PART 1

CHAPTER 2

Reducing Human Vulnerability: Helping People Help Themselves

Families in Bangladesh are deciding whether to rebuild their homes and livelihoods after yet another flood—once occasional, now every few years—or to take their chances in Dhaka, the crowded capital. In the tall forests of southern Australia, communities are reorganizing after the most damaging fires in history—aware that they are still in the grip of the longest and most severe drought on record. With losses from extreme climate events inevitable, societies have explicitly or implicitly chosen the risk they bear and the coping strategies to deal with them. Some losses are so high and the coping so insufficient that development is impeded. As the climate changes, more and more people risk falling into what is called the "adaptation deficit."

Reducing vulnerability and increasing resilience to the climate has traditionally been the responsibility of households and communities[1] through their livelihood choices, asset allocations, and locational preferences. Experience shows that local decision making, diversity, and social learning are key features of flexible, resilient communities[2] and that vulnerable communities can be effective agents of innovation and adaptation.[3] But climate change threatens to overwhelm local efforts, requiring more from national and global supporting structures.

People's vulnerability is not static, and the effects of climate change will amplify many forms of human vulnerability. Crowded cities expand into hazardous zones. Natural systems are transformed through modern agriculture. Infrastructure development—dams and roads—create new opportunities but can also create new risks for people. Climate change, superimposed on these processes, brings additional stress for natural, human, and social systems. People's livelihoods need to function under conditions that will almost certainly change but cannot be predicted with certainty.

Whichever mitigation pathway is followed, the temperature and other climate changes over the next decades will be very similar. Temperatures are already about 1°C above those of the preindustrial era, and all realistic mitigation scenarios suggest that we may expect another 1°C by midcentury. The world of 2050 and beyond, however, will be much different from today's—just how different depends on mitigation. Consider two possibilities for this generation's children and grandchildren. In the first scenario the world is on track to limiting

Key messages

Further climate change is unavoidable. It will stress people physically and economically, particularly in poor countries. Adapting requires robust decision making—planning over a long time horizon and considering a broad range of climate and socioeconomic scenarios. Countries can reduce physical and financial risks associated with variable and extreme weather. They can also protect the most vulnerable. Some established practices will have to be expanded—such as insurance and social protection—and others will have to be done differently—such as urban and infrastructure planning. These adaptation actions would have benefits even without climate change. Promising initiatives are emerging, but applying them on the necessary scale will require money, effort, ingenuity, and information.

temperature increases to 2–2.5°C above preindustrial levels. In the second the emissions are much higher, leading eventually to temperatures about 5°C or more above preindustrial levels.[4]

On the lower temperature trajectory many ecosystems will come under increasing stress, patterns of pests and disease will continue to change, and agriculture will require significant changes in practice or displacement in location. On the higher temperature trajectory most of the negative trends will be even worse, and the few positive trends, such as increases in agricultural productivity in cooler cropping regions, will be reversed. Agriculture will undergo transformational change in practices and locations. Storm intensity will be higher. And sea levels are likely to rise by about one meter.[5] Floods, droughts, and extreme temperatures will be much more common.[6] The past decade has been the hottest on record, but by 2070 even the coolest years are likely to be hotter than now.

On the higher trajectory, warming could trigger feedbacks in Earth systems that would make it difficult to further constrain temperature increases, regardless of mitigation. These feedbacks could rapidly collapse ecosystems, as some are predicting for the Amazon and the boreal peat lands (see focus A). People in that higher-track world would see rapidly accelerating losses and costs reverberate through their societies and economies—requiring adaptation at a scale unprecedented in human history. International tensions could be expected to rise over resources, and migration away from the areas most affected would increase.[7]

On the lower track, adaptation will be challenging and costly, and business-as-usual development will be far from sufficient. Broader and accelerated implementation of policies that have proved successful is paramount as is adaptation that harnesses the ingenuity of people, institutions, and markets. On the higher track the question is whether we may be approaching, or have already exceeded, the limits to adaptation.[8] Some argue convincingly that ethics, culture, knowledge, and attitudes toward risk limit human adaptation more than physical, biological, or economic thresholds.[9] As the physical and biological stresses arising from climate change increase, so will the social tensions. The adaptation effort that will be required by future generations is thus determined by how effectively climate change is mitigated.

Incremental environmental impacts imply stronger physical constraints on future development. Climate-smart policies will have to address the challenges of a riskier and more complex environment. Development practice has to be more adaptive to shifting baselines, grounded in strategies robust to imperfect knowledge.[10] Cropping strategies need to be robust under more volatile weather conditions by seeking to maintain long-term consistency in output rather than to maximize production. Urban planners in coastal cities need to anticipate demographic developments and new risks from rising seas or flooding. Public health workers need to prepare for surprising changes in climate-linked disease patterns.[11] Information is crucial to support risk-based planning and strategies—it is the basis of good policy and better risk management.

Managing ecosystems and their services will be more important and more difficult. Well-managed landscapes can modulate flood waters. Intact coastal wetlands can buffer against storm damage. But management of natural resources will face a rapidly changing climate with more extreme events and with ecosystems under increasing threats from stresses other than climate (such as land-use and demographic change).[12] Managing such physical risks is an integral part of climate-smart development—a “no-regrets” option to avoid avoidable impacts on people.

However, not all physical impacts are avoidable, particularly those linked to extreme and catastrophic events whose probability is difficult to assess under climate change. Eliminating the risk of the most extreme events is not possible, and attempting to do so would be extremely costly given the uncertainty about the location and timing of impacts. Being financially prepared to cope with climate impacts is critical for both households and government. This requires flexible risk-spreading mechanisms.

As chapter 1 discusses, the poor have the least capacity to manage physical and financial risk and to make longer-term adaptation decisions. Their lives are affected more by climate, whether they practice subsistence farming or are landless squatters in a floodplain at the urban fringe. Other social groups share many of the vulnerabilities of the poor stemming from their lack of entitlements, productive assets, and voice.[13] Social policy, a critical complement to physical and financial risk management, provides many tools to help manage the risk affecting the most vulnerable and to empower communities to become agents in climate-change management.

This chapter focuses on measures that will assist people in handling today's variable climate and the climate changes that occur over the next few decades. It first describes a policy framework based on strategies that are robust to climate uncertainty and management practices that are adaptive in the face of dynamic conditions. It then looks at managing physical risks, financial risks, and social risks.

Adaptive management: Living with change

Climate change adds an additional source of unknowns for decision makers to manage. Real-world decision makers make decisions under uncertainty every day, well beyond the realm of climate change. Manufacturers invest in flexible production facilities that can be profitable across a range of production volumes to compensate for unpredictable demand. Military commanders insist on overwhelming numerical superiority. Financial investors protect themselves against fluctuations in markets by diversifying. All these forms of hedging are likely to lead to suboptimal results for any fixed expectation about the future, but they are robust in the face of uncertainty.[14]

A compounding set of uncertainties—about demographics, technology, markets, and climate—requires policies and investment decisions to be based on imperfect and incomplete knowledge. Local and national decision makers face even greater uncertainties because projections tend to lose precision at finer scales—an inherent problem of downscaling from coarse, aggregate models. If decision parameters cannot be observed and measured,[15] robust strategies (see chapter 1) that directly address the reality of a world of shifting baselines and intermittent disturbances[16] are the appropriate framework in a context of unknown probabilities.

Accepting uncertainty as inherent to the climate change problem and robustness as a decision criterion implies changing decision-making strategies for long-lived investment and long-term planning. It demands rethinking traditional approaches that assume a deterministic model of the world in which the future is predictable.

First, priority should be given to no-regrets options: investment and policy options that provide benefits even without climate change. Such options exist in almost every domain—in water and land management (see chapter 3), in sanitation to reduce water-borne diseases (controlling sewer leakage), in disaster risk reduction (avoiding high-risk zones), in social protection (providing assistance to the poor). But such options often are not implemented, partly because of a lack of information and transaction costs but also because of cognitive and political failures (see chapter 8).[17]

Second, buying "safety margins" in new investments can increase climate resilience, often at low cost. For instance, the marginal cost of building a higher dam or including additional groups in a social protection scheme can be small.[18] Safety margins account not only for possible impacts of climate change (more severe events) but also for the uncertainty in socioeconomic development (changes in demand).

Third, reversible and flexible options need to be favored, accepting that decisions can be wrong and thus keeping the cost of reversing them as low as possible. Restrictive urban planning because of uncertain flooding outcomes can be reversed more easily and cheaply than future retreat or protection options. Insurance provides flexible ways of managing risk and protecting necessary investment when the direction and magnitude of change are uncertain.[19]

Farmers transitioning to drought-tolerant varieties (rather than investing in irrigation) can use insurance to protect their seasonal investment in new seeds from an exceptionally severe drought. For storm-prone areas a combination of early warning systems, evacuation plans, and (possibly expensive) property insurance can provide more flexibility to save lives and replace homes than can protecting entire coastal areas with infrastructure or depopulating them unnecessarily.[20]

Fourth, institutionalizing long-term planning requires forward-looking scenario analysis and an assessment of strategies under a wide range of possible futures. This leads to periodic reviews of investment (and, if necessary, revisions), and it improves policies and practices by iterative learning from outcomes. Widening the spatial scope of planning is equally critical to be prepared for changes that may propagate over longer distances, such as the melting of glaciers that change the water supply of urban zones hundreds of kilometers downstream, widespread droughts that affect regional grain markets, or accelerated rural-urban migration caused by environmental degradation. But the required structural changes can be difficult because of the inertia in prevailing management practices.[21]

Implementing such strategies through adaptive management entails continuous information development, flexible and robust planning and design, participatory implementation, and monitoring and evaluation of feedback. It realigns decisions and management with the scale of ecological and social contexts and processes, such as watersheds and ecoregions, and can be driven by local or community management systems.[22] It stresses management informed by scientific and local knowledge, as well as policy experiments that develop understanding, set learning as an objective, and improve the ability to manage under uncertainty (box 2.1).[23]

Involving stakeholders in planning increases ownership and the likelihood that actions will be sustained.[24] Boston and London both have climate-change strategies. In Boston the process was research-led, with inconsistent stakeholder engagement. The completed study, seen as overly technical, has had little impact. London used a bottom-up approach, engaging many stakeholders. And after the London Warming Report was released, the Climate Change Partnership evolved from the stakeholder organization to continue adaptation planning.[25]

A risk-based decision-making model favoring robustness and longer-term planning, and appropriate local, community, and national governance structures is essential for adaptation to climate change.[26] Increasing pressure on scarce resources (land, water), combined with major sociodemographic transformations (population growth, urbanization, globalization) and a shifting climate, provide much less room to leave risks unmanaged. A storm hitting a modern, rapidly growing coastal city has the potential to cause a lot more damage than in the past when the coast was less populated and built up. In the face of the uncertainty arising from climate change, robust strategies and adaptive management provide the appropriate framework to better manage physical, financial, and social risks.

BOX 2.1 *Characteristics of adaptive management: a checklist*

- Management aligned with ecological processes and defined at appropriate spatial scale
- Cooperation among administrative levels, sectors, and line departments
- Broad stakeholder participation and collaboration, including nongovernmental stakeholders and research centers, in problem solving and decision making
- Enabling legislation and legal framework to support local action
- Adaptable legislation and policies to respond to new information
- Long time horizon for planning and capacity building
- Assessment of flexible and reversible measures
- Experimentation and learning through policy experiments to inform management
- Full consideration of alternative scenarios and of structural and nonstructural measures
- Mechanisms to understand and challenge assumptions
- Explicit communication of assumptions and consideration of uncertainty
- Use of information and monitoring to inform policy
- Generation of scientific and technical knowledge to develop new practices
- Appropriate financing system

Sources: Adapted from Raadgever and others 2008; Olsson, Folke, and Berkes 2004.

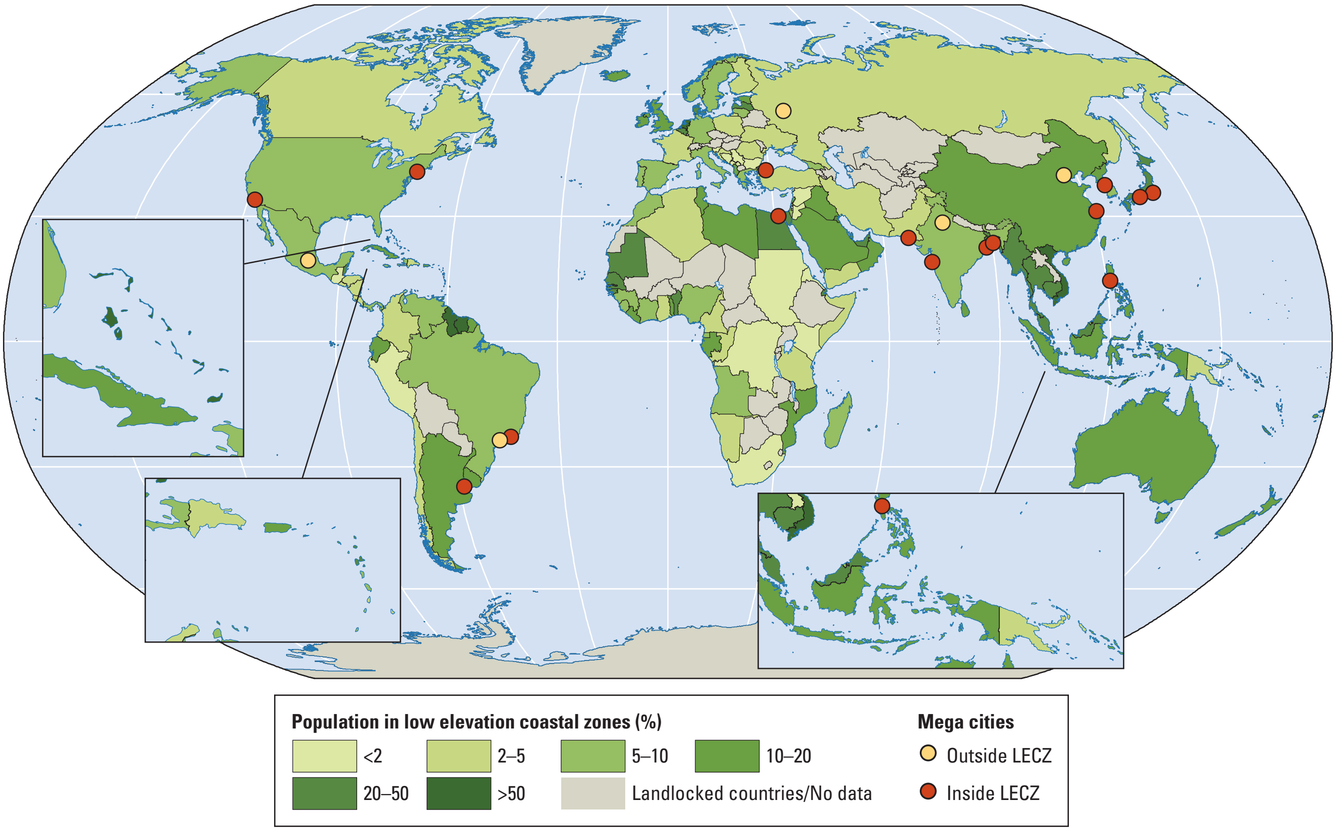
Managing physical risks: Avoiding the avoidable

Natural systems, when well managed, can reduce human vulnerability to climate risks and deliver developmental co-benefits, reduce poverty, conserve biodiversity, and sequester carbon. Ecosystem-based adaptation—maintaining or restoring natural ecosystems to reduce human vulnerability—is a cost-effective approach to reducing climate risks and one that offers multiple benefits (see focus B). For example, forested catchments buffer water flows from moderate rains far better than nonforested catchments, but heavier rains quickly saturate the sponge, and most water moves quickly over the land.[27] Well-vegetated wetlands downstream can further buffer water flows while natural drainage systems carry it away. But wetlands converted to agriculture or urban settlements and simplified drainage systems inevitably fail, leading to flooding. A comprehensive response to flood management includes maintaining catchment cover, managing wetlands and river channels, and siting infrastructure and planning urban expansion appropriately. Similarly, coastal mangrove forests protect against storm surges partly by absorbing the flows and partly by keeping human settlements behind the mangroves farther from the sea.

Build climate-smart cities

Half the world's people now live in cities, a share that will rise to 70 percent by 2050.[28] Of urban population growth (5 million new residents a month), 95 percent will be in the developing world, with small cities growing fastest.[29] Urban areas concentrate people and economic assets, often in hazard-prone areas as cities have historically prospered in coastal areas and at the confluence of rivers. In fact, low-elevation coastal zones at risk from rising sea levels and coastal surges are home to about 600 million people globally and 15 of the world's 20 megacities (map 2.1).[30]

Map 2.1 At risk: population and megacities concentrate in low-elevation coastal zones threatened by sea level rise and storm surges



Source: United Nations 2008a.

Note: Megacities in 2007 included Beijing, Bombay, Buenos Aires, Cairo, Calcutta, Dhaka, Istanbul, Karachi, Los Angeles, Manila, Mexico City, Moscow, New Delhi, New York, Osaka, Rio de Janeiro, Sao Paulo, Seoul, Shanghai, and Tokyo. Megacities are defined as urban areas with more than 10 million inhabitants.

Climate change is only one of many factors that determine urban vulnerability. For many coastal cities, migration increases the population exposed to rising sea levels, storm surges, and floods,[31] as in Shanghai, where the net annual influx of people exceeds the natural growth rate by a factor of four.[32] And many cities in river deltas are sinking as a result of groundwater extraction and declining sediment deposits caused by dams upstream. While subsiding land has been an issue for some time in many coastal cities (New Orleans, Shanghai), it is an emerging threat for Hanoi, Jakarta, and Manila.[33] Urban development farther inland increases the water demand upstream, and many rivers, including the Nile, no longer reach their delta.

Urbanization, done well, can increase resilience to climate-related risks. Higher population densities lower the per capita costs of providing piped treated water, sewer systems, waste collection, and most other infrastructure and public amenities. Sound urban planning restricts development in flood-prone areas and provides critical access to services. Infrastructure developments (embankments or levees) can provide physical protection for many and will require additional safety margins where climate change increases risk. And well-established communication, transport, and early warning systems help evacuate people swiftly, as is the case in Cuba, where up to 800,000 people are routinely evacuated within 48 hours when hurricanes approach.[34] Such measures can increase the ability of urban dwellers to cope with shocks in the short term and adapt to a changing climate in the long term.[35]

Cities are dynamic and highly adaptive systems that offer a wide range of creative solutions to environmental challenges. A number of countries are looking into new urban development strategies that aim at spreading regional prosperity. The Republic of Korea has embarked on an ambitious program to develop "Innovation Cities" as a way to decentralize the country's economic activities.[36] Many of these efforts focus on technological innovation and offer new opportunities to redesign future cities to deal with the climate-change challenges.

Attempts to influence the spatial patterns of urban areas through public policy interventions show mixed results, however. The Arab Republic of Egypt's attempt to create satellite cities to decongest Cairo never attracted the projected population and did little to stop population growth in Cairo.[37] Successful policies facilitate concentration and migration during the early stages of urbanization and interurban connectivity during the later stages. Public investments in infrastructure are most effective when they increase social equity (through broader access to services) and integrate the urban space (through the transport system).[38]

Urbanization seldom is harmonious, generating pollution and inequalities, and urban areas in developing countries are home to 746 million people living below the poverty line (a quarter of the world's poor).[39] But the urban poor suffer from more than low income and consumption. Overcrowding, insecure tenure, illegal settlements sited in landslide- and flood-prone areas, poor sanitation, unsafe housing, inadequate nutrition, and poor health exacerbate the vulnerabilities of the 810 million people in urban slums.[40]

These many vulnerabilities call for comprehensive improvements in urban planning and development. Government agencies, particularly local ones, can shape the adaptive capacity of households and businesses (box 2.2). But action by community-based and nongovernmental organizations (NGOs) is also crucial, particularly those that build homes and directly provide services, as slum-dweller organizations do.[41] Sound planning and regulation can identify high-risk zones in urban areas and allow low-income groups to find safe and affordable housing, as in Ilo, Peru, where local authorities safely accommodated a fivefold increase in the population after 1960.[42] But hard investments in infrastructure may also be required to protect urban zones, such as coastal cities in North Africa, with seawalls and embankments (box 2.3).

A major risk for urban areas is flooding—often caused by buildings, infrastructure, and paved areas that prevent infiltration, exacerbated by overwhelmed drainage systems. In well-governed cities flooding is rarely a problem because surface drainage is built into the urban fabric to accommodate floodwaters from extreme events that exceed

BOX 2.2 *Planning for greener and safer cities: The case of Curitiba*

Despite a sevenfold population increase between 1950 and 1990, Curitiba, Brazil, has proven itself to be a clean and efficient city, thanks to good governance and social cooperation. The cornerstone of Curitiba's success lies in its innovative Plano Director, adopted in 1968 and implemented by the Instituto de Pesquisa Planejamento Urbano de Curitiba (IPPUC). Rather than use high-tech solutions for urban infrastructure, like subways and expensive mechanical garbage separation plants, the IPPUC pursued appropriate technology that is effective both in cost and application.

Land use and mobility were planned in an integrated fashion, and the city's radial (or axial) layout was designed to divert traffic from the downtown area (three-fourths of the city's people use a highly efficient bus system). The industrial center is built close to the city center to minimize the commute for workers. Numerous natural preservation areas are situated around the industrial area to buffer flooding.

Another part of the city's success is its waste management; 90 percent of its residents recycle at least two-thirds of their trash. In low-income areas where conventional waste management is difficult, the "Garbage Purchase" program exchanges garbage for bus tokens, surplus food, and school notebooks.

Replications are under way. In Juarez, Mexico, for example, the Municipal Planning Institute is building new homes and transforming the previously inhabited flood zone into a city park.

Source: Roman 2008.

the capacity of protective infrastructure (see box 2.3). Inadequate solid waste management and drain maintenance, by contrast, can quickly clog drainage channels and cause local flooding with even light rainfall; in Georgetown, Guyana, such a situation led to 29 local floods between 1990 and 1996.[43]

Cities also have to look beyond their borders to prepare for climate change. Many Andean cities are reengineering their water supplies to accommodate the shrinking and eventual disappearance of glaciers. Melting means that dry-season water supply is no longer reliable, and reservoirs will need to compensate for the lost water storage and regulation function of glaciers.[44] In the deltas in Southeast Asia, the rapidly spreading suburbs of cities such as Bangkok and Ho Chi Minh City are encroaching on rice fields, reducing water retention capacity and increasing the risk of floods.[45] The risk can get worse when upstream storage areas reach their capacity and have to discharge water. Peak river discharges in South and

BOX 2.3 *Adapting to climate change: Alexandria, Casablanca, and Tunis*

Alexandria, Casablanca, and Tunis, each with 3 million to 5 million people, are assessing the extent of the projected impacts of climate change and devising adaptation scenarios for 2030 through an ongoing regional study. The cities' early responses to their increasing vulnerability show uneven paths toward adaptation.

In Alexandria the recent construction of the corniche, a major six-lane highway built right on the coast, has worsened coastal erosion and steepened the profile of the seabed, causing storm surges to reach farther into the city. Sea defenses are being built without sufficient engineering studies or coordination among the responsible institutions. A lake near the city, a natural receptacle for drainage waters, is suffering acute pollution and real-estate pressures to reclaim it for construction purposes.

Casablanca responded to recent devastating urban flooding episodes with works to improve upstream watershed management and to broaden the main drainage canals. Leaks in the household water distribution network have been repaired, with the water saving equal to the consumption of about 800,000 people. But coastal zone management remains a concern, given the limited tools to control construction and reduce sand extraction from beaches.

Tunis is also addressing its urban flooding risks by improving drainage canals and controlling informal construction around some natural reservoirs. Seawalls are being built to defend the most threatened coastal neighborhoods, and the new master plan directs urban development away from the sea. But the city center, already below sea level, is subsiding, and harbor and logistic facilities, as well as power-generation and water-treatment plants, are under threat. Major urban redevelopment projects, if carried out, also risk increasing the city's vulnerability to rising seas.

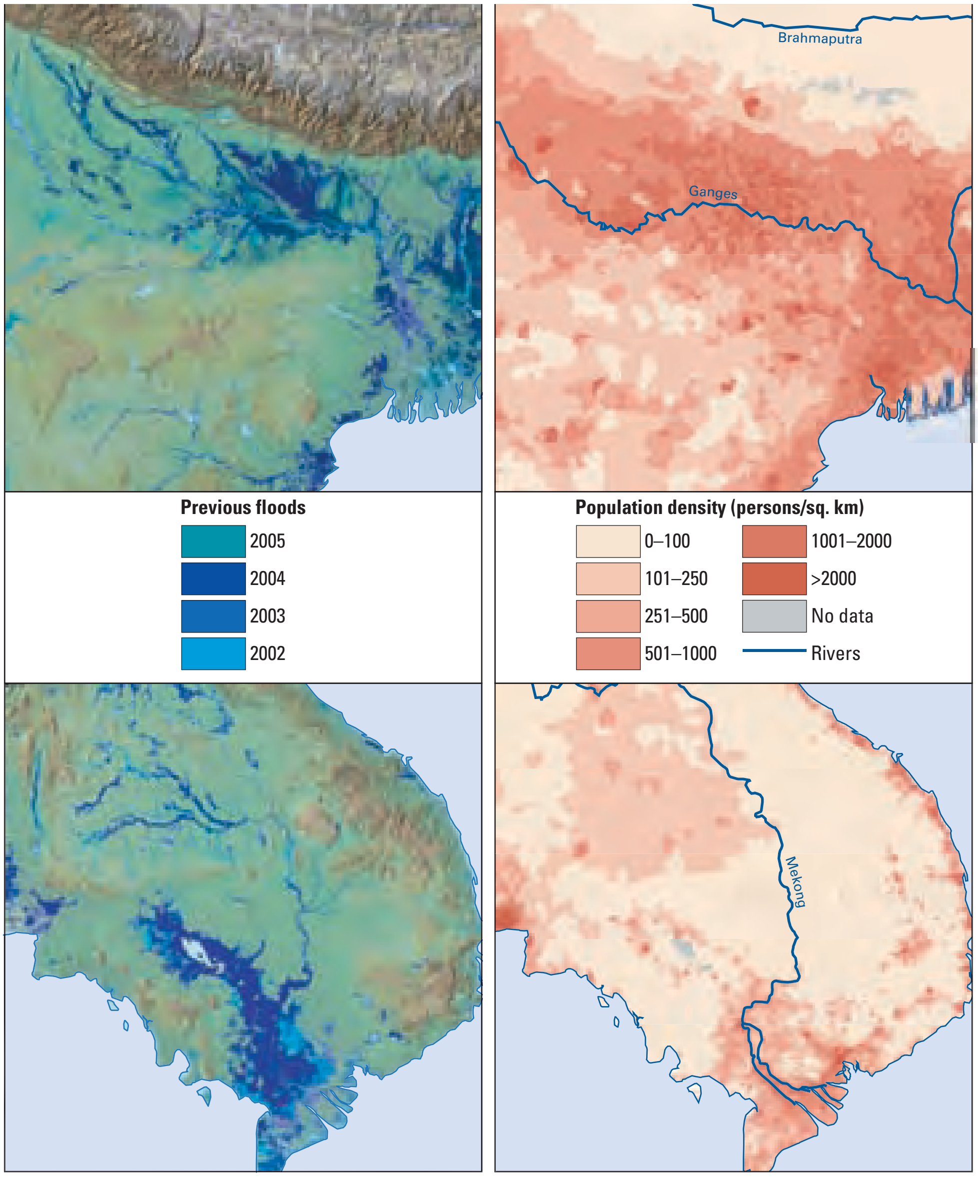
Adaptation to climate change in Alexandria, Casablanca, and Tunis should occur primarily through improving urban planning; identifying land-use and expansion scenarios that would minimize vulnerability; addressing the vulnerability of key infrastructure assets, such as ports, roads, bridges, and water-treatment plants; and improving the capacity of responsible institutions to coordinate responses and manage emergencies. In addition, energy efficiency in buildings and municipal systems can be consistent with increasing resilience to climate change while reducing greenhouse gas emissions.

Source: Bigio 2008.

Southeast Asian river basins are projected to increase with climate change, requiring greater upstream efforts to protect urban centers downstream (map 2.2).[46]

Local city governments can promote risk reduction and risk-based planning. Creating a risk information database, developed jointly with citizens, businesses, and officials, is the first step in setting priorities for intervention and identifying hotspots. And establishing a city mandate through executive orders and council legislation can facilitate mainstreaming, as in storm- and flood-prone Makati City, Philippines, where the Disaster Coordination Council plans the city's disaster risk management.[47]

Map 2.2 A complex challenge: managing urban growth and flood risk in a changing climate in South and Southeast Asia



Sources: WDR team analysis. Flood data: Dartmouth Flood Observatory. Population data: CIESIN 2005.
Note: Living with floods is engrained in the economic activities and culture of people in South and Southeast Asia. The floodplains of some of the major river basins (Ganges, top; Mekong, bottom) concentrate a large number of people and expose agriculture and growing urban centers to seasonal flood risk. Climate change is likely to bring more intense flooding, partly caused by the melting of glaciers in the upper catchment of the Himalaya region and partly by the shorter and more intense monsoon rains, which will likely change flood patterns in the region. At the same time urban centers are rapidly encroaching into agricultural areas that serve as natural retention zones for flood waters, bringing new complexity to managing flood water and urban expansion in the future.

Many municipal actions to promote local development and resilience to extreme events and disasters overlap with the measures for adaptation, including water supply and sanitation, drainage, prevention-focused health care, and disaster preparedness (box 2.4). Such interventions are likely to be in the immediate interest of decision makers in urban contexts (see chapter 8).[48] It is evidently easier to cast adaptation-oriented initiatives as being in the city's immediate interests, in order to break political logjams for climate action.[49]

Building climate-smart cities will involve considerable use of emerging technologies. However, much of the available technical expertise in developing countries is concentrated in the central government, with local authorities often left to draw from a small pool of expertise.[50] Urban universities can play a key role in supporting efforts by cities to adopt and implement climate-smart practices through changes in curriculum and teaching methods that enable students to spend more time in the practical world solving local problems.

Keep people healthy

Diseases linked to climate, namely malnutrition, diarrheal diseases, and vector-borne illnesses (especially malaria), already represent a huge health burden in some regions, particularly Africa and South Asia. Climate change will increase that burden and will be most consequential for the poor (see chapter 1).[51] The estimated additional 150,000 deaths a year attributable to climate change in recent decades may be just the tip of the iceberg.[52] The indirect effects of climate change mediated by water and sanitation, ecosystems, food production, and human habitation could be far higher. Children are especially susceptible, with malnutrition and infectious diseases (mostly diarrheal diseases) part of a vicious cycle causing cognitive and learning disabilities that permanently affect future productivity. In Ghana and Pakistan the costs associated with malnutrition and diarrheal diseases are estimated to be as high as 9 percent of gross domestic product (GDP) when accounting for long-term productivity losses in later years. These costs will only increase with climate change, if adaptation to these conditions is slow.[53]

The recent heat waves, such as the one that killed about 70,000 people in Europe in 2003, showed that even high-income countries can be vulnerable.[54] Heat waves are likely to increase in frequency and intensity (map 2.3),[55] with urban heat islands producing temperatures up to 3.5–4.5°C higher than in surrounding rural areas.[56] For better preparedness several countries and metropolitan areas now have heat-health warning systems (box 2.5).

Vector-borne diseases are increasing their geographic spread and are reappearing in Eastern Europe and Central Asia.[57] Malaria already strains economies in tropical areas,[58] killing almost 1 million people a year (mostly children), and climate change is

BOX 2.4 *Fostering synergies between mitigation and adaptation*

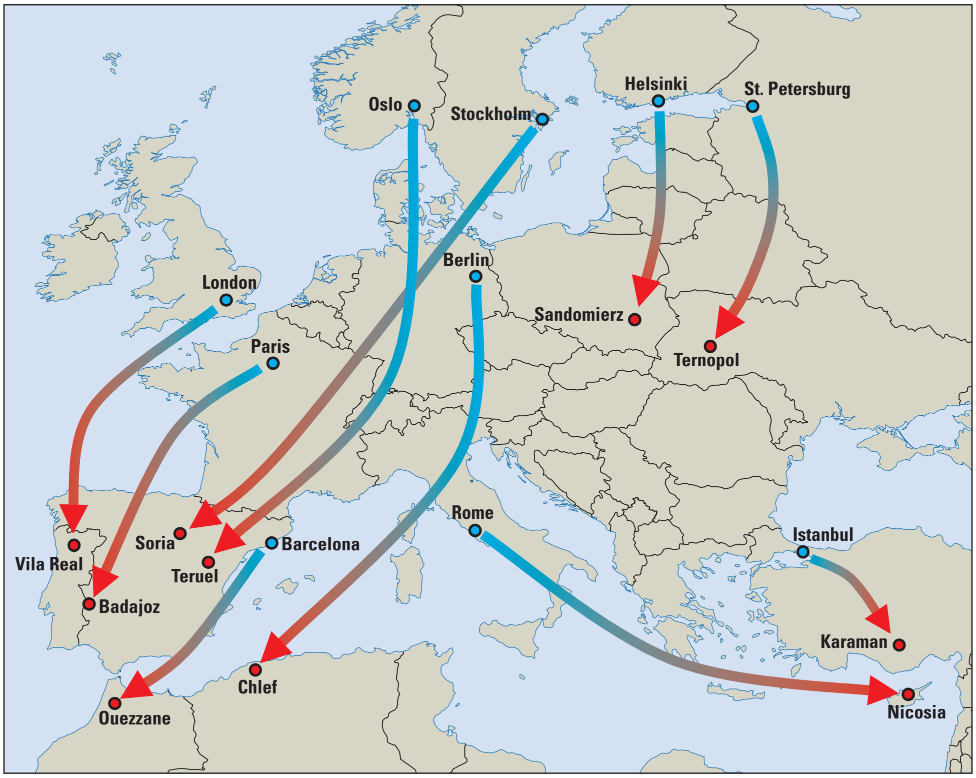
The spatial organization of cities, or their urban form, determines energy use and efficiency. The concentration of population and consumption tends to increase rapidly during the early stage of urbanization and development. Denser urban areas have higher energy efficiency and shorter travel distances (see chapter 4, box 4.7). But increasing the density of people, economic activity, and infrastructure tends to amplify the effects of climate on cities. For instance, green space can reduce the urban heat-island effects, but it can also fall victim to urban densification. Similarly, increased density combined with the paving of infiltration areas hampers urban drainage that mitigates flooding.

Climate-smart urban design can foster synergies between mitigation and adaptation. Promoting renewable energy sources tends to favor the decentralization of energy supply. Green spaces provide shading and cooling, reducing the need to air-condition buildings or to leave the city during heat waves. Green-roofing can save energy, attenuate storm water, and provide cooling. Synergies between adaptation and mitigation are often related to building height, layout, spacing, materials, shading, ventilation, and air-conditioning.

Many climate-smart designs, combining ecological principles, social sensibilities, and energy efficiency, are planned for urban areas in China, such as Dongtan, close to Shanghai, but so far the plans have largely remained blueprints.

Sources: Girardet 2008; Laukkonen and others 2009; McEvoy, Lindley, and Handley 2006; Wang and Yaping 2004; World Bank 2008g; Yip 2008.

Map 2.3 **Northern cities need to prepare for Mediterranean climate—now**



Source: WDR team, reproduced from Kopf, Ha-Duong, and Hallegatte 2008.

