In turn, this theoretically can lead to higher prices of displaced food commodity crops, resulting in pressure to clear forests for cropping (emitting copious amounts of GHGs) and food insecurity. Based on this fear, environmental groups convinced the U.S. Congress to add provisions to the RFS that biofuels account for their carbon emissions from iLUC, as well as an escape hatch for EPA to adjust the mandate if it has negative effect on food and feed prices (EISA 2007). The European Commission is charged under the RED to analyze inclusion of iLUC in carbon accounting methodologies, although it has yet to apply it formally to qualifying fuels. The European Parliament voted in September 2013 to support a legislative report calling to limit the first generation biofuels portion of the RED mandate to 6% (BBC 2013); the Commission had proposed similar limits in 2012 (EC 2012). Although the extent to which biofuels influence higher food and feed prices is debated (Zilberman et al. 2013), biofuels mandates are under fire in the media and legislatures as socially unethical and environmentally destructive.

Sustainability certification of individual producers, however, is not designed to address such macro-level market conditions with multiple causal sources, and governance failures in enforcing protections to directly prevent deforestation. Certification programs, notably RSB, have attempted to address the indirect effects issue through certification by: (1) measures to increase yield; (2) use co-products and residues to increase system efficiency; and, (3) reduce land requirements by utilizing feedstocks from degraded lands, developing biomass (e.g., algae) that can be grown on non-arable land, and feedstocks from residues (with sustainable removal levels) and end-of-life products (without alternative uses). Other proposals considered by RSB included using an iLUC factor in GHG calculations based on volume of production or acre of land used, requiring certified producers to help other producers increase yields, and contribute to an indirect impacts fund to facilitate investment in agricultural productivity gains in developing countries. These recommendations have not made their way into final standards, however, thus perhaps demonstrating the equally difficult time private governance may have in addressing issues around which no scientific consensus has yet been reached.

19.5 Standards Governance and Social Sustainability

Private standards' governance mechanisms and their outcomes must be effective *and* legitimate (Endres 2013b). Particularly in underdeveloped countries, civil society organizations expect that bioenergy projects deploy third-party, voluntary sustainability standards to stand in where public governance fails to provide environmental and social protections, such as labor and employment safeguards, secured land rights, food security, basic community services, and a healthy environment. Thus, internal "processes" within standards organizations in building and applying standards that recognize these basic societal needs have become the focus of increased attention.

Expectations that bioenergy facilities substitute for public governance, however, presents varying challenges depending on what effects can be controlled by the bioenergy facility. Operators theoretically could validate through standards monitoring satisfactory working conditions (e.g., wages, working hours, benefits) on site, the provision of education, health care, food security, and more favorable environmental conditions (e.g., clean drinking water) at the community level. However, the impacts of these "community benefits" may be out of standards' current analytical reach and operators' economic capability without additional research on the causal connection between sustainability practices and potential positive outcomes.

Indeed, policy dialogues' focus on addressing indirect negative effects of biomass-based energy, or direct impacts based solely on general revenues or GDP, should serve as a call to measure more accurately and incrementally the potential societal benefits of bioenergy production. Peters (2013) proposes one way to approach the question, in that "green jobs"—a typical metric to gauge the positive socio-economic outcomes of bioenergy—should be defined more broadly using the diversity, use and relevance of green tasks, versus simple categorization of products produced or numbers of

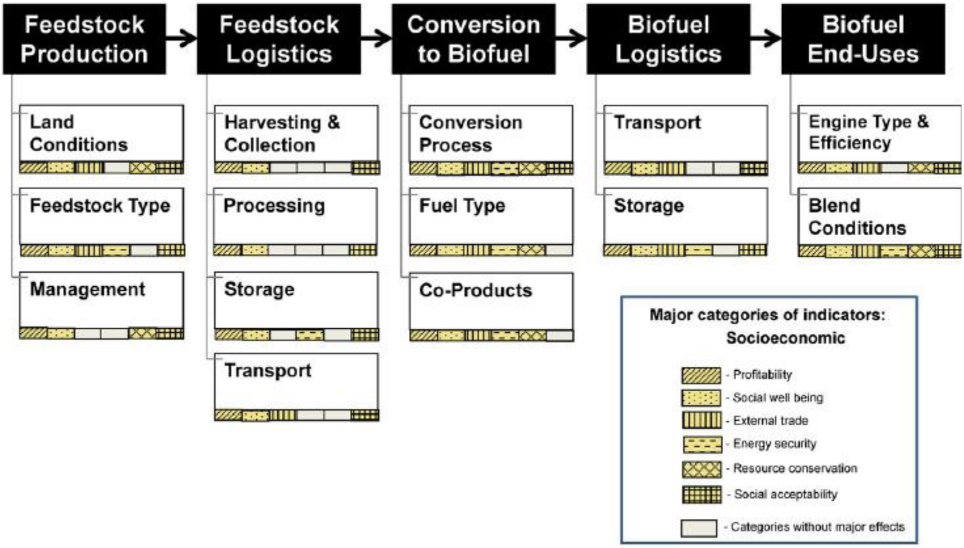

Figure 19.3. Social indicators within the biomass-based supply chain. (Dale et al. 2013).

jobs. In this regard, developed nations, which drive certification requirements, could use certification systems to gather data on skills deployed (Global-BioPact 2013). For example, experience to date shows that certification demands acquisition of new sustainability skill sets by farmers and others who work in the bioenergy sector, which could cumulatively have the potential to shift the sustainability paradigm in all production landscapes. Even in developed countries, standards do not yet account for indirect economic benefits (e.g., better schools and health care, agri-tourism, avoided remediation costs) from field and landscape level improvements that certification may bring. It is questionable whether private certification standards alone, however, can develop comprehensive methodologies and apply them; in developed countries, governments more easily assess socio-economic gaps and community impacts. In underdeveloped countries, private standards are expected, perhaps unrealistically at this stage, to provide this type of information.

While standards governance can affect outcomes positively, on the other hand, good governance arguments could shroud the pursuit of scientific knowledge and verifiable outcomes, and core philosophical disagreement about approaches to sustainability between stakeholder groups. Private standards governance instead should seek a measure of environmental and societal justice, based on shared reasons reached through stakeholder reasonableness and reciprocity. This can be achieved through mapping stakeholder participation and dynamics, accountability, and transparency and openness of deliberative processes. A diverse set of stakeholders can bring together specializations as a first step in building the comprehensive knowledge needed in such a nascent field. While consensus building constitutes an important part of good governance, ultimately, disagreements must be resolved one way or another or progress stalls. Standards organizations should be careful with making the perfect the enemy of the good; in some cases, a more pragmatic (and realistic) position coupled with a continuous improvement requirement can achieve more sustainability gains than none at all stemming from delayed, deadlocked debates.

Like in public democracies, stakeholder groups have their own organizational interests in mind in developing standards. Governments or sectors that use private standards should not make simplistic assumptions about which stakeholders are legitimate guardians of sustainability principles over the pursuit of foundational scientific knowledge through transparent processes. If bioenergy must shoulder uniquely the enormously complicated burden of proving its systemic sustainability, policymakers should emphasize continuous improvement through adaptive management, supported by scientific discovery and participatory processes. Monitoring and evaluating the outcomes of certification regimes can play an important role in gauging the effectiveness of, and fortifying governance structures (Global-BioPact 2013).

19.6 The Efficacy of and Challenges to International Harmonization

Without some level of agreement on sustainability standards, particularly land use change and food security, international trade could be threatened. The stage is being set. Argentina has challenged the EU RED's 35% GHG reduction threshold for qualifying biofuels as arbitrary at the World Trade Organization (Argentina 2013). The challenge is symptomatic of past failures to reach consensus on how to address climate change, fair and equitable agricultural trade, and labor standards that protect vulnerable people against exploitation. Efforts are underway in the International Organization for Standardization (ISO) to finalize sustainability criteria for bioenergy (ISO 13065). Project Committee 248 is focusing on building upon Technical Specification 14067 for GHG methodologies. Its working group for indirect effects has reviewed over 80 publications and has concluded that the science on indirect effects is nascent and evolving, with inconsistent and contradictory model results (Kline 2013). The working group has noted that the state of science makes modeled indirect land use change incompatible with an international standard designed for replicable results (id.), and that the matter is highly contentious. The Global Bioenergy Partnership (GBEP) has developed a set of 24 sustainability indicators for bioenergy (GBEP 2011) that are meant to guide country-level development of policies, but do not take positions on the most difficult debates, such as iLUC methodologies. Assurance programs such as ANAB, ASI and ISEAL can perhaps contribute to ongoing dialogues about minimum requirements through monitoring and evaluation of certification programs outcomes, without dictating the scope of those standards (Global-Bio Pact 2013).

Even if the international community could reach some type of agreement on baseline principles of biofuels' sustainability, some scholars and developing countries view similar agreements with skepticism, contending that developed countries put standards in place not to achieve sustainability, but merely to protect domestic markets. The parties at the GBEP recognize that the ability to measure indicators depends on a country's capacity, but that indicators still remain practical if the required capacity can be developed through technical cooperation.

19.7 Conclusions

If "sustainability" is to have real meaning, government policy (and third party certifiers) must evolve from the theoretical to a serious consideration of the technical and economic requirements needed for measurement and the capacity necessary to transform aspirational standards to on-the-ground results. Case studies demonstrate that even in developed countries, where some programs and tools already exist, gaps remain. Technical capacity problems are likely magnified in developing and underdeveloped countries. Bioenergy policy, therefore, must provide scientific, educational and technical support to producers as an on-ramp to fulfillment of certification requirements. Relatedly, more rigorous and open discussion on the role of continuous improvement must be facilitated within third party certification organization and in public policy. Otherwise, bioenergy policy runs the real risk that producers will not participate in the market, and for those that do participate, certification requirements merely add additional costs without achieving meaningful sustainability gains. In developed countries, producers will see limited value to additional certification because they perceive existing policies to be sufficient. Governments should consider the efficacy of shed-level assessments over individual certifications, as environmental and social issues that certification portends to address in most cases, span beyond one producer's property boundary.

As a corollary, the most appropriate roles for international efforts, such as the GBEP, are to seek agreement first on the most general of principles to achieve a level of consistency among guidelines, models and tools. GHG and indirect effects accounting is particularly challenging; however, the most controversial subjects should be the near-term focus of policy discussions at that level. International efforts should consider implementing support mechanisms for building knowledge networks that translate skill sets and lessons learned to those charged with implementing sustainability practices and outcomes locally. We question whether international standards, without room for regionalization or localization to unique environmental, social and economic conditions, should be adopted even though uniform approaches can reduce costs in some cases. As demonstrated in section 19.3, even in developed countries, capacity is lacking with regard to implementation of certain elements of sustainability certification. Thus, the assumption cannot be automatically made that existing policies in those countries eliminate the need for verification, and that only underdeveloped countries lack the governance structures that warrant oversight. On the other hand, many developed countries will conclude that existing environmental and social protections are ample demonstration of biofuels' sustainability, eliminating the need for costly certification requirements embedded in law for biofuels to qualify toward public policy mandates.

Governments must capitalize on future evaluations of certification and broader programmatic impacts to ensure that: (1) sustainability goals set forth in public policy match certification outcomes, and (2) results are used to provide targeted technical support that fosters continuous improvement. The several evaluations that will be published in coming years, such as the EU Commission report on "measures to respect" certification and the RFS triennial report, should acknowledge lessons learned from certification. Where information gaps exist, these reports and subsequent efforts should seek to fill them through government sponsored research and the establishment of feedback loops into policy decisions. Governments should consider how to use sustainability certification to more broadly inform the country's legal, cultural, environmental and social circumstances that relate to broader sustainable development, not just sustainable bioenergy (Diaz-Chavez 2011b; IEA Bioenergy 2013). Although governance within private standards organizations must observe multi-stakeholder and transparency principles, the argument can be made that it is within democratically elected governments where society's determinations of sustainability ultimately lie.

Policymakers must contemplate how, if at all, sustainability certification can address systemic/indirect effects issues that almost entirely dominate policy debates. In this regard, we implore policymakers to consider more critically and systemically land-use systems and food consumption patterns, and to support research in the implementation of multi-functional landscape design more generally and fortification generally of enforcement to protect against conversion of certain lands outside of biofuels policy. Research and policy should not only focus on the negative impacts of biofuels, and in particular indirect effects, but also measure the potential positive socio-environmental impacts of biofuels and accompanying certification.

19.8 Highlights and Recommendations

- If certification is to provide a meaningful gauge of environmental and socio-economic sustainability progress, aspirational narratives must translate into verifiable measurements of environmental, social, and economic outcomes.
- Certification rigor will require increased investments in technical, scientific, and educational capacity and adaptive management systems that incorporate lessons learned back into policy decisions.
- Particular on the ground challenges include biodiversity and water quality assessment, ecosystem-level analytics, carbon accounting, and the implementation of social indicators.
- Negative indirect effects of bioenergy are better handled through public governance to directly address problems such as deforestation and lack of essential social services such as food security, education, health care, and ecosystems supportive of public health. Policy should focus on this broader problem of public governance failures, and recognize the limitations of private, third-party sustainability certification to address community-level issues.
- While policy is focused on indirect harms associated with bioenergy, more research is needed on the indirect environmental and socio-economic *benefits* that likely may stem from the bioenergy sector.
- While standards governance can affect outcomes positively, on the other hand, good governance arguments should not shroud the pursuit of scientific knowledge and verifiable outcomes, nor core philosophical disagreement about approaches to sustainability. Public policy must reconcile what minimum level of precautions private sustainability standards should meet.
- International harmonization efforts must account for unique regional and local socio-environmental conditions; certification should not lead to north-south trade barriers.