Note: With increasing global temperatures, climate zones will shift north, and by the middle of the 21st century many central and northern European cities will "feel" Mediterranean. This is not good news and has major implications: water utilities will need to adjust management plans, and health services will need to be prepared for more extreme heat episodes (similar to the 2003 European heat wave). While a few degrees of warming may seem appealing on a cold winter day in Oslo (the scenario shown in the map corresponds approximately to a global temperature increase of 1.2°C relative to today), the necessary changes in planning, public health management, and urban infrastructure are substantial. Buildings that were designed and engineered for cold harsh winters will need to function in a drier and hotter climate, and heritage buildings may suffer irreparable damages. Even more challenging is the construction of new buildings today as their design needs to be highly flexible to gradually adjust to drastically different conditions over the coming decades.

BOX 2.5 *Preparing for heat waves*

After heat waves in 2003 the Spanish Ministry of Health and CatSalut (the regional Catalan health service) implemented a comprehensive interministerial and interagency action plan to blunt the effects of future heat waves on health.[a] The plan incorporates health responses and communications (at all levels of health care) triggered by a heat-health warning system.

The plan has three levels of action during the summer season:

- Level 0 starts on June 1 and focuses on preparedness.
- Level 1 is triggered during July and August and focuses on meteorological assessments (including daily recordings of temperature and humidity), disease surveillance, assessment of preventive actions, and protection of at-risk populations.
- Level 2 is activated only if the temperature rises above the warning threshold (35°C in coastal areas and 40°C in inland areas), at which point health and social care and emergency service responses are initiated.

The action plan and its health system response hinge on using primary health care centers (including social services) in the region. The centers identify and localize vulnerable populations to strengthen outreach to them and disseminate public health information during the summer. They also collect health data to monitor and evaluate the health impacts of heat waves and the effectiveness of interventions.

Similar actions are under way elsewhere. Wales has a framework for heat-wave preparedness and response. It establishes guidelines for preventing and treating heat-related illnesses, operates an early warning system during the summer months, and has communication mechanisms with the meteorological office.[b] Metropolitan Shanghai has a heat-health warning system as part of its multi-hazard management plan.[c]

Sources: Rabie and others 2008.

a. CatSalut 2008.

b. Welsh Assembly Government 2008.

c. Shanghai Multi-Hazard Early Warning System Demonstration Project, http://smb.gov.cn/SBQXWebInEnglish/TemplateA/Default/index.aspx (accessed March 13, 2009).

projected to expose 90 million more people (a 14 percent increase) to the disease by 2030 in Africa alone.[59] Dengue has been expanding its geographic range (map 2.4), and climate change is expected to double the rate of people at risk from 30 percent to up to 60 percent of the world population (or 5 billion to 6 billion people) by 2070.[60] To detect and monitor epidemic-prone diseases, national health systems need better surveillance and early warning systems.[61] Today, surveillance in many parts of the world fails to anticipate new disease pressure, for example, in Africa, where malaria is reaching urban dwellers with the expansion of urban settlements into areas of transmission.[62] Satellite remote-sensing and biosensors can improve the accuracy and precision of surveillance systems and prevent disease outbreaks through early detection of changes in climate factors.[63] Advanced seasonal climate forecast models can now predict peak times for malaria transmission and give regional authorities in Africa information to operate an early warning system and longer lead-times to respond more effectively.[64]

Most measures to prevent these diseases are not new, but climate change makes the

Map 2.4 Climate change accelerates the comeback of dengue in the Americas

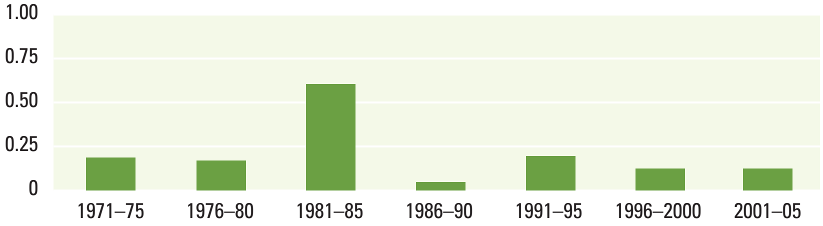
Source: PAHO 2009.

Note: Infectious and vector-borne diseases have been expanding into new geographic areas all over the world. In the Americas the incidence of dengue fever has been rising because of increasing population density and widespread international travel and trade. Changes in humidity and temperature brought about by climate change amplify this threat and allows disease vectors (mosquitoes) to thrive in locations previously unsuitable for the disease; see Knowlton, Solomon, and Rotkin-Ellman 2009.

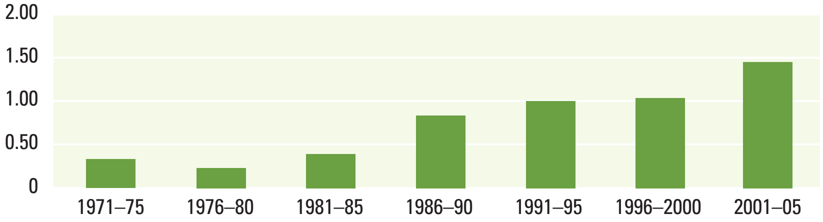
better implementation of well-established public health approaches even more urgent.[65] Breaking the transmission pathways requires better management of water (urban drainage), improved sanitation and hygiene (sewerage systems, sanitation facilities, handwashing behaviors), and effective vector control (through the use of mosquito nets). Better sanitation and hygiene are good for health, as evidenced by the impact of sanitation improvements on urban child health in Salvador, Brazil, a city with 2.4 million people.[66] The program reduced the prevalence of diarrheal diseases by 22 percent across the city in 2003–04 and by 43 percent in high-risk communities. The improvements were mostly attributable to new infrastructure.

Figure 2.1 The number of people affected by climate-related disasters is increasing

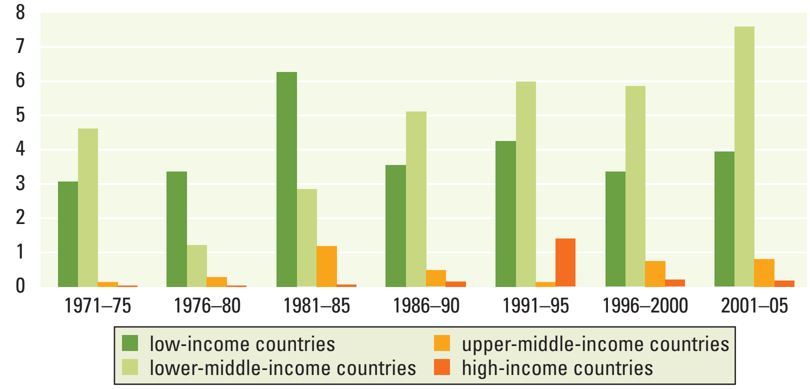
Number of people killed per five-year period (millions)



Number of people affected per five-year period (billions)



People affected as a share of population (%)



Sources: WDR team; CRED 2009.

Note: Over the past 40 years the death toll has fallen but the number of people affected has doubled every decade. (*People affected* are those requiring immediate assistance during a period of emergency and can also include displaced or evacuated people.) In lower-middle-income countries almost 8 percent of the population is affected each year. The increase cannot be attributed only to climate change; much results from population increase, greater exposure of infrastructure and improved reporting of disasters. However, the impacts on people are just as real and show why it is so essential to begin focusing on the current adaptation deficit while looking ahead to a more climatically stressful future.

Such interventions require coordinated intersectoral action and public expenditures. For water-borne diseases, interventions should include the health agency, public works, and utilities.[67] Jointly managed water, sanitation, hygiene, and food security—combined with health and disaster management—can yield high returns. So can engaging the private sector, if it improves performance. Privatizing water services in Argentina in the 1990s dramatically reduced the child mortality linked to water-borne diseases.[68]

Monitoring and managing the health impacts of climate change will require greater use of new diagnostic tools. Advances in genomics and information technology are accelerating the design of a wide range of diagnostic tools that can help in monitoring the spread of diseases and the emergence of new ones. New communications tools will make it easier to collect, analyze, and share health information in a timely manner.[69] But having such tools will not be sufficient without extensive programs to train health care workers. Similarly, major institutional reforms will need to be introduced to integrate health care into other activities. Schools, for example, can be major centers for the provision of basic health care as well as sources of medical information and education

Prepare for extreme events

Natural disasters are having an increasing economic toll, and managing them better is essential for adapting to climate change. While deaths from weather-related natural disasters are on the decline,[70] economic losses caused by storms, floods, and droughts are all rising (from about $20 billion a year in the early 1980s to $70 billion in the early 2000s for high-income countries and from $10 billion a year to $15 billion for low- and middle-income countries).[71] But this increase is largely explained by higher exposure of economic value per area rather than changes in climate.[72] The number of affected people (people requiring humanitarian assistance after disasters) continues to increase, with the largest share in lower-middle-income countries characterized by rapid urban growth (figure 2.1).[73] About

90 percent of the economic losses in developing countries are borne by households, businesses, and governments with the rest covered by insurance or donor funds.

Unless disaster impacts are systematically reduced, past development gains will be at risk. So the focus is shifting from coping with disaster events to forward-looking disaster risk management and toward preventive rather than reactive measures. In line with the Hyogo Framework of Action for reducing disaster risks (the 2005 policy framework defined by the United Nations), recovery and reconstruction are being designed to reduce risks of future disasters, bridging the humanitarian and development agendas.[74] The private sector is instrumental in this framework, providing financial (insurance, risk assessments) and technical (communication, construction, service provision) solutions.[75]

Climate change greatly increases the need for effective management of extreme weather events and for disaster risk management that increases preparedness and prevents losses (box 2.6).[76] In many places previously

BOX 2.6 *Beating the odds and getting ahead of impacts: managing risk of extreme events before they become disasters*

Recurrent extreme climate events—storms, floods, droughts, wildfires—characterize many parts of the world and are part of the climate system. Climate change is likely to change patterns of extreme events, but negative impacts can be reduced through systematic risk management. The basic steps are assessing risk, reducing risk, and mitigating risk.[a]

Assessing risk, a prerequisite for risk management, is the basis for informed decision making. It focuses action and resources. Identifying pertinent risk is the first step and generally does not require sophisticated techniques. Rice farmers in Asia readily point out their most flood-prone fields. Water reservoir managers know the difficulties of managing the competing demands for electricity and water supply when water levels are low. And communities can identify social groups and individuals who tend to be affected first when adverse weather events occur.

Quantifying risk is the next step, and a variety of approaches exist depending on the scope of a risk assessment. Communities use simple participatory techniques based on readily observable indicators (such as the market price for staple crops during droughts) to trigger action at the household and community level, or they use community-based mapping to determine flood-prone areas. Risk assessments at the sector level (agriculture or hydropower) or for a country generally require more systematic and quantitative data analysis (mapping agricultural extent or regional hydrology).

Understanding risk requires investment in scientific, technical, and institutional capacity to observe, record, research, analyze, forecast, model, and map natural hazards and vulnerabilities. Geographic information systems can integrate these sources of information and give decision makers a powerful tool to understand risk—both at the national agencies and the local level. Many low- and middle-income countries are now performing risk assessments and are systematically strengthening their capacity to manage disasters better.[b]

Reducing risk requires mainstreaming risk in the overall strategic framework of development, a task more important than ever as the density of people and infrastructure increases. Since the late 1990s there has been increasing recognition of the need to address risks emanating from natural hazards in medium-term strategic development frameworks, in legislation and institutional structures, in sectoral strategies and policies, in budgetary processes, in individual projects, and in monitoring and evaluation. Mainstreaming requires analysis of how potential hazard events could affect policies, programs, and projects and vice versa.

Development initiatives do not necessarily reduce vulnerability to natural hazards, and they can unwittingly create new vulnerabilities or heighten existing ones. Solutions for jointly sustaining development, reducing poverty, and strengthening resilience to hazards thus need to be explicitly sought. Disaster risk reduction should promote resilience and help communities adapt to new and increased risks. But even this cannot be guaranteed. For instance, investments in structural flood control designed according to current probabilities could add to future losses by encouraging development in flood-prone areas today but leaving them more prone to future major damages. So climate-change predictions have to be taken into account in current decision making and longer-term planning.

Mitigating risk entails actions to minimize impacts during an event and its immediate aftermath. Early warning and surveillance systems harness information technology and communication systems to provide advance warnings of extreme events. For such information to save lives, disaster management agencies need mechanisms in place to receive and communicate information to communities well ahead of the event. This requires systematic preparedness training; capacity building and awareness raising; and coordination between national, regional, and local entities. Taking swift and targeted action after a disaster is equally important, including social protection for the most vulnerable and a strategy for recovery and reconstruction.

Sources: WDR team; Ranger, Muir-Wood, and Priya 2009; United Nations 2007; United Nations 2009; NRC 2006; Benson and Twigg 2007.

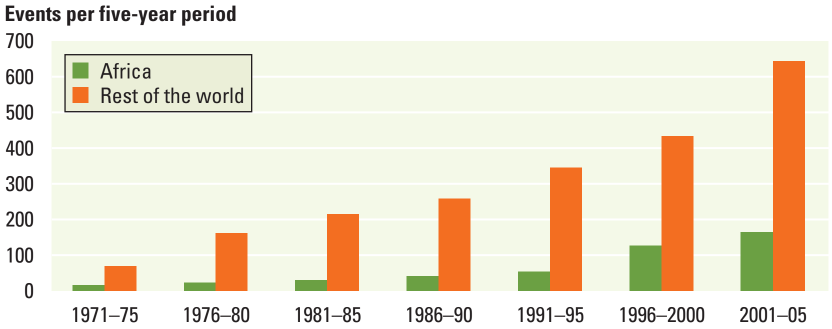
a. Here the term *mitigation* refers to avoidance of losses from extreme weather events, for example, by evacuating people from a flood plain, through short-term measures in anticipation of an immediate threat.

b. Global Facility for Disaster Reduction and Recovery, www.gfdrr.org (accessed May 15, 2009); Prevention, www.proventionconsortium.org (accessed May 15, 2009).

uncommon risks are becoming more widespread, as in Africa, where the number of floods is increasing rapidly (figure 2.2), and in Brazil, which experienced the first South Atlantic hurricane ever in 2004.[77]

Generating information about where extreme weather impacts are likely and the consequences they may have requires socioeconomic data (maps showing population density or land values) as well as physical information (records of precipitation or extreme events).[78] But in a changing climate the past is no longer prologue (once-rare events may become more frequent), and uncertainty about the future climate is an important element in assessing risk and evaluating planning decisions. Equally important are monitoring and periodic updates in socioeconomic data to reflect changes in land use and demographics. Satellite and geographic information technology provide powerful means to generate physical and socioeconomic information rapidly and cost-effectively (box 2.7; see also chapters 3 and 7).

Figure 2.2 Floods are increasing, even in drought-prone Africa



Source: WDR team analysis from CRED 2009.
Note: Flood events are increasing everywhere but particularly in Africa, with new regions being exposed to flooding and with less recovery time between events. Reporting of events may have improved since the 1970s, but this is not the main cause of rising numbers of reported floods, because the frequency of other disaster events in Africa, such as droughts and earthquakes, has not shown a similar increase.

Many developed countries provide detailed flood-risk maps as a public service to homeowners, businesses, and local authorities.[79] In China the government has drawn such maps since 1976 and publishes flood-risk maps that delineate high-risk zones for the most populated river basins. With such tools, residents can have information on when, how, and where to evacuate. The maps can also be used for land-use planning and building design.[80] Put in the hands of local communities, such services foster local action, as in Bogota, where similar risk-based information for earthquake-prone zones strengthens the resilience of communities.[81]

Risk can never be eliminated, and being prepared to cope with extreme events is vital for protecting people. Warning systems and response plans (say, for evacuation in an emergency) save lives and prevent avoidable losses. Engaging communities in preparedness and emergency communication protects their livelihoods. For example, in Mozambique communities along the Búzi River use radios to warn communities downstream of flooding.[82] Even in remote, isolated communities local action can reduce risk, create jobs, and address poverty

BOX 2.7 *Satellite data and geo-information are instrumental in managing risk—and inexpensive*

Satellite data and geo-information technology are often available for free or at moderate cost, and the software and tools to use such technology operate on desktop computers.

Satellites monitor moisture and vegetation and provide invaluable information to agricultural extension services. They track tropical storms and provide early warning to coastal communities. By mapping flood impacts they support recovery and reconstruction operations. They map forests and biomass and empower indigenous forest dwellers with information. High-resolution sensors identify urban encroachment into hazardous zones. Geographic positioning devices used in surveys can reveal new information about how households interact with the natural environment. Geo-information systems streamline data management, ensure information is available when it is needed, and provide a cost-effective and rapid tool to build the knowledge base for informed policy making and for understanding risk patterns in places where such data and knowledge are currently limited.

The use of such services and technology broadly and effectively in developing countries does not require hard investments—investments in higher education, institutional capacity building, mission-focused regional research centers, and promoting private enterprise are the main elements.

Sources: ESA 2002; NRC 2007a, 2007b.

(box 2.8). At the national level, being financially prepared to provide immediate assistance after disasters is critical for avoiding long-term losses for communities.

Managing financial risks: Flexible instruments for contingencies

Public policy creates a framework that delineates clear roles and responsibilities for the public sector, private sector, households, and individuals. Core to such a framework is a spectrum of risk management practices with layered responsibilities. A minor drought that causes small losses in crop production can be managed by households through informal and community-based risk sharing unless several small droughts occur in short sequence (see chapter 1). A more severe drought, one that occurs, say, every 10 years, can be managed through risk transfer instruments in the private sector. But for the most severe and widespread events the government has to act as the insurer of last resort. It has to develop a framework that allows communities to help themselves and the private sector to play an active and commercially viable role, while making provisions to cover its liabilities arising from catastrophic events.

Provide layers of protection

The use and support of insurance mechanisms has gained much attention in the context of adaptation.[83] Insurance can protect against losses associated with extreme climate events and manage costs that cannot be covered by international aid, by governments, or by citizens.[84] Some novel approaches have been developed and tested, such as weather-based derivatives and microinsurance products on the private market. Consider the weather-index insurance for smallholder farmers in India that provides compensation to hundreds of thousands of farmers in case of severe precipitation shortfall—and the Caribbean common insurance pool that quickly provides governments with liquidity after disasters.[85]

But insurance is not a silver bullet—it is only one element in a broader risk management framework that promotes risk reduction (avoiding avoidable losses) and rewards sound risk management practices (just as homeowners receive a premium reduction if they install fire alarms). If climate is trending in a predictable fashion (toward hotter or drier weather conditions, for instance), insurance is not viable. Insurance is appropriate when impacts are random and rare, helping households, businesses, and governments spread risk over time (by paying regular premiums rather than covering the full costs at once) and geographically (by sharing risk with others). So, it does not eliminate risk, but it does reduce the variance of losses associated with short-lived weather events.

Insurance against storms, floods, and droughts, whether provided to governments or individuals, is difficult to manage. Climate risk tends to affect entire regions or large groups of people simultaneously; for example, thousands of breeders in Mongolia saw their livestock decimated in 2002, when a dry summer was followed by an extremely cold winter (box 2.9). Such covariant events characterize many climate risks and make insurance very difficult to provide because claims tend to cluster and require large backup capital and administrative efforts.[86] That is one reason major climate risks are not widely covered by insurance, particularly in the developing world. Indeed, microfinance institutions often limit the share of agricultural loans in their portfolio in case widespread weather impacts cause their clients to default.[87]

The provision of financial services has been a long-standing challenge in development for reasons unrelated to climate change. Access to insurance products is generally much

BOX 2.8 *Creating jobs to reduce flood risk*

Heavy rains are common in Liberia, yet drainage systems have not been maintained for decades because of years of neglect and civil war. As a result, flooding has triggered recurrent disasters in both rural and urban settings. Cleaning the drains was not a priority for government officials or citizens, because nobody had the resources. But after Mercy Corps, an international nongovernmental organization, raised the possibility of cash-for-work options, government officials embraced it. In September 2006 a one-year project to clear and rehabilitate drainage systems was launched in five counties. This significantly increased the flow of rainwater and reduced flooding and related health risks. The project also rehabilitated wells and improved market access by clearing roads and building small bridges.

Source: Mercy Corps 2008.

BOX 2.9 *Public-private partnerships for sharing climate risks: Mongolia livestock insurance*

An important concept of climate-risk management is risk-sharing by communities, governments, and businesses. In Mongolia livestock herders, the national government, and insurance companies developed a scheme to manage the financial risks arising from severe winter-spring cold episodes (*dzuds*) that periodically result in widespread livestock mortality. Such episodes killed 17 percent of livestock in 2002 (in some areas up to 100 percent), amounting to losses of $200 million (16 percent of GDP).

In this scheme herders retain the responsibility for smaller losses that do not affect the viability of their business or household, and they often use arrangements with community members to buffer against smaller losses. Larger losses (of 10–30 percent) are covered through commercial livestock insurance provided by Mongolian insurers. A social insurance program through the government bears the losses associated with catastrophic livestock mortality that would overwhelm herders and insurers alike. This tiered approach defines a clear framework for self-insurance by herders, commercial insurance, and social insurance.

An important innovation is the use of index insurance rather than individual livestock insurance, which had been ineffective because the verification of individual losses tends to be fraught with moral hazard and often prohibitively high costs. With this new type of insurance, herders are compensated based on the average livestock mortality rate in their district, and an individual loss assessment is not required. This gives Mongolian insurers incentives to offer commercial insurance to herders, which they had been reluctant to do.

The scheme provides advantages for all. Herders can buy insurance against unavoidable losses. Insurers can expand their business in rural areas, strengthening the rural financial service infrastructure. The government, by providing a well-structured social insurance, can better manage its fiscal risk. Even though a catastrophic event exposes the government to significant potential risk, the government had been compelled politically to absorb even greater risk in the past. Because the government covers catastrophic outcomes, the commercial insurance, limited to moderate levels of mortality, can be offered at affordable rates.

Sources: Mahul and Skees 2007; Mearns 2004.

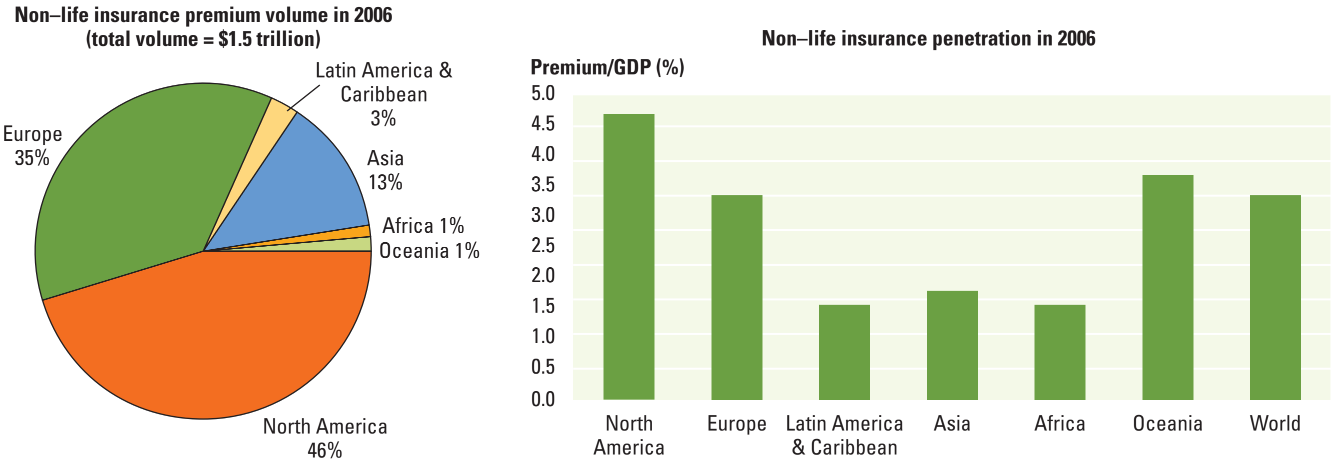
weaker in developing countries (figure 2.3), a fact reflected in the generally lower penetration of financial services in rural areas. The Philippines Crop Insurance Corporation, for example, reaches only about 2 percent of farmers, largely in the more productive and richer zones.[88] Providing financial services to rural populations is challenging and risky, because many rural households are not part of the monetized economy and have weather-sensitive livelihoods. In urban settings people are more concentrated, but it is still difficult to reach the poor in the informal economy.

Climate change could further erode the insurability of climate-related risk. Unchecked climate change could make many climate risks uninsurable or the premiums unaffordable. Insurability requires the ability to identify and quantify (or at least estimate partially) the likelihood of an event and the associated losses, to set premiums, and to diversify risk among individuals or collectives.[89] Meeting all three conditions makes a risk insurable but not necessarily profitable (as reflected in the low premium-to-claims ratio of many agricultural insurance programs) and the transaction costs of operating an insurance program can be considerable.[90] Climate change confounds the actuarial processes that underlie insurance markets.[91] And diversifying risk will be more difficult as climate change leads to more synchronized, widespread, and systemic effects globally and regionally—effects that are difficult to offset in other regions or market segments.

The erosion of market-based insurability implies a strong reliance on governments as insurers of last resort, a role that many governments have implicitly taken. But the track record of governments has not been stellar, in either the developing world or the developed. For instance, Hurricane Katrina in 2005 bankrupted the U.S. flood insurance program 10 times over, with more claims in one year than in its 37-year history. And few government-sponsored crop insurance programs are financially sustainable without major subsidies.[92] At the same time, if the magnitude of losses associated with recent catastrophic events is any indication of the insurability of future losses from climate change, it suggests a more explicit role of the public sector to absorb the damages that are beyond the private sector's capacity.[93]

Insurance is no panacea for adapting to climate risks and is only *one* strategy to address *some* of the impacts of climate change. It generally is not appropriate for gradually and slowly evolving climate impacts, such as sea-level rise and

Figure 2.3 Insurance is limited in the developing world



Source: Swiss Re 2007.

Note: Insurance is primarily a developed-country market as indicated by the regional share of premiums (left), and penetration (premium as percent of GDP) of non–life insurance (right). Non–life insurance includes property, casualty, and liability insurance (also referred to as general insurance), health insurance, and insurance products not defined as life insurance.

desertification, phenomena that would lead to massive losses for insurers and thus be uninsurable. Insurance must also be considered within an overall risk-management and adaptation strategy, including sound regulation of land-use and building codes, to avoid counterproductive behavior—or maladaptation (such as continued settlement on a storm-prone coast)—because of the security in an insurance contract.[94]

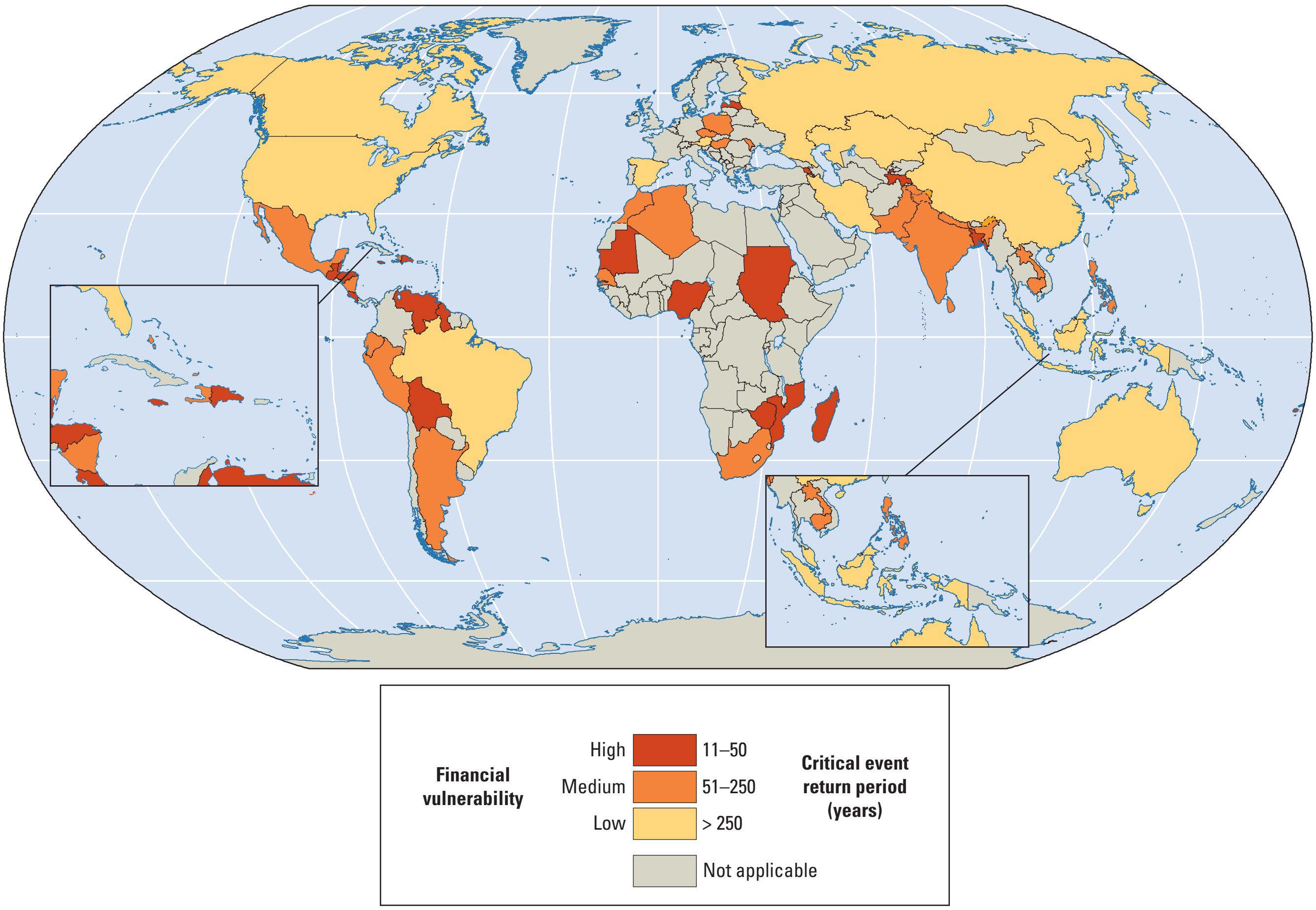
Keep governments liquid

Financial planning prepares governments for catastrophic climate impacts and maintains essential government services in the immediate aftermath of disasters.[95] Prearranged financing arrangements—such as catastrophe reserve funds, contingent lines of credit, and catastrophe bonds—allow governments to respond swiftly, scale up social protection programs, and avoid longer-term losses that accrue to households and communities while people are homeless, out of work, and experience basic deprivations.[96] Having immediate funds available to jump-start the rehabilitation and recovery process reduces the derailing effect of disasters on development.

Many small countries are financially more vulnerable to catastrophic events because of the magnitude of disaster-related losses relative to the size of their economy (map 2.5); in Grenada in 2004, for example, the winds of Hurricane Ivan caused losses equivalent to more than 200 percent of GDP.[97] Because outside aid is not always immediately available, 16 Caribbean countries have developed a well-structured financial risk-management scheme to streamline emergency funding and minimize service interruptions. Operating since 2007, it provides rapid liquidity to governments following destructive hurricanes and earthquakes, using innovative access to international reinsurance markets that can diversify and offset risk globally (box 2.10).

Even poor economies can manage climate risks more effectively by harnessing information, markets, good planning, and technical assistance. By forming partnerships with insurers, governments, and international financial institutions, governments can overcome the private sector's reluctance to commit capital and expertise to the low-income market. In 2008 Malawi pioneered a weather-based risk management contract to protect itself against droughts that would lead to national maize production shortfalls (often accompanied by high volatility in commodity prices and food insecurity). In exchange for a premium an international reinsurance company committed to pay an agreed amount to the government in case of predefined severe drought conditions, as measured and reported by the Malawian

Map 2.5 Small and poor countries are financially vulnerable to extreme weather events



Source: Mechler and others 2009.

Note: The map shows degree to which countries are financially vulnerable to floods and storms. For example, in countries shaded dark red a severe weather event that would exceed the public sector's financial ability to restore damaged infrastructure and continue with development as planned is expected about once every 11 to 50 years (an annual probability of 2–10 percent). The high financial vulnerability of small economies underscores the need for financial contingency planning to increase governments' resilience against future disasters. Only the 74 most disaster-prone countries that experienced direct losses of at least 1 percent of GDP due to floods, storms, and droughts during the past 30 years were included in the analysis.

weather service. The World Bank Treasury acted as a trusted intermediary to the market, increasing confidence in the transaction on both sides. Because payment and drought parameters were defined beforehand, disbursement from such a financial product could be rapid, and the government could forward-purchase maize on regional commodity markets to secure food as soon as possible before drought would affect the most vulnerable, which reduces response costs significantly, and decreases dependence on international appeals for assistance.[98]

For these initiatives to be affordable and sustainable, disaster risk reduction needs to be systematically promoted to minimize government reliance on such financial arrangements for more routine losses. Contingent financing has opportunity costs and should cover only the most urgent government financial needs and most extreme losses. Agricultural extension services, building code enforcement, and strategic urban planning are a few examples showing where government action can reduce avoidable consequences and the likelihood of the most extreme outcomes. Equally important are early warning systems that provide advance warning and prevent the loss of human life and economic damages. Such systems, supported by governments, can have dramatic effects, as in Bangladesh, where they have reduced human deaths from floods and storms and therefore the need for the government to finance the losses.[99]

Managing social risks: Empower communities to protect themselves

Climate change does not affect everyone equally.[100] For poor households even moderate climate stress can result in irreversible losses of human and physical capital.[101] The impacts on children can be long term and affect lifetime earnings through education (withdrawal from school after a shock), health (compounding effect of poor sanitation and water- or vector-borne diseases), and stunting.[102] Women in the developing world experience the effects of climate disproportionately because many of their household responsibilities (gathering and selling wild products) are affected by the vagaries of the weather.[103] Households and communities adapt through their traditional knowledge, livelihood choices, asset allocations, and locational preferences.[104] People will be both more willing and more able to change if they have social support systems that combine community sharing, publicly provided social insurance (such as pensions), privately supplied finance and insurance, and publicly provided safety nets.

Build resilient communities

Building on local and traditional knowledge about managing climate risk is important for two reasons.[105] First, many communities, notably indigenous peoples, already have context-relevant knowledge and strategies for addressing climate risks. Efforts to marry development and climate adaptation for vulnerable communities will benefit from the ways people have always responded to environmental risks, as in Africa where communities have adapted to extended periods of drought.[106] But those traditional coping and adaptation strategies can prepare communities only for some perceived risks, not for the uncertain and possibly different risks brought by climate change.[107] In this way communities might be well adapted to their climates but less able to adapt to climate change.[108] Second, the local nature of adaptation means that sweeping policies with one-size-fits-all prescriptions are not suited to serving the needs of different urban and rural locations.[109]

BOX 2.10 *The Caribbean Catastrophe Risk Insurance Facility: insurance against service interruption after disasters*

Among the many challenges facing the governments of small island states in the aftermath of natural disasters, the most urgent is obtaining access to cash to implement urgent recovery efforts and maintain essential government services. This challenge is particularly acute for Caribbean countries, whose economic resilience is limited by mounting vulnerability and high indebtedness.

The new Caribbean Catastrophe Risk Insurance Facility provides Caribbean Community governments with an insurance instrument akin to business interruption insurance. It furnishes short-term liquidity if they suffer catastrophic losses from a hurricane or earthquake.

A wide range of instruments exists to finance long-term recovery, but this facility fills a gap in financing short-term needs through parametric insurance. It disburses funds based on the occurrence of a predefined event of a particular intensity, without having to wait for onsite loss assessments and formal confirmations. This type of insurance is generally less expensive and settles claims quickly, because measuring the strength of an event is almost instantaneous. The facility allows participating countries to pool their individual risks into one better-diversified portfolio and facilitates access to the reinsurance market, further spreading risks outside the region.

Such insurance mechanisms should be part of a comprehensive financial strategy using an array of instruments to cover different types of events and probabilities.

Sources: Ghesquiere, Jamin, and Mahul 2006; World Bank 2008e.

Building blocks of community resilience—the capacity to retain critical functions, self-organize, and learn when exposed to change—are evident throughout the world.[110] In coastal Vietnam storm surges and rising sea levels are already putting stress on coping mechanisms. After cutbacks of many state services in the late 1990s, local collective decision making and credit and exchange networks substituted social capital and learning for government planning and infrastructure. (In recent years, however, the government has recognized the need to support community resilience and infrastructure development and now promotes a broad agenda of disaster risk management).[111]

In the western Arctic the Inuit, experiencing diminished sea ice and shifting wildlife distributions, have adjusted the timing of subsistence activities and are hunting a higher variety of species. They are increasing the resilience of their communities by sharing food, trading more with one another, and by developing new local institutions.[112] Similarly, indigenous communities in developing countries are adapting to climate change—for instance, through rainwater harvesting, crop and livelihood diversification, and changes in seasonal migration—to alleviate adverse impacts and take advantage of new opportunities.[113]

In general, communities have better time-, place-, and event-specific knowledge of local climate hazards and of how such hazards affect their assets and productive activities. Communities also have greater capacity to manage local social and ecological relationships that will be affected by climate change. And they typically incur lower costs than external actors in implementing development and environmental projects (figure 2.4). A recent review of more than 11,000 fisheries found that the likelihood of stock collapse can be dramatically reduced by moving away from overall harvest limits and introducing individual transferable catch quotas with local enforcement.[114] Active participation of local communities and primary stakeholders in comanagement of fisheries is a key to success.[115]

Beyond resilience-enhancing benefits, decentralized resource management can have synergistic benefits for mitigation and adaptation. For example, forest commons management in tropical regions has produced simultaneous livelihood benefits (adaptation) and carbon storage gains (mitigation) when local communities own their forests, have greater decision-making autonomy, and ability to manage larger forest patches.[116] In many developing countries decentralized governance of forests based on principles of common-pool resources has given local populations the authority to manage forests, use their time- and place-specific knowledge to create appropriate rules and institutions, and work with government agencies to implement the rules they have created.[117] Enhancing indigenous peoples' land rights and ensuring their role in management has resulted in more

Figure 2.4 Turning back the desert with indigenous knowledge, farmer action, and social learning

Sources: WRI and others 2008; Botoni and Reij 2009; Herrmann, Anyamba, and Tucker 2005.

Note: In Niger farmers have turned back the encroaching desert; landscapes that were denuded in the 1980s are now densely studded with trees, shrubs, and crops. This transformation, so vast that its effects can be observed from satellites, has affected 5 million hectares of land (about the size of Costa Rica), which amounts to almost half of the cultivated land in Niger. The new economic opportunities created by the regreening have benefited millions of people through increased food security and resilience to drought. Key to this success was a low-cost technique known as farmer-managed natural regeneration that adapts a centuries-old technique of woodland management. After some earlier success with the reintroduction of this indigenous technique in the 1980s, farmers saw the benefits and spread the word. The social learning effect was enhanced by donors supporting farmer study tours and farmer-to-farmer exchanges. The central government's role was pivotal in reforming land tenure and forest policies.

sustained and cost-effective management of forests and biodiversity resources, as in Mexico and Brazil.[118]

Effective community-based adaptation builds on social learning, the process of exchanging knowledge about existing experiences, and incorporating it with technical scientific information.[119] When people migrate between urban and rural areas for seasonal employment or in the wake of natural disasters, their movements follow flows of earlier movements of relatives and friends.[120] When people adopt new technologies or change cropping patterns, their decisions depend on information flows in social networks.[121] When people choose different areas to strengthen their skills and education, their decisions are tied to those of their peers.[122] Social learning, so decentralized, thus has the potential to generate diversity.

Community and experience-based social learning has been a principal means to cope with climate risks in the past, but it suffers from limitations. As highlighted for the western Arctic Inuit, future climate change may overwhelm the ability of communities to cope, and the resource endowments of rural and urban poor communities to cope with major livelihood threats remain low. The traditional coping responses, while effective for climate variations, may thus prove insufficient for climate change. Consequently, effective community-oriented climate adaptation strategies must balance the assets of communities (greater local capacity and knowledge, potential reserves of social capital, lower costs) against the deficits (limited scientific knowledge, narrow scope for action).

While numerous community-based adaptation activities are supported by a wide range of NGOs and other intermediaries, they reach only a minuscule fraction of those at risk. A pressing challenge is to replicate their successes far more widely. Scaling up has often been limited by poor links, and sometimes tensions, between agents on-the-ground and government institutions. Issues of authority, responsibility, and funding often impede cooperation. Scaling up community-driven development shows that proponents and governments should think of the process beyond the project and of transformation or transition rather than exit. Capacity, pivotal to success, includes motivation and commitment, which in turn require appropriate incentives at all levels.[123] The new Adaptation Fund can greatly increase the support for scaling up because it is expected to manage resources on the order of $0.5 billion to $1.2 billion by 2012 and to directly support governments at all levels, NGOs, and other intermediary agencies.[124]

Provide safety nets for the most vulnerable

Climate change will amplify vulnerabilities and expose more people to climate threats more frequently and for longer periods. This requires social policies to assist groups whose livelihoods may gradually erode with climate change. Extreme events may also directly affect households and require safety nets (social assistance) to prevent the most vulnerable from falling economically. Protracted episodes of climate stress (as is common with drought) can contribute to commodity price increases and volatility, disproportionally affecting the poor and vulnerable, as was the case in the 2008 food crises.[125] High food prices increase poverty, worsen nutrition, reduce use of health and education services, and deplete the productive assets of the poor.[126] In parts of the developing world food insecurity and associated food price fluctuations already represent a systemic source of risk that is expected to increase with climate change.[127]

Climate shocks have two important characteristics. First, there is uncertainty about who exactly will be affected and where. The affected population is often not identified until a crisis is well advanced, when it is difficult to respond swiftly and effectively. Second, the timing of possible shocks is not known ahead of time. Both aspects have implications for conceptualizing and designing social policies in response to future climate threats. Social protection should be thought of as a system, rather than isolated interventions, and should be put in place during good times. Safety nets need to have flexible financing and contingent targeting so they can be ramped up to provide effective responses for episodic shocks.[128]

To address chronic vulnerabilities, a wide set of safety net instruments provides cash or in-kind transfer to poor households.[129] Used effectively, they have an immediate impact on reducing inequality and are the first-best approach to addressing the poverty implications of commodity price increases; they allow households to invest in their future livelihoods and manage risk by reducing the incidence of negative coping strategies (such as selling of livestock during droughts). Safety nets allow households to invest in human capital (education, training, nutrition) that increases resilience in the long term.

In response to shocks, safety nets can have an insurance function if they are designed to be scalable and flexible. They are often phased, with the priorities shifting from immediate provision of food, sanitation, and cleanup to eventual recovery, rebuilding, and, possibly, disaster prevention and mitigation. To fulfill an insurance function, safety nets need countercyclical and scalable budgets, targeting rules to identify people with transitory needs, flexible implementation that allows rapid response following a shock, and basic organizational procedures and responsibilities agreed on well before a disaster.[130] Early warnings provided through seasonal forecasts and bulletins can mobilize safety nets ahead of time and prepare logistics and food deliveries.[131]

Safety nets will need to be strengthened substantially where they exist and developed where they are lacking. Many low-income countries cannot afford permanent transfers to their poor, but scalable safety nets that provide a basic form of noncontributory insurance can represent a core social protection that prevents mortality and excessive depletion of assets, even in poor countries where they have not commonly been used.[132]

For instance, the Productive Safety Net in Ethiopia combines permanent social assistance (a longer-term workfare program targeted at 6 million food-insecure households) and scalable safety nets that can be rapidly expanded to serve millions of transitory poor households during a major drought. An important innovation is the use of indexes based on observed weather impacts to quickly provide more scalable and targeted assistance to food-insecure areas and insurance-based mechanisms to access contingent financing.[133]

Workfare programs can be part of a safety net's response.[134] They are labor-intensive public works programs that provide income to a target population while building or maintaining public infrastructure. These programs focus on assets and high-return activities that can increase the resilience of communities, such as water storage, irrigation systems, and embankments. To be fully effective, however, they need clear objectives, suitable and well-conceived projects, predictable funding, professional guidance in selection and implementation, and credible monitoring and evaluation (box 2.11).

Safety nets can also facilitate the reform of energy policy. Raising fuel prices brings energy efficiency, economic gains, and fiscal savings, but also bears significant political and social risks. Safety nets can protect the poor from high energy prices and help eliminate large, burdensome, regressive, and climate-damaging energy subsidies (see chapter 1).[135] Energy subsidies, a common response to high fuel prices, are often inefficient and not well targeted, but eliminating them is often problematic. Several middle-income countries (Brazil, China, Colombia, India, Indonesia, Malaysia, and Turkey) have recently used safety nets to facilitate the removal of fossil-fuel subsidies.[136] Cash transfer payments following the removal of subsidies must be carefully targeted to ensure that the poor are reasonably compensated—the reform in Indonesia showed that, even with substantial mistargeting, the bottom four deciles of the population still gained during the transfer period.[137] Careful planning, detailed options analysis, and design of the cash transfer program are critical for success.

Migrate in response to climate change

Migration will often be an effective response to climate change—and unfortunately the only response in some cases. Estimates of the number of people at risk of migration, displacement, and relocation by 2050 vary from to 200 million to as high as 1 billion.[138]

BOX 2.11 *Workfare in India under the Indian National Rural Employment Guarantee Act*

India over time has developed an employment guarantee program built on an earlier successful scheme in the state of Maharashtra. The program establishes, through self-selection, the right of up to 100 days of employment at the statutory minimum wage for every household that volunteers. Households do not have to demonstrate need, and some wages are paid even if work cannot be provided.

The program makes provision for at least a third of the work to be available to women, on-site child care, and medical insurance for work injuries; work must be provided promptly and within five kilometers of the household where possible. The operation is transparent with lists of works and contractors publicly available and on the program's Web site, allowing public oversight against corruption and inefficiency. Since the program's inception in 2005, 45 million households have contributed 2 billion days of labor and undertaken 3 million tasks.[a]

With appropriate guidance, the program can support climate-smart development. It operates at scale and can direct significant labor toward appropriate adaptive works, including water conservation, catchment protection, and plantations. It provides funds for tools and other items necessary to complete activities and technical support for designing and implementing the projects. It can thus become a core part of village development through productive, climate-resilient asset creation and maintenance.[b]

Source:

a. National Rural Employment Guarantee Act—2005, http://nrega.nic.in/ (accessed May 2009).

b. CSE India, http://www.cseindia.org/programme/nrml/update_january08.htm (accessed May 15, 2009); CSE 2007.

But these estimates are based on broad assessments of people exposed to increasing risks rather than analyses of whether exposure will lead them to migrate.[139] Adaptation, such as coastal protection, will offset climate impacts and reduce migration.[140]

Today's movements are a crude guide to the geography of movements in the near future (box 2.12). Migration related to climate change is likely to be predominantly from rural areas in developing countries to towns and cities. Policies to facilitate migration should consider that most of the world's migrants move within their own countries and that the migration routes used by economic and involuntary migrants overlap significantly.

Little evidence suggests that migration caused by climate change provokes or exaggerates conflict, but that could change. People migrating because of environmental changes are likely disempowered, with little capacity to wage conflict.[141] Where migration coincides with conflict, the relationship may not be causal.[142] Similarly, the link between violent conflict and resource scarcity (water wars)[143] or degradation has rarely been substantiated (poverty and dysfunctional institutions have more explanatory power).[144] But uncertainty about the causal chains does not imply that future climate-induced migration would not increase the potential for conflict when coinciding with pressure on resources, food insecurity, catastrophic events, and lack of governance in the receiving region.[145]

The negative portrayal of migration can foster policies that seek to reduce and control its incidence and do little to address the needs of those who migrate, when migration may be the only option for those affected by climate hazards. Indeed, policies designed to restrict migration rarely succeed, are often self-defeating, and increase the costs to migrants and to communities of origin and destination.[146] In facilitating migration as a response to climate impacts, it is better to formulate integrated migration and development policies that address the needs of voluntary migrants and support their entrepreneurial abilities and technical skills.

Policies should discourage settlement of migrants in areas with high exposure to persistent climate hazards (map 2.6). Between 1995 and 2005, 3 million people were displaced by civil unrest in Colombia, mostly to small urban centers or mid-sized cites. Many have moved to marginal city areas prone to flooding or landslides or near waste dumps, while their lack of education and job skills leaves them earning only 40 percent of the minimum salary.[147] Anticipating involuntary migration and resettlement, forward-looking plans should identify alternative sites, apply compensation formulas that allow migrants to relocate and develop new sources of livelihoods, and build public and social

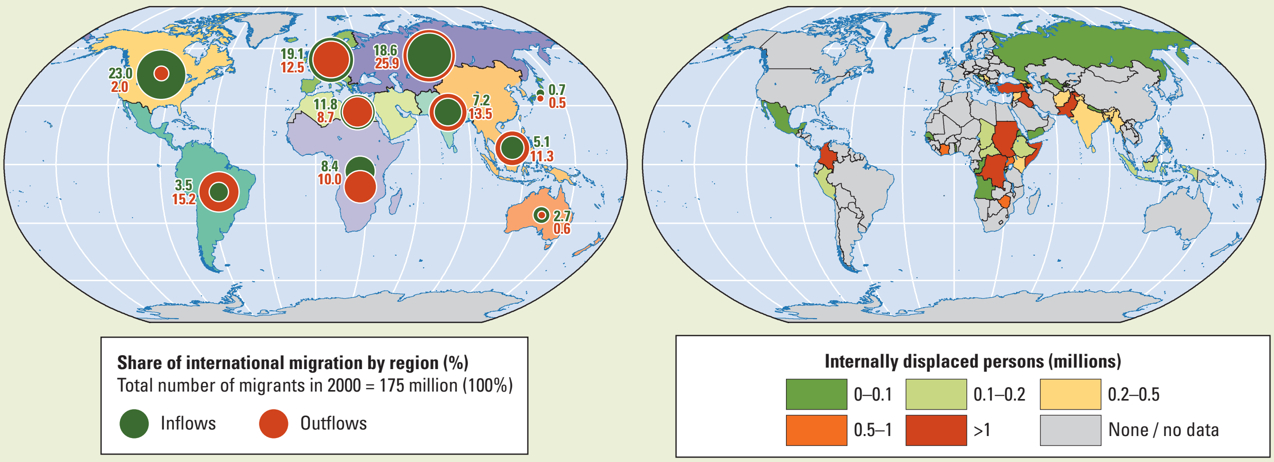
BOX 2.12 *Migration today*

The estimates of climate-change-induced migration are highly uncertain and ambiguous. In the short term climate stress is likely to add incrementally to existing migration patterns (map at left) rather than generating entirely new flows of people. The majority of the world's migrants move within their own countries. For example, there are nearly as many internal migrants in China alone (about 130 million) as there are international migrants in all countries (estimated to be 175 million in 2000). Most internal migrants are economic migrants, moving from rural areas to urban areas. There is also significant, if poorly estimated, rural-rural migration, which tends to smooth demand and supply in rural labor markets, and which serves as a step in the migration path of rural migrants.

International migration is largely a phenomenon in the developed world. Of international migrants, about two-thirds move between developed countries. The growth in new arrivals is higher in the developed than the developing countries, and about half of all international migrants are women. Half of the world's international migrants originate from 20 countries. Less than 10 percent of the world's international migrants are refugees (people forced to cross an international border for fear of persecution). Many of the world's forced migrants, however, fall under the definition of internally displaced persons (map at right), estimated to number 26 million people globally. The routes and intermediaries used by migrants fleeing conflicts, ethnic strife, and human rights violations are increasingly the same as those used by economic migrants. The available international statistics do not allow a specific attribution of internal displacement due to environmental degradation or natural disasters, but most of the forced migration linked to climate change is likely to remain internal and regional.

Migration flows are not random, but patterned, with flows of migrants concentrating around places where existing migrants have demonstrated that a life can be established and can help future migrants to overcome the barriers to movement. These patterns are largely explained by barriers to movement and the requirements to overcome them. Financial barriers include the costs of transport, housing on arrival, and living expenses while developing new income streams. Observations suggest that there is a "migration hump," where the rate of migration from a community increases as incomes increase beyond a level necessary to meet subsistence needs, and then net migration decreases again as the gap between incomes at the place of origin and the main destination closes. The migration hump explains why the poorest of the poor do not migrate or migrate only very short distances. This suggests that while the volume of resources sent home by poor migrants may be small, and the other benefits of migration less pronounced, the relative contribution to household incomes and capital are large and so significantly increase adaptive capacity (albeit from a low base).

Sources: Tuñón 2006; World Bank 2008f; United Nations 2005; United Nations 2006; Migration DRC 2007; De Haas 2007; Lucas 2006; Sorensen, van Hear, and Engberg-Pedersen 2003; Amin 1995; Lucas 2006; Lucas 2005; Massey and Espana 1987; De Haan 2002; Kolmannskog 2008.



International labor migration

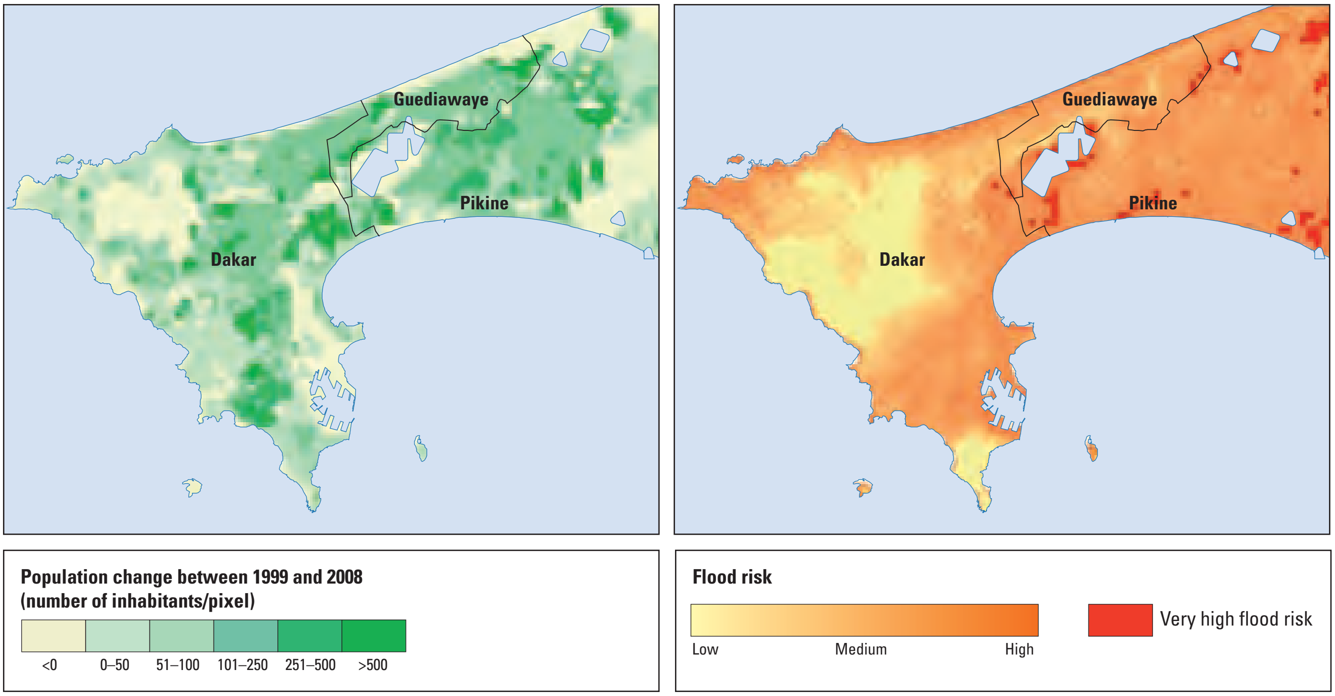
Internal displacement

Sources: Parsons and others 2007; IDMC 2008

infrastructure for community life. Again, such policies stand in sharp contrast to existing efforts to address the needs of involuntary migrants and refugees—whether they are internally displaced or cross international borders.

Recent experience has suggested some lessons for resettling migrants. The first is to involve the communities to be resettled in planning the move and in reconstruction—and to rely as little as possible on outside contractors and agencies. Those

Map 2.6 Senegalese migrants settle in flood-prone areas around urban Dakar



Source: Geoville Group 2009.

Note: Slow economic growth in the agricultural sector has made Dakar the destination of a rural exodus. 40 percent of Dakar's new inhabitants between 1988 and 2008 have moved into zones of high relative flood potential, twice as high compared with Dakar's urban (19 percent) and rural communes (23 percent). Because urban expansion is geographically limited, the influx of migrants has resulted in a very high concentration of people in urban and peri-urban zones.

being resettled must receive compensation at the standards and prices in the receiving region, and they should be involved in the design and construction of infrastructure in the new location. Where possible, the decision-making structures in the community being resettled should be respected to the fullest extent.

Looking ahead to 2070: which world?

A recurring theme of this Report is that the inertia in social, climate, and biological systems supports a case for action now. Some children alive today will be in leadership positions in 2070. Heading

> *"I would like to reach out to our world leaders to help initiate educational awareness and local government efforts to empower children to protect and restore the environment. Social and Political Institutions must respond and adapt strategies to protect public health, particularly for children. As a fifth grader, I think these are possible ways in order to ensure the survival of our Mother Earth."*
>
> Dave Laurence A. Juntilla, Philippines, age 11

Artist: Raisa Kabir, Bangladesh, age 10 toward a 2–2.5°C warmer world, they will face the challenges in managing dramatic changes. But they will have evidence that the challenges can be met, and managing climate change will be but one of their many challenges. Heading toward a 4°C warmer world, the outlook will be far more dismal. It will be clear that mitigation efforts over almost a century have been inadequate—that the impacts of climate change will already be severe, with more to come. Climate change will not be simply a challenge—it will be the dominant challenge.

Notes

1. WRI and others 2008; Heltberg, Siegel, and Jorgensen 2009.

2. Tompkins and Adger 2004.

3. Enfors and Gordon 2008.

4. The first is approximately the B1 SRES scenario where the world is on track to stabilization of greenhouse gases at 450–550 ppm CO_2e and eventually a temperature of about 2.5°C above preindustrial levels, and the second where emissions are significantly higher is approximately the A1B SRES scenario, which would lead to stabilization at about 1,000 ppm and eventually temperatures about 5°C above preindustrial levels; see Solomon and others 2007.

5. Horton and others 2008; Parry and others 2007; Rahmstorf and others 2007.

6. Allan and Soden 2008.

7. WBGU 2008.

8. Adger and others 2008.

9. Repetto 2008.

10. Lempert and Schlesinger 2000.

11. Keim 2008.

12. Millennium Ecosystem Assessment 2005.

13. Ribot forthcoming.

14. Lempert and Schlesinger 2000; Lempert 2007.

15. Lewis 2007.

16. Lempert and Schlesinger 2000; Lempert and Collins 2007.

17. Bazerman 2006.

18. Groves and Lempert 2007.

19. Ward and others 2008.

20. Hallegatte 2009.

21. Pahl-Wostl 2007; Brunner and others 2005; Tompkins and Adger 2004; Folke and others 2002.

22. Cumming, Cumming, and Redman 2006.

23. Olsson, Folke, and Berkes 2004; Folke and others 2005; Dietz, Ostrom, and Stern 2003.

24. Dietz and Stern 2008.

25. Ligeti, Penney, and Wieditz 2007.

26. Pahl-Wostl 2007.

27. FAO and CIFOR 2005.

28. United Nations 2008b.

29. United Nations 2008a.

30. Balk, McGranahan, and Anderson 2008. Low-elevation coastal zones are defined as coastal land below 10 meters elevation; see Socioeconomic Data and Application Center, http://sedac.ciesin.columbia.edu/gpw/lecz.jsp (accessed January 8, 2009).

31. McGranahan, Balk, and Anderson 2007.

32. The net migration rate in Shanghai has been 4–8 percent, compared with approximately minus 2 percent attributable to natural growth between 1995 and 2006; see United Nations 2008a.

33. Nicholls and others 2008.

34. Simms and Reid 2006.

35. World Bank 2008a.

36. Seo 2009.

37. World Bank 2008g.

38. World Bank 2008g.

39. Using a $2.15 a day poverty line; see Ravallion, Chen, and Sangraula 2007.

40. United Nations 2008a.

41. Satterthwaite 2008.

42. Diaz Palacios and Miranda 2005.

43. Pelling 1997.

44. World Bank 2008c.

45. Hara, Takeuchi, and Okubo 2005.

46. Bates and others 2008.

47. World Bank 2008a.

48. Satterthwaite and others 2007.

49. McEvoy, Lindley, and Handley 2006.

50. Laryea-Adjei 2000.

51. Confalonieri and others 2007.

52. Only includes major cause-specific mortality and excludes indirect effects and morbidity; see McMichael and others 2004; Global Humanitarian Forum 2009.

53. World Bank 2008b.

54. Robine and others 2008.

55. Solomon and others 2007; Luber and McGeehin 2008.

56. Coburn 2009.

57. Fay, Block, and Ebinger 2009.

58. Gallup and Sachs 2001.

59. Hay and others 2006; this estimation only accounts for the expansion of the disease vector; population growth will compound this effect and increase the population at risk by 390 million people (or 60 percent) relative to the 2005 population baseline.

60. Hales and others 2002; without climate change only 35 percent of the projected global population in 2085 would be at risk.

61. WHO 2008; de la Torre, Fajnzylber, and Nash 2008.

62. Keiser and others 2004.

63. Rogers and others 2002.

64. World Climate Programme 2007.

65. WHO 2005; Frumkin and McMichael 2008.

66. Barreto and others 2007.

67. AMWA 2007.

68. Galiani, Gertler, and Schargrodsky 2005.

69. Richmond 2008.

70. A growing body of evidence suggests that existing disaster loss data miss most of the small events that may account for as much as a quarter of deaths attributed to natural hazards, and that decision makers in many municipalities have relatively low awareness of the risks climate change poses for their cities' populations and infrastructure; see Awuor, Orindi, and Adwera 2008; Bull-Kamanga and others 2003; Roberts 2008.

71. Hoeppe and Gurenko 2006.

72. United Nations 2009.

73. United Nations 2008a.

74. International Strategy for Disaster Reduction, http://www.unisdr.org/eng/hfa/hfa.htm (accessed March 12, 2009).

75. World Economic Forum 2008.

76. Milly and others 2002.

77. The Nameless Hurricane, http://science.nasa.gov/headlines/y2004/02apr_hurricane.htm (accessed March 12, 2009).

78. Ranger, Muir-Wood, and Priya 2009.

79. An example is the information services provided by the Scottish Environment Protection Agency, www.sepa.org.uk/flooding (accessed March 12, 2009).

80. Lin 2008.

81. Ghesquiere, Jamin, and Mahul 2006.

82. Ferguson and others 2005.

83. Linnerooth-Bayer and Mechler 2006.

84. Mills 2007.

85. Manuamorn 2007; Gine, Townsend, and Vickery 2008; World Bank 2008e.

86. Hochrainer and others 2008.

87. CGAP 2005.

88. Llanto, Geron, and Almario 2007.

89. Kunreuther and Michel-Kerjan 2007; Tol 1998.

90. World Bank 2005.

91. Mills 2005; Dlugolecki 2008; ABI 2004.

92. Skees 2001.

93. This raises important issues: land-use regulation and codes are required and need to be enforced. Mandatory insurance may be required by law in high-risk areas. There are also equity concerns: what to do with people who have lived in high-risk areas all along but cannot afford true risk-based premiums?

94. Kunreuther and Michel-Kerjan 2007.

95. Cummins and Mahul 2009.

96. See Cardenas and others 2007 for an example of the use of market instruments for sovereign financial risk management for natural disasters in Mexico.

97. Mechler and others 2009.

98. World Bank to Offer Index-based Weather Derivative Contracts, http://go.worldbank.org/9GXG8E4GP1 (accessed May 15, 2009).

99. Government of Bangladesh 2008.

100. Bankoff, Frerks, and Hilhorst 2004.

101. Dercon 2005.

102. Alderman, Hoddinott, and Kinsey 2006; Bartlett 2008; UNICEF 2008; del Ninno and Lundberg 2005.

103. Francis and Amuyunzu-Nyamongo 2008; Nelson and others 2002.

104. Ensor and Berger 2009; Goulden and others 2009; Gaillard 2007.

105. Adger and others 2005; Orlove, Chiang, and Cane 2000; Srinivasan 2004; Wilbanks and Kates 1999.

106. Stringer and others forthcoming; Twomlow and others 2008.

107. Nelson, Adger, and Brown 2007.

108. Walker and others 2006.

109. Gaiha, Imai, and Kaushik 2001; Martin and Prichard 2009.

110. Gibbs 2009.

111. Adger 2003.

112. Berkes and Jolly 2002.

113. Macchi 2008; Tebtebba Foundation 2008.

114. Costello, Gaines, and Lynham 2008.

115. Pomeroy and Pido 1995.

116. Chatre and Agrawal forthcoming.

117. Ostrom 1990; Berkes 2007; Agrawal and Ostrom 2001; Larson and Soto 2008.

118. Sobrevila 2008; White and Martin 2002.

119. Bandura 1977; Levitt and March 1988; Ellison and Fudenberg 1993; Ellison and Fudenberg 1995.

120. Granovetter 1978; Kanaiaupuni 2000; Portes and Sensenbrenner 1993.

121. Buskens and Yamaguchi 2002; Rogers 1995.

122. Foskett and Helmsley-Brown 2001.

123. Gillespie 2004.

124. World Bank 2009.

125. Ivanic and Martin 2008.

126. Grosh and others 2008.

127. Lobell and others 2008.

128. Kanbur 2009; Ravallion 2008.

129. Grosh and others 2008.

130. Grosh and others 2008; Alderman and Haque 2006.

131. Famine Early Warning Systems Network, www.fews.net (accessed May 15, 2009).

132. Alderman and Haque 2006; Vakis 2006.

133. Hess, Wiseman, and Robertson 2006.

134. del Ninno, Subbarao, and Milazzo 2009.

135. IEG 2008; Komives and others 2005.

136. World Bank 2008d.

137. World Bank 2006.

138. Myers 2002; Christian Aid 2007.

139. Barnett and Webber 2009.

140. Black 2001; Anthoff and others 2006.

141. Gleditsch, Nordås, and Salehyan 2007.

142. Reuveny 2007.

143. Barnaby 2009.

144. Theisen 2008; Nordås and Gleditsch 2007.

145. WBGU 2008; Campbell and others 2007.

146. De Haas 2007.

147. Bartlett and others 2009.

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focus B

Biodiversity and ecosystem services in a changing climate

Earth supports a complex web of 3 million to 10 million species of plants and animals[1] *and an even greater number of microorganisms. For the first time a single species, humankind, is in a position to preserve or destroy the very functioning of that web.*[2] *In people's daily lives only a few species appear to matter. A few dozen species provide most basic nutrition—20 percent of human calorie intake comes from rice,*[3] *20 percent comes from wheat;*[4] *a few species of cattle, poultry, and pigs supply 70 percent of animal protein. Only among the 20 percent of animal protein from fish and shell fish is a diversity of dietary species found.*[5] *Humans are estimated to appropriate a third of the sun's energy that is converted to plant material.*[6]

But human well-being depends on a multitude of species whose complex interactions within well-functioning ecosystems purify water, pollinate flowers, decompose wastes, maintain soil fertility, buffer water flows and weather extremes, and fulfill social and cultural needs, among many others (box FB.1). The Millennium Ecosystem Assessment concluded that of 24 ecosystem services examined, 15 are being degraded or used unsustainably (table FB.1). The main drivers of degradation are land-use conversion, most often to agriculture or aquaculture; excess nutrients; and climate change. Many consequences of degradation are focused in particular regions, with the poor disproportionately affected because they depend most directly on ecosystem services.[7]

Threats to biodiversity and ecosystem services

In the past two centuries or so, humankind has become the driver of one of the major extinction events on Earth. Appropriating major parts of the energy flow through the food web and altering the fabric of the land cover to favor the species of greatest value have increased the rate of species extinction 100 to 1,000 times the rate before human dominance of Earth.[8] In the past few decades people have become aware of their impacts on biodiversity and the threats of those impacts. Most countries have biodiversity protection programs of varying degrees of effectiveness, and several international treaties and agreements coordinate measures to slow or halt the loss of biodiversity.

Climate change imposes an additional threat. Earth's biodiversity has adjusted to past changes in climate—even to rapid changes—through a mix of species migration, extinctions, and opportunities for new species. But the rate of change that will continue over the next century or so, whatever the mitigation efforts, far exceeds past rates, other than catastrophic extinctions such as after major meteorite events. For example, the rates of tree species migration during the waxing and waning of the most recent ice age about 10,000 years ago were estimated to be about 0.3–0.5 kilometers a year. This is only a tenth the rate of change in climate zones that will occur over the coming century.[9] Some species will migrate fast enough to thrive in a new location, but many will not keep up, especially in the fragmented landscapes of today, and many more will not survive the dramatic reshuffling of ecosystem composition that will accompany climate change (map FB.1). Best estimates of species losses suggest that about 10 percent of species will be condemned to extinction for each 1°C temperature rise,[10] with even greater numbers at risk of significant decline.[11]

Efforts to mitigate climate change through land-based activities may support the maintenance of biodiversity and ecosystem services or threaten them further. Carbon stocks in and

BOX FB.1 *What is biodiversity? What are ecosystem services?*

Biodiversity is the variety of all forms of life, including genes, populations, species, and ecosystems. Biodiversity underpins the services that ecosystems provide and has value for current uses, possible future uses (option values), and intrinsic worth.

The number of species is often used as an indicator of the diversity of an area, though it only crudely captures the genetic diversity and the complexity of ecosystem interactions. There are 5 million to 30 million distinct species on Earth; most are microorganisms and only about 1.75 million have been formally described. Two-thirds of the diversity is in the tropics; a 25 hectare plot in Ecuador was found to have more tree species than exist in all of the United States and Canada, along with more than half the number of mammal and bird species in those two countries.

Ecosystem services are the ecosystem processes or functions that have value to individuals or society. The Millennium Ecosystem Assessment described five major categories of ecosystem services: *provisioning,* such as the production of food and water; *regulating,* such as the control of climate and disease; *supporting,* such as nutrient cycles and crop pollination; *cultural,* such as spiritual and recreational benefits; and *preserving,* such as the maintenance of diversity.

Source: Millennium Ecosystem Assessment 2005, Kraft, Valencia, and Ackerly 2008, Gitay and others 2002.