19.9 The Much Needed Science

First generation standards operating currently in the market can be complex and are mostly narrative in application. The quantity of verbiage in a standard, however, should serve as a proxy for rigor and has the potential to unnecessarily stand in the way of meaningful achievements by the nascent bioenergy sector. The next step in standards development must be the critical pursuit of the technical, scientific, and educational capacity to assess baseline conditions and tailor implementation solutions that provide measureable outcomes at the sub-field, field, and landscape levels. These capacity needs are particularly pressing in the area of biodiversity, water quality, carbon accounting, and socio-economic conditions within broader communities. At least from a certification perspective, it is questionable whether additional research dollars should be spent in the pursuit of more indirect effects modeling. Instead, investments should be made in building capacities in public governance parallel to those for certification.

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chapter 20

Bioenergy Economics and Policies

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Highlights

- Policies and energy prices are key drivers for current bioenergy and the emergent bioeconomy;
- Bioenergy is part of a larger transition to a bioeconomy;
- Technological change and full biomass utilization might create a competitive industry;
- A coherent policy package can temporarily stimulate an immature industry and regulation can deal with indirect effects of the bioeconomy.

Summary

This chapter describes developments in the bioenergy market and related policies. Recent bioenergy developments, often induced by policies, lead to a greater interconnectedness between energy and agricultural markets and influenced relative food and feed prices and land-use changes. An analytical framework is presented that places bioenergy within the bioeconomy. The impacts of supply push and demand pull polices are analyzed, and the reasons for policy interventions are introduced. The effectiveness of policy intervention is likely to increase if they are directly connected to a target such as the reduction of emissions or the stimulation of economic growth. Because the bioeconomy is an immature or infant industry, policies that temporarily stimulate its development might be justified. Technological change and full biomass utilization for food, feed, energy, materials and chemicals may lead to a competitive bioeconomy sector. Regulation could potentially deal with indirect effects of bioenergy such as social (land grabbing) and environmental effects (land, water, biodiversity). Given the importance of private sector investments in the development of biotechnologies, excessive regulation might create a disincentive to innovation.

20.1 Introduction

Currently, more than fifty countries have adopted biofuel blending targets or mandates and many others are implementing or considering biofuel quotas (REN21 2013). Also, the use of biomass for heat and power is increasing rapidly, mainly as a result of policies aimed at, among others, reducing greenhouse gas (GHG) emissions, improving energy security and enhancing rural economic development especially in industrialized countries. The global demand for bioenergy in 2010 was 1277 Mtoe, which is expected to increase to 1881 Mtoe in 2035 according to the New Policies scenario or 2235 Mtoe in case of the 450 Scenario that is aimed at limiting climate change to an average long-term increase in average global temperature of 2°C (IEA 2012a).

In a wider context, these developments are part of a transition from an economy that is based on non-renewable resources (especially for energy production) to a biobased economy based on the use of biomass residues from multiple sources and farming renewable resources (Zilberman et al. 2013a). This transition is partly policy and partly market driven, as non-renewable resources such as oil and minerals, are finite and will become increasingly scarce (new sources such as shale gas and oil may temporarily increase in the short run). Another driver is the potential emergence of new technologies that can convert biomass into a wide array of products (WEF 2010). Within the development of the bioeconomy, this chapter focuses on the economic aspects and policies related to bioenergy.

Biomass has been a traditional source of energy in the form of wood or dung. The modern biofuel industry aims to harness advances in biology and engineering to produce fuels for transportation and energy. The competitiveness of biomass based energy systems compared to conventional energy depends on the price of fossil energy feedstock and biomass, and the conversion efficiency and costs. Given the current market conditions, it is unlikely that the industry of ethanol and biodiesel would survive in the absence of tax credits and blending mandates (IEA 2011). The world ethanol price was about USD 1.20/liter gasoline equivalent in 2012 and biodiesel was around USD 1.55/liter (REN21 2013). Biodiesel prices are higher than in 2006 - 2011, when prices varied between USD 0.90 and USD 1.50 per liter. However, the price of conventional gasoline was “only” USD 0.78/liter. Few biofuel systems are currently economically viable. The Brazilian sugarcane based system has in recent years been the most competitive biofuel industry. However, this biofuel industry is currently struggling because of recent costs increases (e.g., land and labor), as well as the appreciation of the Brazilian Real versus the US dollar which affects export markets, decrease of oil prices, and the government’s induced cap-price on gas which keeps gas and therefore domestic biofuel prices and demand low. Corn based ethanol in the US is now competitive with oil in various states and the US is exporting it to the rest of the world. In contrast, biofuel use in the EU and most other countries is quite costly, mainly because of higher feedstock costs and the use of biodiesel in the EU. More efficient technologies might be emerging, such as the production of biofuels and biochemicals from cheap lignocellulose biomass through biochemical or thermo-chemical conversion (see Chapter 12, this volume), which may increase the economic competitiveness of the liquid biofuel industry (Kamm 2004; WEF 2010; OECD and IEA 2013). However, Smolker (2008), and Latham and Wilson (2013) challenge this optimistic view and wonder if the prospects of the bioeconomy are realistic.

The economic viability of bioenergy derived electricity and/or heat depends on the feedstock, conversion technology, scale of operation and the availability of heat sinks in the case of

Combined Heat and Power (CHP) (IEA 2012b). Electricity generation can be competitive today if wastes or residues are used, in case of large-scale operation or if heat from CHP systems can be used. The IEA (2012b) states that as long as the external costs of fossil fuel based generation are not fully taken into account, power generation from biomass will require some level of financial support. An example of economically profitable biobased heat and electricity production and use is the use of bagasse from sugarcane in Brazil.

The increasing production of biomass feedstock and conversion to energy has important economic consequences, which, directly and indirectly, influence the environmental and socio-economic performance of bioenergy systems and policies. The increased use of conventional agricultural crops and wood pellets increases the correlation between energy markets and conventional markets for agricultural commodities and forestry production (Du and McPhail 2012). In 2022, biofuel production is projected to consume a significant share of the world's total production of sugarcane (28%), vegetable oils (15%) and coarse grains (12%) (OECD-FAO 2013). Energy prices increasingly drive long-run agricultural price levels and energy market fluctuations are increasingly transferred to agricultural markets (Baffes and Dennis 2013). The tighter market integration is perhaps the most fundamentally important change to occur in agriculture in decades. The impacts of the increased integration and correlation are transmitted to other parts of the world through the trade of feedstock used for bioenergy production and through the trade of biofuels (Banse et al. 2008; Hertel et al. 2010; Laborde 2011). These indirect effects are key to the issue of indirect land use change (iLUC) and the resulting impact on GHG savings from first-generation biofuel policies. iLUC issues have received widespread attention, but economic mechanisms and correlations are also potentially crucial for many other social, economic and environmental issues, such as the impact on biodiversity, food prices and food security, fresh water resources, employment, economic competitiveness, and growth. To ensure that bioenergy policies truly contribute to sustainable development, it is crucial to gain insight on the economic impacts of bioenergy systems and the resulting direct and indirect effects.

In this chapter, we first describe the developments in the bioenergy market and its policies. Second, we provide an analytical framework that places bioenergy within the larger picture of the bioeconomy and its direct and indirect effects. Third, we discuss in more depth the arguments for policy intervention and we discuss the impacts of demand pull and supply push policies used to achieve the policy targets. The chapter ends with conclusions and recommendations.

20.2 Key Findings

20.2.1 Economic Developments in the Bioenergy Market

World bioenergy use in 2010 was 1277 Mtoe, which is about 10% of the total global primary energy use (IEA 2012a). About 60% concerned the traditional use of biomass for cooking and heating. Traditional use of bioenergy is the combustion of solid fuels such as firewood, charcoal and agricultural residues for cooking, heating and lighting. The remaining 40% is used in modern bioenergy systems. Modern bioenergy involves the use of biomass in producing higher value energy carriers, such as electricity and liquid and gaseous fuels, or heat and power in modern installations.

The industry and power sectors use more than half biomass in modern energy systems (Figure 20.1). Non- traditional biomass is expected to grow from 526 Mtoe in 2010

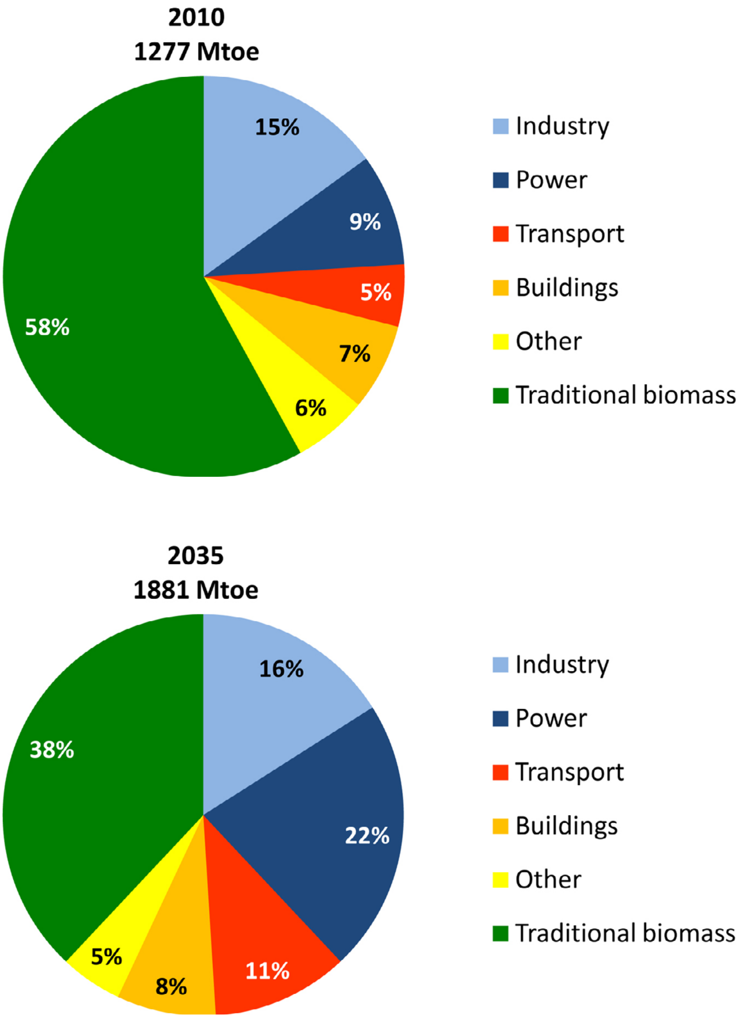

Figure 20.1. World Bioenergy use by sector and use of traditional biomass in 2010 and 2035. Source: IEA, World Energy Outlook, 2012a. Figures are based on the *New Policies Scenario* that takes account of broad policy commitments and plans that have been announced by countries.

to nearly 1200 Mtoe by 2035, growing at a rate of 3.3% per year (IEA 2012a). Both biofuels and power more than double their share in world energy use and are expected to reach 210 Mtoe and 420 Mtoe by 2035, respectively. Biomass for heat and power and industrial applications has traditionally been locally sourced, but trade is increasingly becoming important (e.g., pellets).

International trade grows quickly to complement local supply due to the growing demand of biomass for electricity, heat, and transport fuels. Wood pellets, biodiesel, and ethanol are now traded internationally (HLPE 2013). Others include methane, fuel wood, charcoal, and agricultural residues. The global biomass energy markets are diverse, volatile and vary according to the fuel type (see Figure 20.2). Figure 20.2 shows, among others, ethanol trade flows for Brazil and the US in 2011. Shortages of sugar have lead to sugar price peak due to bad weather and low sugar stocks caused an increase of the use of cane to sugar instead of ethanol. The US had been an importer of sugarcane ethanol for many years until about 2010 when imports fell close to zero as the costs of sugarcane ethanol increased relative to corn ethanol (see Crago et al. 2010). In the last 2-3 years, imports from Brazil have resumed, but mainly to meet the low carbon fuel standard in California.

Ethanol and biodiesel based on agricultural crops are the most commonly produced biofuels for transport. Among the two, bioethanol is far more important than biodiesel: in 2012, the production of bioethanol reached over 87 billion liters, while biodiesel was only

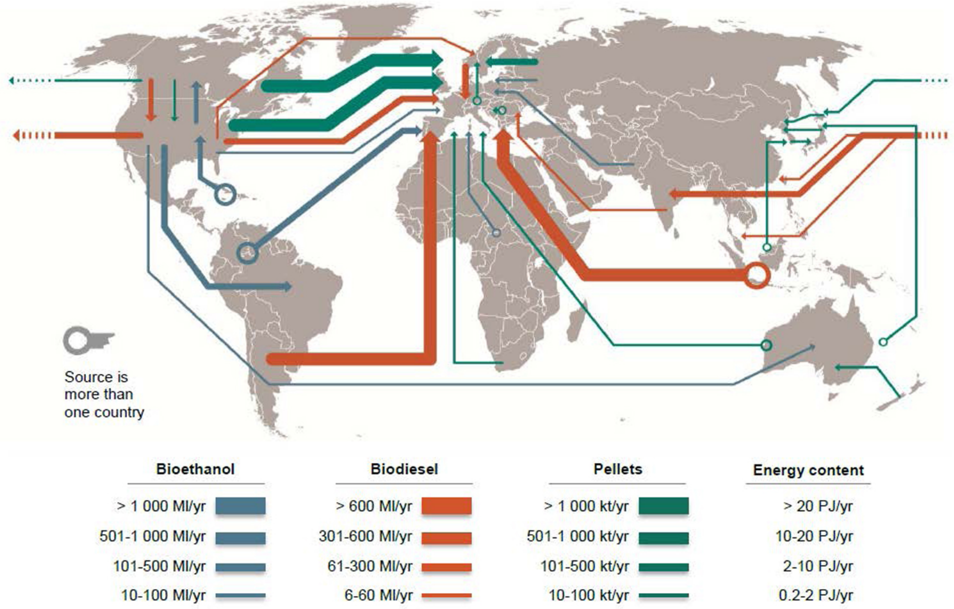

Figure 20.2. Net trade streams of wood pellets, biodiesel, and ethanol in the year 2011 (HLPE 2011).

roughly 18 billion liters (FAO-OECD 2013). The leading producer in 2012 was the US, which produced 45 billion liters of bioethanol, followed by Brazil (24 billion liters), China (9 billion liters), the EU (7 billion liters) and Canada (1.7 billion liters). Biodiesel production is heavily focused in the EU. Almost 11 billion liters of biodiesel were produced in the EU, which represents almost 60% of the total biodiesel production in 2012. The other biodiesel producers are the USA (4.2 billion liters) and Brazil (2.7 billion liters).