Table FB.1 **Assessment of the current trend in the global state of major services provided by ecosystems**

Service	Subcategory	Status	Notes
Provisioning services			
Food	Crops	↑	Substantial production increase
	Livestock	↑	Substantial production increase
	Capture fisheries	↓	Declining production due to overharvest
	Aquaculture	↑	Substantial production increase
	Wild foods	↓	Declining production
Fiber	Timber	+/–	Forest loss in some regions, growth in others
	Cotton, hemp, silk	+/–	Declining production of some fibers, growth in others
	Wood fuel	↓	Declining production
Genetic resources		↓	Lost through extinction and crop genetic resource loss
Biochemicals, natural medicines, pharmaceuticals		↓	Lost through extinction, overharvest
Fresh water		↓	Unsustainable use for drinking, industry, and irrigation; amount of hydro energy unchanged, but dams increase ability to use that energy
Regulating services			
Air quality regulation		↓	Decline in ability of atmosphere to cleanse itself
Climate regulation	Global	↑	Net source of carbon sequestration since mid-century
	Regional and local	↓	Preponderance of negative impacts
Water regulation		+/–	Varies depending on ecosystem change and location
Erosion regulation		↓	Increased soil degradation
Water purification and waste treatment		↓	Declining water quality
Disease regulation		+/–	Varies depending on ecosystem change
Pest regulation		↓	Natural control degraded through pesticide use
Pollination		↓	Apparent global decline in abundance of pollinators
Natural hazard regulation		↓	Loss of natural buffers (wetlands, mangroves)
Cultural services			
Spiritual and religious values		↓	Rapid decline in sacred groves and species
Aesthetic values		↓	Decline in quantity and quality of natural lands
Recreation and ecotourism		+/–	More areas accessible but many degraded

Source: Millennium Ecosystem Assessment 2005.

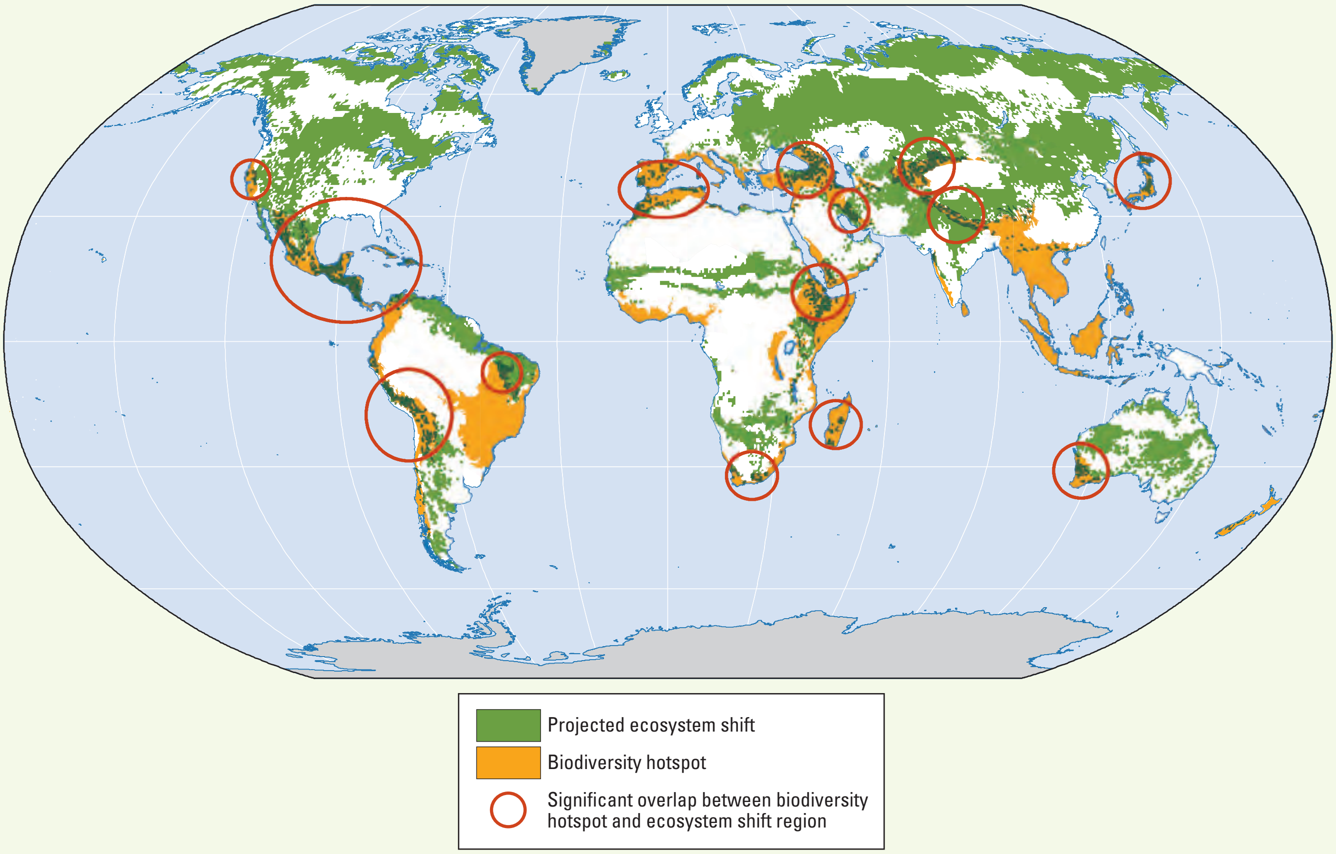
on the land can be increased through reforestation and revegetation and through such agricultural practices as reduced soil tillage. These activities can create complex and diverse landscapes supportive of biodiversity. But poorly planned mitigation actions, such as clearing forest or woodland to produce biofuels, can be counterproductive to both goals. Large dams can provide multiple benefits through irrigation and energy production but also can threaten biodiversity through direct inundation and dramatic changes in downstream river flows and the dependent ecosystems.

What can be done?

Changes in priorities and active and adaptive management will be needed to maintain biodiversity under a changing climate. In some places active management will take the form of further improving protection from human interference, while in others conservation may need to include interventions in species and ecosystem processes that are stronger and more hands-on than today's. In all cases biodiversity values must be actively considered—in the face of climate change and in the context of competing uses for land or sea.

This requires an ongoing process to anticipate how ecosystems will respond to a changing climate while interacting with other environmental modifiers. Some species will die out, others will persist, and some will migrate, forming new combinations of species. The ability to anticipate such change will always be incomplete and far from perfect, so any management actions must

Map FB.1 While many of the projected ecosystem changes are in boreal or desert areas that are not biodiversity hotspots, there are still substantial areas of overlap and concern



Source: WDR team based on Myers and others (2000) and Fischlin and others (2007).

Note: The figure shows the overlap between biodiversity hotspots (Conservation International and Myers and others 2000) and the projected changes in terrestrial ecosystems by 2100 relative to the year 2000, as presented by the Intergovernmental Panel on Climate Change in Fischlin and others (2007), figure 4.3 (a), p. 238. The changes should be taken as only indicative of the range of possible ecosystem changes and include gains or losses of forest cover, grassland, shrub- and woodland, herbaceous cover, and desert amelioration.

be within a framework that is flexible and adaptive.

Some species loss is inevitable, and some species may need to be protected in botanical and zoological gardens or in seed banks. It is essential that key species in the delivery of ecosystem services are identified and, if necessary, actively managed. Proactive management of land and the seas under a changing climate is a fairly new and ill-defined process. Relatively little knowledge has been developed on identifying realistic management responses, so significant sharing of learning, best practices, and capacity building will be necessary

Conservation reserves

Any extensions or modifications to the conservation priority areas (conservation reserves) need to capture altitudinal, latitudinal, moisture, and soil gradients. Proposals to expand or modify conservation reserves could lead to clashes over priorities for land allocation and for resources within biodiversity management (such as money for land acquisition versus that for active habitat manipulation). Powerful tools exist for selecting the optimal allocation of lands to achieve particular conservation goals that could balance competing demands.[12]

But protected areas alone are not the solution to climate change. The current reserve network has increased rapidly over the past decade to cover about 12 percent of Earth's land area,[13] but it is still inadequate to conserve biodiversity. Given demographic pressures and competing land uses, protected areas are not likely to grow significantly. This means that the lands that surround and connect areas with high conservation values and priorities (the environmental matrix), and the people who manage or depend on these lands will be of increasing importance for the fate of species in a changing climate.

There will be a greater need for more flexible biodiversity conservation strategies that take the interests of different social groups into account in biodiversity management strategies. So far the principal actors in creating protected areas have been nongovernmental organizations and central governments. To ensure the flexibility needed to maintain biodiversity, a wide range of managers, owners, and stakeholders of these matrix lands and waters will need to be engaged in management partnerships. Incentives and compensation for these actors may be required to maintain a matrix that provides refugia and corridors for species. Some of the options include extending payments for environmental services, "habitat banking,"[14] and further exploration of "rights-based approaches to resources access," as used in some fisheries.

Biodiversity planning and management

A plan for actively managing the viability of ecosystems as the climate changes should be developed for all conservation lands and waters and significant areas of habitat. Elements include:

- Climate-smart management plans for coping with major stressors, such as fire, pests, and nutrient loads.
- Decision procedures and triggers for changing management priorities in the face of climate change. For example, if a conservation area is affected by two fires within a short period, making the reestablishment of the previous habitat and values unlikely, then a program to actively manage the transition to an alternative ecosystem structure should be implemented.
- Integration into the plans of the rights, interests, and contributions of indigenous peoples and others directly dependent on these lands or waters.

Such proactive planning is rare even in the developed world.[15] Canada has a proactive management approach to climate change in the face of rapid warming in its northern regions.[16] Other countries are outlining some of the core principles of proactive management: forecasting changes; managing regional biodiversity, including conservation areas and their surrounding landscape; and setting priorities to support decision making in the face of inevitable change.[17] But in many parts of the world basic biodiversity management is still inadequate. In 1999 the International Union for Conservation of Nature determined that less than a quarter of protected areas in 10 developing countries were adequately managed and that more than 10 percent of protected areas were already thoroughly degraded.[18]

Community-based conservation

Community-based conservation programs could be adopted on a much larger scale. These programs attempt to enhance local user rights and stewardship over natural resources, allowing those nearest to natural resources, who already share in the costs of conservation (such as wildlife depredation of crops) to share in its benefits as well. But such programs are not panaceas, and more effort needs to go into designing effective programs.

Community participation is the sine qua non of successful biodiversity conservation in the developing world, but long-term success stories (such as harvesting sea turtle eggs in Costa Rica and Brazil) are rare.[19] Certain elements clearly contribute to the success that some programs have had regionally, such as the wildlife-focused programs in southern Africa. These elements include stable governments, high resource value (iconic wildlife), strong economies that support export-oriented resource use (including tourism and safari hunting), low human population densities, good local governance, and government policies that offer a social safety net to buffer against lean years. Even when these conditions are met, the benefits in some countries typically do not accrue to the poor.[20]

Managing marine ecosystems

Effective land management also has benefits for marine ecosystems. Sedimentation and eutrophication caused by land-based runoff reduce the resilience of marine ecosystems such as coral reefs.[21] The economic value of coral reefs is often greater than the value of the agriculture on the land that affects them.[22]

For fisheries the main tools for managing biodiversity are ecosystem-based fisheries management,[23] integrated coastal zone management including protected marine areas,[24] and binding international cooperation within the framework of the Law of the Sea.[25] Fisheries are seen as being in crisis, and fisheries mismanagement is blamed. But the fundamental requirements for fisheries management are known.[26] Climate change may provide an additional impetus to implement reforms, primarily by reducing fishing fleet overcapacity and fishing effort to sustainable levels.[27] A sustainable, long-term harvesting strategy must be implemented—one that assesses stock exploitation in relation to reference points that take uncertainty and climate change into account.[28] The key challenge is to translate high-level policy goals into operational actions for sustainable fisheries.[29]

Payment for ecosystem services

Payment for ecosystem services has for some time been considered an efficient and equitable way to achieve many outcomes related to conservation and the provision of ecosystem services. Examples include paying upstream land managers to manage the watershed in ways that protect ecosystem services such as flows of clean water, sharing profits from game reserves with surrounding landholders whose property is damaged by the game, and most recently paying landholders to increase or maintain the carbon stocks on their land. Box FB.2 provides examples of the provision of multiple services of conservation and carbon sequestration.

Experience suggests that, because payments are provided only if a service is rendered, user-financed schemes tend to be better tailored to local needs, better monitored, and better enforced than similar government-financed programs.[30]

A significant opportunity for additional payments for conservation and improved land management may flow from the scheme for Reduced Emissions from Deforestation and Forest Degradation (REDD) under consideration by the United Nations Framework Convention

BOX FB.2 *Payment for ecosystem and mitigation services*

Two successful payment programs are the Moldova Soil Conservation project and the bird conservation and watershed protection program in Bolivia's Los Negros Valley, both funded through the World Bank BioCarbon Fund. In Moldova, 20,000 hectares of degraded and eroded state-owned and communal agricultural lands are being reforested, reducing erosion and providing forest products to local communities. The project is expected to sequester about 2.5 million tons of carbon dioxide equivalent by 2017. In Bolivia, farmers bordering Amboró National Park are paid to protect a watershed containing the threatened cloud forest habitat of 11 species of migratory birds, with benefits both for local biodiversity and for dry-season water supplies.

Source: World Bank Carbon Finance Unit.

on Climate Change. REDD seeks to lower emissions by paying countries for reducing deforestation and degradation. These payments could be part of a market-based mechanism within an enhanced Clean Development Mechanism process, or they could be nonmarket payments from a new financial mechanism that does not impinge on the emissions compliance mechanisms. The challenge of REDD is in its implementation, which is discussed in more detail in chapter 6.

REDD could make a significant contribution to both the conservation of biodiversity and mitigation of climate change if it protects biologically diverse areas that have high carbon stocks and are at high risk of deforestation. Techniques for identifying such areas are available and could be used to guide the allocation of financial resources (map FB.2).[31]

To deal effectively with the changing impacts and competing uses of ecosystems under a changing climate, governments will need to introduce strong, locally appropriate policies, measures, and incentives to change long-established behaviors, some of which are already illegal. These actions will run counter to some community preferences, so the balance between appropriate regulation and incentives is critical. REDD holds potential benefits for forest-dwelling indigenous and local communities, but a number of conditions will need to be met for these benefits to be achieved. Indigenous peoples, for example, are unlikely to benefit from REDD if their identities and rights are not recognized and if they do not have secure rights to their lands, territories, and resources (box FB.3). Experience from community-based natural resource management initiatives has shown that the involvement of local people, including indigenous peoples, in participatory monitoring of natural resources can provide accurate, cost-effective, and locally anchored information on forest biomass and natural resource trends.

Ecosystem-based adaptation

"Hard" adaptation measures such as coastal defense walls, river embankments, and dams to control river flows all present threats to biodiversity.[32] Adaptation goals can often be achieved through better management of ecosystems rather than through physical and engineering interventions; for example coastal ecosystems can be more effective as buffer zones against storm surges than sea walls. Other options include catchment and flood plain management to adjust downstream water flows and the introduction of climate-resilient agroecosystems and dry-land pastoralism to support robust livelihoods.

Ecosystem-based adaptation aims to increase the resilience and reduce the vulnerability of people to climate change through the conservation, restoration, and management of ecosystems. When integrated into an overall adaptation strategy, it can deliver a cost-effective contribution to adaptation and generate societal benefits.

In addition to the direct benefits for adaptation, ecosystem-based adaptation activities can also have indirect benefits for people, biodiversity, and

BOX FB.3 *Excerpts from the Declaration of Indigenous Peoples on Climate Change*

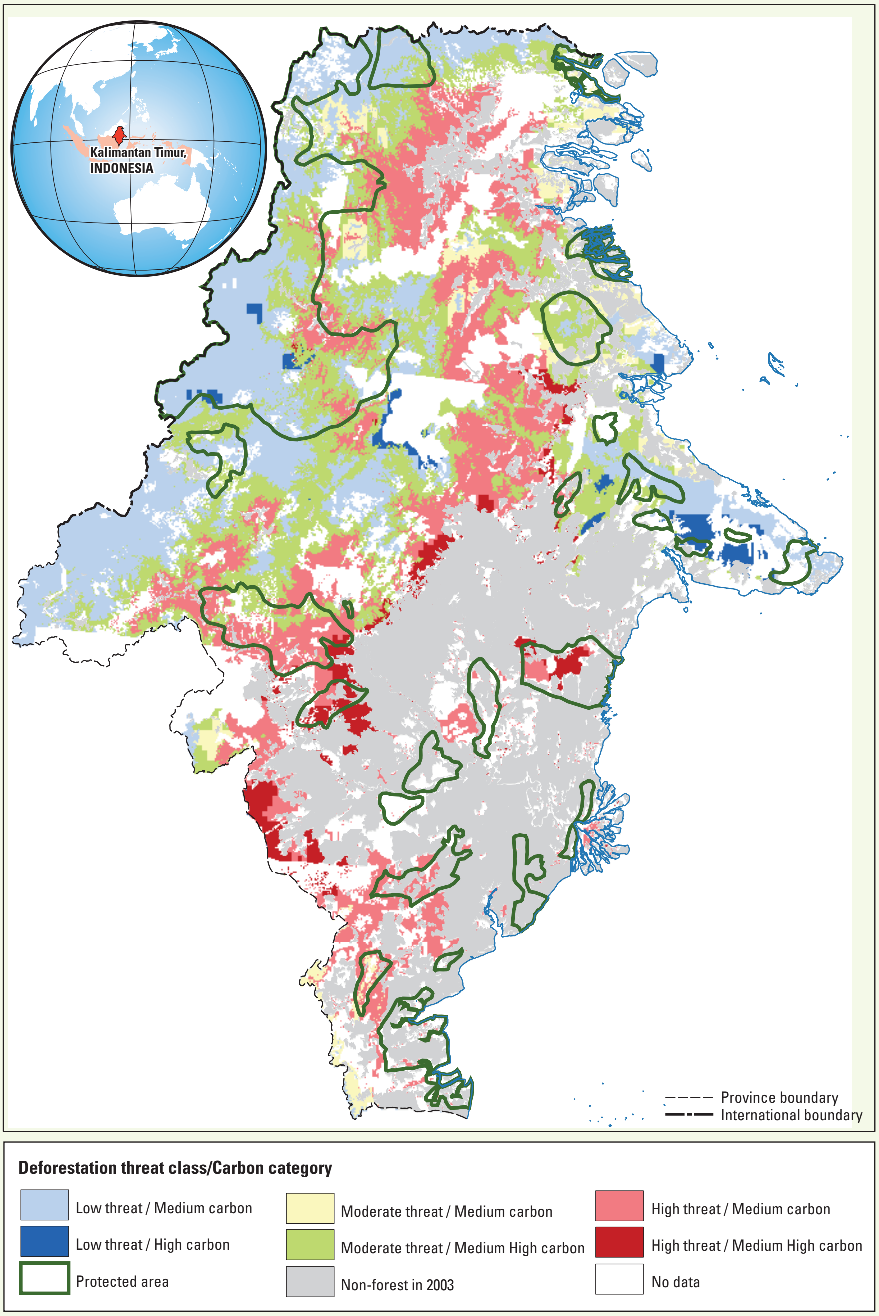
"All initiatives under Reducing Emissions from Deforestation and Degradation (REDD) must secure the recognition and implementation of the rights of Indigenous Peoples, including security of land tenure, recognition of land title according to traditional ways, uses and customary laws and the multiple benefits of forests for climate, ecosystems, and peoples before taking any action." (Article 5)

"We call for adequate and direct funding in developed and developing States and for a fund to be created to enable Indigenous Peoples' full and effective participation in all climate processes, including adaptation, mitigation, monitoring, and transfer of appropriate technologies, in order to foster our empowerment, capacity building, and education. We strongly urge relevant United Nations bodies to facilitate and fund the participation, education, and capacity building of Indigenous youth and women to ensure engagement in all international and national processes related to climate change." (Article 7)

"We offer to share with humanity our Traditional Knowledge, innovations, and practices relevant to climate change, provided our fundamental rights as intergenerational guardians of this knowledge are fully recognized and respected. We reiterate the urgent need for collective action." (Concluding Para).

The declaration was issued during the Indigenous Peoples Global Summit on Climate Change held in Anchorage on April 24, 2009.

Map FB.2 Unprotected areas at high risk of deforestation and with high carbon stocks should be priority areas to benefit from a REDD mechanism.



Source: Brown and others 1993; Harris and others 2009.

Note: A recent study for the East Kalimantan region of Indonesia used GEOMOD and a database of carbon stocks in Indonesia's tropical forests to identify the best areas for REDD activities. The final map identifies areas with high deforestation threat that also have high carbon stocks. The overlay of the existing or proposed protected areas allows decision makers to see where to direct financial resources and focus the protection efforts to get the most benefits under a REDD mechanism (namely, the dark red areas—high threat/high carbon—not included within the boundaries of already existing protected areas).

mitigation. For example, the restoration of mangrove systems to provide shoreline protection from storm surges can also increase fishery opportunities and sequester carbon. Ecosystem-based adaptation options are often more accessible to the rural poor, women, and other vulnerable groups than options based on infrastructure and engineering. Consistent with community-based approaches to adaptation, ecosystem-based adaptation builds effectively on local knowledge and needs.

Ecosystem-based adaptation may require giving priority to some ecosystem services at the expense of others. Using wetlands for coastal protection may require emphasis on silt accumulation and stabilization, for example, possibly at some expense to wildlife and recreation. Slope stabilization with dense shrubbery is an effective ecosystem-based adaptation to increasing rainfall intensity under climate change. However, in the dry periods often associated with the increasingly variable rainfall patterns under climate change the slopes may be exposed to wildfires that destroy the shrubs and lead to disastrous reversals of the adaptation goals. So, ecosystem-based adaptation must be assessed for risk and cost-effectiveness.

Notes

1. McGinley 2007.
2. Vitousek and others 1999.
3. Fitzgerald, McCouch, and Hall 2009.
4. Brown 2002.
5. WHO and FAO 2009.
6. Haberl 1997.
7. Millennium Ecosystem Assessment 2005.
8. Lawton and May 1995.
9. England and others (2004) estimated the average rate of glacial retreat to be 0.1 kilometer a year about 8,000 years ago during the last ice age, which ultimately placed a constraint on how fast species could migrate poleward.
10. Convention on Biological Diversity 2009; Fischlin and others 2007.
11. Foden and others 2008.
12. Bode and others 2008; Joseph, Maloney, and Possingham 2008; McCarthy and Possingham 2007.
13. UNEP-WCMC 2008.
14. This is a form of trading high-conservation-value lands. Some holders of such lands will choose to place them in a habitat bank. If a need arises to damage similar land elsewhere, such as for highway easements, the project proponents must buy the rights to land of equivalent conservation value from the bank.

15. Heller and Zavaleta 2009.

16. Welch 2005.

17. Hannah and others 2002; Hannah, Midgley, and Miller 2002.

18. Dudley and Stolton 1999.

19. Campbell, Haalboom, and Trow 2007.

20. Bandyopadhyay and Tembo 2009.

21. Smith, Gilmour, and Heyward 2008.

22. Gordon 2007.

23. FAO 2003; FAO 2005; Stiansen and others 2005.

24. Halpern 2003; Harmelin-Vivien and others 2008.

25. Lodge and others 2007.

26. Bostock and Cunningham 2005.

27. OECD 2008; World Bank 2008.

28. Beddington, Agnew, and Clark 2007.

29. FAO 2003; FAO 2005; ICES 2008a; ICES 2008b.

30. Wunder, Engel, and Pagiola 2008.

31. Brown and others 2007, Harris and others 2008.

32. This section draws upon material being prepared by the Ad Hoc Technical Expert Group on Biodiversity and Climate Change 2009 for the Convention on Biological Diversity and the UN Framework Convention on Climate Change.

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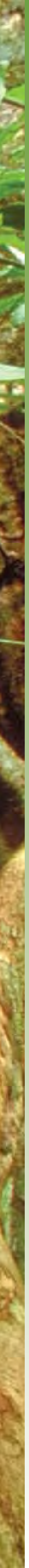


CHAPTER 3

Managing Land and Water to Feed Nine Billion People and Protect Natural Systems

Climate change is affecting the natural and managed systems—forests, wetlands, coral reefs, agriculture, fisheries—that societies depend on for food, fuel, and fiber, and for many other goods and services. Climate change will suppress agricultural yields in many regions, making it harder to meet the world's growing food needs. It will also increase competition for land, water, biodiversity, fish, and other natural resources. At the same time, societies will be under pressure to reduce the 30 percent of greenhouse gas emissions that come from agriculture, deforestation, land-use change, and forest degradation.

To meet the competing demands and reduce vulnerability to climate change, societies will need to balance producing more from their natural resources with protecting these resources. That means managing water, land, forest, fish, and biodiversity more efficiently to obtain the services and products societies need without further damaging these resources through overuse, pollution, or encroachment.

Key messages

Climate change will make it harder to produce enough food for the world's growing population, and will alter the timing, availability, and quality of water resources. To avoid encroaching into already-stressed ecosystems, societies will have to almost double the existing rate of agricultural productivity growth while minimizing the associated environmental damage. This requires dedicated efforts to deploy known but neglected practices, identify crop varieties able to withstand climate shocks, diversify rural livelihoods, improve management of forests and fisheries, and invest in information systems. Countries will need to cooperate to manage shared water resources and to improve food trade. Getting basic policies right matters, but new technologies and practices are also emerging. Financial incentives will help. Some countries are redirecting their agricultural subsidies to support environmental actions, and future credits for carbon stored in trees and soils could benefit emission reductions and conservation goals.

Water will have to be used more efficiently. To do that, managers need to think on basin-wide scales and to devise efficient and flexible ways to allocate water among the different competing uses—cities, biodiversity, the hydrological cycle, agriculture, hydropower, forestry, fisheries—while making sure that users do not use too much or pollute it.

Countries also need to get more from their agriculture. The rate of increase in yields for key agricultural commodities has been declining since the 1960s. Countries will have to reverse that trend if the world is to meet its food needs in the face of climate change. Models vary, but all show the need for a marked increase in productivity.[1] That increase in productivity cannot come at the expense of soil, water, or biodiversity as it has so often in the past. So countries need to accelerate research and improve extension services and market infrastructure to get crops to market. But they also need to help farmers reduce carbon emissions from soil and deforestation, hedge against an uncertain climate by diversifying income sources and genetic traits of crops, and benefit from integrating biodiversity into the landscape.

Applying climate-smart practices will hinge on managing biodiversity better—integrating natural habitats into rural landscapes, protecting wetlands that provide natural buffers, and maintaining aquifers that provide water storage. Increasingly many countries are making use of techniques that improve soil and water productivity. But these innovations will bear fruit only if decisions are based on solid intersectoral analysis and only if users have the right incentives—the right policies, institutions, and market conditions.

Two other factors can help natural resource management worldwide: international cooperation and information. Governments will have to cooperate to better manage water resources, forests, and fish stocks that cross administrative borders. They will also need to rely more and more often on international food trade and so will benefit from a number of measures—from stock management to more competitive procurement techniques to customs and port logistics—that make food trade more reliable and efficient.

Climate change also puts a premium on information about natural resources. Information—traditional and new, international and local—will have a high payoff under a more variable and often more uncertain climate, where poor decisions will have greater negative effects. Information supports resource management, food production, and greater trade. If societies generate information they can trust about their resources and can get it to the people who can use it, from international river basin authorities to farmers in their fields, those people can make more informed choices.

Many actions, long advocated in the natural resource literature, have been frustratingly slow in coming to fruition. But three new factors, all related to climate change, could provide new incentives. The first is the expected increase in food prices resulting from more climate shocks as well as from growing demand. Increasing food prices should spur innovation to increase productivity. The second factor is the possibility of extending carbon markets to pay farmers to store carbon in soil or in the broader landscape. This step would create incentives to conserve forests and adopt more sustainable farming techniques. The techniques are not yet proven at the needed scale, but the potential is great, and the additional benefits for agricultural productivity and poverty reduction are substantial. At a high enough carbon price, global emission reductions from agriculture could equal reductions from the energy sector (see overview, figure X).[2] Third, countries, particularly rich countries, could change the way they support agriculture. Rich countries provide $258 billion annually in agriculture support,[3] more than half of which depends only on the amount of crop produced or input used. Though politically difficult, countries could change the terms of these subsidies to encourage climate-smart activities and show how climate-smart natural resource management can be feasibly implemented on a large scale.

This chapter first discusses what can be done at the national level to increase productivity and protect water, agriculture, and fisheries. It next discusses what can be done to support national efforts, focusing on international cooperation and the essential role of information both at the global and the local level. Then it focuses on how incentives might change to accelerate implementation of beneficial practices and to help societies balance the need for increased production with better protection of natural resources.

Put in place the fundamentals for natural resource management

An extensive literature recommends strengthening the policy and institutional conditions that improve the management of soil, water, forests, biodiversity, and fisheries while increasing the productivity of agriculture and aquaculture. Several measures can increase productivity in all sectors, while protecting the long-term health of natural systems. None of these approaches functions alone. All require the support of the others to work effectively, and any change in one can alter the whole system.

Several themes recur across sectors, climates, and income groups.

- *Innovative decision-making tools* allow users to determine the impacts of different actions across the ecosystems.

- *Research and development* that produce new technologies and adapt them to local conditions can improve resource management, as can *advisory services* that help users learn about the options available to them.
- *Property rights* give users incentives to protect or invest in their resources.
- *Pricing resources* in a way that reflects their full value gives incentives to use them efficiently.
- *Well-regulated markets* are important for many agricultural and natural resource functions; infrastructure is also critical so that producers can access those markets effectively.
- *Strong institutions* are important for setting and enforcing rules.
- *Information*, again at all levels, permits users and managers to make informed choices.

These fundamentals apply, if in different ways, to water, agriculture, and fisheries, the sectors discussed in this chapter.

To understand how these drivers affect the incentives of a particular community, consider farmers on the plains of the Oum Er-Rbia river basin of Morocco. Engineers have designed a feasible drip irrigation system that would allow these farmers to generate higher revenue from the water they receive (increasing yields or growing higher value crops). Economists have figured out that it will be profitable. Hydrologists have calculated how much water they can safely allocate to these farmers without prejudicing other needs. Sociologists have talked to the farmers and found that 80 percent of them want to invest in this technology. Marketing specialists have talked to agro-processors who want to buy the new crops. And the government is willing to pay for a large share. But even then, getting things moving is fiendishly difficult.

It is not worth investing in new improved pipes between the dam and the field unless most farmers will install the drip irrigation on their fields. Yet the farmers will not put down a deposit on the drip systems until they are convinced that the new pipes will really be laid and the water will really flow. They also need information about how to use the new systems. The irrigation agency, used to providing advice to farmers, is moving toward contracting advisory services out to private firms. It will have to find, contract, and supervise these firms—tasks that require a very different set of skills. And the farmers will need to trust these new advisors as well.

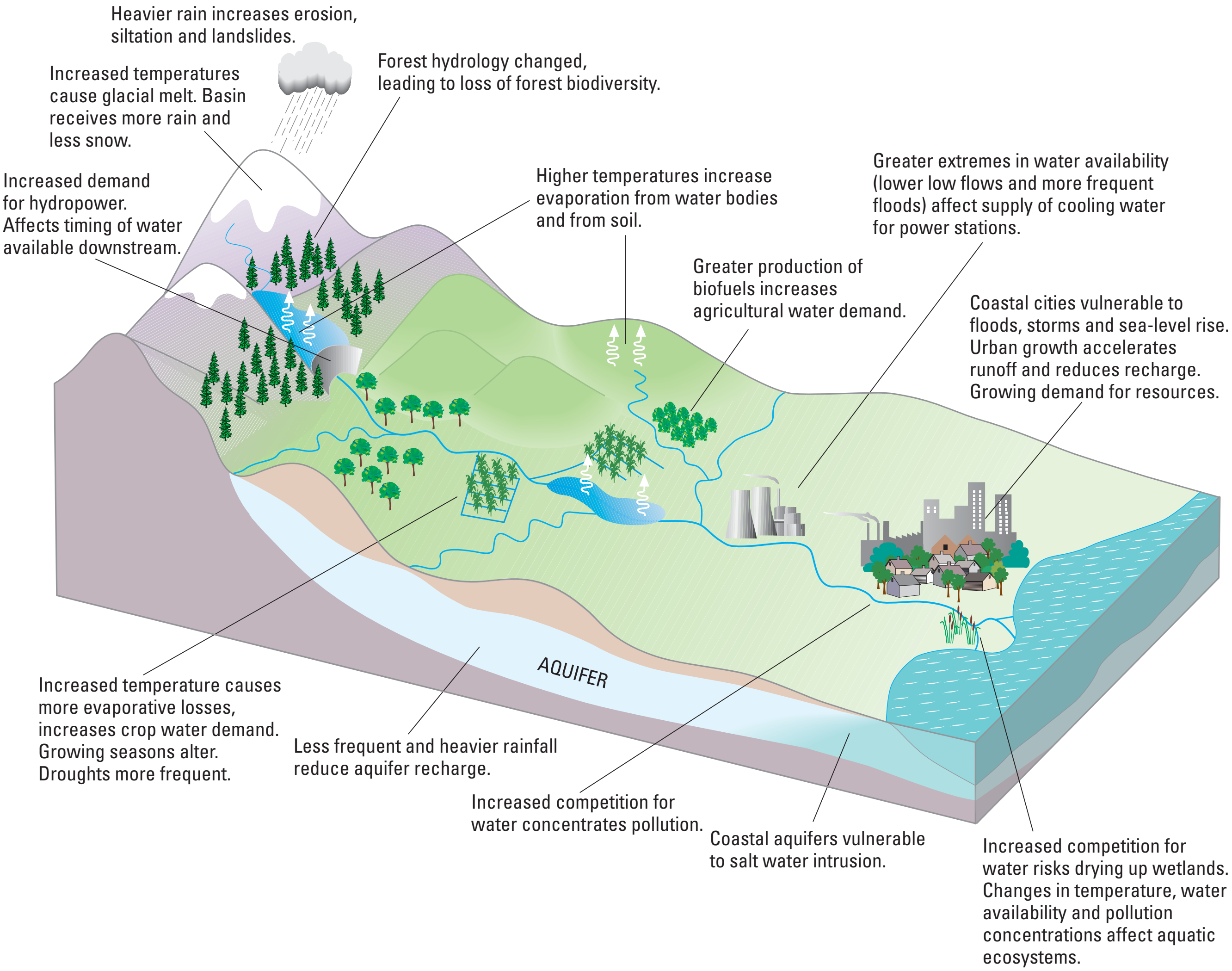
Similar factors drive the farmers' choice of crops. Government price supports for sugar and wheat, implemented to protect Morocco from the vagaries of the world market, give the farmers little incentive to turn to other crops, even though they would receive a higher return on fruits and vegetables. If international trade agreements make it easier to ensure a reliable market for new fruit crops, the farmers might make the switch. But without good roads, refrigerated transport, and state-of-the-art packaging facilities, the fruit will rot before it reaches its destination.

If the new advisory services are good, farmers will learn about the higher income they can make by switching to growing fruit and vegetables for export. The extension services will also help them to organize and interact with European buyers. New infrastructure (a reliable weigh station, a cold-storage facility) will make it feasible to assume the risk of switching crops. If the farmers can get information they trust about the impacts of their actions on their aquifer, they may determine as a group to use water more responsibly. If the river basin agency has new planning tools, it can allocate water more effectively across different users priorities, including the environment, and how the hydrology is likely to change over the life of the infrastructure. In the long term new international initiatives that set a price on soil carbon and institute a water trading market may provide the final incentives for farmers to grow crops using different soil management techniques. Each step in the process is feasible—and in the long run will provide gains for every player. The challenge comes in coordinating all the efforts across multiple institutions and in persisting to see things through over a long time.