The main feedstock for biofuel production is maize in terms of production of biofuels on energy basis (Figure 20.3). To a large degree, this can be attributed to the use of corn for bioethanol production in the US. The second most important crop is sugarcane. Molasses, wheat, and vegetable oils played a smaller role in terms of quantity, though it should be noted that, especially for vegetable oils, direct comparison of the quantities is misleading as the oil represents only a fraction of the oilseed.

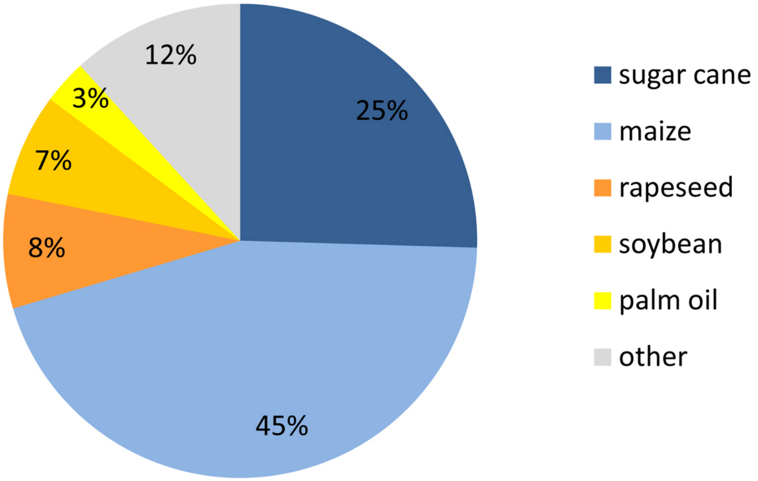

Figure 20.3. Feedstock use for biofuels production (% of total biofuels on energy basis), 2010. Source: New Climate Economy (2014).

20.2.2 Bioenergy Policies are a Key Driver

Policy support for the production and use of bioenergy is provided in virtually all countries. Biofuels policies consist primarily of biofuel blend mandates and subsidies, and also sustainability certification schemes. Subsidies are given mainly as fuel tax exemptions, but partially also as R&D grants. Table 20.1 shows the biofuel mandates in the world.

Table 20.1. Overview of national and state level biofuel blend mandates.

Country	Mandate
Angola	E10
Argentina	E5 and B7
Australia	Provincial: E4 and B2 in New South Wales; E5 in Queensland
Belgium	E4 and B4
Brazil	E18–25 and B5
Canada	National: E5 and B2. Provincial: E5 and B4 in British Columbia; E5 and B2 in Alberta; E7.5 and B2 in Saskatchewan; E8.5 and B2 in Manitoba; E5 in Ontario
China	E10 in nine provinces
Colombia	E8
Cost Rica	E7 and B20
Ethiopia	E5
Guatemala	E5
India	E5
Indonesia	B2.5 and E3
Jamaica	E10
Malawi	E10
Malaysia	B5
Mozambique	E10 in 2012-2015;E15 in 2016-2020; E20 from 2021
Paraguay	E24 and B1
Peru	B2 and E7.8
Philippines	E10 and B2
South Africa	E10
South Korea	B2.5
Sudan	E5
Thailand	E5 and B5
Turkey	E2

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Country	Mandate
United States	National: The Renewable Fuels Standard 2 (RFS2) requires 136 billion liters (36 billion gallons) of renewable fuel to be blended annually with transport fuel by 2022. State: E10 in Missouri and Montana; E9–10 in Florida; E10 in Hawaii; E2 and B2 in Louisiana; B4 by 2012, and B5 by 2013 (all by July 1 of the given year) in Massachusetts; E10 and B5, B10 by 2013, and E20 by 2015 in Minnesota; B5 after 1 July 2012 in New Mexico; E10 and B5 in Oregon; B2 one year after in-state production of biodiesel reaches 40 million gallons, B5 one year after 100 million gallons, B10 one year after 200 million gallons, and B20 one year after 400 million gallons in Pennsylvania; E2 and B2, increasing to B5 180 days after in-state feedstock and oil-seed crushing capacity can meet 3% requirement in Washington
Uruguay	B5; E5 by 2015
Vietnam	E5
Zambia	E10 and B5
Zimbabwe	E5, to be raised to E10 and E15

Source: REN21 2013

All stages in the chain for biobased heat and power systems are supported by government policies (Bahar et al. 2013). This ranges from production to conversion of biomass, distribution of bioenergy, and support to final consumers of bioenergy. Policies might be directed to all forms of renewable energy or bioenergy, or may focus on certain production chains such as biomass-powered combined heat and power (CHP) plants or biogas. Examples of support at various levels of the production chains are listed by Bahar et al. (2013).

Renewable energy targets, tax exemptions, and feed-in tariffs for renewable electricity, public investment, loans or grants, are the most common support measures, provided both by a large number of high income countries and elsewhere (Figure 20.4).

Figure 20.5 shows estimates of the global level of subsidies for renewables based electricity production and biofuels in the New Policy scenario that takes broad policy commitments and plans that have been announced by countries into account (IEA 2012). Global subsidies reached more than 60 billion USD in 2010 and are anticipated to increase to almost 250 billion USD in 2035 should these policies be maintained at the level of the conducted analyses.

20.2.3 Analyses Framework of Bioenergy within the Emerging Bioeconomy

The increasing production of biomass feedstock and conversion to energy has important direct and indirect economic consequences which influence the environmental and socio-economic performance of bioenergy systems and policies. In the past, agricultural markets and energy markets were not closely correlated. The higher energy prices and the use of conventional agricultural crops and wood pellets for bioenergy increased

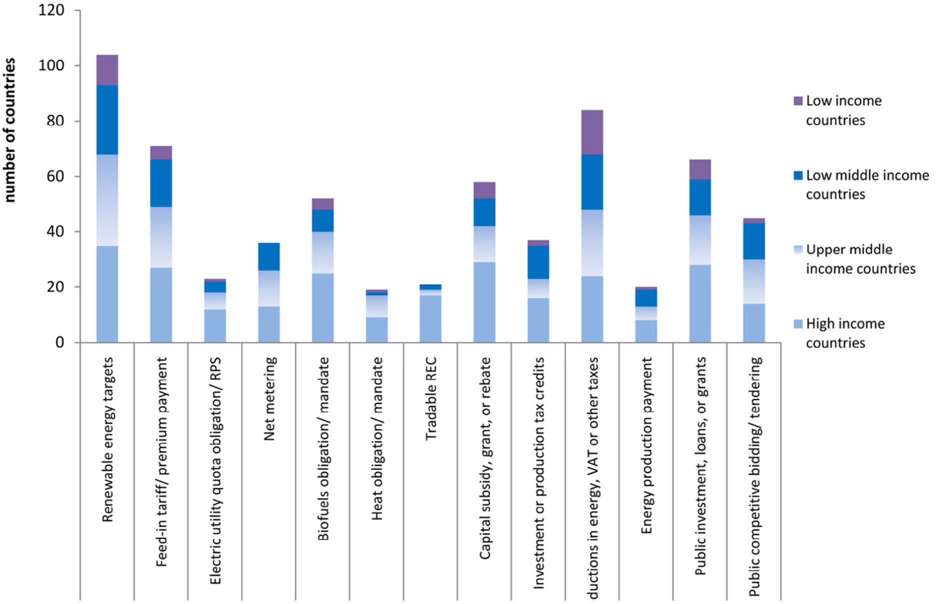
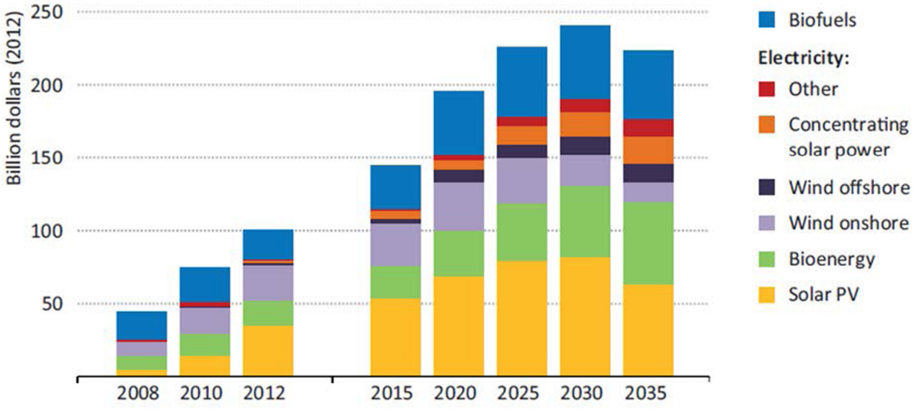


Figure 20.4. Frequency of policy measures to promote renewable power energy. Source: REN 21 (2013).



Notes: Other includes geothermal, marine and small hydro.

Figure 20.5. Global subsidies to renewables-based electricity and biofuels by technology and fuel. Source: IEA, World Energy Outlook (2012a). Figures are based on the *New Policies Scenario* that takes broad policy commitments and plans that have been announced by countries into account.

the correlation between energy markets and conventional markets for agricultural commodities and forestry production (Du and McPhail 2012; Baffes and Dennis 2013). Figure 20.6 shows that ethanol, gasoline, and corn prices are correlated.

In order to encompass a comprehensive overview for the complex economic analyses of the bioeconomy in general and bioenergy specifically, we use a supply-demand framework that connects the building blocks (drivers, impact, response) for our analyses (see Figure 20.7). The current fossil-based economy is the starting point, whereby the pathway of transition to a sustainable bioeconomy (including bioenergy) is influenced by system and policy drivers. The demand for the bioeconomy is coming from a linked system of food, wood, energy, chemicals and non-market services. The supply of biomass uses land, water, waste and human capital resources and these are linked to the demand system. The broader policy objectives or policy targets for establishing a sustainable bioeconomy are:

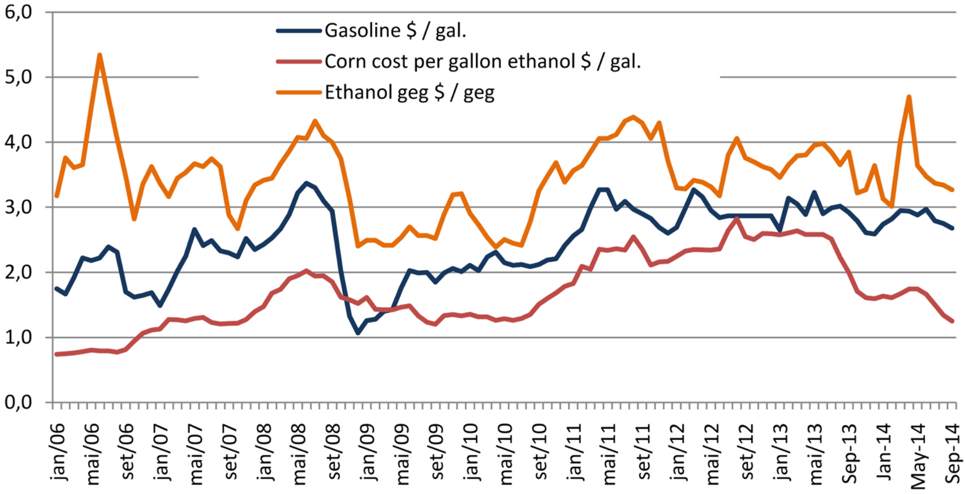


Figure 20.6. Fuel ethanol, corn and gasoline prices, by month. Source: USDA, Economic Research Service, US Bioenergy statistics (USDA 2014).

- reducing dependence on non-renewable resources;
- adapting to and mitigating climate change;
- enhancing economic growth and creating jobs;
- improving trade balance in various countries[1]
- ensuring food security; and
- managing natural resources sustainably.

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[1] It has been a major reason for countries like Brazil, the US and some EU countries. This will be discussed it in more detail later.

The policy objectives provide guidance for the choice of indicators to measure whether a bioeconomy and its policies contributes to these objectives. The bioeconomy is a complex system that encompasses the land based food and forestry sectors and interacts with the fossil based system. Its developments will have many direct and indirect effects and (potential) developments. Policies should be assessed for sustainability and therefore people, planet and profit indicators can be taken into account. Sustainability indicators may include the dependency on non-renewable resources, GHG emissions, biodiversity, jobs and economic growth, trade balance and food security (see red boxes in Figure 20.7).

The system drivers of the bioeconomy (blue boxes in figure 20.7) are related to the supply and demand of the bioeconomy. Demographic growth, consumer preferences and economic growth are identified as key drivers of demand, and technological and climate change as key drivers of supply of biomass (light blue boxes). Natural and human capital resources are also important supply key drivers (dark blue boxes).

The third block includes policy and management initiatives and responses for achieving the policy targets by influencing the demand and supply system drivers. For many applications, the cost of renewable energy is currently higher than technologies that

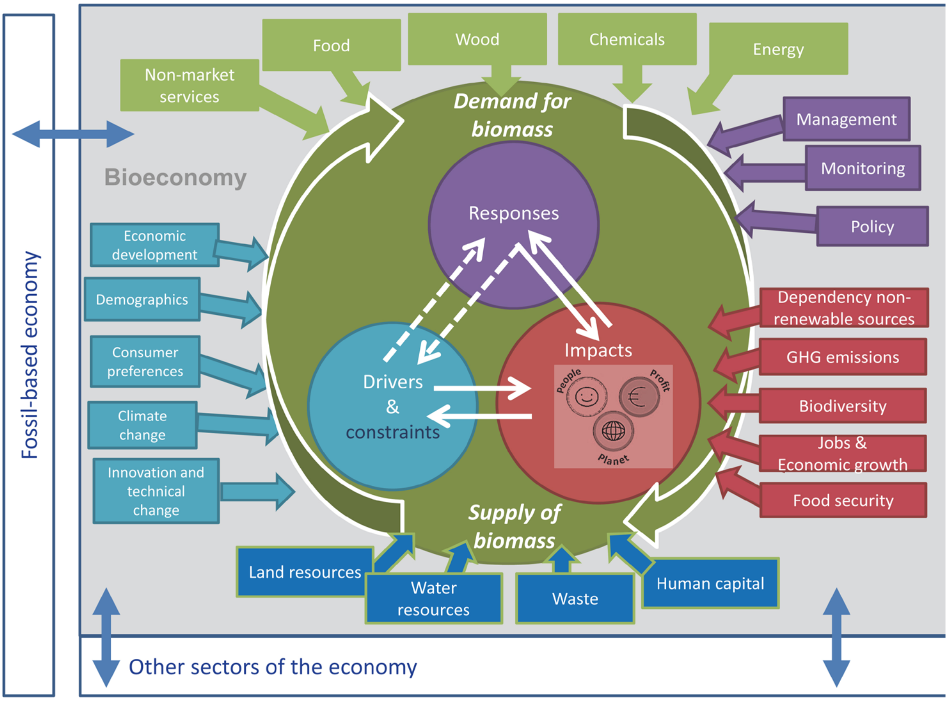

Figure 20.7. Systems analysis framework for the bioeconomy (Van Leeuwen et al. 2013).

produce electricity, heat or fuel from fossil fuels. One assumption behind the current incentives is that they will eventually drive down the cost of these technologies, through economies of scale and learning-by-doing. Indeed, there is evidence of learning-by-doing in the production and processing of biofuels (Chen et al. 2012). In that sense, these incentive policies play a critical role in the innovation process of renewable-energy technologies. According to Bahar et al. (2013), some policies focus on creating demand for these technologies in order to pull them into the market place (market-pull policies), while others focus on production of the technology or fuel itself in order to increase supply or foster innovation (technology-push policies). Section 20.2.5 describes the implications of market-pull and technology-push policies. In general, consumer, agricultural, energy, economic growth, technology and environmental policies can be used to facilitate the transition from a fossil based to a bioeconomy.

Computable general and partial equilibrium (CGE and PE) economic models connect the natural and human resources to the various demand developments in the fossil and bioenergy economy and focus on the interconnectedness of all these markets (e.g. Banse et al. 2008; Hertel et al. 2010; Laborde 2011). Therefore a main contribution is that beyond the direct effects on for example, production, prices, trade, land use and emissions they also take some indirect effects into account. Two important indirect effects are the indirect land use effect (iLUC) and the rebound effect. iLUC is the change in land use outside a feedstock's production area needed to replace the supply of that commodity and that is induced by changing the use or production quantity of that feedstock (see Chapter 17, this volume). A second important effect studied in the field of economics is the effect that substitution of fossil resources by biomass decreases the demand for fossil resources and therefore induces a lower price. A lower price leads to higher fuel consumption in other markets which partly offsets the initial fossil fuel and GHG savings. This is called the rebound effect (Hochman et al. 2010; De Gorter and Just 2009; Rajogopal et al. 2011)[2].The iLUC and rebound effects in the context of mitigating climate change will be discussed in section 20.2.4.

20.2.4 Arguments for Policy Interventions

One of the six key arguments for an active bioenergy policy, mentioned in the previous section, is *reducing dependence on non-renewable resources* and increasing energy security. Most economies rely heavily on fossil resources as carbon and energy sources, making them vulnerable to insecure and dwindling supplies and market volatility. Several countries, in the EU and the US, maintain trade barriers to promote and protect domestic production of biofuels (OECD 2014). Critics argue that many countries are unable to displace a significant share of their oil consumption to bioenergy, and as a result, are unable to control the fluctuation in fuel prices (Bento 2009). Even a limited share in gasoline consumption requires a large share of their land devoted to biofuels, which may be unacceptable from a food security perspective as long as agricultural

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[2] The rebound effect of biofuel use is also known as indirect fuel use change, indirect energy use change, indirect output use change or carbon leakage.

productivity is not significantly enhanced. Exceptions might include countries like Brazil where there is a large and underutilized land base (Youngs and Somerville 2012).

A second key argument is the assertion that bioenergy will contribute to an overall reduction in GHG emissions and is therefore important toward *mitigating climate change effects*. The GHG savings from biofuels are heavily debated. There is a consensus based on life cycle assessments (LCA) that ethanol from sugarcane and corn reduce GHG emissions. However, LCA methods do not take market interactions into account and might be misleading when a large amount of biofuel is produced (iLUC and rebound effects). The iLUC effects are usually calculated by economic market equilibrium models. Searchinger, et al. (2008) calculated the initial LUC effect of 104 g CO_2 equivalent (CO_2e) per megajoule (MJ) of US corn ethanol while the emission factor of gasoline is 92 g CO_2e/MJ. Wicke et al. (2011) conclude that due to various model improvements the estimated LUC related GHG emissions decreased to 32 g CO_2e/MJ (CARB 2010) and more recently to 15 g CO_2e/MJ (Hertel et al. 2010; Tyner et al. 2010). Also Al-Riffai et al. (2010) and Laborde (2011) have found significantly lower values for corn ethanol (e.g. 7 g CO_2e/MJ in the latter). Wicke et al. (2011) and Tyner et al. (2010) identified that model improvements consisted of factors such as improved data, increased spatial resolution, including pasture land as an option for conversion to bioenergy production, crop yields on existing agricultural land and newly converted land for agricultural and bioenergy crops, treatment of co-products for animal feed, and the modeling of wood products (including by-products and the fraction of carbon that is stored for a longer period). Furthermore, GHG savings are very dependent on the feedstock used. Khanna and Crago (2012) also show the wide uncertainty in estimates of iLUC in the US and EU. Recently, it has been suggested that the use of residues and waste for bioenergy production also has an iLUC effect, as the use of residues and waste increases the profitability of the sector that produces the biomass (Smeets et al. 2014a).

Rebound effects, caused by increased fuel consumption due to a lower induced oil price, are crucial for the renewable energy policies being effective in reducing GHG emissions, yet they are presently under-researched. The net worldwide rebound effect is usually positive, which means that GHG emissions do not decrease as much as usually assumed. Estimated rebound effects are highly dependent on the applied method, scenario assumptions, the assumed supply and demand elasticities of oil and biofuels and the time frame. With regard to biofuel policies the reviewed studies indicate that biofuel credits and other financial policies promoting biofuels typically lead to higher positive rebound effects compared to biofuel blend mandates. 2010; De Gorter and Just 2009; Rajogopal et al. 2011). Chen and Khanna (2012) show how the rebound effect depends on the implementation of biofuel policies in the US and its implications for greenhouse gas emissions. They state that “The likely range of the change in GHG emissions with the average iLUC effect is (-) 1.2% to 0.4% under the Renewable Fuels Standard, (-)1.9% to (-)3.3% under the proposed national Low Carbon Fuel Standard, and (-)3% to (-)5.3% under a $60 per-metric-ton carbon tax policy relative to US GHG emissions under the BAU scenario over the 2007-2030 period”. Estimations with the CGE model MAGNET indicate a (positive) global rebound effect of the biofuel blend mandate in the EU in the year 2020 of 22% to 34%, i.e. the use of 1 energy unit of biofuel reduces global oil consumption from 78% to 66% (Smeets et al. 2014b). A complicating issue for direct and indirect GHG emission effects is that the fossil system is evolving as well and therefore analyses should be temporal (dynamic).

Enhancing economic growth and creating jobs is a third key argument for promoting bioenergy. The macro-economic impacts of a biobased economy in general and bioenergy in particular are not well known. A key result is that as long as bioenergy needs policies or subsidies to exist, its contribution to the macro-economic GDP growth is almost always negative (Meijl et al. 2012). From a job perspective, bioenergy might be beneficial, because in general, bioenergy is more labor intensive than its fuel equivalent. Advanced applications of biomass require large investments in research and development, production plants, logistics and human capacity. Existing sectors may potentially benefit, directly or indirectly, from the emergence of a green, bio-based economy, although there will also be threads for immobile factors in other sectors. There will also be opportunity costs involved in replacing existing production systems and in shifting resources that are being used in existing sectors to the biobased economy.

A CGE model framework is designed to identify and quantify these types of economic trade-offs. Two developments are critical to making biomass a profitable venture from a macro-economic point of view. The first is the efficiency of technologies to produce and collect biomass in a sustainable manner, and convert it into final products relative to fossil based technologies. The second is the (development) price of fossil based substitutes. The difference between the costs of production of the biobased product and the fossil-based substitute is an important determinant of the economic viability. These developments are (obviously) partially uncertain. To emphasize these uncertainties, as well as other risks and trade-offs involved in producing various biomass products. Meijl et al. (2012) calculated a series of possible effects on Malaysia's GDP of using palm biomass substitutes based on a range of technological and fossil fuel price scenarios. At an oil price of US$125, the predicted net contribution to GDP per ton biomass is three times as high for biobased chemicals as for pellets and bioethanol. Electricity from palm biomass has a negative contribution to GDP as it is not competitive with electricity from coal, although small-scale production might be economically viable under conditions that were not investigated in this study (such as remote, non-grid connected locations). The fact that Malaysia enjoys full employment limits the economic benefits of the use of biomass for energy and other applications. Also, the availability of capital is a constraint, as the development of a bioeconomy requires huge capital investments (e.g., logistics).

The prospects of increased farm income and rural economic development, primarily in less developed countries, can justify some degree of government intervention to promote the increase of biofuels production. Many studies show the positive impact on farm prices and income (Banse et al. 2008; Hertel et al. 2010; Laborde 2011). The crop sectors especially benefit from biofuel production and studies show some mixed results for the livestock sectors. On the one hand, traditional feed costs (e.g., corn and soy) for livestock farmers increase due to increasing feedstock prices resulting from a higher bioenergy demand; on the other, cheap co-products of biofuels (e.g., Distillers Dried Grains and Solubles, DDGS) can be used to feed animals and this reduces their costs. Biofuel production might increase the price of some crucial inputs such as land and fertilizer, which might harm non-biomass for energy sectors. According to IFPRI (2005), there is a potential for developing countries to specialize in bio-energy crops, especially crops that can be produced in poorer soils and adverse climatic conditions. Due to the substantial yield gaps to be explored in these countries, increased biofuels production can be partially achieved through intensification of existing cultivated areas. Cash from bioenergy crops enables farmers to buy better seeds and fertilizer to improve their yields. In turn, this will represent increases in farm income. The use of marginal lands in developing countries for second-generation biofuels production could also translate into an increase in rural income. In general, land abundant developing countries might have a comparative advantage in biomass for bioenergy, but potential trade barriers from developed countries could prevent developing countries from using this advantage. This might result in outside groups acquiring larger areas of farmland in developing countries where safeguards against exploitation are weak. Therefore, traditional market-based instruments may have to be complemented with regulatory schemes that characterize land based on its social and ecological potential, so as to prevent the conversion of land that can have adverse consequences that exceed the benefits from its use.

Improving the balance of trade has been a fourth major reason for investment in biofuel. It was the major driver for the introduction of the biofuel program in Brazil. In the 1970s, Brazil could not afford importation costs of fuel to meet local needs (Azanha and Zilberman 2014). Zilberman et al. (2014) argue that balance of trade considerations are a major driver of current US biofuel and energy policies.

To achieve social acceptance of bioenergy *ensuring food security and the sustainable management of natural resources* are the fifth and sixth important objectives to take into account, respectively. Managing natural resources in a sustainable manner requires conservation of biodiversity, water and other ecosystem land services. This section focuses, however, on whether and how bioenergy can be produced within the context of food insecurity. The food crisis of 2007-08 led to the re-emergence of the old food-versus-fuel debate, raising concerns about biofuels increasing food insecurity (Sagar and Kartha 2007). Biofuel and bioenergy use has in the past and is expected to in the future, induce higher pressure on the global demand for biomass unless a commensurate supply response is initiated. A clear distinction has been noted, however, between highly productive crops and applications, particularly sugarcane ethanol in Brazil, versus the relatively lower yielding production of biodiesel from soya and rapeseed (Rosillo-Calle and Johnson 2010). Some empirical studies suggest that biofuels contributed to 10-15% of food prices increases (see Figure 20.8). This is in direct contrast to previous studies (Mitchell 2008; NPR 2008; Rosegrant et al, 2006) which had stated a much higher impact on food prices arising from the conventional biofuel programs of Brazil, USA, EU and others, e.g. up to 75% of the 2008 increase in food prices. Analysis of observed data has not identified an impact at these higher levels.Recent econometric evidence by Baffes and Dennis (2013) found that oil prices were the main driver of the higher food prices.