In managing natural systems under climate change, resources cannot be considered in isolation. New ways are needed to put water, agriculture, and fisheries into a broader context with a web of related outcomes. Farmers are moderating their fertilizer use to protect aquatic ecosystems, and fisheries managers are considering how setting catch limits for one species will affect others. These management tools appear under a wide variety of names: ecosystem-based management, integrated soil-fertility management, adaptive management, to name a few. But all share key features: they coordinate a broader range of variables (wider landscapes, longer time frames, more adaptive choices) than do traditional approaches. And they stress the need for reliable information about the managed resource to ensure that recommendations are accurate, site specific, and adaptable to changing conditions. By increasing climate variability, climate change will make ecosystems' responses less predictable; resource managers will need to cope with that uncertainty with robust long-term plans that can consider the potential outcomes of multiple actions under multiple conditions.

Adaptive management will need to be applied at all levels of resource management (see chapter 2). Individual farmers can monitor their soil to tailor fertilizer use to local soil, water, climate, and crop conditions without harming ecosystems. Communities can use adaptive management strategies to provide enough water for

Figure 3.1 Climate change in a typical river basin will be felt across the hydrological cycle



Source: WDR team based on World Bank 2009e and Bates and others 2008.

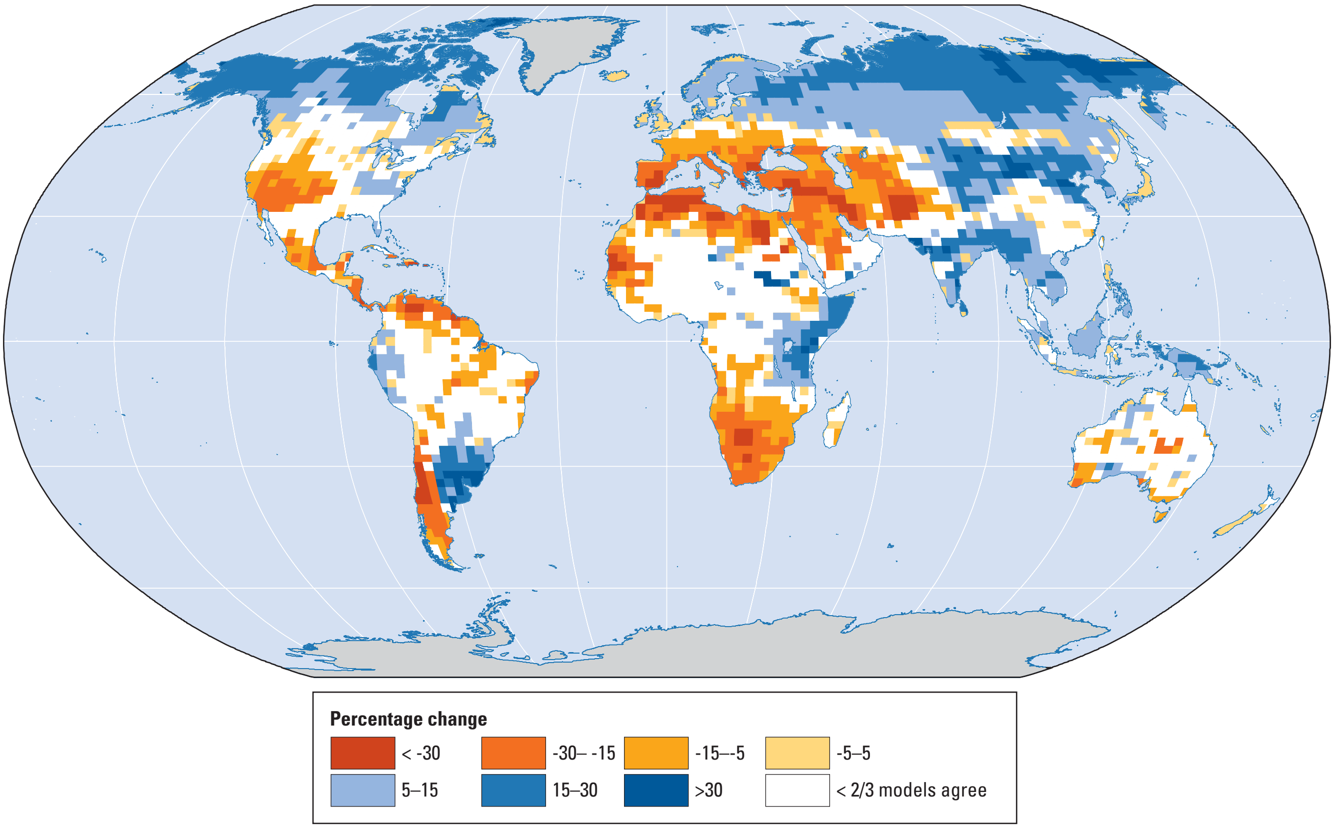
irrigating crops while maintaining their aquifer. And policy makers can use robust decision-making tools to forge more resilient international agreements for sharing resources. This chapter offers specifics on applying new tools and technologies adaptive management to water, agriculture, and fisheries and advocates a systemwide approach for coping with climate change across all three sectors.

Produce more from water and protect it better

Climate change will make it harder to manage the world's water

People will feel many of the effects of climate change through water. The entire water cycle will be affected (figure 3.1). While the world as a whole will get wetter as warming speeds up the hydrological cycle, increased evaporation will make drought conditions more prevalent (map 3.1). Most places will experience more intense and variable precipitation, often with longer dry periods in between (map 3.2).[4] The effects on human activity and natural systems will be widespread. Areas that depend on glaciers and snowmelt may see fresh water increase initially but decline over time.[5] The shifts may be so rapid and unpredictable that traditional agricultural and water management practices are no longer useful. This is already the case for the indigent community in the Cordillera Blanca in Peru, where farmers are facing such rapid changes that their traditional practices are failing. The government and scientists are starting to work with them to try to find new solutions.[6]

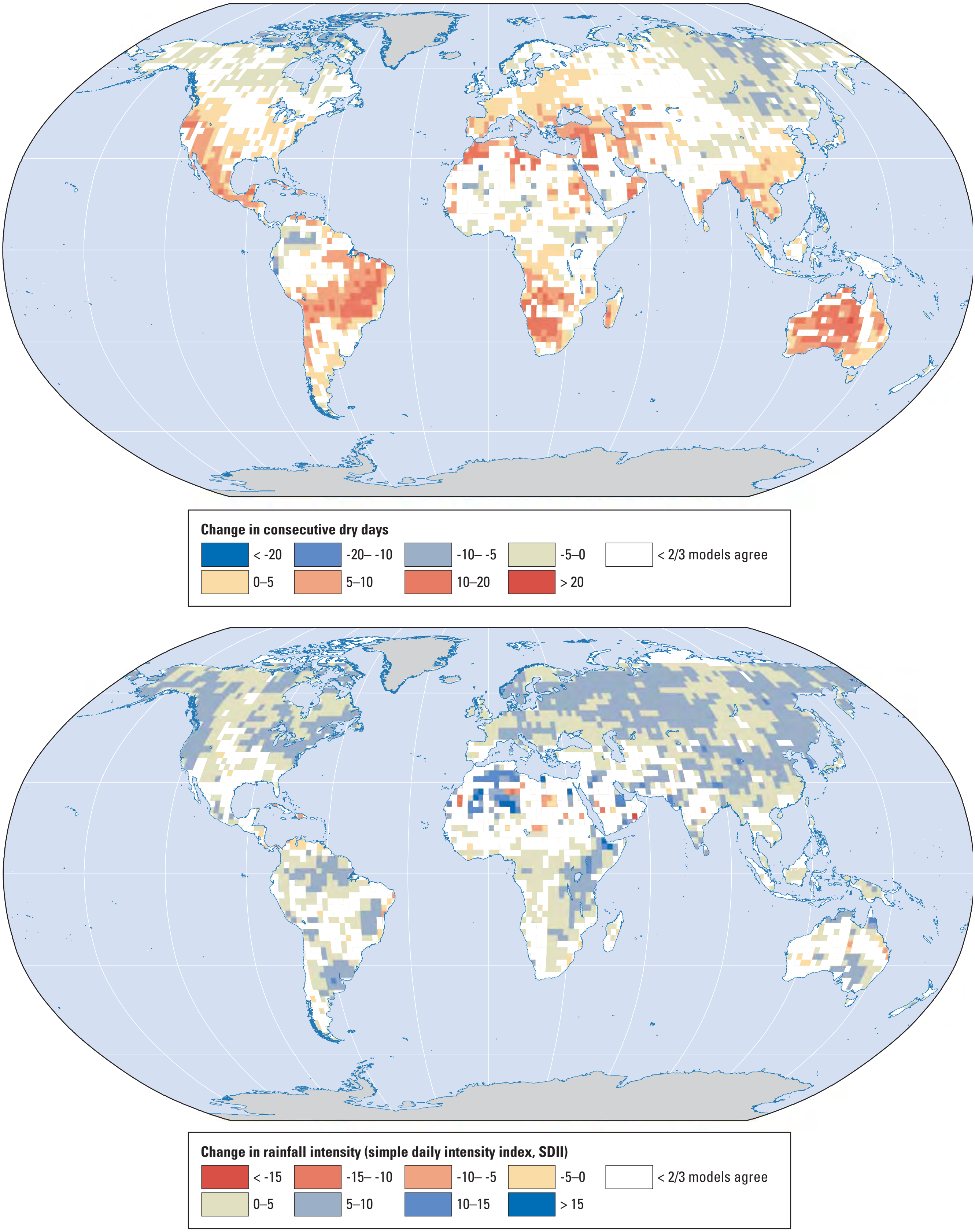
Map 3.1 Water availability is projected to change dramatically by the middle of the 21st century in many parts of the world.



Source: Milly and others 2008; Milly, Dunne, and Vecchia 2005.

Note: The colors note percentage changes in annual runoff values (based on the median of 12 global climate models using the IPCC SRES A1B scenario) from 2041 to 2060 compared with 1900 to 1970. The white denotes areas where less than two-thirds of the models agree on whether runoff will increase or decrease. Runoff is equal to precipitation minus evaporation, but the values shown here are annual averages, which could mask seasonal variability in precipitation such as an increase in both floods and droughts.

Map 3.2 **The world will experience longer dry spells and more intense rainfall events**



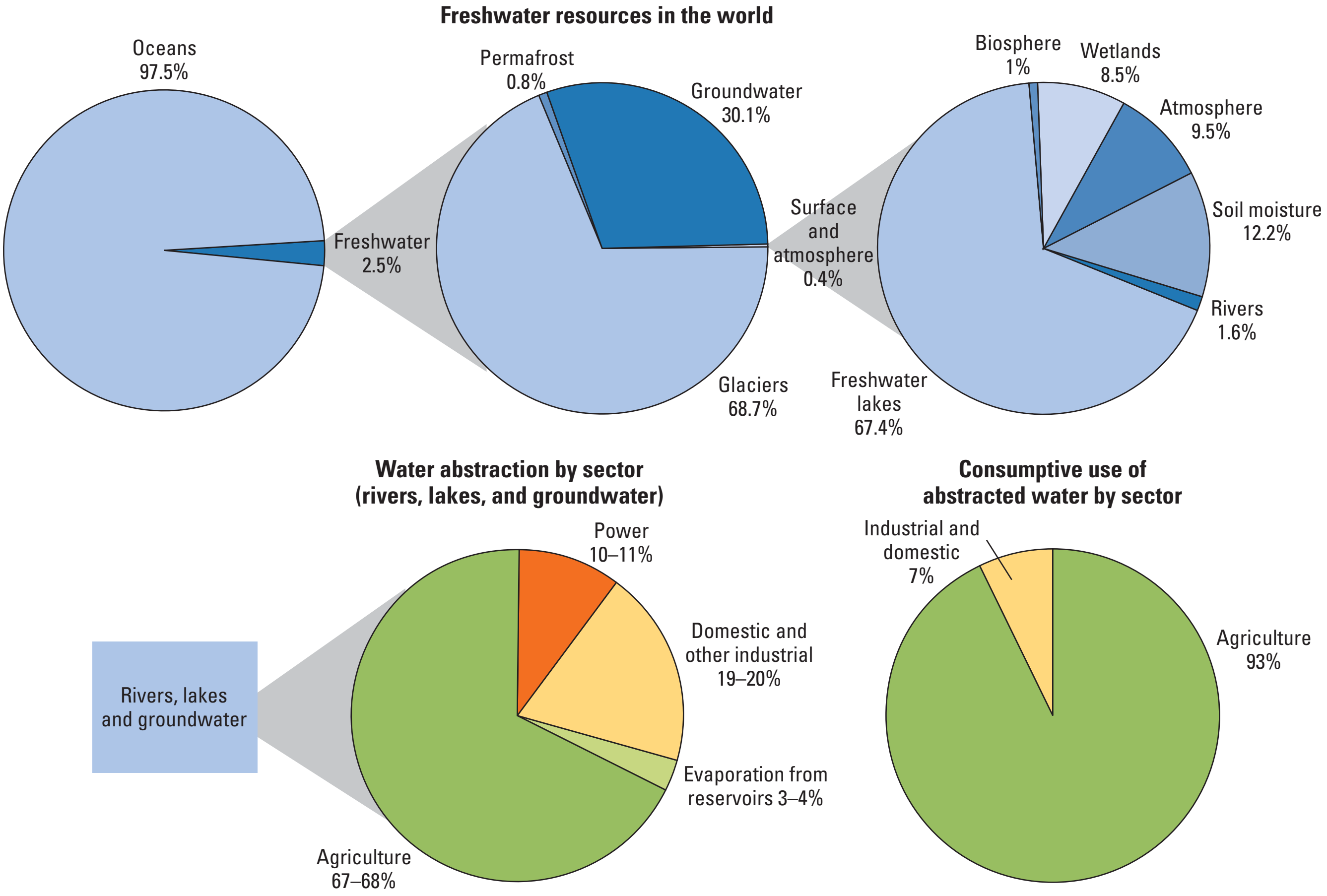
Source: The World Climate Research Program CMIP3 Multi-model Database (https://esg.llnl.gov:8443/). Analysis by the World Bank.

Note: The maps show the median change (based on 8 climate models using SRES A1B) in annual values between 2030 and 2049, compared with 1980–1999. A "dry" day is defined as one with precipitation less than 1millimeter whereas a "rainy" day has more than 1 millimeter. Precipitation intensity (SDII, or simple daily intensity index) is the total projected annual precipitation divided by the number of "rainy" days. White areas show areas of high model disagreement (fewer than two-thirds of the models agree on the sign of change).

Increasing knowledge about the world's water will improve management. To manage water well, it is critical to know how much water is available in any basin and what it is used for. This may sound straightforward, but it is not. The UN's World Water Development Report states: "Few countries know how much water is being used and for what purposes, the quantity and quality of water that is available and can be withdrawn without serious environmental consequences, and how much is being invested in water infrastructure."[7] Water accounting is complex. Definitions and methods vary, and confusion is common. For 2007 the Pacific Institute puts the Arab Republic of Egypt's annual renewable water resource at 86.8 cubic kilometers, whereas Earthtrends reports it at 58 cubic kilometers. Both reports cite the same source of information. The confusion stems from different interpretations of the term *use* (the higher figure includes reuse of water applied upstream while the lower figure does not).[8]

The planet contains a fixed amount of water, with the form and location varying over space and time.[9] Humans have little control over most of it—saltwater in oceans, freshwater in glaciers, water in the atmosphere. Most investment concentrates on water in rivers and lakes, but soil moisture and groundwater together account for 98 percent of the world's available freshwater (figure 3.2).[10] Similarly, many people worry about how much drinking water is

Figure 3.2 Freshwater in rivers makes up a very small share of the water available on the planet—and agriculture dominates water use



Source: Shiklomanov 1999; Shiklomanov and Rodda 2003; Vassolo and Doll 2005.

Note: When humans use water, they affect the quantity, timing, or quality for other users. Water for human use typically involves withdrawing water from lakes, rivers, or groundwater and either consuming it so that it reenters the atmospheric part of the hydrological cycle or returning it to the hydrological basin. Diverting water from a river to agriculture is a consumptive use—it becomes unavailable for use elsewhere in the basin. In contrast, releasing water from a dam to drive hydroelectric turbines is a nonconsumptive use because the water is available for downstream users but not necessarily at the appropriate time. Withdrawals by a city for municipal supplies are mainly nonconsumptive, but if the returning water is inadequately treated, the quality of water downstream is affected.

available, not realizing that agriculture dominates human water use. Each day, a person drinks 2–4 liters of water but eats food that requires 2,000–5,000 liters of water in its production.[11] These averages mask considerable variation. Cities and industries dominate water use in some basins, and that number is likely to increase because of the rapid urban growth many parts of the world are experiencing.[12]

Climate change will reduce the natural water storage in snowpacks and glaciers, which will in turn affect aquifer storage and require water managers to design and operate reservoirs differently. Adaptive responses require improved knowledge, planning, and management of water. Water managers will have to manage the entire water cycle. They can no longer afford to concentrate on the small share that relates to water in rivers and lakes and ignore groundwater and soil moisture. And climate change will narrow the margin of error in many basins. This means that in many areas increased demand will combine with reduced availability and increased variability, leaving water managers with less room to maneuver if their decisions are not robust to a variety of outcomes. Tools, ranging from policy instruments to planning tools, and from monitoring techniques to hard infrastructure, are available to help societies cope with these changes.

New decision-making tools are being developed to help users take increasingly uncertain hydrological risk into account. The effects of climate change on hydrological patterns mean that the past can no longer be used as a guide for future hydrological conditions. So, like other natural resource managers, water engineers are developing new tools that consider impacts across a number of scales and time frames to help evaluate tradeoffs and make choices robust to an uncertain future (box 3.1).[13]

Climate change will make applying and enforcing sound water policies even more important

Allocating water efficiently, limiting water consumption to safe levels, and pricing water will all be increasingly useful as water managers deal with the effects of climate change.

BOX 3.1 *Robust decision making: Water management in a changing world*

Traditional decision making under uncertainty uses probability distributions to rank different options for action, based on how likely each option is to achieve the objective. But this approach is inadequate when decision makers do not know or cannot agree on how actions relate to consequences, how likely different events are, or how different outcomes should be evaluated. As chapter 2 shows, robust decision making is an alternative. Robust strategies perform better than the alternatives across a wide range of plausible future states This method uses computer simulation models not to predict the future but to create large ensembles of plausible futures to identify candidate robust strategies and systematically assess their performance. The process does not choose an optimal solution—instead, it finds the strategy that minimizes vulnerability.

Southern California's Inland Empire Utilities Agency has used this technique to respond to the effects of climate change on its long-range urban water management plan First, the agency derived probable regional climate projections by combining outputs from 21 climate models. Coupled with a water management simulation model, hundreds of scenarios explored assumptions about future climate change, the quantity and availability of groundwater, urban development, program costs, and future water import costs. Then the agency calculated the present value of costs—both the cost of supplying water and the cost of purchasing imported water in case of shortages—for 200 scenarios. Any cost exceeding $3.75 billion over 35 years was considered unacceptable. Scenario discovery analysis concluded that the costs would be unacceptable if three things happened at the same time: large precipitation declines, large climate-change effects on water imports, and reductions of natural percolation into the groundwater basin.

The goal of the process is to reduce the agency's vulnerability if those things all happen at the same time. The agency identified new management responses including increasing water-use efficiency, capturing more storm water for groundwater replenishment, water recycling, and importing more water in wet years so that in dry years more groundwater can be extracted. If all these actions were undertaken, the agency found that the costs would almost never exceed the threshold of $3.75 billion. So, robust decision making allows managers to explore options depending on the risk they are willing to tolerate.

Source: Groves and others 2008; Groves and Lempert 2007; Groves, Yates, and Tebaldi 2008.

When water is scarce, individual users can take too much, making water unavailable to others or harming ecosystems and the services they provide. When consumption in a basin exceeds the amount of water available, users must use less, and the water must be shared according to some process or principles. Policy makers have two options: they can either set and enforce fixed quantities for specific users, or they can use prices to encourage users to cut back. Either way, good policies are based on accurate information and made and enforced by strong institutions.

Quantitative allocations are most common, and it is difficult to do them well. South Africa has one of the most sophisticated schemes with an integrated approach. Its 1998 National Water Act stipulates that water is public property and cannot be privately owned.[14] All users must register and license their water use and pay for it, including river or groundwater extracted at their own expense. The payments fund catchment management activities. *Streamflow reduction activity* is a category of water use, which means that owners of plantation forests must apply for a license just like an irrigator or a town's water utility. Only plantation forestry has been categorized as a streamflow reduction activity, but rainfed agriculture or water harvesting techniques could follow. Including forestry as a water user makes land use compete squarely with other water users. The only rights to water are for ecological reserves and to ensure each person 25 liters daily for basic human needs.[15]

Water is almost always priced below its value, giving users little incentive to use it efficiently.[16] The literature is virtually unanimous in calling for economic instruments to reduce demand.[17] Charging for water services (irrigation, drinking water, wastewater collection and treatment) can also recover the cost of providing the service and maintaining infrastructure.[18]

The role of pricing to influence demand varies for different types of water use. For municipal water, pricing tends to be effective at reducing demand, especially when combined with user outreach. When the price is high, many utilities and users fix leaks and use only what they need.[19] But because urban consumption accounts on average for only 20 percent of water abstractions, the effects on overall use are limited. And because municipal use is basically nonconsumptive, the impact of reduced use in cities does little to increase availability elsewhere in the basin.

For irrigation, a consumptive use, pricing is more complex. First, the amount of water actually consumed is difficult to measure. Second, farmers do not reduce consumption until the price is several multiples of the operating cost (the costs of providing the service.) Yet most countries find it politically unacceptable to charge much more than is required to recover operational costs. Third, too steep an increase in the price of surface water will simply encourage any farmer who can drill into an aquifer to switch to groundwater.[20]

In most countries the state or another owner of the water charges the city utility or irrigation agency for the water extracted from the river or aquifer. This is known as bulk water. For a host of technical and political reasons few countries charge enough for bulk water to affect the way resources are allocated between competing uses.[21] Indeed, no country allocates surface water by price,[22] although Australia is moving toward such a system.[23] Although far from straightforward, fixed quotas on the combined quantity of surface and groundwater allocated to irrigation, or, better, to the total evapotranspiration cycle, are politically and administratively more realistic than pricing to limit overall consumptive use.[24]

Tradable water rights could improve water management in the long term but are not realistic short-term options in most developing countries. Tradable rights have great potential for making water allocation more efficient and for compensating people who forgo their water use.[25] Formal tradable water rights schemes are in place in Australia, Chile, South Africa, and the western United States. In Australia evaluations indicate that these trading rights help farmers withstand droughts and spur innovation and investment without government intervention.

But the details of the design greatly affect the success of the venture, and establishing the necessary institutions is a lengthy process. It took decades to develop this capacity in Australia, a country with strong institutions and a long history of good governance, where customers were educated and accustomed to following rules, and where allocation rules were broadly in place and enforced before the rights system was established.[26] Countries that allow water trading without the institutional ability to enforce the quotas assigned to each user, or to assess the impacts of trades on other users, increase overextraction considerably (box 3.2).

Climate change, which makes future water resources less predictable, complicates the already challenging task of establishing tradable water rights.[27] Even in a stable climate, sophisticated agencies find it difficult to determine in advance how much water can safely be allocated to different users, and how much should be set aside for environmental purposes.[28] By not properly accounting for certain uses (such as plantation forestry and natural vegetation) or for changes in user behavior, the schemes in Australia and Chile assigned rights for more water than they had to allocate and had to undergo the painful process of reassigning or reducing the allocations.[29] Properly regulated markets for fixed quantities of water are a good long-term goal, but most developing countries need to take basic steps before adopting such a system.[30]

Climate change will require investing in new technologies and improving the application of existing technologies

Water storage can help with increased variability. Storage in rivers, lakes, soil, and underground is a key aspect of any strategy to manage variability—both for droughts (storing water for use in dry periods) and for floods (keeping storage capacity available for excess flows). Because climate change will reduce natural storage in the form of ice and snow and in aquifers (by reducing recharge), many countries will need increased artificial storage.

Accurate water accounting and the use of storage capacity across the entire water cycle can be done well only by considering the entire landscape. Water stored in soil can be used more efficiently by managing land cover, particularly by improving the productivity of rainfed agriculture (see the next section on agriculture). Managing groundwater, already challenging, will be more important as surface water becomes less reliable. Groundwater is a cushion for

BOX 3.2 *The dangers of establishing a market for water rights before the institutional structures are in place*

A review based on the Australian experience concludes that "with the benefit of hindsight and emerging experience, it is becoming clearer that . . . it is necessary to attend to many design issues. Water trading is likely to be successful unambiguously if and only if allocation and use management regimes are designed for trading and associated governance arrangements prevent over-allocation from occurring. Opposition to the development of markets without attention to design detail is justified."

Design concerns include accounting issues (proper assessment of the interconnected surface- and groundwater, planning for climatic shifts to drier conditions, and expanded consumption by plantation forestry because of public subsidies), and institutional issues (designing separate rules and agencies to define entitlements, manage allocations, and control the use of water; developing accurate registers early in the process; allowing unused water to be carried over from year to year; developing a private brokerage industry; and ensuring timely flow of information to all parties).

Some countries have long-standing informal water-trading arrangements. The ones that work are often based on customary practices. Farmers in Bitit, Morocco, for example, have traded water for decades, based on rules established by customary practices. The system operates from a detailed list available to the entire community, which specifies each shareholder and the amount of water each is entitled to, expressed as hours of flow.

Schemes that allow trading in the absence of established water rights and institutional regulation can worsen overexploitation. Farmers near the city of Ta'iz, in the Republic of Yemen, sell their groundwater to tankers to supply the city. Before this market existed, the farmer withdrew only as much water from the aquifer as his crops needed. By increasing the price of a unit of water, the trading increases the benefits of using groundwater. And because the farmer's extraction from his well is not controlled, there is no limit to the amount he can extract. The unregulated market accelerates the aquifer overdraft.

Source: CEDARE 2006; World Bank 2007b.

managing unreliable public and natural water supplies. For example, it supplies 60 percent of irrigated agriculture and 85 percent of rural drinking water in India as well as half the drinking water received by households in Delhi. Well managed, it can continue to act as a natural buffer, but it is far from well managed. Up to a quarter of India's annual harvest is estimated to be at risk because of groundwater depletion.[31]

In arid regions across the world, aquifers are overexploited. Improving groundwater management requires actions to improve both supply (artificial recharge, enhanced natural recharge, barriers within aquifers to retard underground flows) and demand—and to coordinate management of surface and groundwater supplies.[32] But artificial recharge is of limited use when water and suitable aquifer storage sites are not in the same places as the overstressed aquifers. For example, 43 percent of the funds allocated for India's $6 billion artificial recharge program will be spent recharging aquifers that are not overexploited.[33]

Dams will be an important part of the story of climate change and water, but only part. And they will need to be designed with flexibility to deal with potential precipitation and runoff changes that may occur over time in their basins. Many of the best sites for dams are already exploited, yet the potential for new dams does exist, particularly in Africa. Managed well, dams provide hydropower and protect against droughts and floods. Comprehensive analyses of the economic impacts of dams are rare. Four case studies indicate positive direct economic effects and large indirect effects, with the poor sometimes benefiting disproportionately.[34] The High Dam at Aswan in Egypt, for example, has generated net annual economic benefits equivalent to 2 percent of Egypt's gross domestic product (GDP).[35] It has generated 8 billion kilowatt-hours of energy, enough to electrify all of the country's towns and villages. And it has allowed the expansion of agriculture and year-round navigation (stimulating huge investments in Nile cruises) and has saved the country's crops and infrastructure from droughts and floods. But dams have negative effects as well, requiring careful weighing of the tradeoffs. [36] And climate change puts a premium on identifying robust designs: where countries face uncertainty about even whether their rainfall will increase or decrease, it can be cost-effective to build structures that are specifically designed to be changed in the future. As hydraulic systems grow ever more complex, solid hydrological, operational, and economic analysis and capable institutions all matter (box 3.3).

Investing in technologies to generate nonconventional water will increase availability in some water-scarce regions. Water supplies can be enhanced by desalinating seawater or brackish water and reusing treated wastewater. Desalination, which accounted for less than 0.5 percent of all water use in 2004,[37] is set to become more widely used.

BOX 3.3 *Managing water resources within the margin of error: Tunisia*

Tunisia is a good example of the demands on water managers in countries that are approaching the limits of their resources. To succeed they need a combination of water policies, investments, and institutional capacities. With only 400 cubic meters of renewable and highly variable resources per capita, Tunisia has a huge challenge managing its water. Yet in contrast to its Maghreb neighbors, it has withstood consecutive droughts without rationing water to farmers or resorting to supplying cities from barges. It has built dams with conduits to connect them and to transfer water between different areas of the country.

As the most promising schemes were developed, the country built additional infrastructure in more marginal areas. This included damming rivers on the other side of the mountain ranges from the areas of water demand (storing water that previously flowed into the sea or into a neighboring country). The water stored in the most marginal dams is pumped across the mountain range before it is used. Despite the energy costs, this method makes more water available and dilutes the salinity of the water coming in from the country's principal river basin.

Tunisia does not address its problems only through dams. It treats and reuses one-third of its urban wastewater for agriculture and for ecologically important wetlands. It also recharges aquifers artificially and has invested heavily in data to help manage its scarce resources.

Source: El Louati 2009.

Technical developments, including energy-efficient filtering membranes, are causing desalination prices to fall, and pilot schemes are powering desalination plants with renewable energy.[38] Depending on the scale of the plant and the technology, desalinated water can be produced and delivered to the utility for as little as $0.50 per cubic meter. This does remain more expensive than conventional sources when water is available,[39] so desalinated water makes sense only for the highest-value uses, such as urban water supply or tourism.[40] It also tends to be limited to coastal areas, because distribution of desalinated water inland would add to the costs.

Nonconventional resources, such as desalination and reuse of treated wastewater, will be part of a comprehensive water strategy in arid regions, but, except for small islands, they will augment supplies only by a small amount. Even Israel, which has invested heavily in both technologies, uses these resources for less than a quarter of its withdrawals.[41]

Producing more food with the same amount of water will not be easy, but some new approaches will help. Managing water well will involve adopting good pricing and allocation policies as well as making more water available through storage and nonconventional resources. But that is not enough. Using water more efficiently matters too, particularly in agriculture, which accounts for 70 percent of freshwater withdrawals from rivers and groundwater.[42]

Rainfed agriculture provides livelihoods for the majority of the world's poor people and accounts for more than half the gross value of crop production. It also consumes 80 percent of the water used by the world's food crops.[43] The scope for getting more production from that water appears to be high. Options, described in the next section, include mulching, conservation tillage, and similar techniques that retain water in the soil so that less is lost to evaporation and more is available to plants. Other options involve small-scale rainwater storage, sometimes called water harvesting.

Of the various interventions to increase rainfed production, some (mulching, conservation tillage) divert water that would otherwise evaporate unproductively. Others (water harvesting, groundwater pumps) divert water that would otherwise have been available to users downstream. When water is plentiful, impacts on users are imperceptible, but as water becomes scarcer, the impacts are obvious. Once again, comprehensive accounting for water and integrated planning of land and water at local, watershed, and regional scales can make these interventions productive, with the tradeoffs properly evaluated.

Irrigated land, fairly resilient to climate change in all but the most water-scarce basins, is expected to produce a greater share of the world's food as the climate changes.[44] Crop productivity per hectare will have to increase, because there is little scope for increasing the total area under irrigation. Indeed, irrigated land is expected to increase by just 9 percent between 2000 and 2050.[45] And water productivity (agricultural output per unit of water allocated to irrigation) will also have to improve to meet the growing demands of urban and industrial sectors. Fortunately, new technologies offer great potential for improving water productivity.[46]

Getting more "crop per drop" involves a complex combination of investments and institutional changes. Countries from Armenia to Zambia are investing in new infrastructure that delivers the water efficiently from the reservoir to the crops, reducing evaporative losses. However, as the example of the Moroccan farmers described earlier indicates, the investments can work only if local institutions deliver the water reliably and farmers have a voice in decision making and can get the advice they need on how to make the most of the new infrastructure or technological developments. The new infrastructure will help water management only if combined with strong quantitative limits on each individual's water consumption, covering both ground and surface water. Otherwise, because the profitability of irrigation is increased, farmers will be tempted to expand their cultivated area or double- or triple-crop their fields, drawing ever more water from their wells. This is good for the farmer, certainly, but not for the other water users in the basin.[47]

Good crop management can increase water productivity by shifting growing seasons from summer to winter or developing varieties resistant to cold so that crops can be grown under conditions that require less water.[48] Growing crops in greenhouses or under shade screens also can reduce the evaporative demand of open fields, though it does increase production costs.[49] Genetically engineered varieties that are less vulnerable to pests or droughts will also improve water productivity, because they suffer fewer losses *after* immature plants have consumed significant quantities of water.[50]

Well-timed applications of irrigation water can also help. If farmers do not know exactly how much water is needed, they often overirrigate to avoid stressing the plant at key points in its growing cycle. By monitoring water intake and growth throughout the growing season, farmers can deliver the exact amount of water that their crops need and irrigate only when really necessary. Remote-sensing systems are beginning to allow farmers to see the water needs of plants with great accuracy even before the plants show signs of stress.[51] But because of the technological requirements precision agriculture of this type is limited to a small number of the world's farmers.[52]

Even before this technology becomes widely available, it is possible to apply simple automated systems to help poorer farmers increase the precision of applying irrigation water. The Moroccan farmers who convert to drip irrigation under the government scheme discussed earlier will benefit from a simple technology using a standard irrigation formula adapted to local growing conditions. This system will adjust the formula daily, depending on the weather in that area, and deliver a message to their cell phones telling them how many hours they should irrigate that day. Acting on this information will allow them to avoid overirrigating.[53]

Producing more while protecting the environment in agriculture

Climate change will push societies to accelerate agricultural productivity growth

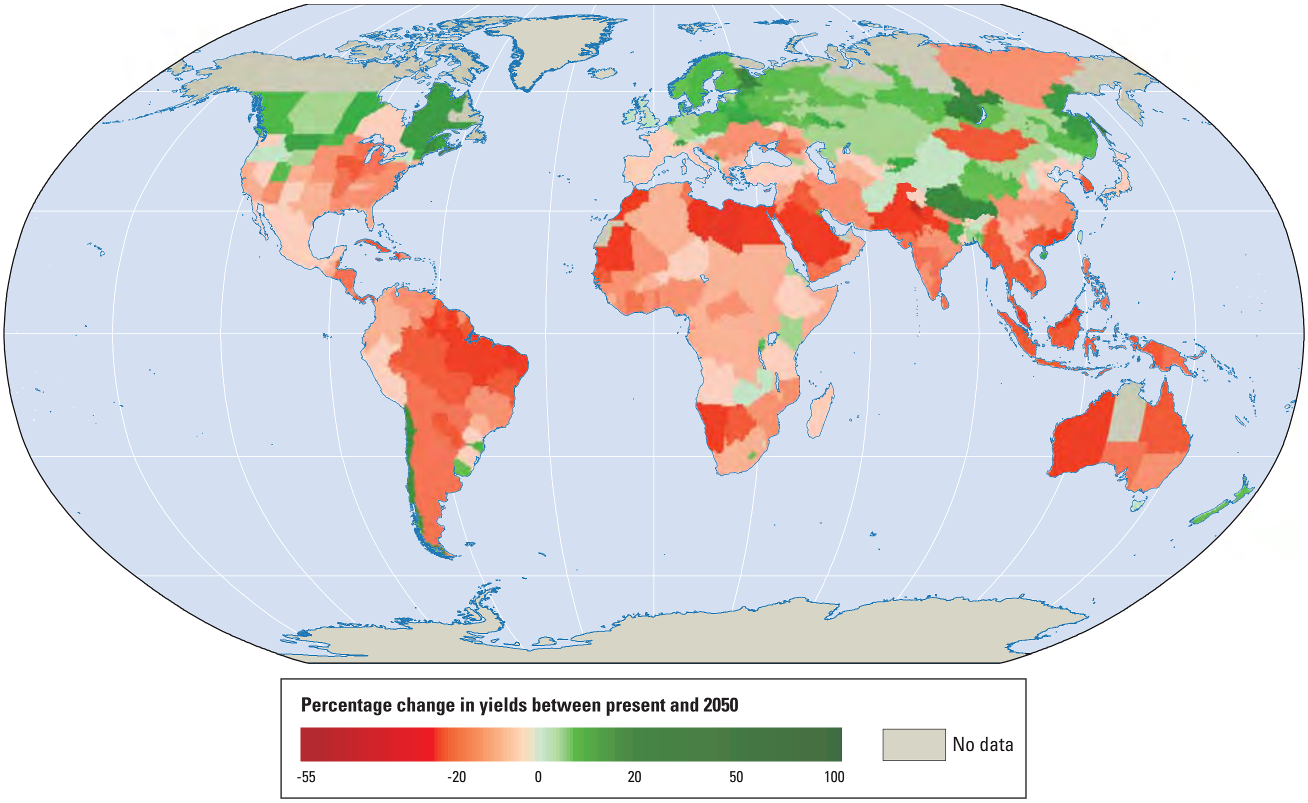
Climate change will depress agricultural yields. Climate change adds several conflicting pressures to agricultural production. It will affect agriculture directly through higher temperatures, greater demand for water, more variable rainfall, and extreme climate events such as floods and droughts. It will increase yields in some countries but lower them in most of the developing world, reducing global average yields (map 3.3).