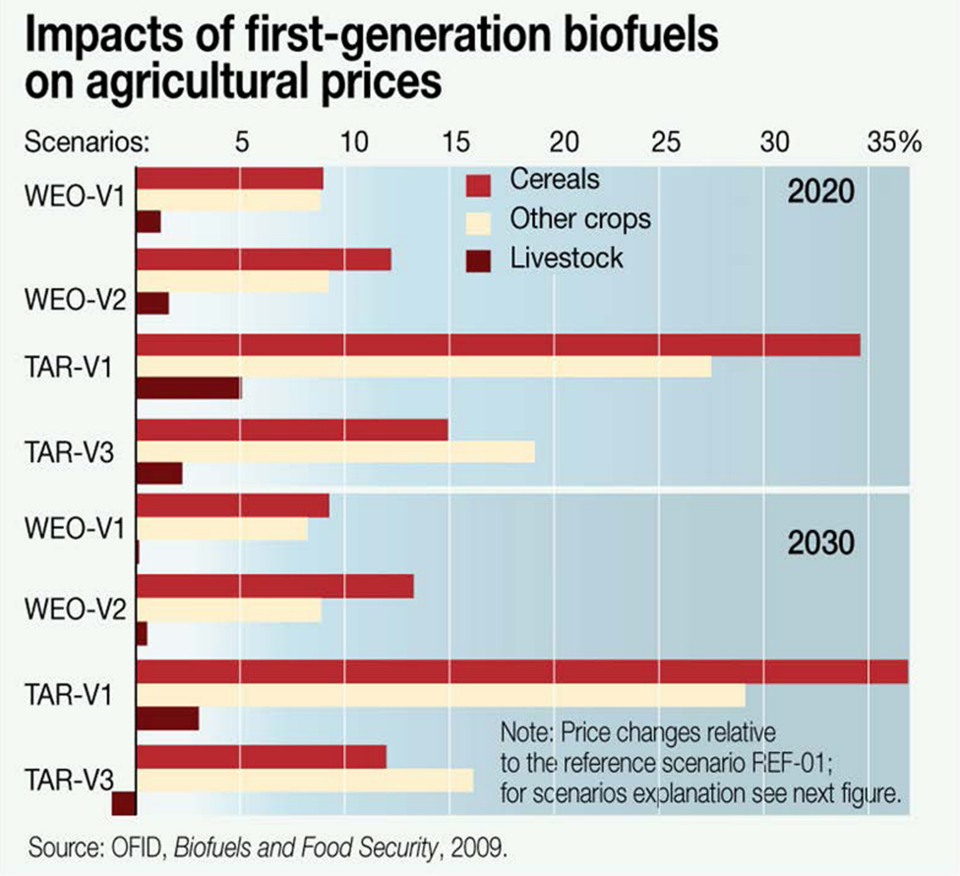

Figure 20.8. Impacts of conventional biofuel production on agricultural prices (UNEP, GRID Arendal 2011).

Van Ittersum (2011) suggests that agricultural output will need to triple between 2010 and 2050, if global agricultural biomass is to deliver 10 per cent of global energy use by 2050. More fundamental objections to increased demand for biomass for energy are voiced by Krausmann et al. (2013) who estimated that a 250 EJ/y bioenergy scenario by 2050 would increase the human appropriation of net primary production (HANPP) from 27-29% to 44%, and caution against a further increase. The HANPP provides a useful measure of human intervention in the biosphere. However, the analysis is not so simple, for example higher food prices might also lead to higher farm income in poor rural areas, with subsequent investments in the agricultural system leading to higher food security over the long run (Achterbosch et al. 2013). Direct and indirect or more dynamic effects may have different impacts on food security over various time-scales.

Food security according to the frequently cited FAO (2006) definition takes availability, access, utilization and stability into account. The effect of bioenergy production on food security through these variables is sometimes positive (e.g. improving access to food through higher producer prices and more secure household income based on sales to markets for bioenergy), sometimes negative (on food availability through food production, food trade or food access through consumer prices) and sometimes goes either way (on utilization and stability dimensions through macro-economic variables, see Figure 20.9 for an illustration in the case of biofuels). As a result, simple assertions that bioenergy production is a risk to food security or benefits food security should be treated with caution. Such claims often reflect a partial view on the issues at hand.

Public policy intervention in bioenergy is motivated by diverse concerns and objectives that vary in scale. While rural economic development can be considered a local concern, energy security is a national concern and reducing GHG emissions is a global one. Depending on how different governments weigh each concern, some policy interventions will make more sense than others. For example, if the chief goal of biofuels expansion is the reduction of GHG emissions, then it is important to learn “where”, “how much”, and “what type” of biofuels to produce.

20.2.5 Economic Impact of Government Policies

In this section we discuss the implications of some key market-pull and technology push policies for bioenergy. We focus on government incentives, first from a more static perspective and then from a more dynamic or innovation imperative.

Many countries have established national targets for renewable energy, typically to be achieved by 2020 (demand pull). Most of these targets are only aspirational, but

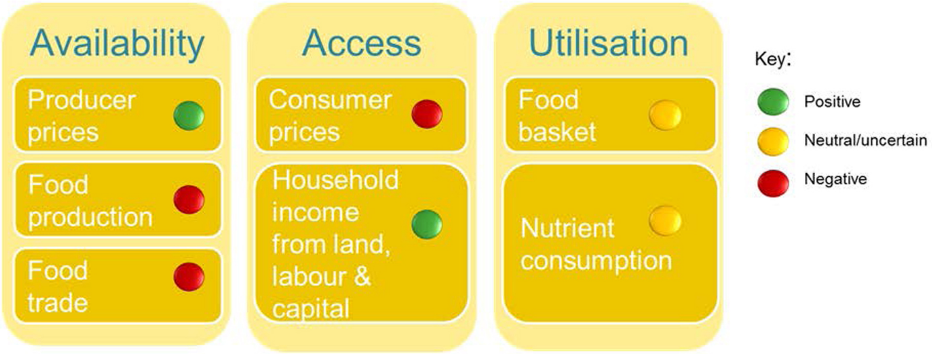

Figure 20.9. The impact of increased biofuel production on three dimensions of food security. Source: Shutes et al. (2013).

some - like those established by the European Union's Renewable Energy Directive (RED) - are legally binding. Where the targets are binding, systems for crediting renewable-energy production or sales (green certificates) are usually created. With respect to electricity, the most common policies are special feed-in tariffs (FITs) that either guarantee a fixed price for electricity sold to the electricity grid, usually for at least a decade, or a fixed premium per kilowatt-hour sold (REN 21 2013). The extra costs of these FITs and premiums are usually passed on to electricity consumers, but in a few countries they are paid out of government funds (which comes from taxpayers). Excise tax credits are often used in transport to make biofuels competitive against fossil fuels. Fuel excise tax credits are the most direct and widely used instrument. Because most countries tax the consumption of gasoline, the excise tax credit effectively lowers the cost of biofuel relative to gasoline, and thus promotes its expansion up to the point where the blender is indifferent between using gasoline and biofuels (Bento and Landry 2008). The FIT paid by government funds and tax credits reduces the price of fuel and therefore increases the rebound effect as consumption of fuels increases. The increase in fuel consumption increases externalities associated with GHG emissions and other factors such as congestion and accidents. Tax credits generally favor current (first generation) technologies and might delay better technologies as the former reduce costs by learning effects. There could be exceptions when there are synergy effects between first and second generation technologies such as the use of sugarcane bagasse for cellulosic ethanol.

Mandatory blendings, such as the Renewable Energy Directive in the EU and the Fuel Standard and renewable portfolio standards at the state level (RFSs) in the USA are a kind of command and control regulation (quota) which, from an economic point of view, are more costly than an incentive based approach such as subsidies as the costs of achieving the same outcomes are substantially higher (e.g. Markusen and Melvin, 1988). There are economic costs associated as a mandate creates an (sub-optimal) excessive production of biofuels\bioenergy. A difference with all kind of subsidies is that mandates are government budget neutral and the costs are paid directly by fuel consumers (i.e. higher fuel prices) and not by all taxpayers. Another crucial difference of mandates with subsidies is that the indirect rebound effect is reversed, as mandates lead to higher instead of lower fuel prices and therefore lead to less fuel consumption and related negative externalities (e.g. Khanna et al. 2008). If the policies strive to reduce GHG emissions, then GHG related taxes are most effective from an economic point of view. From a dynamic point of view they stimulate GHG friendly technologies and this induces learning effects. Large additional subsidies for renewable energy may not be necessary; instead, getting the price right on GHG emissions that raise fossil based prices and improving the competitiveness of renewable energy is more critical. The welfare impacts at national level in an open economy of a mandate and a subsidy are not straightforward and dependent on, for example, initial level of policy distortions and the ability of a country to influence (world) market prices. Lapan and Moschini (2012) and Cui et al. (2011) show, for example, that for the US, a mandate might lead to higher social welfare than a subsidy. Chen et al. (2014) show that the cost-effectiveness of a carbon tax relative to a biofuel mandate in an open economy is not necessarily the case. It depends on the relative impact of the two policies on the terms of trade. Since a biofuel mandate (e.g. in the US) raises the price of corn exports and can lower the price of fuel imports, it improves the terms of the trade and can provide positive economic benefits for the US. This chapter also compares the cost effectiveness of a biofuel mandate in the US to a carbon tax for achieving a reduction in GHG emissions and shows that while both policies lead to positive economic benefits for the US, the biofuel mandate in the US can have a large negative economic impact on the rest of the world. Trade policies such as import tariffs on ethanol in the USA and the EU favor domestic producers and can be justified from a domestic energy security perspective. However, from an economic point of view they generally lead to lower welfare, as countries do no exploit their comparative advantage.

Technological push policies, which support invention and innovation through R&D, production and sales, have been forwarded by the work of the economist Joseph Schumpeter (1934) who regarded innovative technologies as the essential forces behind social and economic changes. In Schumpeter‘s view, though process innovations are vital, only product innovations can give rise to new industries. The knowledge market is characterized by market failures that may take the form of knowledge spillovers from learning-by-doing, or R&D spillovers. Because the value of these positive externalities is not fully captured by the firms that generate them, they may undertake less of the activities that generate them than would be socially optimal. To correct for these market failures, extensive research, development and demonstration (RD&D) programs relating to renewable energy are present in rich countries. According to the IEA these countries spent at least USD 4.1 billion on RD&D related to renewable energy in 2011 (www.iea.org/stats/rd.asp).

With regard to agriculture, genetic improvement and improved fertilizer use have been major contributors to the Green Revolution. Qaim and Zilberman (2003) state that “the introduction of new biotechnologies that are based on a better understanding of the principles of molecular and cell biology are also major contributors to further increases in agricultural productivity and, in particular, increases in yield per acre and reductions in the use of inputs”. Barrows et al. (2014) argue that the use of genetically modified (GM) varieties in soybean and corn enabled societies in Asia to meet the high increase demand by enhancing their production. Qaim and Zilberman (2003) state, furthermore, that “these technologies may further reduce the environmental footprint of agriculture and increase the amount of land available for biomass and biofuels”. However, the public (especially in Europe) is concerned about the social and environmental sustainability of these new technologies and also about other environmental aspects, such as soil fertility and carbon stock maintenance. Regulation has banned these technologies in Europe and Africa, or made them very expensive. Zilberman et al. (2013a) stress that “while regulation is important both for the protection of society as well as for the development of goodwill toward the technology, excessive regulation may be harmful to technological innovation, especially given the importance of private sector investment in the development of new biotechnologies”.

The emergence of the bioeconomy in the EU and the USA is criticized for its heavy focus on technology and economics and for not placing ethical questions and risk first (Hilgartner 2013; Birch 2012). Birch et al. (2012) argue that these techno-knowledge fix visions of the bioeconomy might create “the conditions for what they seek to promote,” in other words are self-fulfilling. McCormick and Kautto (2013) argue that “policy making should include a wide range of perspectives – also critical – to enable innovation and not restrict societal development only to one perspective”. Additional visions for a bioeconomy should be developed such as agro-ecological food chains (Levidow et al. 2012a, 2012b, Levidow, 2013) and a “glocal” (both global and local) distributed bioeconomy that focuses on the nearness and interconnectivity of biomass locations and locations where products and energy are consumed and produced (Luoma et al. 2011). This later vision would seem to support local bioenergy production.

20.3 Conclusion

Bioenergy has grown rapidly due to high oil prices and especially a variety of government policies, such as feed-in-tariffs, tax exemptions and biofuel mandates. This increase led to more interconnectedness between energy and agricultural markets and influenced relative food and feed prices and land-use changes. In turn, this resulted in concerns from a food security and environmental perspective. Whether the policies are justified depends on their goal or vision. There is much optimism about the benefits of developing a bioeconomy, but considerable trade-offs and risks are also expressed. The bioeconomy has been criticized for stressing a technology-fix vision and neglecting incorporation of additional ones. To achieve broad public support, the general public and key stakeholders should be involved in an open and informed participatory dialogue. Commitments for a *sustainable* development of a bioeconomy by government and industry is another key condition.

Justification of bioenergy policies depends on its goals and the various goals can be in conflict with each other. Different goals have different scales and this creates conflicts. While rural economic development can be considered as a local concern, energy security is a national concern and reducing GHG emissions is a global one. The goal of reducing dependence on non-renewable resources has to be viewed critically, as a significant reduction in the use of non-renewable resources requires large amounts of land, which may cause problems from a biodiversity and food security point of view. The mitigation of climate change is heavily debated. While LCA studies show GHG savings, they do not take indirect effects such as iLUC and rebound effects into account. These indirect effects might limit or change GHG savings. Multisectoral economic models are naturally equipped to assess these indirect effects although this requires major data and model improvements.

As long as an economy is not at full employment the bioeconomy can create jobs as it is a more labor intensive technology than a fossil based one. A bioeconomy can contribute to economic growth if biobased technologies are competitive with fossil based technologies. On one hand, it depends on the efficiency of biobased and fossil based technologies and on the other on the volatile price level of biomass versus fossil energy prices. The bioeconomy can contribute to increased farm and rural economic development but regulatory schemes are necessary to deal with social and environmental adverse consequences. Stimulating a bioeconomy improves trade balance if one exports biomass (including agriculture) and imports energy.

To achieve social acceptance of bioenergy while ensuring food security and managing natural resources is key. Managing natural resources in a sustainable manner requires conservation of biodiversity, water and other ecosystem services of land. The effect of bioenergy production on food security is sometimes positive (e.g. improving access to food through higher producer prices and more secure household income based on sales to markets for bioenergy), sometimes negative (on food availability through food production, food trade or food access through consumer prices) and sometimes goes either way (on utilization and stability dimensions through macro-economic variables). As a result, simple assertions that bioenergy production is a risk to food security or benefits food security should be treated with caution.

In general, policies could be much more directly connected to their targets. If policies strive to reduce GHG emissions then GHG related taxes are most effective from an economic point of view. If policies should contribute to a higher economic growth than productivity enhancing policies are most desired.

As the bioeconomy is an immature or an infant industry it is in general not competitive with the fossil-based economy. Policies might be justified to temporarily stimulate its development. Technological change that reduces costs and full biomass utilization for food, feed, energy, materials and chemicals might create a competitive industry. The development of more efficient biomass conversion routes, especially those that can convert lignocellulose biomass into biofuel and biochemical, can potentially contribute to a transition towards a competitive biobased economy.

Regulation could deal with the indirect effects of bioenergy such as social and environmental effects (land, water, biodiversity). However, given the importance of private sector investments in the development of biotechnologies, excessive regulation might create a disincentive to innovation. One of the biggest challenges is the development of a regulatory framework that limits externalities from new bioenergy and, at the same time, does not curb innovation.

20.4 Recommendations (Policy)

- Policies could be much more effective if they are directly connected to a target. E.g. CO_2 taxes to reduce emissions.
- The bioeconomy is an immature industry which may justify temporary policies to stimulate its development. Policies directed at technological change and full biomass

utilization for food, feed, energy, materials and chemicals may create a competitive industry focused on reduction of emissions and stimulate economic growth.

- Regulation could potentially deal with the indirect effects of bioenergy such as social and environmental effects (land, water, biodiversity). One of the biggest challenges is the development of a regulatory framework that limits social and environmental externalities from new bioenergy and, at the same time, does not curb innovation.
- To achieve broad public support the general public and key stakeholders should be involved in an open and informed participatory dialogue. Commitment from government and industry toward the sustainable development of a bioeconomy is a key condition.

20.5 The Much Needed Science

- Integrative approaches addressing the emerging bioeconomy within society are essential.
- System analyses tools of the bioeconomy are necessary to assess the impact of technology, demand, and policy drivers on sustainability.
- Economic models should be enhanced to better quantify the indirect land use and rebound effects of the bioeconomy, better understand the impact of bioenergy on the various dimensions of food security, and improve the modeling of technological change.
- Evidence is needed on the effectiveness of policies with regard to the various sustainability dimensions (people, profit, and planet).
- Data collection, harmonization of concepts and monitoring is needed for the development of the bioeconomy. What part of the economy is biobased?
- Additional visions for a bioeconomy should be developed and integrated into policy. For example, in addition to a focus on promoting technologies (including biorefineries) and fixing all undesired side effects with regulation and other policies visions, agro-ecological food chains and “glocal” (both global and local) distributions systems could be developed.

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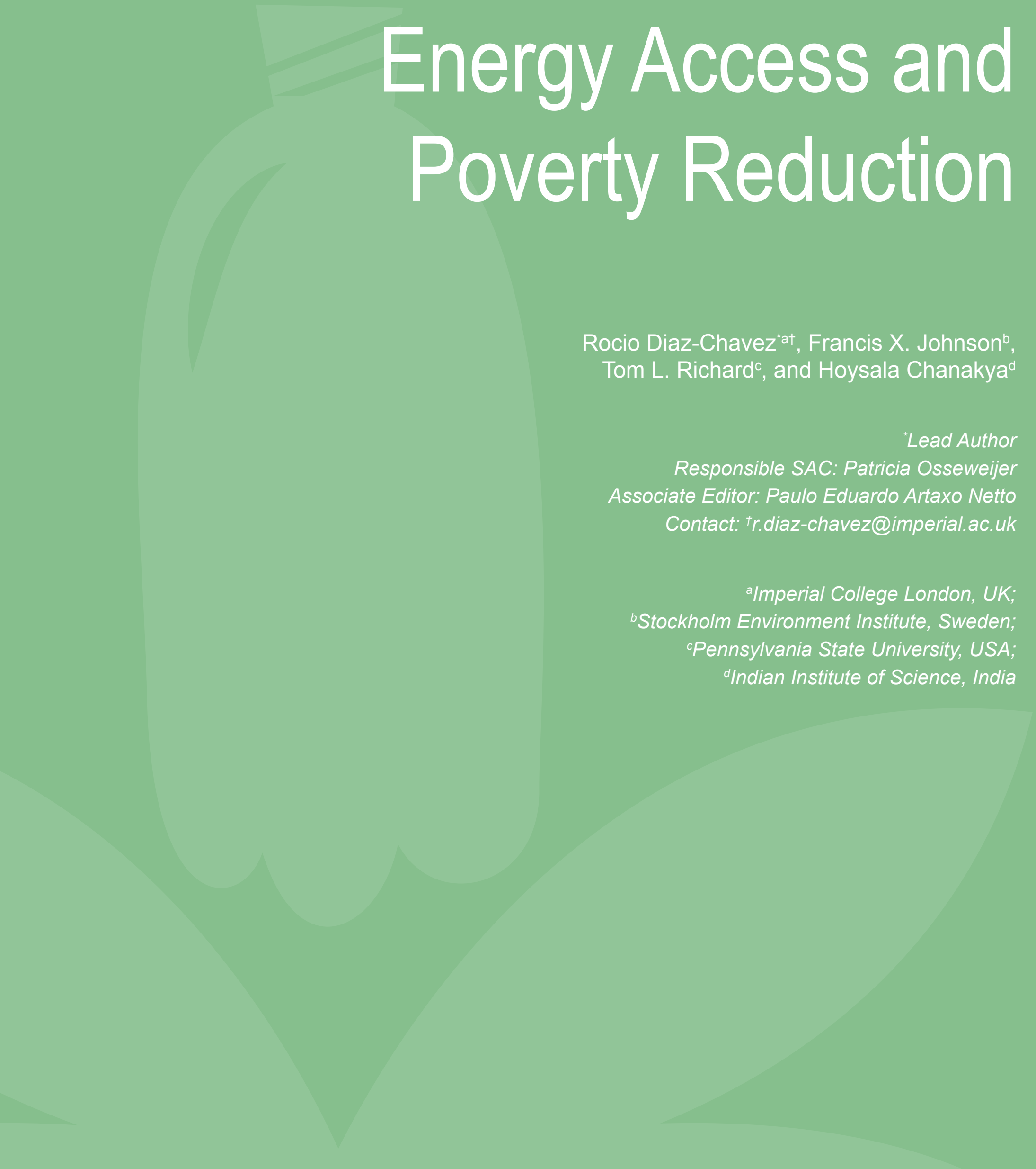
chapter 21

Biomass Resources, Energy Access and Poverty Reduction



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Highlights

- Energy poverty and lack of access to modern energy is still a problem in developing countries, mainly in rural areas and particularly in Sub-Saharan Africa and Asia;
- Bioenergy can be harnessed to support sustainable development and should be included in the Sustainable Development Goals;
- Energy poverty reduction may contribute in reducing inequality in terms of the livelihoods and number of people living in extreme poverty;
- Modern technologies for bionergy will contribute to poverty reduction, health and development in poor areas.

Summary

Energy has been recognized in recent decades as a key driving force for sustainable development. Access to reliable and affordable energy supports income-generating activity, increases productivity and promotes sustainable livelihoods. Poor people around the world, particularly subsistence farmers living in rural areas in developing countries, often lack adequate access to basic infrastructure, electricity and modern fuels. They depend heavily on traditional biomass to meet their energy needs, causing serious health impacts, contributing to degradation of forest resources and lowering household productivity. Improved energy access and more effective delivery of energy services - including through the use of modern bioenergy - offers opportunities to contribute to poverty reduction and rural development. This chapter provides an overview of the relationships between energy and its role in poverty reduction, focusing especially on the role of modern bioenergy and on rural areas.

21.1 Introduction

Energy has been recognized in the last decades as an important promoter of development through achievement of social and economic goals and as a basic input for sustaining people's livelihoods. Although not included in the Development Millennium Goals, energy access has been considered essential and is included in the Post-2015 Development Agenda, within the Sustainable Development Goals. According to the

World Bank (2014), over 1.2 billion people (nearly 17% of global population) lack access to electricity, while another 2.8 billion people depend on traditional bioenergy for their cooking and heating needs. Most are poor people living in rural areas of the developing world, and their dependence on bioenergy for cooking makes them vulnerable to a range of illnesses as a result of indoor pollution.

Around three-quarters of the world's population depend directly on agriculture and so the sector has a significant role to play in poverty reduction (UNDP 2007), particularly for the 2.7 billion poor people worldwide who currently live under USD$2.00 per day (Diaz-Chavez 2010). The poor lack adequate access to infrastructure and services, including modern, clean energy sources, and are thus heavily reliant on traditional biomass to meet their energy needs. Most are dwellers in rural areas in developing countries who depend on traditional fuels, such as biomass, to meet their heating and lighting needs. As Goldemberg (2000) notes, lack of access to adequate energy services in rural areas in developing countries has a number of social, environmental and health implications. Furthermore, improving delivery of affordable and reliable energy services especially to rural communities, will contribute to the development of human and economic capacity to adapt to impacts resulting from climate change (Casillas and Kammen 2010).

Clancy (2013) and Diaz-Chavez (2010) have highlighted the relationships between agriculture and bioenergy production. Bioenergy, especially that produced through the so-called 'first generation crops', requires intensive use of labor, land and other resources, leading to the creation of jobs, the extension of supply chains and infrastructural development. Diaz-Chavez (2010) noted empirical evidence demonstrating these positive relationships for small scales of production (see for instance COMPETE 2009; PISCES 2009; Global-Bio-Pact 2013). This chapter presents an overview of the links between energy and poverty and highlights the ways through which bioenergy can contribute to development, particularly in rural areas.

21.2 Poverty, Inequality and Poverty Reduction

There is no widely accepted definition of poverty. Definitions vary, for instance, according to country, the international organizations that report on poverty, and the method used to measure it. Common methods to measure poverty refer to levels of income or expenditure. This is translated into what is called the "poverty line", which specifies the income (or level of spending) required to purchase essential goods, such as food, clothing, shelter, water, electricity, schooling, and healthcare.

The poverty line enables decision makers to gauge the number and geographical distribution of the poor. It allows them to channel resources towards the poor as well as monitor progress towards a clear target (Morduch 2006).

Currently the poverty line ranges from $1 to $2 USD per day per person. Figure 21.1 shows the estimated total population worldwide and the number of people living under the poverty line at $1.25 (Povcal 2014). These are estimates from the World Bank Poverty calculator.

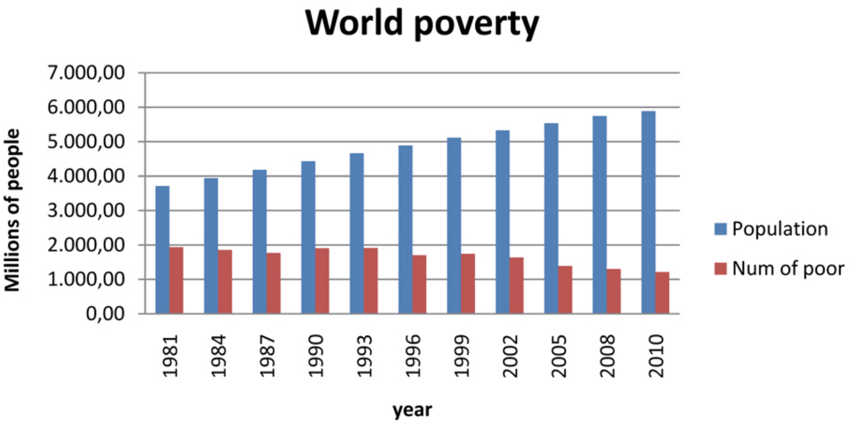

Figure 21.1. Estimated Total World Population and Estimated number of people living under $1.25 USD (Data from Povcal 2014).