In mid to high latitudes local increases in temperature of only 1–3°C, along with associated carbon fertilization[54] and rainfall changes, may have small beneficial impacts on crop yields.[55] Kazakhstan, the Russian Federation, and Ukraine are all geographically positioned to benefit from these temperature increases, but they may not be able to capitalize fully on the opportunities. Since the breakup of the Soviet Union, they have together removed 23 million hectares of arable land from production, almost 90 percent of which was used for grain production.[56] Although world grain yields have been rising on average by about 1.5 percent a year since 1991, yields in Kazakhstan and Ukraine have fallen, and Russia's yields have risen only slightly. Building stronger institutions and better infrastructure will be the only way these countries can take advantage of improvements in their climate.[57] To make matters worse, extreme climate events may wipe out the improved average conditions: when the increased likelihood of extreme climate events is taken into consideration for Russia, the years of food production shortfalls are projected to triple by the 2070s.[58]

In most developing countries, climate change is projected to have an adverse effect on current agriculture. In low-latitude regions even moderate temperature increases of another 1–2°C will reduce yields of major cereals.[59] One recent assessment of multiple studies estimates that by the 2080s world agricultural productivity will decline 16 percent under a high-carbon-emission scenario without carbon fertilization or 3 percent with it.[60] For the developing world, the decline is projected to be even larger, at between 9 and 21 percent.

An analysis of 12 food-insecure regions using crop models and outputs from 20 global climate models indicates that without adaptation South Asia and southern Africa will suffer particularly severe drops in yields by 2030. These losses will include some of the crops critical for regional food

Map 3.3 Climate change will depress agricultural yields in most countries by 2050 given current agricultural practices and crop varieties



Source: Muller.

Note: The figure shows the projected percentage change in yields of 11 major crops from 2046 to 2055, compared with 1996–2005. The values are the mean of three emission scenarios across five global climate models, assuming no CO_2 fertilization.

security, including wheat in South Asia, rice in Southeast Asia, and maize in southern Africa.[61] And these projections are likely to underestimate impact: models that project the effect of climate change on agriculture typically look at average changes and exclude the effects of extreme events and agricultural pests, both of which are likely to increase. Climate change will also make some land less suitable for agriculture, particularly in Africa.[62] One study projects that by 2080 land in Sub-Saharan Africa with severe climate or soil constraints will increase by 26 million to 61 million hectares.[63] That is 9–20 percent of the region's arable land.[64]

Efforts to mitigate climate change will put more pressure on land. In addition to reducing yields, climate change will put pressure on farmers and other land managers to reduce greenhouse gas emissions. In 2004 about 14 percent of global greenhouse gas emissions came from agriculture (excluding carbon dioxide, or CO_2, emissions from such sources as soil management practices, savannah burning, or deforestation).[65] Developing regions produce the largest share of these emissions, with Asia, Africa, and Latin America accounting for 80 percent of the total. The emissions include nitrous oxide from fertilizers; methane from livestock, rice production, and manure storage; and carbon dioxide from burning biomass.

Forestry, land use, and land-use change account for 16 percent of greenhouse gas emissions each year, three-quarters of which come from tropical deforestation.[66] The remainder is largely from draining and burning tropical peatland. About the same amount of carbon is stored in the world's peatlands as is stored in the Amazon rainforest. Both are the equivalent of about 9 years of global fossil fuel emissions. In equatorial Asia (Indonesia, Malaysia, Papua New Guinea), emissions from fires associated with peat draining and deforestation are comparable to those from fossil fuels in those countries.[67] Livestock production is also a significant part of anthropogenic greenhouse gas emissions, contributing up to 18 percent globally.[68]

The cultivation of biofuels to mitigate climate change will create even more competition for land. Current estimates indicate that dedicated energy crop production takes place on only 1 percent of global arable land, but biofuel legislation in developed and developing countries supports expanding production. Global ethanol production increased from 18 billion liters a year in 2000 to 46 billion in 2007, while biodiesel production increased nearly eightfold to 8 billion liters. Land allocated to biofuels is projected to increase fourfold by 2030, with most of the growth in North America (accounting for 10 percent of arable land in 2030) and Europe (15 percent). Only 0.4 percent of arable land in Africa and about 3 percent in Asia and Latin America are projected to be dedicated to biofuel production by 2030.[69] Under some scenarios for mitigating climate change, projections beyond 2030 suggest that land allocated to biofuels production by 2100 will grow to more than 2 billion hectares, an impressive number when compared to the 1.6 billion hectares that are currently covered by cropland. These scenarios project that most of the land for such large-scale biofuel production will originate from conversion of natural forests and pastureland.[70]

If demand increases rapidly, biofuels will be a significant factor in agricultural markets, increasing commodity prices. Much of the current demand for biofuel crops is spurred by government targets and subsidies and by high oil prices. Without artificial support the competitiveness of biofuels is still poor, with the exception of Brazil's sugarcane ethanol. Nor is it clear how much biofuels reduce greenhouse gas emissions because of the fossil fuels used during production and the emissions from land clearing. Despite the potential that biofuels have to decrease greenhouse gas emissions in comparison with traditional fossil fuels, the actual net carbon savings that are embodied in current-generation biofuels, from the production process through to final combustion as fuel, is under debate, especially when indirect biofuel production-induced land-use changes are considered. Carbon sequestration benefits may not be realized for decades when biofuel production causes land conversion from land cover with a high-carbon sequestration value, such as forests. In addition, the demand for land for biofuels may compete with other uses, such as biodiversity conservation and animal habitat among other ecosystem services. As a result, it is important to establish guidelines for the expansion of biofuel production so that other environmental goals are not marginalized. Comprehensive life-cycle accounting for biofuels—which includes their contribution to emission reductions as well as their water and fertilizer use—may change the pace of conversion (box 3.4)

Second-generation biofuels now under development, such as algae, *jatropha*, sweet sorghum, and willows, could reduce competition with agricultural land for food crops by using less land or marginal land, although this development could still lead to the loss of livestock pasture land and grassland ecosystems. Perennial crops with deeper root systems, such as switchgrass, can better combat soil and nutrient erosion, require fewer nutrient inputs, and sequester higher rates of carbon than current biofuel feedstocks.[71] But their water needs may prohibit their sustainable production in arid regions. More research is needed to improve the productivity and energy efficiency of future generations of biofuels.

Growing populations, more carnivorous palates, and climate change will require large increases in agricultural productivity. The amount of land needed to feed the world in 2050 will depend significantly on how much meat people eat. Meat is a resource-intensive way for humans to consume protein, because it requires land for pasture and coarse grain for feed. The resource implications depend on the type of meat and how it is produced. One study estimates that about 3,700 liters of water are required to produce 1 kilogram of boneless beef in feedlot beef production systems in the United States.[72] Another study shows

BOX 3.4 *Palm oil, emission reductions, and avoided deforestation*

Palm oil plantations represent the convergence of many current land-use issues. Palm oil is a high-yielding crop with food and biofuel uses, and its cultivation creates opportunities for smallholders. But it is seen by many as a major threat both to tropical forests and to greenhouse gas mitigation. Cultivation of palm oil has tripled since 1961 to cover 13 million hectares, with most of the expansion in Indonesia and Malaysia and more than half on recently deforested lands. Recent announcements for new palm oil concessions in the Brazilian Amazon, Papua New Guinea, and Madagascar raise concerns that the trend is likely to continue.

Smallholders currently manage 35 to 40 percent of the land under palm oil cultivation in Indonesia and Malaysia, providing a profitable diversification in livelihoods. However, harvested palm nuts must be delivered to mills for processing within 24 hours of harvesting, so holdings tend to cluster around mills. Thus a high proportion of the area around mills is converted to palm oil, either as large tract commercial plantations or densely clustered smallholdings. Certain landscape design practices, such as the creation of agroforestry belts to smooth the transition between palm oil plantations and forest patches, can help make the plantation landscape less inimical to biodiversity while providing further diversification for smallholders.

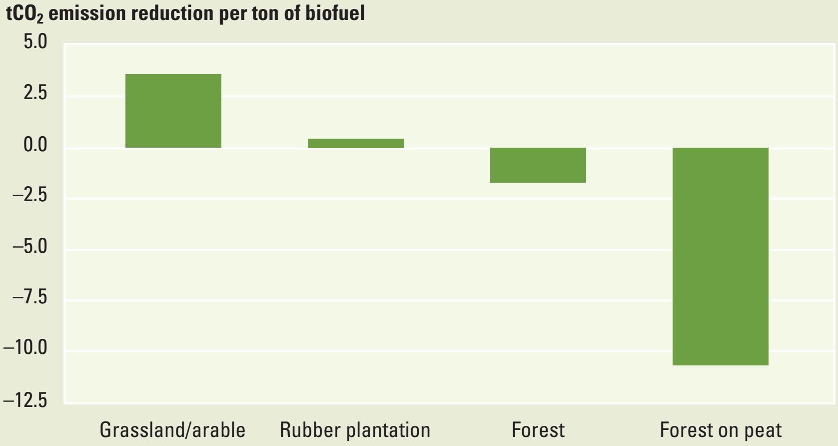
The mitigation value of biodiesel derived from palm oil is also questionable. Detailed life-cycle analysis shows that the net reduction in carbon emissions depends on the land cover existing before the establishment of the palm oil plantation. Significant emission reductions derive from plantations developed on previous grasslands and cropland, whereas emissions will increase greatly if peatland forests are cleared for producing palm oil.

The expansion of the carbon market to include REDD (Reduced Emissions from Deforestation and Forest Degradation) is an important tool to balance the relative values of palm oil production and deforestation on one hand, and forest protection on the other. This balance will be critical to ensure biodiversity protection and emission reduction.

Recent studies shows that converting land to palm oil production may be between six to ten times more profitable than maintaining the land and receiving payments for carbon credits through REDD, assuming that this mechanism will be limited to the voluntary market (box figure). If REDD credits are given the same price as carbon credits traded in compliance markets, the profitability of land conservation would increase dramatically, perhaps even exceeding profits from palm oil, therefore driving land away from agricultural conversion. This would allow REDD to become an economically attractive option in Indonesia and Malaysia, to reach its "avoided deforestation" goals, and to contribute substantially to a global mitigation effort.

Source: Butler, Koh, and Ghazoul forthcoming; Henson 2008; Koh, Levang, and Ghazoul forthcoming; Koh and Wilcove 2009; Venter and others 2009.

Emission reductions from biodiesel derived from palm oil differ greatly according to the previous land use on the palm oil plantation site.



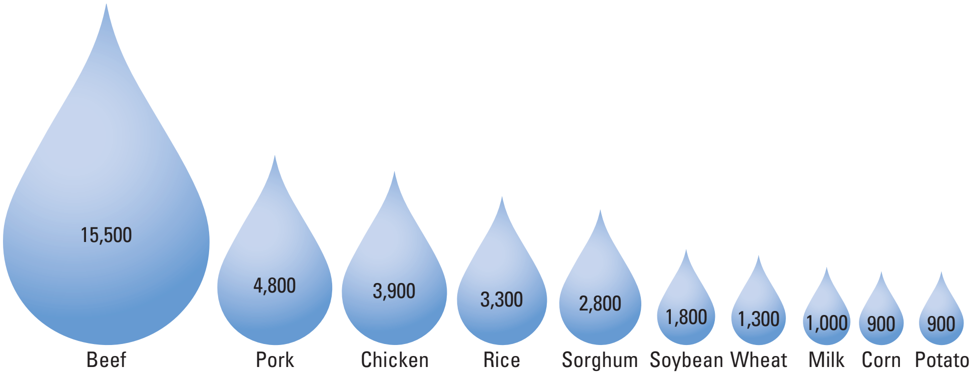
Source: Henson 2008.

that 1 kilogram of beef produced in an industrial feedlot requires about 15,000 liters of water, mostly to grow the animal's food.[73] But extensive beef production in Africa requires only 146–300 liters per kilogram depending on the weather (figure 3.3).[74] Per kilogram, beef production is greenhouse-gas intensive, even compared with other meat production, emitting 16 kilograms of CO_2 equivalent (CO_2e) for every kilogram of meat produced (figure 3.4).[75]

Despite the resource implications, demand for meat is expected to increase as population and incomes grow. More meat will be beneficial for poor consumers who need the protein and micronutrients contained in meat.[76] But by 2050 the production of beef, poultry, pork, and milk is expected to at least double from 2000 levels to respond to the demand of larger, wealthier, and more urban populations.[77]

The world will have to meet the growing demand for food, fiber, and biofuel in a changing climate that reduces yields—while at the same time conserving ecosystems that store carbon and provide other

Figure 3.3 Meat is much more water intensive than major crops
(liters of water per kilogram of product)



Source: Waterfootprint (https://www.waterfootprint.org), accessed May 15, 2009; Gleick 2008.

Note: Chart shows liters of water needed to produce one kilogram of product or one liter of milk. Water use for beef production refers only to intensive production system.

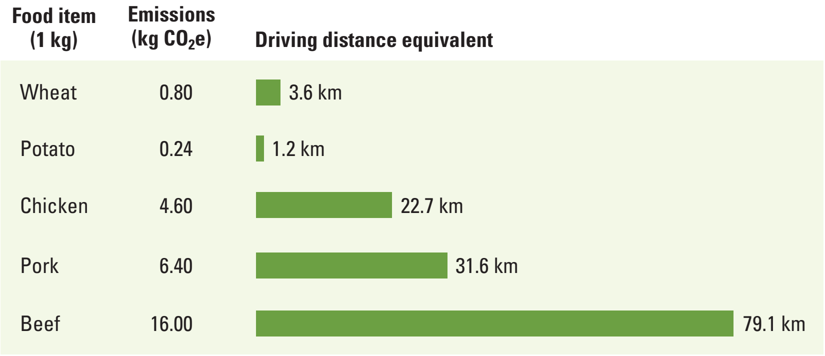
increasingly essential services. Obtaining more land suitable for agricultural production is unlikely. Studies indicate that globally the amount of land suitable for agriculture will remain the same in 2080 as it is today,[78] because increases in suitable land in the higher latitudes will be largely offset by losses in the lower latitudes.

Models vary, but most suggest that the combination of climate change and related pressures (such as rising demand for bioenergy, more carnivorous palettes, curbing cropland expansion into forest areas, and trade restrictions) will require agricultural productivity increases (tons per hectare) in the range of 1.8 percent a year through 2055—almost twice the 1 percent a year that would be needed under business as usual (figure 3.5).[79] This means that yields will have to more than double over 50 years. Many of the world's breadbaskets, such as North America, are approaching maximum feasible yields for major cereals,[80] so a significant portion of this agricultural growth will need to occur in developing countries. Overall, the world will have to reverse the downward trend in yield: in developing countries the yield growth rate for all cereals slipped from 3.9 percent a year between 1961 and 1990 to 1.4 percent a year between 1990 and 2007.[81]

Climate change will require highly productive and diverse agricultural landscapes

Productivity gains must not come at the expense of soil, water, and biodiversity. Intensive agriculture often damages natural systems. Highly productive agriculture, such as is practiced in much of the developed world, is usually based on farms that specialize in a particular crop or animal and on the intensive use of agrochemicals. This kind of farming can damage water quality and quantity. Fertilizer runoff has increased the number of low-oxygen "dead zones" in coastal oceans exponentially since the 1960s: they now cover about 245,000 square kilometers, mostly in coastal waters of the developed world (map 3.4).[82] Intensive irrigation often causes salt to build up in soils, reducing fertility and limiting food production. Salinization currently affects between 20 million and 30 million of the world's 260 million hectares of irrigated land.[83]

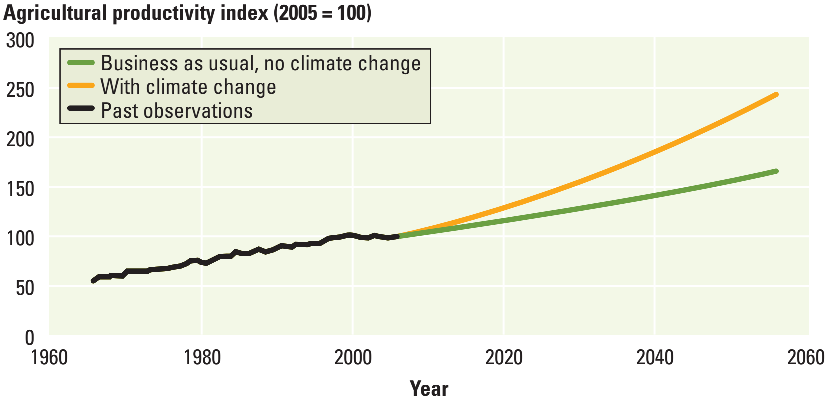
Figure 3.4 Intensive beef production is a heavy producer of greenhouse gas emissions



Source: Williams, Audsley, and Sandars 2006.

Note: The figure shows CO_2 equivalent emissions in kilograms resulting from the production (in an industrial country) of 1 kilogram of a specific product. The car and road image conveys the number of kilometers one must drive in a gasoline-powered car averaging 11.5 kilometers a liter to produce the given amount of CO_2e emissions. For example, producing 1 kilogram of beef and driving 79.1 kilometers both result in 16 kilograms of emissions.

Figure 3.5 Climate change means that increases in agricultural productivity must accelerate if the world is to meet the demands of a larger, richer, and more urban population



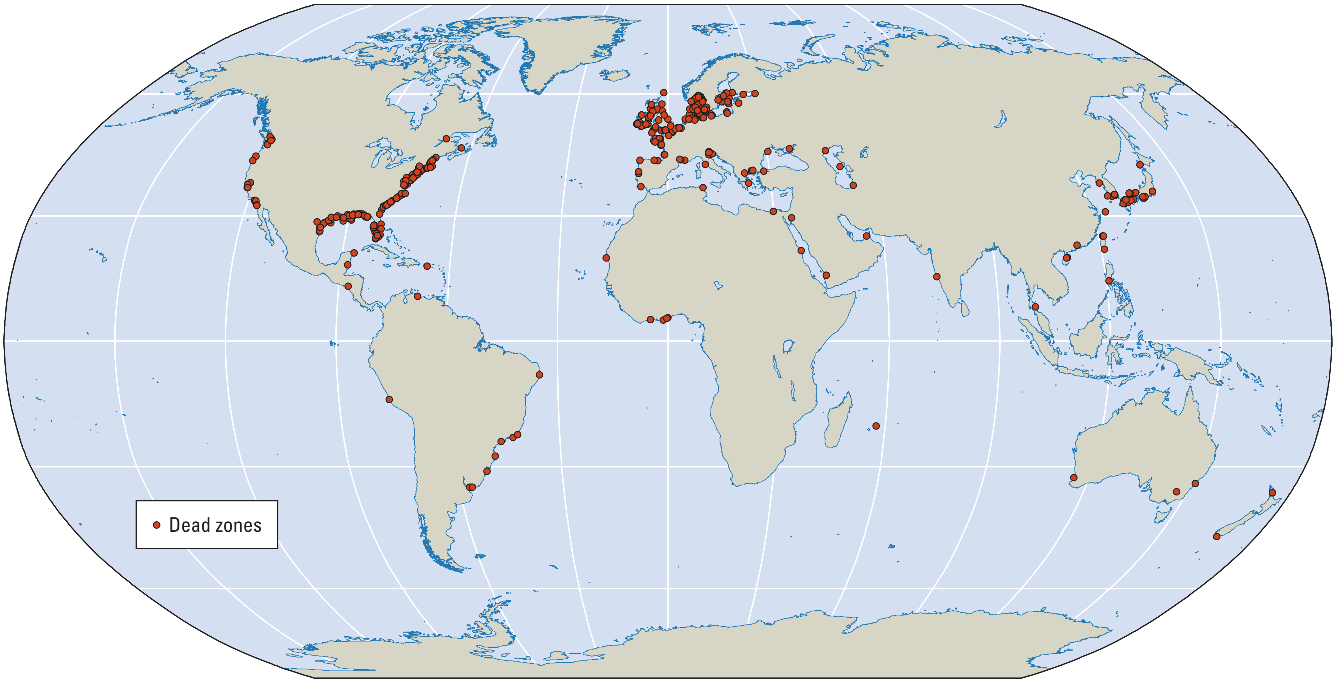
Source: Lotze-Campen and others 2009.

Note: The figure shows the required annual growth in an agricultural productivity index under two scenarios. In this index, 100 indicates productivity in 2005. The projections include all major food and feed crops. The green line indicates a business-as-usual scenario of global population increasing to 9 billion in 2055; total calorie consumption per capita and the dietary share of animal calories increasing in relation to rising per capita income from economic growth: further trade liberalization (doubling the share of agricultural trade in total production over the next 50 years); and cropland growing at historical rates of 0.8 percent a year; and no climate change impacts. The orange line indicates a scenario of climate change impacts without CO_2 fertilization (IPCC SRES A2), reduced trade (the share of agricultural trade in total production at 1995 levels of about 7 percent), avoided deforestation (cropland expansion into forests is curbed), and rising demand for bioenergy (until it reaches 100 exajoules (10^{18}) globally in 2055).

Less environmentally deleterious agricultural intensification is essential, particularly considering the environmental problems associated with further extensification of agriculture. Without increased crop and livestock yields per hectare, pressure on land resources will accelerate as crop and pasture areas expand under extensive production. Since the middle of the 20th century, 680 million hectares, or 20 percent of the world's grazing lands, have been degraded.[84] Converting land for agriculture has already reduced the area of many ecosystems (figure 3.6).

The Green Revolution illustrates both the immense benefits from increasing agricultural productivity and the shortcomings when technology is not supported by appropriate policies and investments to protect natural resources. New technology, coupled with investments in irrigation and rural infrastructure, drove a doubling of cereal production in Asia between 1970 and 1995. The agricultural growth and the associated decline in food prices during this time led to a near doubling of per capita income, and

Map 3.4 Intensive agriculture in the developed world has contributed to the proliferation of dead zones



Source: Diaz and Rosenberg 2008.

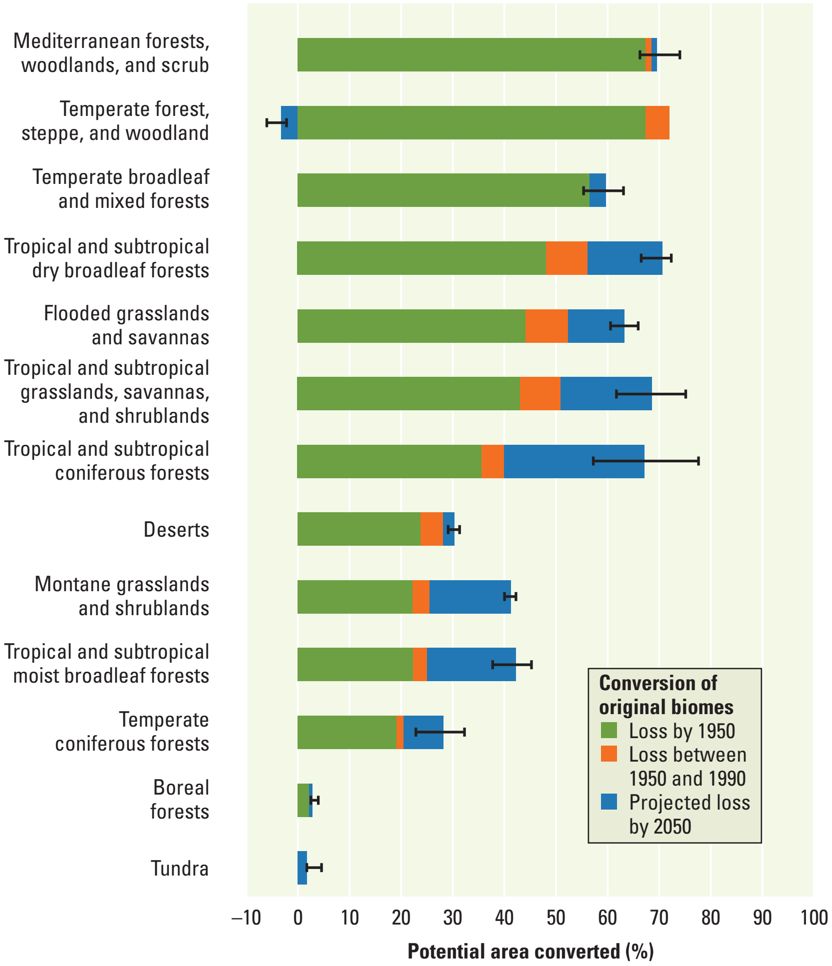
Note: In the developed world intensive agriculture has often come at high environmental cost, including runoff of excess fertilizers leading to dead zones in coastal areas. Dead zones are defined as extreme hypoxic zones, that is, areas where oxygen concentrations are lower than 0.5 milliliters of oxygen per liter of water. These conditions normally lead to mass mortality of sea organisms, although in some of these zones organisms have been found that can survive at oxygen levels of 0.1 milliliter per liter of water.

the number of poor people fell from about 60 percent of the population to 30 percent, even as the population increased 60 percent.[85] Latin America experienced significant gains as well. In Africa poor infrastructure, high transport costs, low investment in irrigation, and pricing and marketing policies that penalized farmers all impeded adoption of the new technology.[86] Despite the overall success of the Green Revolution, in many parts of Asia it was accompanied by environmental damages stemming from overuse of fertilizer, pesticides, and water. Perverse subsidies and biased pricing and trade policies that encouraged monoculture rice and wheat systems and excessive use of inputs were the main factors behind these environmental problems rather than the technology itself.[87]

Climate-resilient farming requires diverse income sources, production choices, and genetic material. Climate change will create a less predictable world. Crops will fail more often. One way to buffer the uncertainty is to diversify on all levels (box 3.5). The first type of diversification relates to sources of income, including some beyond agriculture.[88] Farmers will look for profitable activities compatible with their diminishing land-labor ratios and increasing land, water, and other input prices under climate change—a well-established pattern. Indeed, in much of Asia smallholders and landless workers typically earn more than half their total household income from nonagricultural sources.[89]

A second type of diversification involves increasing the types of production on the farm. The market opportunities for crop diversification are expanding in many intensively farmed areas as a result of more open export markets and buoyant national demand in rapidly growing economies, especially in Asia and Latin America.[90] In these regions farmers may be able to diversify into livestock, horticulture, and specialized agricultural production.[91] These activities typically give high returns per unit of land and are labor intensive, which makes them suitable to small farms. Retail prices for some specialized foods that offer health benefits beyond nutrition are typically 30–500 percent above comparable foods. The global market for such products is estimated to be between $30 billion and $60 billion.[92]

Figure 3.6 Ecosystems have already been extensively converted for agriculture



Source: Millennium Ecosystem Assessment 2005.

Note: The projections are based on four scenarios of how the world will approach ecosystem services and include assumptions about ecosystem management, trade liberalization, technology, and the treatment of public goods.

The third type of diversification involves increasing the genetic variability within individual crop varieties. Most high-yielding varieties in use on highly productive farms were bred on the assumption that the climate varied within a stable envelope; the breeders aimed for seed to be increasingly homogenous. In a changing climate, however, farmers can no longer rely on a handful of varieties that work under a narrow set of environmental conditions. Maintaining food security in a more variable climate requires higher diversity in

BOX 3.5 *Product and market diversification: An economic and ecological alternative for marginal farmers in the tropics*

Tropical areas face great challenges: the increasing poverty of rural populations, including indigenous peoples; the degradation of natural resources; the loss of biodiversity; and the consequences of climate change. The volatility of prices for tropical products on the international markets also affects the local economy. Many farmers around the world have their own survival mechanisms, but efforts to improve livelihoods and address the anticipated impacts from climate change will require innovative institutions and creative methods for income generation and security.

One strategy that shows great potential for climate-smart development is agricultural and agroforestry product diversification This strategy allows farmers to feed themselves and maintain a flow of products to sell or barter at the local market despite droughts, pests, or low prices on international markets.

Consider small coffee farms in Mexico. In 2001 and 2002 a dramatic drop in the international price of coffee pushed coffee prices in Mexico below production costs. To rescue farmers the Veracruz state government raised the prices of coffee produced in the area by establishing the "designation of origin of Veracruz" and by providing subsidies only to farmers cultivating high-quality coffee more than 600 meters above sea level. Because this policy would hurt thousands of producers living in the low-quality production area below 600 meters, the government invited the Veracruzana University to find alternatives to coffee monoculture.

The diversification of productive lowland coffee lands found financial support through the UN Common Fund for Commodities, with the sponsorship and supervision of the International Coffee Organization. It started in two municipalities with a pilot group of 1,500 farmers, living in communities with 25–100 households and a high degree of marginalization.

Many of the farmers had traditionally produced coffee in a multicrop system, providing the opportunity to test in each plot different configurations of alternative woody and herbaceous species of economic and cultural value: Spanish cedar and Honduras mahogany trees (for wood and furniture), the Panama rubber tree, cinnamon, guava (as food and phytomedicine), *jatropha* (for food and biofuel), allspice, cocoa, corn, vanilla, chile, *maracuja* (passion fruit), and coffee. All trees, herbs, and produce were locally familiar, except the cinnamon tree. There is a potentially large market for cinnamon, which is usually imported. The farmers are now learning which practices and configurations hold the best production potential in this innovative diversified system.

A cooperative company pooled different agricultural products in groups with similar market values but with different exposures to climate, pest, and market risks. Early results indicate that this bundling seems to work well, improve livelihoods, and increase the resilience of the communities. The company has been able to sell all product-types, several of them at a better price than before the project started. And in the first two years the project introduced a million native timber trees.

Locals report that the practices have reduced erosion and improved soils, benefiting the surrounding ecosystem while buffering against potential future flooding associated with climate change.

Contributed by Arturo Gomez-Pompa.

genetic traits to provide higher tolerance to changes in water, temperature, and other conditions, even if overall yields are lower in "good" years.

Experiments using standard cultivation practices indicate that under increased CO_2 concentrations and higher temperatures (reflecting projections of the Intergovernmental Panel on Climate Change for 2050) older varieties of wheat or barley may grow faster and have an advantage over more modern varieties introduced in the late 20th century.[93] Furthermore, the weedy and wild relatives of today's crops retain higher genetic diversity and may be a useful base for enhancing crops' plasticity, and their adaptability to changing conditions—some weeds, for example, thrive in conditions of higher CO_2 and warmer temperature.[94] It has been suggested recently that genetic characters of the wild weedy red rice could be transferred to the cultivated variety to increase yields.[95]

Productive landscapes can integrate biodiversity. While protected areas may be the cornerstones of conservation, they will never be enough to conserve biodiversity in the face of climate change (see focus 2 on biodiversity). The world's reserve network roughly quadrupled between 1970 and 2007 to cover about 12 percent of Earth's land,[96] but even that is inadequate to conserve biodiversity. To adequately represent the continent's species in reserves, while capturing a large proportion of their geographic ranges, Africa would have to protect an additional 10 percent of its land, almost twice its current protection.[97] Geographically fixed and often isolated by habitat destruction, reserves are ill-equipped to accommodate species range shifts due to climate change.

One study of protected areas in South Africa, Mexico, and Western Europe estimates that between 6 and 20 percent of species may be lost by 2050.[98] Moreover, existing land reserves remain under threat given future economic pressures and frequently weak regulatory and enforcement systems. In 1999 the International Union for the Conservation of Nature determined that less than a quarter of protected areas in 10 developing countries were adequately managed and that more than 10 percent of protected areas were already thoroughly degraded.[99] At least 75 percent of protected forest areas surveyed in Africa lacked long-term funding, even though international donors were involved in 94 percent of them.[100]

A landscape-scale approach to biodiversity can make land outside protected areas more suitable for biodiversity, which is essential to allow for ecosystem shifts, species dispersal and the promotion of ecosystem services. The field of ecoagriculture holds promise.[101] The idea is to improve the farmland's productivity and simultaneously conserve biodiversity and improve environmental conditions on surrounding lands. With these methods, farmers increase their agricultural output and reduce their costs, reduce agricultural pollution, and create habitat for biodiversity (figure 3.7).

To conserve biodiversity, farmers must minimize or reverse the conversion of natural areas, protect and expand large patches of high-quality habitat, and develop well-connected ecological networks and corridors. Studies in North America and Europe show that lands withdrawn from conventional agricultural production (set-asides) unequivocally increase biodiversity.[102] In Rajasthan, India, a community-led water restoration program has reinstated *johads*, a traditional water-harvesting technology that uses simple mud barriers built across uphill tributaries. This practice encourages groundwater recharge and improves hillside forest growth, while providing water for wildlife, livestock, irrigation, and domestic use.[103]

Agriculture practices that enhance biodiversity often have many co-benefits, such as reducing vulnerability to natural disasters, enhancing farm income and productivity, and providing resilience to climate change. During Hurricane Mitch in 1998 farms using ecoagricultural practices suffered 58 percent, 70 percent, and 99 percent less damage in Honduras, Nicaragua, and Guatemala, respectively, than farms using conventional techniques.[104] In Costa Rica vegetative windbreaks or fence rows in an area of pasture and coffee farms increased income and bird diversity.[105] In Zambia the use of leguminous trees[106] and herbaceous cover crops in improved fallow practices increased soil fertility, suppressed weeds, and controlled erosion, thereby almost trebling annual net farm incomes.[107] Bee pollination

Figure 3.7 Computer simulation of integrated land use in Colombia.

Source: Photograph by Walter Galindo, from the files of Fundación CIPAV (Centro para Investigación en Sistemas Sostenibles De Producción Agropecuaria), Colombia. The photograph represents the Finca "La Sirena," in the Cordillera Central, Valle del Cauca. Arango 2003.