However, it has been widely recognized that poverty is multi-dimensional – it may have to do with lack of voice as much as with lack of income. Informal markets and transactions are important, particularly for the rural poor, who may have access to assets and resources that are not measured in monetary terms. Also, income levels constitute an imperfect proxy for measuring wellbeing: higher incomes may not necessarily translate into improvements in health or education, for example. Some indices have been developed to capture these other dimensions of poverty – such as the Human Poverty Index (HPI), the Human Development Index (HDI) and the Multidimensional Poverty Index (MPI) (UNDP 2010). Definitions of all these indices are provided in Box 21.1.

Following the Rio+20 declaration on “making sustainable energy for all a reality and, through this, help to eradicate poverty and lead to sustainable development and global prosperity”, the discussion on the new Sustainable Development Goals has included the consideration of a goal on energy: “Securing Sustainable Energy For All By 2030”. This goal includes three targets and indicators for 2030: 1) Ensuring universal access to modern energy services; 2) Doubling the global rate of improvement in energy efficiency; and 3) Doubling the share of renewable energy in the global energy mix. It is suggested to measure the second target with an indicator that links poverty reduction with the capacity to afford power through rate improvement in primary energy intensity of GDP measured in purchasing power parity (UNenergy 2014).

Box 21.1. Indices used for measuring poverty

HPI Rather than measure poverty by income, the HPI uses indicators of the most basic dimensions of deprivation: a short life, lack of basic education and lack of access to public and private resources. The HPI concentrates on the deprivation in the three essential elements of human life already reflected in the HDI: longevity, knowledge and a decent standard of living. The HPI is derived separately for developing countries (HPI-1) and a group of select high-income OECD countries (HPI-2) to better reflect socio-economic differences and also the widely different measures of deprivation in the two groups (UNDP 2010).

HDI The Human Development Index (HDI) is a summary composite index that measures a country's average achievements in three basic aspects of human development: health, knowledge, and income. It was introduced as an alternative to conventional measures of national development, such as level of income and the rate of economic growth (UNDP 2010).

MPI The Multidimensional Poverty Index (MPI) is a new measure designed to capture the severe deprivations that people face at the same time. The MPI reflects both the incidence of multidimensional deprivation, and its intensity – how many deprivations people experience at the same time. It can be used to create a comprehensive picture of people living in poverty, and permits comparisons both across countries, regions and the world and within countries by ethnic group, urban/rural location, as well as other key household and community characteristics. The Index includes three dimensions (health, education and standard of living). The health dimension includes an indicator on nutrition which is also a proxy to measure hunger (UNDP 2010).

Income levels are commonly measured through per capita GDP, or GDP divided by total population (UNstat 2012). However, average data on poverty or income may mask major inequalities. Two countries with similar average incomes may have very different poverty profiles, depending on how income is distributed. For this reason, it is useful to complement average data with the Gini Index or coefficient (World Bank 2013) which measures inequality. Definitions of GDP and the Gini index are provided in Box 21.2. Figure 21.2 shows a diagram of the links between the access to energy and the Gini and GDP indicators. The distribution of energy resources may result in significant social, environmental and economic inequalities. This relationship, especially in the context of access to electricity, was reviewed by Wu et al. (2012) who suggest that concerns related to inequality of energy consumption must be integrated into development strategies for all countries, irrespective of their human development level.

Box 21.2. Definitions of Indicators related to poverty and inequality

Gini Coefficient of inequality is the most commonly used measure of inequality. The coefficient varies between 0, which reflects complete equality and 1, which indicates complete inequality (one person has all the income or consumption, all others have none). It is sometimes argued that one of the disadvantages of the Gini coefficient is that it is not additive across groups (i.e. the total Gini of a society is not equal to the sum of the Ginis for its sub-groups) (World Bank 2013).

GDP Gross domestic product is an aggregate measure of production equal to the sum of the gross values added of all resident institutional units engaged in production (plus any taxes, and minus any subsidies, on products not included in the value of their outputs). The sum of the final uses of goods and services (all uses except intermediate consumption) measured in purchasers' prices, less the value of imports of goods and services, or the sum of primary incomes distributed by resident producer units (World Bank 2013).

Another important source of information on poverty is the Millennium Development Goals report. In September 2000, the Millennium Summit adopted the UN Millennium Declaration. Member nations committed to a new global partnership to reduce extreme

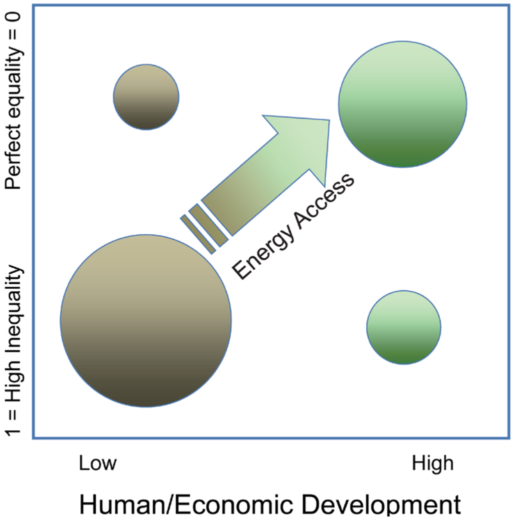

Figure 21.2. Representation of equality and energy access.

poverty and set out targets with a 2015 deadline, These are known as the Millennium Development Goals (MDGs) (UN 2000). They are the world's time-bound and quantified targets for addressing extreme poverty in its many dimensions including income poverty, hunger, disease, lack of adequate shelter, and exclusion, while promoting gender equality, education, and environmental sustainability (UN 2013). The 2013 UN report on MDGs shows that the target of halving the number of poor people living in extreme poverty (Goal 1.a "Halve, between 1990 and 2015, the proportion of people whose income is less than $1 a day") has been achieved: the proportion of population in developing regions living under less than $1.25 a day fell from 47% in 1990, to 22% in 2010. This is about 700 million fewer people living in conditions of extreme poverty in 2010 than in 1990. Thus, the goal was reached five years sooner than the deadline. Nevertheless, there are still 1.2 billion people who live under extreme poverty, mainly in Sub-Saharan Africa and Asia. The MDGs will be superseded by the Sustainable Development Goals still under discussion. The Sustainable Development Goals initiative was decided at the UN Rio + 20 Conference (UN 2014).

Energy is considered to be an essential input for people's livelihoods. It is used for basic activities from cooking and boiling water to heating (Clancy 2013). Biomass is the most basic energy source especially in poor households and in rural areas. Energy poverty is a wide and contextual term but is generally considered to be related to access and affordability problems in the developing world (Day and Walker 2013). It has been defined as the lack of choices for accessing energy services that are adequate, affordable and reliable (Clancy, 2013). This has led to other terms including fuel poverty, energy insecurity, energy injustice among others (Bickerstaff et al. 2013). People live in energy poverty either because there is no availability of quality energy carriers where they live or because they cannot afford them (Clancy 2013). Nwanyek (2010) pointed out two requirements for reducing poverty: to have sufficiently high and sustained economic growth and equality in income distribution or reduction of the inequality index. Additionally, diversification of income-generating activities is seen as another mean to move away from poverty as energy access is also related to household income. According to Clancy (2013) in order to end energy poverty, it is necessary to have access to modern and cleaner energy carriers (e.g. biogas, electricity) or better conversion technologies and equipment. Bioenergy crops provide an opportunity for diversifying rural activities and creating jobs and infrastructure (Clancy 2013). Although there is yet little evidence that biofuels production can reduce poverty directly, it has been demonstrated that it plays an important role in creating jobs and local markets (Diaz-Chavez 2010).

In urban, rural and peri-urban areas, vulnerable groups are more affected by poverty. These include women headed households, young people, indigenous groups, disabled and elderly people. As shown in Chapter 15, this volume, different business models may contribute to job creation and development. Nevertheless, ending energy poverty will require enabling access to modern and clean energy sources (e.g. electricity, biogas) as well as more efficient equipment for using biomass (e.g. cooking stoves).

21.3 Bioenergy and Poverty Reduction. International Programs

The International Energy Agency (IEA 2014) defines energy poverty as the lack of access to modern energy services, whilst access to modern energy services implies household access to electricity and clean cooking facilities (e.g. cooking stoves and fuels that do not cause indoor pollution) (OECD/IEA 2010). The IEA also acknowledges that access to energy services contributes both to human welfare and to national economic development. The larger part of the human population that lacks access to modern energy services is located in Sub-Saharan African and Asia. Table 21.1 illustrates selected indicators related to energy production and consumption of electricity regarding the GDP of main regions in the world.

Table 21.1. Selected energy indicators.

Region/Country/ Economy	Population (millions)	GDP (billions 2005 USD)	Energy prod (Mtoe)	Electricity consumption (TWh)
World	6958	52486	13202	20407
OECD	1241	38239	3854	10205
Middle East	209	1271	1788	737
Non-OECD Europe and Eurasia	340	1597	1822	1525
China	1351	4426	2433	4475
Asia	2313	3386	1405	1904
Non-OECD Americas	460	2298	797	942
Africa	1045	1267	1104	619

Source: IEA 2013

As Table 21.1 shows, Africa (mainly Sub-Saharan) poses the greatest challenge. According to the SE4ALL Global Tracking Framework (SE4ALL 2013), Sub-Saharan Africa is the only region where the rate of progress on energy access (1990–2010) fell behind population growth, both for electricity and for non-solid fuels. Access to modern energy is essential for development. It helps to provide clean water, sanitation, healthcare and other services including lighting, cooking, transport, and mechanical power. Sustainable development requires considering the double causality links, whereby income enables access to energy, and access to energy contributes to economic growth (OECD/IEA 2010).

Energy access therefore plays an important role in development. Recognizing this role, different programs have been implemented over the last few decades focusing on a wide range of objectives, from aiding access through to the tradeoffs between energy and poverty (Table 21.2).

Table 21.2. Selected energy programs.

Name of initiative	Acronym	Year created	Initiative funder/ organizer	Goals	Geographical scale
Global Network on Energy and Sustainable Development	GNESD[1]		UNEP	to increase the capacity of developing country centers of excellence for effective knowledge management of energy for sustainable development issues	Global/ National
Global Bioenergy Partnership	GBEP[2]	2005	initially organized by G8+5	promote global high-level dialogue on bioenergy policy-related issues and facilitate international cooperation • support national and regional bioenergy policy discussions and market development; • favor the transformation of biomass use towards more efficient and sustainable practices; • foster exchange of information and skills through bilateral and multilateral collaboration; and • facilitate bioenergy integration into energy markets by tackling barriers in the supply chain	National
Integrated food-energy systems	IFES[3]	2010	FAO	To demonstrate the function at various scales and configurations, from small-scale operations managed at the village or household level primarily to meet domestic needs and sustain local livelihoods to large-scale operations designed for commercial activities	project

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Name of initiative	Acronym	Year created	Initiative funder/ organizer	Goals	Geographical scale
Sustainable Energy for All	SEFA[4]	2012	United Nations	to achieve by 2030: • universal access to electricity and safe household fuels, • a doubled rate of improvement of energy efficiency • a doubled share of renewable energy in the global energy mix	Global/ National
Energy-smart Food for People and Climate Program	ESF[5]	2012	FAO/ UNEP/ IRENA	• Better energy efficiency • Increased energy diversification, with a gradual but steady emphasis on renewable energy; and Improved access to modern energy services through better integration of food and energy production	National

[1] http://www.gnesd.org/ABOUT/Energy-Access

[2] http://www.fao.org/energy/81319/en/

[3] http://www.fao.org/energy/78517/en/

[4] http://www.se4all.org/

[5] http://www.fao.org/energy/81350/en/

The list of programs in table 21.2 is not exhaustive as many other initiatives have been undertaken by the World Bank, the United Nations, international and local Non Governmental Organizations (e.g. Global Alliance for Cooking Stoves), as well as other research centers and non-profit organizations (e.g. Practical Action).

21.4 Technologies: Biogas, Cooking Stoves, Minigrids

Biomass has traditionally been a main source of energy in many parts of the developing world. However, in recent decades the sustainability of biomass production and consumption has been compromised, leading to increased concerns about accessibility, environmental impacts and human health. In some regions, biomass resources have been exploited beyond their ability to regenerate, resulting in scarcity and contributing to the degradation of soil and water, as well as loss of biodiversity (Sovacool 2012; Global-Bio-Pact 2013).

The widespread use of stoves for cooking and heating that require large quantities of biomass have played a role in reducing the availability of this resource. In addition, these inefficient devices produce large amounts of smoke that impinge on indoor air quality and affect mostly the health of women and children. In Africa and India, for instance, over 10% of children under the age of 5 suffer from acute respiratory illness associated with smoke from biomass burning (Mishra 2003; Mishra et al. 2005; Kilabuko and Nakai 2007). However, new technologies now exist that address both the issue of high biomass consumption and negative health effects.

One emerging system is that of biogas, which is obtained from millions of small-scale anaerobic digesters that animal waste to a clean fuel (family-size biogas plants, f-BGP). Conversion to gas allows 24% of the energy content in dung and crop residues to reach the cooking vessel, while over 90% of the nutrients and more than 80% of the humus are returned to cropland.

The biogas system has several advantages. It helps reduce both pathogens and greenhouse gas emissions from manure. It also increases soil fertility as manure is recycled to cropland. In addition, it helps improve health and safety in cooking and lighting, as well as contributing to better sanitation (Tricase and Lombardi 2012). Biogas digesters have helped do away with the need to gather fuelwood, thus improving school attendance, and eliminated smoke from kitchens and contributing to cleaner air and improved health.