Note: The first photo is the real landscape. The second figure is computer generated and shows what the area would look like if farm productivity were increased by using ecoagricultural principles such as reducing grazing pressure on hillsides, protecting watersheds, sequestering carbon through afforestation, and increasing biodiversity-friendly habitat between fields.

is more effective when agricultural fields are closer to natural or seminatural habitat,[108] a finding that matters because 87 of the world's 107 leading food crops depend on animal pollinators.[109] Shade-grown coffee systems can buffer crops against extreme temperature and drought.[110]

In Costa Rica, Nicaragua, and Colombia silvopastoral systems that integrate trees with pastureland are improving the sustainability of cattle production and diversifying and increasing farmers' incomes.[111] Such systems, organized under the Project for Regional Integrated Silvopastoral Approaches to Ecosystem Management, will be particularly useful as a climate-change adaptation, because trees retain their foliage in most droughts, providing fodder and shade and thus stabilizing milk and meat production. Other benefits include improvements in hydrological services, that is, irrigation and other water services (less sediment and better water quality). Agricultural production and revenues can go together with biodiversity conservation. Indeed, in many cases intact ecosystems generate more revenues than converted ones (see overview, figure 7). In Madagascar managing a 2.2 million hectare forest over 15 years cost $97 million, when accounting for the forgone economic benefits that would have occurred if the land had been converted to agriculture. But the benefits of the well-managed forest (half of which come from watershed protection and reduced soil erosion) were valued between $150 million and $180 million over the same period.[112]

New initiatives are beginning to realize financial flows from the services that ecosystems provide to society (see focus 2). The developing world has great potential for expanding these and other schemes, such as conservation easements, which pay farmers to take sensitive land out of production,[113] and tradable development rights.[114]

Climate change will require faster adoption of technologies and approaches that increase productivity, cope with climate change, and reduce emissions

Several options will need to be pursued simultaneously to increase productivity. The recently concluded Integrated Assessment of Agricultural Knowledge, Science, and Technology for Development showed that successful agricultural development under climate change will involve a combination of existing and new approaches.[115] First, countries can build on farmers' knowledge, including that of traditional farmers. Such knowledge embodies a wealth of location-specific adaptation and risk management options that can be applied more widely. Second, policies that change the relative prices that farmers face have great potential to encourage practices that will help the world adapt to climate change (by increasing productivity) and mitigate it (by reducing agricultural emissions). Agriculture research and extension has been underfunded in the past decade. The share of official development assistance for agriculture dropped from 17 percent in 1980 to 4 percent in 2007,[116] despite estimates that rates of return to investment in agricultural research and extension are high (30–50 percent).[117] Public expenditures on agricultural research and development (R&D) in low- and middle-income countries have increased slowly since 1980, from $6 billion in 1981 to $10 billion in 2000 (measured in 2005 purchasing power dollars), and private investments remain a small share (6 percent) of agricultural R&D in those countries.[118] Those trends will have to be reversed if societies are to meet their food needs.

Third, new or unconventional farming practices can increase productivity and reduce carbon emissions. Farmers are beginning to adopt "conservation agriculture," which includes minimum tillage (where seeds are sowed with minimum soil disturbance and residue coverage on the soil surface is at least 30 percent), crop residue retention, and crop rotations. These tillage methods can increase yields,[119] control soil erosion and runoff,[120] increase water and nutrient use efficiency,[121] reduce production costs, and in many cases sequester carbon.[122]

In 2008, 100 million hectares, or about 6.3 percent of global arable land, were farmed with minimum tillage—about double the amount in 2001.[123] Most takeup has been in developed countries, because the technique has heavy equipment requirements and has not been modified for conditions in Asia and Africa.[124] Minimum tillage also makes the control of weeds, pests, and diseases more complex, requiring better management.[125] Nevertheless, in the rice-wheat farming system of the Indo-Gangetic plain of India, farmers adopted zero-tillage on 1.6 million hectares in 2005.[126] The adoption of minimum tillage has continued to diffuse; in 2007–08 an estimated 20–25 percent of the wheat in two Indian states alone (Haryana and Punjab) was cultivated under minimum tillage, corresponding to 1.26 million hectares.[127] Yields increased by 5–7 percent, and costs came down by $52 a hectare.[128] About 45 percent of Brazilian cropland is farmed using these practices.[129] The use of minimum tillage will probably continue to grow, particularly if the technique becomes eligible for payments for soil carbon sequestration in a compliance carbon market.

Biotechnology could provide a transformational approach to addressing the tradeoffs between land and water stress and agricultural productivity, because it could improve crop productivity, increase crop adaptation to climatic stresses such as drought and heat, mitigate greenhouse gas emissions, reduce pesticide and herbicide applications, and modify plants for better biofuel feedstocks (box 3.6). There is, however, little likelihood of genetic modification affecting water productivity in the short term.[130]

Climate-smart farming practices improve rural livelihoods while mitigating and adapting to climate change. New crop varieties, extended crop rotations (notably

BOX 3.6 *Biotech crops could help farmers adapt to climate change*

Conventional selection and plant breeding have produced modern varieties and major productivity gains. In the future a combination of plant breeding and the selection of preferred traits through genetic techniques (genetic modification, or GM) is likely to contribute most to producing crops better adapted to pests, droughts, and other environmental stresses accompanying climate change.

Some crops with genetically modified traits have been broadly commercialized in the last 12 years. In 2007 an estimated 114 million hectares were planted with transgenic crop varieties, mostly with insect-resistant or herbicide-tolerant traits. More than 90 percent of this acreage was planted in only four countries (Argentina, Brazil, Canada, and the United States). These technologies will significantly reduce environmental pollution, increase crop productivity, cut production costs, and reduce nitrous oxide emissions. To date successful breeding programs have produced crop varieties, including cassava and maize, that resist a number of pests and diseases, and herbicide-tolerant varieties of soybean, rapeseed, cotton, and maize are available. Farmers using insect-resistant GM crops have reduced the amount of pesticides they use and the number of active ingredients in the herbicides they apply.

Genes affecting crop yield directly and those associated with adaptation to various types of stress tolerance have been identified and are being evaluated in the field. New varieties could improve the way crops cope with unreliable water supplies and potentially improve how they convert water. Breeding plants that can survive longer periods of drought will be even more critical in adapting to climate change. Initial experiments and field testing with GM crops suggest that progress may be possible without interfering with yields during nondrought periods, a problematic tradeoff for drought-tolerant varieties developed through conventional breeding. Drought-tolerant maize is nearing commercialization in the United States and is under development for African and Asian conditions.

Despite the prospects GM crops are controversial, and public acceptance and safety must be addressed. Potential risks of GM crops include food safety, environmental impacts, and ethical concerns. After more than 10 years of experience, there has been no documented case of negative human health impacts from GM food crops. Environmental risks include the possibility of GM plants cross-pollinating with wild relatives, creating aggressive weeds with higher disease resistance and the rapid evolution of new pest biotypes adapted to GM plants. However, scientific evidence and 10 years of commercial use show that safeguards, when appropriate, can prevent the development of resistance in the targeted pests and the environmental harm from commercial cultivation of transgenic crops, such as gene flow to wild relatives. Crop biodiversity may decrease if a small number of GM cultivars displace traditional cultivars, but this risk also exists with conventionally bred crop varieties. Impacts on biodiversity can be reduced by introducing several varieties of a GM crop, as in India, where there are more than 110 varieties of Bt (*Bacillus thuringiensis)* cotton. Although the track record with GM crops is good, establishing science-based biosafety regulatory systems is essential so that risks and benefits can be evaluated on a case-by-case basis, comparing the potential risks with alternative technologies and taking into account the specific trait and the agroecological context for using it.

Source: Benbrook 2001; FAO 2005; Gruere, Mehta-Bhatt, and Sengupta 2008; James 2000; James 2007; James 2008; Normile 2006; Phipps and Park 2002; Rosegrant, Cline, and Valmonte-Santos 2007; World Bank 2007c.

for perennial crops), reduced use of fallow land, conservation tillage, cover crops, and biochar can all increase carbon storage (box 3.7). Draining rice paddies at least once during the growing season and applying rice straw waste to the soil in the off-season could reduce methane emissions by 30 percent.[131] Methane emissions from livestock can also be cut by using higher-quality feeds, more precise feeding strategies, and improved grazing practices.[132] Better pasture management alone could account for about 30 percent of the greenhouse gas abatement potential from agriculture (1.3 gigatons of CO_2e a year by 2030 over 3 billion hectares globally).[133]

As countries intensify agricultural production, the environmental impacts of soil fertility practices will come to the fore.[134] The developed world and many places in Asia and Latin America may lower fertilizer use to reduce both greenhouse gas emissions and the nutrient runoff that harms aquatic ecosystems. Changing the rate and timing of fertilizer applications reduces the emissions of nitrous oxide from soil microbes. Controlled-release nitrogen[135] improves efficiency (yield per unit of nitrogen), but so far it has proved too expensive for many farmers in developing countries.[136] New biological inhibitors that reduce the volatilization of nitrogen could achieve many of the same goals more cheaply. They are likely to be popular with farmers because they involve no extra farm labor and little change in management.[137] If producers and farmers have incentives to apply new fertilizer technology and to use fertilizers efficiently, many countries could maintain agricultural growth even as they reduce emissions and water pollution.

In Sub-Saharan Africa, by contrast, natural soil fertility is low, and countries cannot avoid using more inorganic fertilizer. Integrated adaptive management programs with site-specific testing and monitoring can reduce the risk of overfertilizing. But such programs are still rare in most developing countries because there has not been enough public investment in the research, extension, and information services necessary for effective implementation—a recurring theme of this chapter.

Part of achieving the necessary increase in agricultural productivity in the developing world, sound fertilizer policy includes measures to make fertilizers affordable to the poor.[138] It also includes broader programs, such as the Farm Inputs Promotion program in Kenya that works with local companies and subsidiaries of international

BOX 3.7 *Biochar could sequester carbon and increase yields on a huge scale*

Scientists investigating some unusually fertile soils in the Amazon basin found that the soil was altered by ancient charcoal-making processes. The indigenous people burned wet biomass (crop residues and manure) at low temperatures in the almost complete absence of oxygen. The product was a charcoal-type solid with a very high carbon content, called biochar. Scientists have reproduced this process in modern industrial settings in several countries.

Biochar appears to be highly stable in soil. Studies on the technical and economic viability of the technique are continuing but early results indicate that biochar can lock carbon into the soil for hundreds or even thousands of years. That carbon would otherwise be released into the atmosphere through burning or decomposition.

So biochar could have great carbon mitigation potential. Three separate biochar sources could sequester about 30 percent of the annual U.S. fossil-fuel emissions: forest residues from 200 million hectares of U.S. forests that are used for timber production, fast-growing vegetation grown on 30 million hectares of U.S. cropland idled for this purpose, and crop residues from 120 million hectares of harvested U.S. cropland. Biochar can also increases soil fertility. It binds to nutrients and could thus help regenerate degraded lands as well as reduce the need for artificial fertilizers and thus the pollution of rivers and streams. Despite the potential of biochar for carbon sequestration and improved soil health, it is far from proven for large-scale application.

Research is needed on a number of key issues, including development of a comprehensive database containing rapid screening techniques and information on biochar products, their composition, and utilization; development of methodologies for measurement of the potential of biochar for long-term carbon sequestration and for environmental risk assessment of biochar; assessment of the underlying processes that determine the impact of biochar on particular soil types; examination of the economic viability of biochar; and analysis of the benefits obtained from biochar from the environmental and societal perspectives in developing countries.

Source: Lehmann 2007a; Lehmann 2007b; Sohi and others 2009; Wolf 2008.

seed companies to improve agricultural inputs (by formulating fertilizers using locally available minerals, providing improved seed varieties, and distributing fertilizer in rural areas) and to promote sound agronomic practices (correct fertilizer placement, soil management, and effective weed and pest control).

Produce more and protect better in fisheries and aquaculture

Marine ecosystems will have to cope with stresses as least as great as those on land

The oceans have absorbed about half the anthropogenic emissions released since 1800,[139] and more than 80 percent of the heat of global warming.[140] The result is a warming, acidifying ocean, changing at an unprecedented pace with impacts across the aquatic realm (see focus 1 on science).[141] *Ecosystem-based management can help coordinate an effective response to fisheries in crisis.* Even without climate change, between 25 and 30 percent of marine fish stocks are overexploited, depleted, or recovering from depletion—and are thus yielding less than their maximum potential. About 50 percent of stocks are fully exploited and producing catches at or close to their maximum sustainable limits, with no room for further expansion. The proportion of underexploited or moderately exploited stocks declined from 40 percent in the mid-1970s to 20 percent in 2007.[142] It may be possible to get more value from the fish caught—for example, by reducing the bycatch (fish caught unintentionally), estimated at one-quarter of the world fish catch.[143] It is likely that the maximum potential of fisheries in the world's oceans has been reached, and only more sustainable practices can maintain the productivity of the sector.[144]

Ecosystem-based management, which considers an entire ecosystem rather than a particular species or site and recognizes humans as integral elements in the system, can effectively protect the structure, functioning, and key processes of coastal and marine ecosystems.[145] Policies include coastal management, area-based management (see chapter 7), marine protected areas, limits on fishing effort and gear, licensing, zoning, and coastal law enforcement. Managing marine ecosystems effectively also involves managing activities on land to minimize the sedimentation and eutrophication that stress marine ecosystems, such as coral reefs, in many parts of the world.[146] The economic value of coral reefs can be many times that of the agriculture that caused the problems.[147]

The developing world already has some success stories. A program at Danajon Bank reef in the central Philippines has begun increasing fish biomass over the historical level.[148] Indeed, some developing countries implement ecosystem-based management more effectively than many developed countries.[149]

The rise in food prices, the increased need for fish protein, and the need to ensure that marine ecosystems are resilient to climate change pressures could prompt governments to implement long-advocated policy and governance reforms: reducing fishing fleet overcapacity, reducing catch to sustainable levels, and getting rid of perverse subsidies.[150] The annual number of newly built fishing vessels is less than 10 percent of the level in the late 1980s, but overcapacity is still a problem.[151] The global cost of poor governance of marine capture fisheries is an estimated $50 billion a year.[152] Rights-based catch shares can provide individual and community incentives for sustainable harvests. These schemes can grant rights to various forms of dedicated access, including community-based fishing, as well as impose individual fishing quotas.[153]

Aquaculture will help meet growing demand for food

The demand for fish has grown fast, with global consumption doubling since 1973.[154] Fish and shellfish supply about 8 percent of the world animal protein consumed.[155] And with world population growing by about 78 million people a year,[156] fish and shellfish production must grow by about 2.2 million metric tons every year to maintain current consumption of 29 kilograms per person a year.[157] If capture fish stocks fail to recover, only aquaculture will be able to fill the future demand.[158]

Aquaculture contributed 46 percent of the world's fish food supply in 2006,[159] with average annual growth (7 percent) outpacing population growth over the last decades. Productivity has increased by an order of magnitude for some species, driving down prices and expanding product markets.[160] Developing countries, mostly in the Asia-Pacific region, dominate production. Of the fish eaten in China, 90 percent comes from aquaculture.[161]

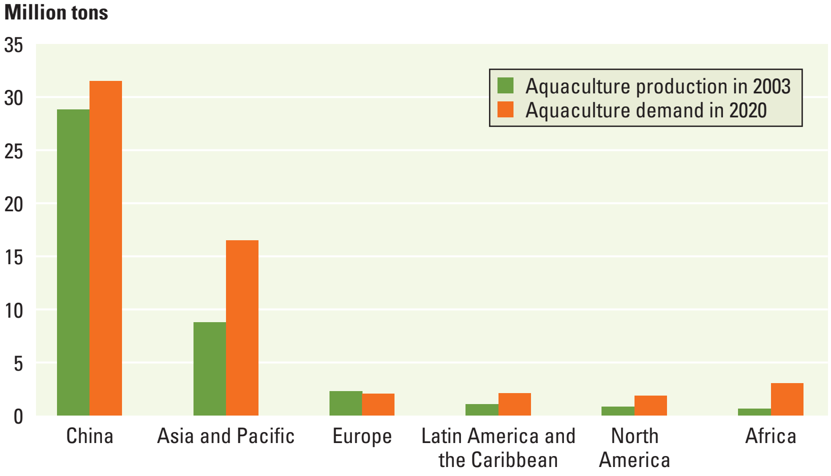
Demand for fish from aquaculture is projected to increase (figure 3.8), but climate change will affect aquaculture operations worldwide. Rising seas, more severe storms, and saltwater intrusion in the deltas of the tropics will damage aquaculture, which is based on species with limited saline tolerance, such as catfish in the Mekong Delta. Higher water temperatures in temperate zones may exceed the optimal temperature range of cultivated organisms. And as temperatures rise, diseases affecting aquaculture are expected to increase both in incidence and impact.[162]

While climate change may hurt some types of aquaculture, it opens new opportunities as more species are cultured, as the sea encroaches on coastal lands, as more dams and impoundments are constructed in river basins to buffer changing rainfall patterns, and as demands increase for more innovative waste disposal and water quality techniques (such as the use of aquatic plants and bivalves).

Aquaculture is expected to grow at a rate of 4.5 percent a year between 2010 and 2030.[163] But sustainable growth for the sector entails overcoming two major obstacles. First is the extensive use of fish proteins and oils as fishmeal, which keeps the pressure on capture fisheries.[164] The growth in aquaculture will have to come from species not dependent on feed derived from fishmeal; today, 40 percent of aquaculture depends on industrial feeds, much from marine and coastal ecosystems, which are already stressed.[165] Plant-based[166] aquaculture feeds are promising (such as oil-seed-based feed), and some operations have completely replaced fishmeal with plant-based feeds in the diets of herbivorous and omnivorous fish, without compromising growth or yields.[167] The emphasis on cultivating herbivorous and omnivorous species, as opposed to carnivorous finfish species, currently about 7 percent of total production, makes sense for resource efficiency.[168] For example, production of one kilogram of salmon, marine finfish, or shrimp in aquaculture systems is highly resource-intensive, requiring between 2.5–5 kilograms of wild fish as feed for one kilogram of food produced.[169]

Second, are the environmental problems aquaculture can cause. Coastal aquaculture has been responsible for 20 to 50 percent of the loss of mangroves worldwide;[170] further losses compromise climate resiliency of the ecosystems and make coastal populations more vulnerable to tropical storms. Aquaculture also can result in the discharge of wastes into marine ecosystems that in some areas contributes to eutrophication. New effluent management techniques—such as recirculation of water,[171] better calibration of feed, and integrated and polyculturing in which complementary organisms are raised together to reduce wastes[172]—can lessen the environmental impacts. So can appropriate aquaculture development in underexploited bodies of water, such as rice paddies, irrigation canals, and seasonal ponds. Integrated agriculture-aquaculture schemes promote recycling of nutrients, so that wastes from aquaculture can become an input (fertilizer) for agriculture and vice-versa, thereby optimizing resource use and reducing pollution.[173] These systems have diversified income and provided protein for households in many parts of Asia, Latin America, and Sub-Saharan Africa.[174]

Figure 3.8 Demand for fish from aquaculture will increase, particularly in Asia and Africa



Source: De Silva and Soto 2009.

Building flexible international agreements

The improved management of natural resources required by climate change entails better international collaboration on those natural resources that cross borders. It also demands more reliable international food trade so that countries are better placed to cope with climate shocks and reduced agricultural potential.

Countries that share water courses will need to agree on how to manage them

About one-fifth of the world's renewable freshwater resources cross or form international borders, and in some regions, particularly in developing countries, the share is far higher. However, only 1 percent of such waters is covered by any kind of treaty.[175] Moreover, few of the existing treaties on international watercourses encompass all the countries touching the watercourse in question.[176] The United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses, which was adopted by the UN General Assembly in 1997, has yet to command sufficient ratifications to enter into force.[177]

Cooperation among riparian countries is essential to address water challenges caused by climate change. Such cooperation can be achieved only through inclusive agreements that make all the riparian countries responsible for the joint management and sharing of the watercourse and that are designed to address increased variability from both droughts and floods. Typically water agreements are based on allocating fixed quantities of water to each party; climate change makes this concept outdated. Allocations based on percentages of flow volume would better address variability. Even better is the "benefit- sharing" approach, where the focus is not on water volumes but on the economic, social, political, and environmental values derived from water use.[178]

Countries will need to work together to better manage fisheries

Fish is the most international of food commodities. One-third of global fish production is traded internationally, the highest ratio for any primary commodity.[179] As their fish stocks decline because of overfishing, pollution, and other factors, European, North American, and many Asian nations have imported more fish from developing countries.[180] This increased demand, combined with the overcapitalization of some fishing fleets (the European fleet is 40 percent larger than the fish stocks can accommodate), is spreading the depletion of marine resources to the southern Mediterranean, West Africa, and South America. And despite the multibillion dollar-a-year international trade in fisheries, developing countries receive relatively little in fees from foreign fishing fleets while they face resource depletion. Even in the rich tuna fishery of the western Pacific, small island developing states receive only about 4 percent of the value of the tuna taken.[181] By modifying the distribution of fish stocks, changing food webs, and disrupting the physiology of already stressed fish species, climate change will only make things worse.[182] Fleets facing further declines in stocks may venture even farther afield, and new agreements on resource sharing will need to be negotiated.

To facilitate adaptation and regulate fishery rights, it is important to develop international resource management regimes, both legal and institutional, and associated monitoring systems. Such agreements might be facilitated through the strengthening of regional fisheries management organizations.[183] The Benguela Current's Large Marine Ecosystem Programme is a promising development. Running along the west coast of Angola, Namibia, and South Africa, this ecosystem is one of the most highly productive in the world, supporting a reservoir of biodiversity including fish, seabirds, and sea mammals. Already within the ecosystem there is evidence that climate change is shifting the distributional ranges of some key commercial species poleward from the tropics.[184] This shift compounds existing stresses from overfishing, diamond mining, and oil and gas extraction. The three countries established the Benguela Current Commission in 2006, the first such institute created for a large marine ecosystem. Implementing an ecosystem-based approach to fisheries management, the three countries are committed to integrated management, sustainable development, and environmental protection, in the belief that they will be well positioned to adapt offshore activities to climate change.[185]

More reliable trade in agricultural commodities will help countries experiencing unexpected weather extremes

Even if farmers, businesses, governments, and water managers dramatically increase the productivity of land and water, some parts of the world will not have enough water to grow all of their food. Deciding how much food to import and how much to grow domestically has implications for agricultural productivity and water management (box 3.8). Seeking food self-sufficiency when resource endowments and growth potential are inadequate will impose heavy economic and environmental costs.

Many countries already import a large share of their food: most Arab countries import at least half the food calories they consume.[186] With climate change expected to make today's arid countries drier, plus growing income and populations, more people will live in regions that import food. In addition, more people will live in countries that experience shocks to domestic agriculture, as climate change increases the likelihood and severity of extreme climate events. Several global scenarios project a 10–40 percent increase in net imports as a result of climate change.[187] Trade in cereals is projected to more than double in volume by 2050, and trade in meat products to more than quadruple.[188] And most of the increased dependence on food imports will come in developing countries.[189]

As the sharp rise of food prices in 2008 illustrated, the global food market is volatile. Why did the prices spike? First, grain markets are thin: only 18 percent of world wheat and 6 percent of world rice are exported. The rest is consumed where it is grown.[190] And only a few countries export grain (map 3.5). In thin markets, small shifts in either supply or demand can make a big difference in price. Second, per capita global food stocks were at one of the lowest

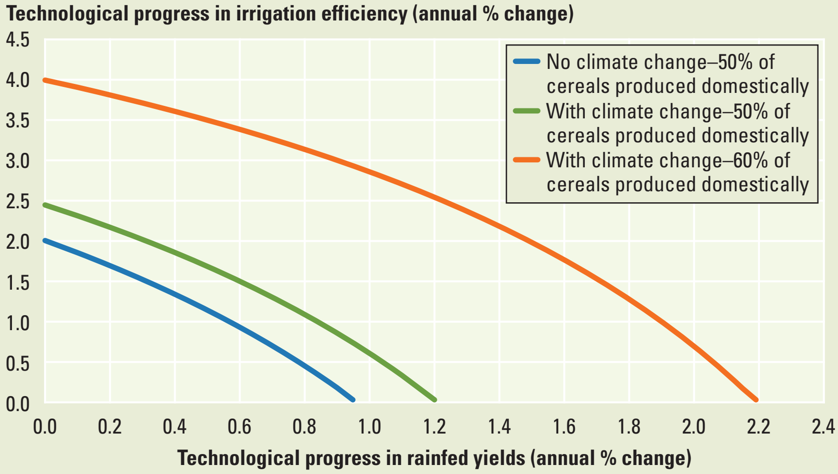
BOX 3.8 *Policymakers in Morocco face stark tradeoffs on cereal imports*

Morocco, with severe water constraints and a growing population, imports half its cereals. Even without climate change, if it wishes to maintain cereal imports at no more than 50 percent of demand without increasing water use, Morocco would have to make technical improvements to achieve a combination of two options: either 2 percent more output per unit of water allocated to irrigated cereals or 1 percent more output per unit of land in rainfed areas (blue line in box figure).

Adding in the effects of higher temperatures and reduced precipitation makes the task more challenging: technological progress will need to be 22–33 percent faster than without climate change (depending on the policy instruments selected) (green line on box figure). But if the country wants more protection against domestic climate shocks to agriculture and against market price shocks and decides to increase the share of its consumption produced domestically from 50 percent to 60 percent, it has to increase water efficiency every year by 4 percent in irrigated agriculture, or by 2.2 percent in rainfed areas, or any combination in between (red line). In other words, a robust response to climate change could require Morocco to implement technical improvements between 100 percent and 140 percent faster than it would have had to without climate change. Reducing trade means that Morocco has to make disproportionate efficiency gains domestically.

Source: World Bank 2009a.

Achieving cereal self-sufficiency without increasing water use in Morocco



levels on record. Third, as the market for biofuel increased, some farmers shifted out of food production, contributing significantly to increases in world food prices.

When countries do not trust international markets, they respond to price hikes in ways that can make things worse. In 2008 many countries restricted exports or controlled prices to try to minimize the effects of higher prices on their own population, including Argentina, India, Kazakhstan, Pakistan, Russia, Ukraine, and Vietnam. India banned exports of rice and pulses, and Argentina raised export taxes on beef, maize, soybeans, wheat.[191]

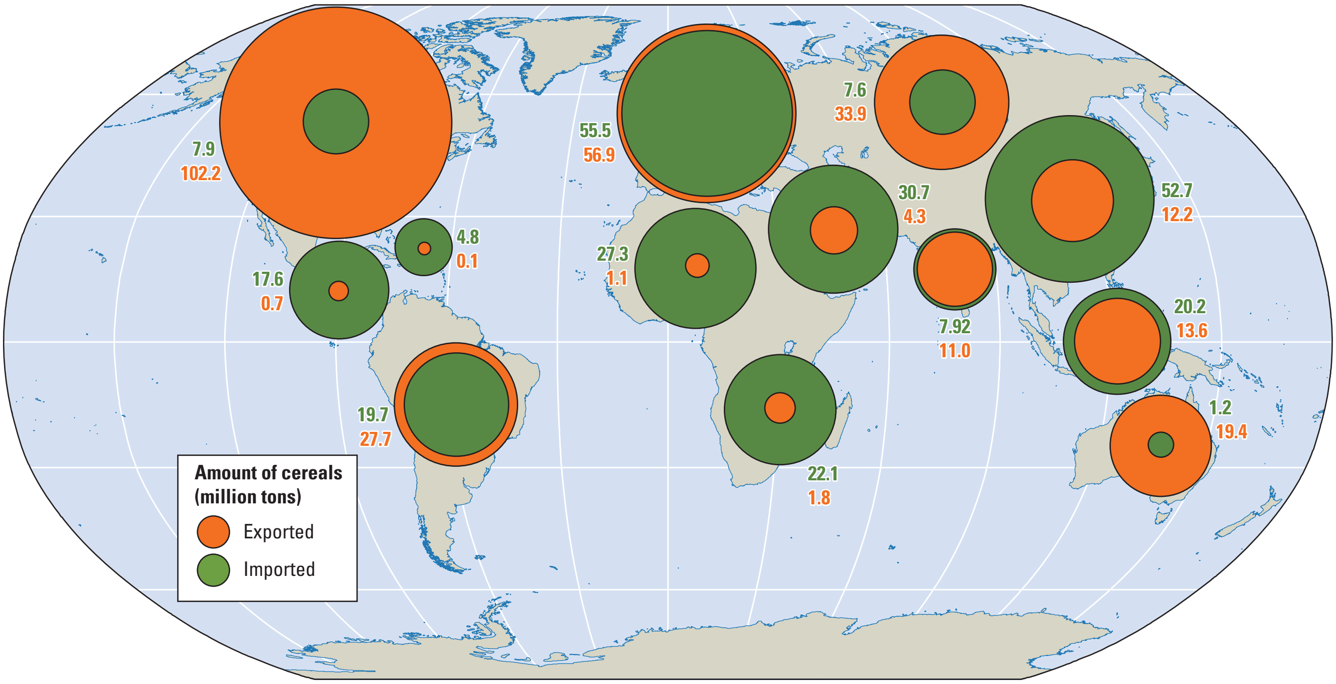
Export bans or high export tariffs make the international market smaller and more volatile. For example, export restrictions on rice in India affect Bangladeshi consumers adversely and dampen the incentives for rice farmers in India to invest in agriculture, a long-term driver of growth. In addition, export bans stimulate the formation of cartels, undermine trust in trade, and encourage protectionism. Domestic price controls can also backfire by diverting resources from those who need them most and by reducing incentives for farmers to produce more food and adopt more biodiversity-friendly agricultural practices.

The high volatility in prices generated by these measures is one of the factors, along with water scarcity, behind the decision by countries like China and Saudi Arabia to ensure their own food security through the purchase of large swaths of land in Sudan and Ethiopia.[192] It is too early to say whether this course of action will bring more opportunities or present more threats for food security and for the environment. For the time being, it has been suggested that a code of conduct is necessary to ensure that these deals are benefiting both the investors and the national interests of the "host" country.[193]

Countries can take measures to improve access to markets

Countries can take unilateral action to improve their access to international food markets, a particularly important step for small countries whose actions do not affect the market but that nonetheless import a large share of their food. One of the simplest ways is to improve procurement methods. Yemen, for example, does not yet use sophisticated measures when issuing

Map 3.5 World grain trade depends on exports from a few countries



Source: FAO 2009c.

tenders to import food. But electronic tendering and bidding and sophisticated credit and hedging products would all help the government get a better deal. Another option would be to relax national laws that prohibit multinational procurement so that small countries can group together for economies of scale.[194]

A third measure is active management of stocks. Countries need robust national stockpiling and the latest instruments in risk hedging, combining small physical stockpiles with virtual stockpiles purchased through futures and options. Models indicate that futures and options could have saved Egypt between 5 and 24 percent of the roughly $2.7 billion it spent purchasing wheat between November 2007 and October 2008, when prices were soaring.[195] Global collective action in managing stocks would also help prevent extreme price spikes. A small physical food reserve could allow a smooth response to food emergencies. An international coordinated global food reserve could reduce pressures to achieve grain self-sufficiency. And an innovative virtual reserve could prevent market price spikes and keep prices closer to levels suggested by long-run market fundamentals without putting the coordinated global reserves at risk.[196]

Weatherproofing transport services to ensure year-round accessibility is critical, particularly in countries such as Ethiopia, with high variability in regional rainfall. Increased investments in improving logistics in the supply chain—from roads to ports and customs facilities, wholesale markets, weighbridges, and warehouses—would help get more food to consumers at a lower price. But institutional infrastructure is also needed. Transparency, predictability, and honesty in customs and warehousing are as important as the facilities.

Importing countries can also invest in various parts of the supply chain in producing countries. It may also be possible, and indeed less risky, to focus on supply chain infrastructure or agricultural research and development in the producing countries.