Today this biogas system reaches 5 million homes in India, and 15 million homes in China. Families have used manure from their livestock (typically a few heads of cattle or pigs) to feed small-scale biogas digesters which help both meet their domestic energy needs and reduce expenditure on fertilizer by effectively recycling nutrients to the soil. In the case of India, the take up of this system has been 40% over the last 30 years. But insufficient local maintenance and high installation costs remain important deterrents to increased use of f-BGPs. A higher adoption rate will require the biogas system to widen the feedstock base to include crop residues that are currently underutilized or are non-marketable. Social and cultural factors also place limitations on the type of residue to be used which will need addressing. Many common crop residues and weeds are highly efficient in energy conversion and can help meet energy security targets and livelihood security in sub-tropical climates, providing an effective alternative to environmentally sensitive woody biomass combustion.

Although biogas digesters have attracted investments from countries and NGOs interested in rural energy security and sustainability, other technologies have become increasingly attractive. In recent years, efficient woodstove designs have improved significantly. For instance, there are hybrid systems that mix metal components with local clay or bricks with improved ventilation. There are also systems based on conversion of waste heat into electricity that can be used to charge cell phones and other devices.

More efficient systems that take biogas and solid and liquid biomass have been increasingly available to households in the developing world, and particularly in India and China. Governments in these countries have promoted initiatives that help set up small-scale bioenergy systems to meet the domestic demand for cooking and lighting of communities unable to access national grids. Villages have been building micro-grids using biomass or biogas to generate steam. These approaches hold considerable promise for increasing energy access in rural communities. See examples in Chapter 14, this volume.

21.5 Energy Access and Rural Development: the Role of Modern Bioenergy

Given the low rate of electrification and high dependence on traditional biomass in rural areas of Least Developed Countries, a potential role for modern bioenergy is of particular interest. Whereas developed countries phased out biomass many decades ago in favor of fossil fuels and then started developing modern bioenergy, the developing countries can take advantage of technological development that has already occurred. Although there are many different options and pathways, three aspects have particular significance for the connections between energy access, biomass resources and poverty reduction: (1) the use of wastes and residues; (2) the role of bioenergy in agricultural value chains and productivity; and (3) bioenergy in agro-industries. Each of these aspects is discussed briefly below.

Unlike dedicated bioenergy systems, the initial set-up costs for using residues and wastes are lower. If supplied and/or sourced sustainably, biomass wastes and residues offer the most widely available and least-cost biomass resource options. Table 21.3 provides a classification and some examples of biomass residues and wastes. More details on the different uses and applications of residues can be found in Chapter 12, this volume. The principal challenge is to develop reliable, cost-effective handling methods to reduce the costs of gathering and processing (FAO 2011). Competition for residues in such uses as animal feeds and soil protection should also be considered, as it can also impact feasibility and/or cost-effectiveness.

Countries and regions that lack energy access are almost always dominated by subsistence agriculture where farmers struggle to maintain a surplus so they can gain additional cash income. At the same time, they face difficulties in agricultural supply chains, due to the lack of refrigeration, storage and fuel for transport. Consequently, improvements in energy access and in agricultural supply chains can go hand-in-hand,

Table 21.3. Classification and examples of biomass residues and wastes.

Biomass type/ source	Woody biomass	Herbaceous biomass	Biomass from fruits and seeds	Others (including mixtures)
Direct (by-products)	Logging by-products Thinning by-products	Straw Bagasse husks	shells and husks fruit bunches	Animal dung Landscape management by-products
Indirect	Sawmill wastes Black liquor (from pulp/ paper production)	Fiber crop processing wastes Recycled fiber products	Food processing by-products Waste oils	Bio-sludge Slaughterhouse by-products Municipal solid waste

Source: Adapted from FAO, 2004

thus revealing the linkages between energy access for households and enterprises. It does not necessarily matter what the energy source is, but the question of value chains suggests some synergies when bioenergy and food markets can be developed together, since the sources and processing of biomass may be the same.

As agriculture becomes modernized, it assumes a smaller role in relation to industrial development. Yet a chicken and egg problem arises: companies and entrepreneurs will not invest without infrastructure and reliable energy, but at the same time such investment and the economic linkages it brings are needed in order to develop the infrastructure and reliable energy systems. Investments in agro-industries and agro-forestry, including liquid biofuels, can directly address this chicken-and-egg problem. Essentially, their comparative advantage is that they bring their energy with them! Such investments can spur further economic development since they are strongly linked to agricultural, energy and industrial development all at the same time. A recent example is the investment by Addax Bioenergy in Sierra Leone, near the town of Makeni; the investment includes a sugarcane estate, production of ethanol and production of co-generated electricity from bagasse (ABSL 2013; see Box 21.3). The surplus electricity after supplying the factory will be sent to the grid, and its availability will complement the hydro capacity.

Box 21.3. Addax Bioenergy Sierra Leone (ABSL)

The Addax Bioenergy Sierra Leone (ABSL) project is located near the town of Makeni in the Bombali district of Sierra Leone, approximately 160 kilometers from the capital, Freetown. The region around the town of Makeni is a fast-growing area due to its strategic location and its ability to attract investment in agriculture and mining. The ABSL project includes greenfield development of sugarcane cultivation, establishment of an ethanol distillery and export of sugarcane bagasse-based electricity to the national grid. The capital investment of some 267 million EUROs is the largest agricultural project ever undertaken in Sierra Leone and has been financed with the support of eight European and African development finance institutions. Commercial production commenced in mid-2014. The electricity exported from the factory to the grid will increase by 20% the current national power production, and thus improve energy access considerably in the region and in the country as a whole. The project will have significant effects on surrounding communities' livelihoods and access to resources, thus requiring careful monitoring in order to insure improvements in food security and local development opportunities. Furthermore, the project has international significance not only due to its unique agricultural and energy characteristics but also because it will be the first case where biofuels are exported to the EU from Africa on a large scale. In later years when the government is mature enough to implement fuel blending, the domestic market for ethanol could be developed. The cogeneration plant is the first Clean Development Mechanism (CDM) project in Sierra Leone while the ethanol plant was the first biofuels project in all of Africa to receive international sustainability certification (required for the EU market), which was given by the Roundtable on Sustainable Biomaterials (RSB).

21.6 Case Studies: Improved Cookstoves for Energy Access, the EnDev Program in Kenya

The Energizing Development (EnDev) initiative[1] aims to provide economically sustainable energy access and distribution schemes in rural areas and now operates

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[1] Energising Development (EnDev) is an impact-oriented global sector-wide initiative between the German Federal Ministry for Economic Cooperation and Development (BMZ) and the Directorate-General for International Cooperation of the Dutch Ministry of Foreign Affairs (DGIS). EnDev cooperates with several partner countries in Africa, Latin America and Asia, and is currently carrying out activities in 20 countries. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH is acting as the principal agency for implementing the partnership.

in twenty different countries. The Kenyan program focuses especially on improved cookstoves (ICS) and, since 2006, has disseminated over 1.4 million household stoves, benefiting 7 million people (EnDev 2012). See Bailis et al. (2005) for an assessment of the potential health and climate impacts of programs across sub-Saharan Africa. Key reasons for the program's success include:

- *Targeting fuel scarce regions:* Densely populated and/or biomass-scarce regions were initially targeted. Successful stove programs tend to be in areas where people pay for fuelwood or have to walk long distances to obtain it (Barnes et al. 1994).
- *Balancing efficiency, cost and acceptability:* EnDev prioritizes reliability, affordability and social acceptance. Stoves use locally available construction material, but follow established engineering principles. The price of €2.45-€6.50 is affordable for rural Kenyans and thus no subsidies are needed. Local construction allows users to help design non-critical parts such as pot rests, leading to higher acceptability.
- *Aiming for market transformation:* While the objective is access to energy, the program also strived to build a sustainable market for modern cooking options, through supporting production and marketing in a way that responds to user demands.
- *Alignment with national goals and policies:* The Kenyan program is implemented in partnership with the Ministry of Agriculture and in line with the Ministry of Energy strategy to increase ICS use to 30% by 2020 (KIPPRA 2006).
- *Facilitation role:* The introduction of the stoves follows a commercial approach, with the implementers' role limited to technical and management training, public awareness and marketing and evaluation of stove performance.

The 1.4 million stoves equate to annual savings of 1.3 million metric tons of firewood, 74,964 ha of forest cover and 897,120 tCO2 emissions (EnDev 2012). Some of these outcomes have been verified in scientific studies, focusing on indoor air pollution, fuel efficiency and acceptability (Ochieng 2013). Other achievements identified in previous evaluations included the following (GIZ-PSDA 2008):

- A majority of households without ICS used the three-stone-fire every day (81%), but only 21% of ICS households used the three-stone-fire daily. In other words, ICS households generally abandoned use of traditional fireplaces.
- Establishment of a 'Stove Dealers Association' to allow skills transfer and capacity-building, so as to take over once the project was phased out. The association was linked to the Kenyan Bureau of Standards to address technical standards for stoves.
- The project created synergies with agro-industries, especially tea factories, so as to include stove promotion within their environmental and livelihood initiatives.
- New businesses associated with stove production, marketing and installation created local employment for women and men and hence increased household incomes.

- In addition to households, many social institutions (schools, hotels and small businesses) also adopted the stoves to reduce firewood consumption.
- Profits accruing to producers, installers and marketers changed the perception of the sector to that of a sustainable business, rather than a 'women's promotional activity'.

It is important to recognize the need for a balance between efficiency and acceptability. While cookstove technologies that are up to 90% efficient now exist (in laboratories), they have a narrow tolerance to fuel size and moisture and thus generally require special care or pre-processing. In addition to the high cost, these factors may hinder wide scale adoption. On the other hand widely acceptable improved wood stoves with medium level efficiency can have substantial impact on efficiency based on the scale of adoption. The early success case with the EnDev program in Kenya shows that energy efficiency can be achieved on wide scale in developing countries, and the efforts can reach commercial level where program subsidies are no longer required. More effort should be geared towards learning from these successes, and replicating the programs in other regions.

21.7 Cross Sector-Synergies: Including Investment and Institutions

Current technology transfer rates are an important factor in deterring widespread adoption of biogas systems. They have been low, reaching only a fraction of the population in India and China (between 0.06%-0.2%) through implementation of a subsidized spread model that maximizes demonstration effects. One major shortcoming is that current on-site installation times are two to three weeks, although conventional plastic water tanks may be modified into biogas plants within one day with very low maintenance costs. The use of recycled plastics could reduce the f-BGP costs further, encouraging widespread bio-methane production and use. Overall costs could be reduced by adopting a less decentralized system based on ready-to- install designs available through new financing schemes that encourages local entrepreneurship whilst providing technological backup. A f-BGP program that converts animal waste and crop residues has the potential to offset 180mt of fuel wood or coal in India and China annually at the same time as contributing significantly to less methane emissions from animal waste (see Chapter 14, this volume).

21.8 Conclusions and Recommendations

The links between energy and poverty reduction are manifold. Although many of these links are indirect, the benefits that access to energy can create in poor regions are undeniable, as demonstrated by the examples discussed in this chapter. Enabling the 1.2 bn of people who lack access to electricity, along with the 2.8 bn people who are dependent on biomass mainly in poor regions in Africa and Asia to access modern sources of energy as a means of escaping poverty will require ambitious and concerted action, as envisioned in the UN initiative *Sustainable Energy for All*.

In spite of these ambitious targets, biomass is likely to continue to be the primary renewable energy resource for the world's least advantaged populations and one of the forms to reduce carbon emissions in the developed world. For this reason, rapid implementation of new bioenergy technologies is needed to avoid debilitating health and environmental outcomes.

General recommendations:

1. There is a need to better integrate the efforts of international programs working on reducing energy poverty and facilitating energy access to meet their ambitious goals by 2050.
2. There is still a need to facilitate incentives at local and regional level for the provision of energy, particularly in developing countries and rural and peri-urban areas.
3. Research and development require focus on the synergies between the social, environmental and economic dimensions of the access to energy.
4. More research and capacity building to reduce subsidies and promote new technologies and their acceptability at community level are necessary to deploy the benefits of modern energy.

21.9 The Much Needed Science

There is a clear link between energy access and poverty. Although energy poverty is also related to two main factors, either the lack of access to energy or the inability to pay for the service. There is ongoing research on this topic but there still is a need to improve datasets regarding positive cases where projects have clearly demonstrated the link between reduction of energy poverty and access to energy through the improvement of livelihoods, particularly in the use of bioenergy.

These links have not been incorporated in the reports of the United Nations regarding the Millennium Development Goals on poverty reduction. It mainly focuses on job creation but there is need of more primary data regarding the use of bioenergy and also the reduction of health problems.

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section V

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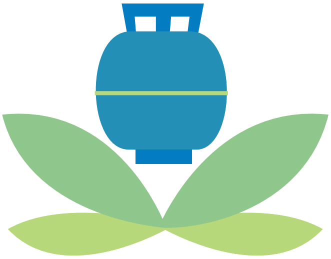

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Bio-based chemicals
Bio-oil
Biochemical conversion
Biodiesel
Biodiversity
Biodiversity protection
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Harvest
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iLUC
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Improved human health
Improved soils
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Innovation
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Livelihoods
Logistics
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Pasture intensification
Planted forests
Policy
Pollutants
Pre-processing
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Renewable diesel
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Resource use
Rural development
Scaling-up
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The volume is the outcome of an assessment that included a meeting held at UNESCO, Paris, in December 2013. Fifty experts discussed bioenergy sustainability across its whole lifeline and crosscutting aspects including energy security, food security, environmental and climate security, sustainable development and innovation.

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