International rules to regulate trade will remain an important part of the picture

The World Trade Organization's Doha Development Agenda sought to eliminate trade barriers and improve market access for developing countries. But negotiations were suspended in 2008. A recent study concludes there would be a potential loss of at least $1.1 trillion in world trade if world leaders fail to conclude the Doha Round and instead implement protectionist policies such as those observed since the end of the Uruguay Round.[197] Completing this agreement would be a key first step in improving international food trade. Key measures include pulling down effective tariff rates and reducing agricultural subsidies and protection by developed countries. [198]

Reliable information is fundamental for good natural resource management

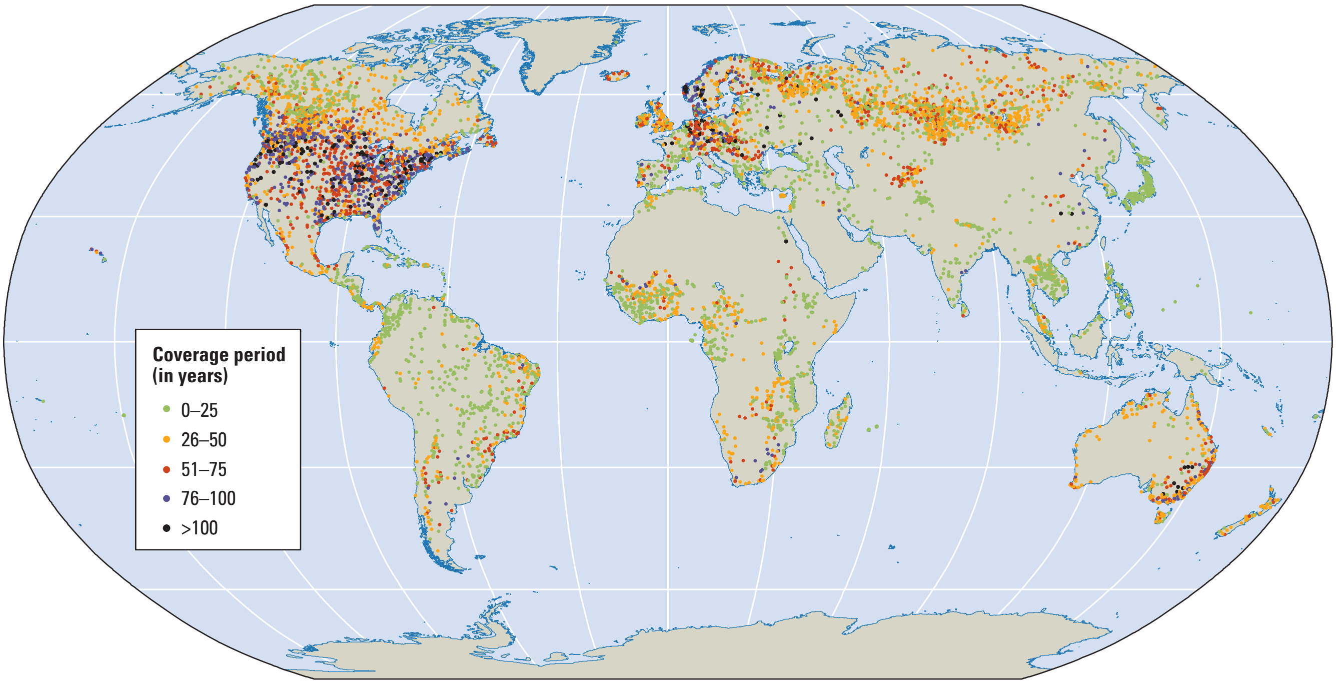
Investments in weather and climate services pay for themselves many times over, yet these services are sorely lacking in the developed world

Typically the ratio of the economic benefits to the costs of national meteorological services is in the range of 5–10 to 1,[199] and in China in 2006 it was estimated to be 69 to 1.[200] Weather and climate services can ameliorate the impacts of extreme events to some degree (see chapters 2 and 7). According to the United Nations International Strategy for Disaster Reduction, advance flood warnings can reduce flood damage by up to 35 percent.[201] Much of the developing world, particularly in Africa, urgently needs better monitoring and forecasting systems for both weather and hydrological change (map 3.6). According to the World Meteorological Organization, Africa has only one weather station per 26,000 square kilometers—one-eighth the recommended minimum.[202] Data rescue and archiving will also be important because long records of high-quality data are necessary to fully understand climate variability. Many of the world's climate datasets contain digital data back to the 1940s, but only a few have digital archives of all available data before then.[203]

Better forecasts would improve decision making

In Bangladesh the forecasts for precipitation extend only to one to three days; longer forecasts would allow farmers time to

Map 3.6 Developed countries have more data collection points and longer time series of water monitoring data



Source: Global distribution and time series end from the Global Runoff Data Center dataset.
Note: The image shows the discharge monitoring stations that provide information on river runoff.

modify planting, harvesting, and fertilizer applications, especially in rainfed cropping areas where food crises can last for many months. There have been significant improvements in seasonal climate forecasts (how precipitation and temperature over the course of a few months will vary from the norm), particularly in the tropics and especially in areas affected by the El Niño Southern Oscillation (ENSO).[204] The onset of monsoon rainfall in Indonesia and the Philippines and the number of rainy days in a season in parts of Africa, Brazil, India, and Southeast Asia can be predicted to some degree.[205] ENSO-based seasonal forecasts in South America, South Asia, and Africa have good potential for improving agricultural production and food security.[206] For example, in Zimbabwe subsistence farmers increased yields (ranging from 17 percent in good rainfall years to 3 percent in poor rainfall years) when they used seasonal forecasts to modify the timing or variety of the crops planted.[207]

There have already been some dramatic successes with forecasts of floods and cyclones. In Bangladesh extending forecasts from two or three days to seven could reduce losses to infrastructure, crops, and livestock by 20 percent.[208] However, it can be difficult to communicate seasonal forecasts and to get stakeholders to act on them. In Zimbabwe farmers who attended annual participatory forecasting workshops were more likely to use forecasts in making decisions.[209]

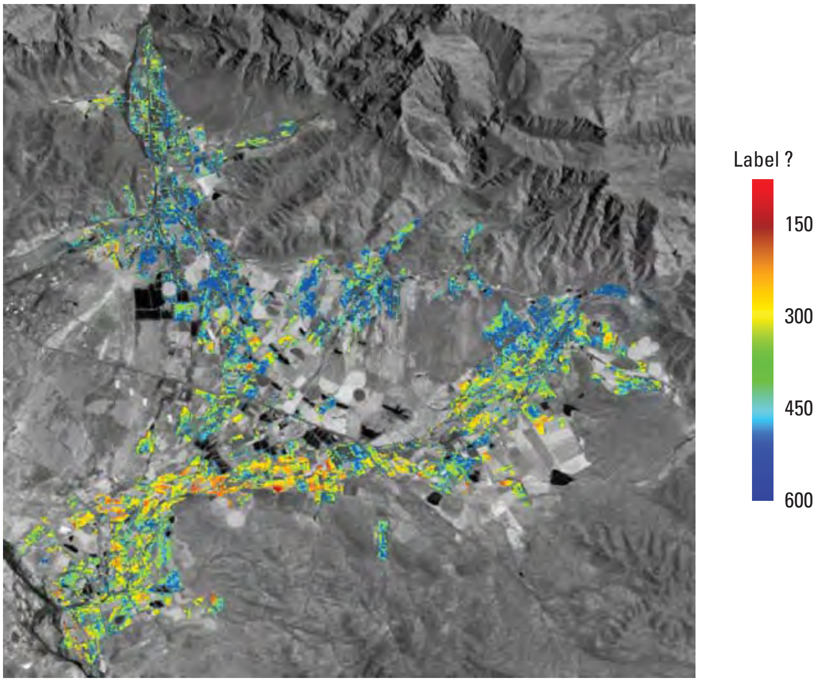
New remote-sensing and monitoring technologies hold great promise for sustainability

One reason that policy makers have found it so difficult to curb the overexploitation of land and water and their related ecosystems is that neither the managers nor the users of the resources have accurate and timely information. They don't know how much of the resource is present, how much is being used, or how their actions will affect quantities in the future. But new remote-sensing technologies are beginning to fill some of that gap, informing decisions about more efficient allocations of water and helping with enforcement of water limits.

One of the most promising applications measures water's productivity.[210] When images from satellites with a thermal imaging band (which can come from many different sources depending on the scale) are combined with field data on crop types and linked to maps from geographic information systems, scientists can measure yields on any geographic scale (the farm, the basin, or the country). That allows water managers to make better decisions about water allocations and to target advisory services to the farmers with lowest water productivity. It also guides important investment decisions—say, between increasing the productivity of rainfed or irrigated agriculture. And it can help managers measure the actual results of investments in irrigation water-saving techniques, difficult in the past (figure 3.9).

Until recently, measuring groundwater consumption was difficult and expensive in all countries, and it simply was not done in many developing countries. Taking inventories of hundreds of thousands of private wells and installing and reading meters was too costly. But new remote-sensing technology can measure total evaporation and transpiration from a geographic area. If the surface water applied to that area through precipitation and surface water irrigation deliveries is known, the net consumption of groundwater can be imputed.[211] Various countries are experimenting with using information from new remote-sensing technologies to enforce groundwater limits,[212] including those Moroccan farmers who are considering converting to drip irrigation. Options for enforcement include pumps that shut off automatically when the farmer exceeds the evapotranspiration limit and systems that send text messages to farmers' cell phones warning them they are about to exceed their allocation of groundwater and alerting inspectors to monitor those particular farms.[213]

Figure 3.9 Remote-sensing techniques are used in the vineyards of Worcester (West Cape, South Africa) to gauge water productivity.



Source: Water Watch, www.waterwatch.nl (accessed May 1, 2009).

Note: Farmers whose fields are red are getting four times more wine per liter of water than those whose fields are shown in blue. In addition to gauging water productivity, governments can also use these techniques to target the activities of advisory and enforcement services.

Digital maps created from remote-sensing information will help resource managers at many levels. Using information from remote sensing to create digital maps of all of Africa's soils will be very useful for sustainable land management. Current soil maps are 10–30 years old and generally not digitized, making them inadequate to inform policies to address soil fertility and erosion. An international consortium is using the latest technologies to prepare a digitized global map, starting with the African continent.[214] Satellite imagery and new applications now allow scientists to measure streamflow and water storage (such as surface waters, soil moisture, underground waters, and snow mass) and to forecast floods. They also make it possible to show crop yields, crop stress, CO_2 uptake, species composition and richness, land cover and land-cover change (such as deforestation), and primary productivity. They can even map the spread of individual invasive plant species.[215] The scales vary, as does the timing of updates. But rapid advances allow managers to measure with a precision and regularity undreamed of a few years ago. Depending on the satellite and weather conditions, the data can be available daily or even every 15 minutes.

Research and development will be necessary to take full advantage of these new information technologies. There is great scope for applying new technologies and information systems to manage natural resource issues associated with climate change. Investments in satellite data for natural resource management can pay off in the long run. But the potential is far from being met, especially in the poorest countries A study in the Netherlands concluded that additional investments in satellite observations for water quality management (eutrophication, algal blooms, turbidity), including the capital costs of the satellite, has a 75 percent probability of producing financial benefits.[216] Additional funding for research and development of these tools and their application in developing countries would be of great help.[217]

More reliable information can empower communities and change the governance of natural resources

Natural resource management often requires governments to set and enforce laws, limits, or prices. Political and other pressures make this very difficult, especially where formal institutions are weak. But when resource users have the right information about the impacts of their actions, they can bypass governments and work together to reduce overexploitation, often increasing their revenues. Making a strong economic case for reform can help, as in a recent World Bank study that highlighted the global cost of poor governance in marine capture fisheries.[218]

India offers several examples of better information producing more efficient agricultural production and welfare gains. In the state of Madhya Pradesh a subsidiary of Indian Tobacco Company (ITC) developed eChoupals to lower its procurement cost and improve the quality of soybeans that it received from farmers. eChoupals are village Internet kiosks run by local entrepreneurs who provide price information on soybean futures to farmers and enable them to sell their produce directly to ITC, bypassing the middlemen and wholesale market yards (*mandis*). Through the eChoupals ITC spends less per ton of produce, and farmers immediately know the price they will receive, reducing waste and inefficiency. The payback period for the initial capital cost of developing the kiosks is about four to six years.[219]

A project sponsored by the UN's Food and Agriculture Organization in Andhra Pradesh, India, has dramatically reduced the overexploitation of aquifers. It used low-tech and low-cost approaches to enable communities to assess the state of their own resources. Rather than use expensive equipment and specialist hydrogeologists, the project brought in sociologists and psychologists to assess how best to motivate the villagers to cut current water consumption. It created "barefoot hydrogeologists," by teaching local people about the aquifer that sustained their livelihoods (figure 3.10). The villagers now even sell their data to government hydrogeological services. Awareness of the impacts of their actions, social regulation, and information about new varieties and techniques led the villagers to agree to change crops and adopt practices to reduce evaporative losses.

With almost 1 million farmers, the project is entirely self-regulating, and there are no financial incentives or penalties for noncompliance. Participating villages have reduced withdrawals, while withdrawals from neighboring villages continue to increase. For an undertaking of this scale, the cost is remarkably low—$2,000 a year for each of the 65 villages.[220] It has great potential for replication, but principally in the hard-rock aquifers that empty and refill quickly and that do not have vast lower layers common in other geological formations.[221]

These initiatives to encourage users to reduce overexploitation of natural resources

Figure 3.10 In Andhra Pradesh, India, farmers generate their own hydrological data, using very simple devices and tools, to regulate withdrawals from aquifers

Source: Bank staff.

Note: Armed with information, each farmer sets his or her own limit for how much water to safely extract each growing season. Technical assistance helps them get higher returns for the water they use by managing soil water better, switching crops, and adopting different crop varieties.

can reduce dependence on overstretched government agencies and overcome broader governance issues. They can also be tools for governments, working with communities, to change user behavior. The Hai basin, the most water-scarce in China, is extremely important for agriculture. Together with two neighboring basins, it produces half of China's wheat. Water resources in the Hai basin are polluted, wetland ecosystems threatened, and groundwater severely overexploited. Every year the basin uses 25 percent more groundwater than it receives as precipitation.[222]

In this same basin, the Chinese government, working with the World Bank, implemented innovations in water management for 300,000 farmers. The pilot focuses on reducing overall water consumption rather than simply increasing water productivity. It combines investments in irrigation infrastructure with advisory services to help optimize soil water. It limits the use of aquifer water. It introduces new institutional arrangements, such as transferring responsibility for managing irrigation services to groups of farmers and improving cost-recovery for surface water irrigation. And it uses the latest monitoring techniques, measuring water productivity and groundwater consumption at the plot level with satellite data, combined with more traditional agronomic services. The monitoring provides real-time information to policy makers and farmers so that they can make better decisions, change their practices, and detect noncompliance.[223]

The results are impressive. Farmers increased their incomes while reducing water consumption by switching to higher-value crops. Cash crop production tripled, farm incomes increased up to fivefold in many areas, and agricultural production per unit of water consumed increased 60–80 percent. Total water use in the area fell by 17 percent, with groundwater depletion at 0.02 meters a year, compared with 0.41 meters a year outside the project areas.

In summary, technologies and tools exist or are being developed to help farmers and other resource managers manage water, land, farms, and fisheries. In an ideal world the right people would have access to these technologies and tools. But they will be effective only with the right policies and infrastructure. This ideal world is represented pictorially in figures 3.11 and 3.12. Many of the steps toward this ideal world have frustrated societies for decades in the past. But circumstances are changing in ways that might accelerate progress.

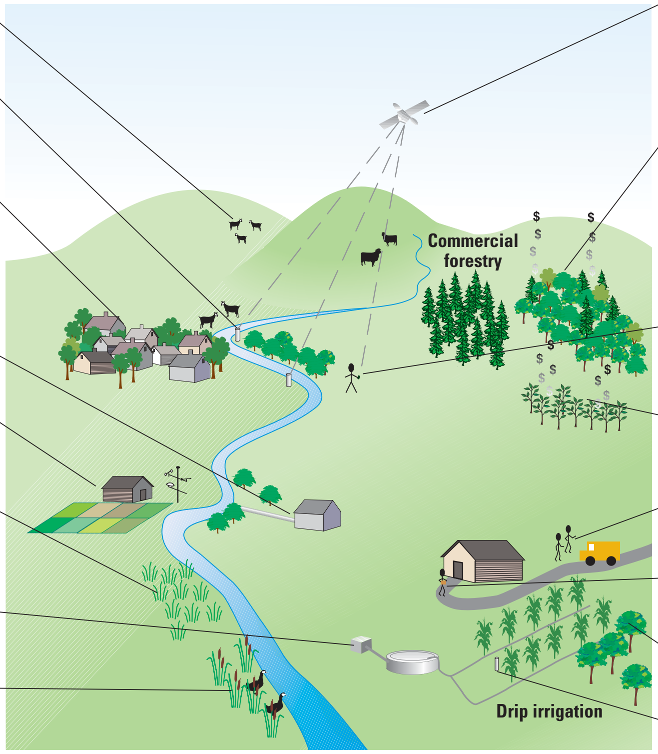
Pricing carbon, food, and energy could be the springboard

This chapter suggests many new approaches to help developing countries cope with the additional stress that climate change will put on efforts to manage land and water resources well. It emphasizes repeatedly that new technologies and new investments will bear fruit only in a context of strong institutions and sensible policies—when the "fundamentals" are right. Yet the fundamentals are not right in many of the world's poorest countries. And getting them right—building strong institutions, changing subsidy regimes, changing the way valuable commodities are allocated—is a long-term process even in the best of circumstances.

To compound the problems, many of the responses this chapter proposes to help countries improve land and water management in the face of climate change require farmers, many of them among the world's poorest, to change their practices. It also requires some of the most lawless people (illegal loggers, illegal miners) to stop practices that have brought them extreme profits. This chapter is proposing accelerating actions that have at best seen slow progress in the past few decades. Is it realistic to expect change on a sufficient scale to really tackle the challenge climate change confronts us with?

Three new factors might provide the stimulus for change and overcome some of the barriers that have hampered these innovations in the past. First, climate change is expected to increase the price of energy, water, and land and thus of food and other agricultural commodities. That will increase the pace of innovation and accelerate the adoption of practices that increase productivity. Of course higher prices will also make it more profitable to overexploit resources or encroach on natural habitats. Second, a carbon price applied to carbon in the landscape, may encourage landowners

Figure 3.11 An ideal climate-smart agricultural landscape of the future would enable farmers to use new technologies and techniques to maximize yields and allow land managers to protect natural systems. Natural habitats are integrated into agriculturally productive landscapes



Rangeland
with hardy varieties of livestock

Physical monitoring systems
- measure available water
- provide flood and other natural disaster warnings

Traditional communities -
- self regulate groundwater and grazing
- in response to carbon credit incentives: farmers use soil and water conservation techniques; plant natural windbreaks; establish buffer zones and fallow land to provide habitats for biodiversity

Conveyance
to direct stormwater to recharge aquifers

Research station
finds new ways to adopt crops and management techniques to new climatic conditions

Conservation tillage and intercropping
used to grow rain-fed crops
Biochar made from crop residue sequesters carbon and fertilizes the soil

Pump accesses groundwater for dry years and automatically shuts off when safe extraction is exceeded

Planned reserves
to allow species movement in response to ultimate change

Remote sensing systems
- measure species movement
- monitor safe extraction of water
- provide early warning for floods, droughts and landslides
- detect deforestation

Original forest ecosystem
- investors receive income based on carbon stored in soil and biomass
- indigenous communities receive income for verifying that deforestation is avoided and biodiversity preserved
- planned reserves to allow species movement in response to changing climate

Farmer receiving SMS messages from remote sensing system alerting about excess water consumption, early warning of water stress etc.

Tea plantation
pays forest conservation fund for pollination and soil preservation services provided by the forest

Private and public advisory services
help farmers adopt new agronomic developments

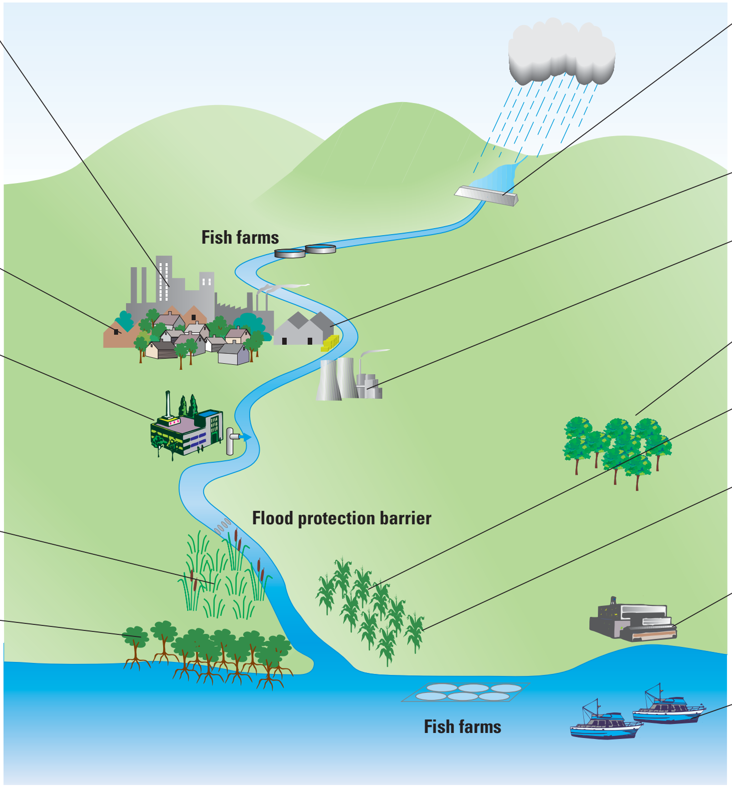
Skilled employees
store, process and pack products for direct contracts with markets

Carbon credits encourage farmers to intersperse crops with trees and provide habitat biodiversity

Water monitors
measure soil moisture

Source: WDR team.

Figure 3.12 An ideal climate-smart landscape of the future would use flexible technology to buffer against climate shocks through natural infrastructure, physical infrastructure, and market mechanisms



City
built away from the flood plain
- distributed energy system including renewables
- planned for low-carbon transport
- buildings use low environmental-impact materials
- road materials and drainage designed for increased temperatures and severe storms

Bonded warehouse
for grain stocks to buffer price shocks in international grain market

Wastewater treatment plant
treated water
- injected into aquifer to protect against saline intrusion
- piped to coastal wetlands to counteract excess abstraction
- used for irrigation upstream

Wetland
peatlands preserved to sequester carbon

Mangroves protected for:
- protected in response to incentives from carbon credits
- provide ecosystem services, including fish nursery

Dam
- provides energy, irrigation and drought and flood protection
- re-engineered to cope with extreme rainfall and minimize environmental damage

Upgraded port and customs facility
to facilitate international trade

Power station
carbon captured and stored underground

Bio-engineered trees
sequester carbon in former wasteland

Modern crop varieties
adapted to climate change stress

Coastal agriculture
with irrigation from coastal aquifers protected from saline intrusion

Desalination plant
- uses renewable energy
- provides water to city and coastal agriculture

Regulated fishery
ensures catch is at sustainable levels

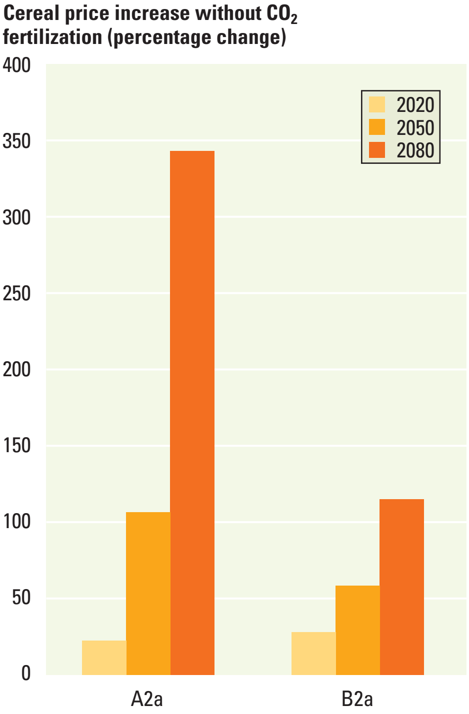
Source: WDR team.

to conserve the natural resources. If implementation difficulties could be overcome, this could buy down the risk to farmers of adopting new practices and help aggregate many small disparate actions. It might also give the right incentives to protect the natural systems on which agriculture and so much else depend. Third, if the world's $258 billion a year in agricultural subsidies were even partially redirected to carbon sequestration and biodiversity conservation, it could demonstrate that the techniques and approaches outlined in this chapter could help cope with and reduce the effects of climate change on the necessary scale.

Rising energy, water, and agricultural prices could spur innovation and investment in increasing productivity

A combination of factors will drive up food prices in the next few decades. They include increased demand for food from growing and increasingly rich populations. They also include increased production of biofuels, which could result in competition for agricultural land and water. Furthermore, it will become more difficult to grow food because of climate change. And as chapter 4 shows, climate-change policies are likely to drive up energy prices.[224]

Figure 3.13 Global cereal prices are expected to increase 50 to 100 percent by 2050, depending on the scenario



Source: Parry and others 2004.

Note: The IPCC A2 family of emission scenarios describes a world where population continues to grow, and the trends of per capita economic growth and technological change vary between regions and are slower than in other story lines. The B2 scenario family describes a world where global population grows at a rate lower than A2 and economic development is intermediate and technological change is less rapid than in the B1 and A1 scenarios.

Higher electricity prices mean higher water prices when water is pumped. In those cases, efficient water allocation mechanisms will become more important, as will efforts to reduce leaks from any poorly maintained water transfer and distribution networks. Higher energy prices also increase the cost to the government of subsidizing water services. This could increase incentives for long-needed reform of water management policies and investments.[225] And higher petroleum prices increase the costs of fertilizers because of their petroleum-based inputs and high transportation costs, thereby encouraging judicious use.

Food prices are expected to be higher and more volatile in the long run. Modeling for the IAASTD (International Assessment of Agricultural Science and Technology for Development) projected that maize, rice, soybean, and wheat prices will increase by 60–97 percent between 2000 and 2050 under business as usual, and prices for beef, pork, and poultry, by 31–39 percent.[226] Other simulations of the world food system also show that climate-induced shortfalls of cereals increase food prices.[227] In most estimates cereal prices are projected to increase, even if farmers adapt.[228] By 2080 different scenarios project that world food prices will have increased by around 7–20 percent with CO_2 fertilization and by around 40–350 percent without (figure 3.13).[229]

Poor people, who spend up to 80 percent of their money on food, probably will be hardest hit by the higher food prices. The higher prices associated with climate change risk reversing progress in food security in several low-income countries. Although scenario results differ, nearly all agree that climate change will put more people at risk of hunger in poorer nations, with the largest increases in South Asia and Africa.[230]

Like energy prices, high food prices have profound effects on the potential adjustments in land and water use stemming from climate change. With longer-term high prices—caused in significant part by climate change—investments in agriculture, land, and water become more profitable for farmers and the public and private sectors. Private agricultural companies, international aid donors, international development banks, and national governments can see and act on the higher international prices fairly quickly. But the transmission of increases in international food prices to farmers is imperfect, as shown in the 2007–08 food price crisis. Farmers in most of Sub-Saharan Africa did see higher food prices after some lag, and the transmission of higher prices was faster and more complete in most of Asia and Latin America.[231]

The better the quality of rural infrastructure, the more farmers benefit from higher international prices. High food prices can spur land conversion to crops and livestock, with negative impacts on ecosystems. But they can also induce significant new investments in agricultural research, irrigation development, and rural infrastructure to intensify production and save land. The simultaneous rise in energy and food prices will also make some big investments profitable again, including large multipurpose dams for power and irrigation. It will be important to channel the incentives from high food prices into innovative investments and policy reforms to save land and water while boosting agricultural productivity.

An international price that paid for avoiding emissions and sequestering carbon in agriculture could encourage better protection of natural systems

Under the Clean Development Mechanism of the Kyoto Protocol, agricultural soil carbon sequestration projects in the developing world are not eligible for selling carbon credits to investors in the developed world. If they could, incentives for farmers and other land users would change fundamentally. Carbon markets that cover greenhouse gases from agricultural practices and integrate across the landscape could be one of the most important mechanisms to drive sustainable development in a world affected by climate change. Recent model projections show that such markets would help prevent the conversion of intact ecosystems (“unmanaged land” in figure 3.14) to meet rising demand for biofuel.

Although the mechanisms for conserving soil carbon through a carbon price are not yet developed, the potential to reduce emissions from agriculture is large: one source estimates 4.6 gigatons of CO_2 or more a year by 2030, which is more than half of the potential from forestry (7.8 gigatons of CO_2 a year).[232] At $100 a ton of CO_2e, potential emission reductions from agriculture are on par with those from energy (see overview, box 9, figure 1).

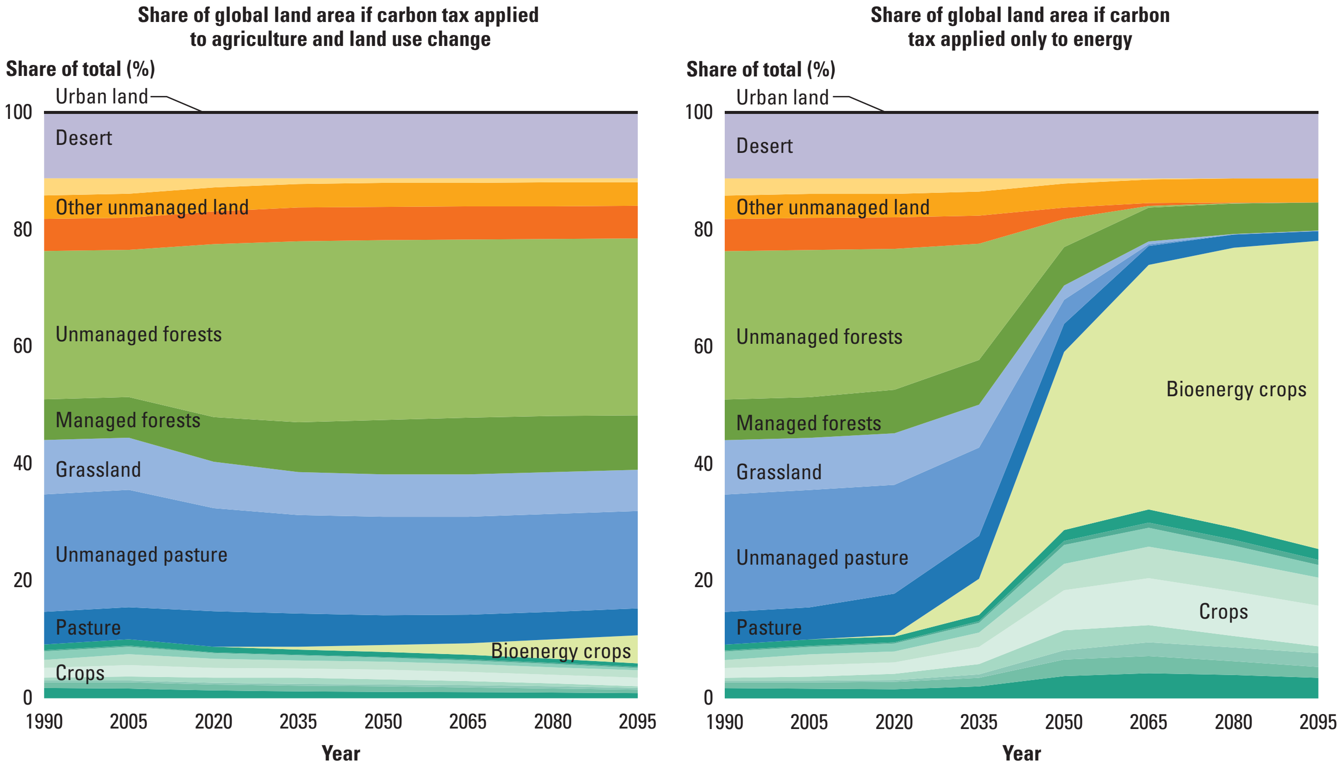
Even in Africa, where relatively carbon-poor drylands make up 44 percent of the continent, the possibility for agricultural carbon sequestration is great.[233] The projected mean agricultural mitigation potential across the continent is significant: about 100 million to 400 million tonnes of CO_2e a year by 2030.[234] With a relatively low carbon price of $10 a ton in 2030, this financial flow would be comparable to the annual official development assistance to Africa.[235] For African pastoralists even modest improvements in natural resource management could produce additional carbon sequestration of 0.50 tonne of carbon a year per hectare; assuming the above price, that would increase incomes by 14 percent.[236]

Carbon sequestration in agriculture would be a relatively inexpensive and efficient response to climate change. The abatement cost in 2030 is estimated to be almost an order of magnitude lower than that in the forestry sector (€1.2 per tonne of CO_2 equivalent compared with €9.0 per ton of CO_2 equivalent).[237] One reason for this is that many agricultural techniques that improve carbon sequestration also increase agricultural yields and revenues.

As chapter 6 discusses, including landscape-based emissions from a diverse array of practices such as agriculture, forestry, and agroforestry in any carbon market mechanism would greatly increase the capacity of that mechanism to conserve biodiversity, increase agricultural productivity, and support rural livelihoods. The techniques for storing more carbon in soil already exist. New developments in

EMBARGOED: Not for newswire transmission, web posting, or any other media use until 10:00 a.m. EDT on Tues., Sept. 15, 2009 (Washington time).

Figure 3.14 A carbon tax applied to emissions from agriculture and land-use change would encourage protection of natural resources.



Source: Wise and others 2009a.

Note: Projections based on the MiniCAM Global Integrated Assessment Model. Both scenarios represent a path to achieve a CO_2 concentration of 450 ppm by 2095. In figure 3.14a, a price is put on carbon emissions from fossil fuels, industry, and land-use change. In figure 3.14b, the same price is applied but only to fossil-fuel and industry emissions. When a price is not applied to terrestrial emissions, growers are likely to encroach into natural habitats, mainly in response to the demand for biofuels.

financing indicate that carbon sequestration from land-based sources could accelerate. But, as discussed earlier, these techniques have not been widely adopted.[238] The list of causes is long—inadequate knowledge of management techniques appropriate to tropical and subtropical soils, weak extension infrastructure to deliver the available innovations, lack of property rights to encourage investments with long-term payoffs but short-term costs, inappropriate fertilizer taxation policies, and poor transport infrastructure.

The world community could take four practical steps to develop this expanded carbon market. First, scientists and people involved in the carbon markets (local and international) need to agree to use activity-based monitoring. This would entail monitoring the type of agricultural practices used and estimating the carbon sequestration, rather than monitoring actual emissions savings for each field.[239] It would not be cost-effective or tractable to measure carbon sequestration across smallholder parcels in the developing world. Moreover, activity-based monitoring is transparent and would allow the farmer to know up front what the payments would be for various activities.

The processes by which soils take up or emit carbon are complex. They vary from place to place (even within a field) and depend on soil properties, climate, farming system, and land-use history. Further, annual changes are usually small relative to existing stocks. And the sequestration is relatively short-lived. Carbon accumulation in soil saturates after about 15–30 years, depending on the agricultural practice, and few emission reductions would occur after that time.[240] Recent studies have shown that in heavy clay soils, no-till agriculture can result in releases of nitrous oxide—a powerful greenhouse gas—that can more than offset the soil CO_2 sink during the first five years after adoption of the soil conservation practice. This finding suggests that the potential of no-till for decreasing net greenhouse gas emissions may be limited in some soils.[241] But it is possible, based on existing data and modeling, to broadly estimate carbon sequestration per agricultural practice for agroecological and climatic zones. Moreover, cost-effective techniques for measuring soil carbon in the field (using lasers, ground-penetrating radar, and gamma ray spectroscopy) now allow for faster measurement of carbon sequestration and the updating of model estimates at smaller spatial scales.[242] In the meantime, programs could use conservative estimates of sequestration across soil types and focus on regions where there is more certainty about soil carbon stocks and flows (such as the more productive agricultural areas). Moreover, no carbon sequestration technique (such as conservation tillage) is a panacea in every cropping system and across every soil type. Myriad practices will have to be implemented.

A model for such a system may be the Conservation Reserve Program administered by the U.S. Department of Agriculture on more than 34 million acres of land since 1986.[243] This voluntary program was initially established to reduce soil erosion, with landowners and agricultural producers entering contracts to retire highly erodible and environmentally sensitive cropland and pasture from production for 10–15 years in return for payments. Over time the program expanded its objective to include the conservation of wildlife habitat and water quality, and the payments are based on an aggregate Environmental Benefits Index of the parcel and the specific activity (such as riparian buffers and shelterbelts). The actual environmental benefits of each parcel are not directly measured but rather estimated based on activities, and a similar scheme-based system could apply to agricultural carbon sequestration.[244]

The second practical step involves developing "aggregators"—typically private or nongovernmental organizations that reduce transaction costs by integrating activities over multiple smallholder farmers, forest dwellers, and pastoralists. Without them the market will tend to favor large reforestation projects in forestry, because the average individual smallholder farmer in the developing world cannot sequester very large amounts. Scaling up spatially will also address issues related to the uncertainty of the carbon stock and impermanence (reversals of carbon sequestration gains). By adopting an actuarial approach and pooling across a portfolio of projects and by making conservative estimates, soil carbon sequestration can be fully equivalent to CO_2 reductions in other sectors.[245]

Third, the up-front costs for carbon-sequestering management practices must be addressed. The relative costs of altering practice are likely higher for poor farmers than for middle- and high-income farmers.[246] Two pilot projects in Kenya provide payments only on delivery of the emission reductions (box 3.9). But this can be remedied by coupling carbon finance projects with other grants, as collateral for loans, or by having investors make some of the payments up front.

Fourth, farmers need to know about their options. This will involve better agricultural advisory services in the developing world. Agricultural extension services are good investments: the average rate of return globally is 85 percent.[247] Companies or organizations that can measure or verify results will also be required.

The Chicago Climate Exchange, one subset of the voluntary market, shows the possible benefits of trading the carbon sequestration potential from landscape-related activities.[248] It allows emitters to receive carbon credits for continuous conservation tillage, grassland planting, and rangeland management. For agricultural carbon trading, the exchange requires that members place 20 percent of all earned offsets in a reserve to insure against possible future reversals. It shows that simplifying rules and using modern monitoring techniques can overcome technical barriers, although some critics claim that "additionality" has not been fully assessed: the net emission reductions may not be additional to what would have happened in the absence of a market.

In the near term the voluntary market incubates methods for agricultural and landscape-level sequestration. But for an expanded carbon market to make really dramatic development gains, it will need to be linked to a future global compliance

BOX 3.9 *Pilot projects for agricultural carbon finance in Kenya*

Preliminary results from two pilot projects in western Kenya indicate that smallholder agriculture can be integrated into carbon finance. One involves mixed cropping systems across 86,000 hectares, using a registered association of 80,000 farmers as the aggregator. Another smaller coffee project encompasses (initially) 7,200 hectares, and a 9,000-member farmer cooperative serves as the aggregator. The average size of landholdings for both projects is small (about 0.3 hectare).

The amount of carbon sequestration is estimated to be 516,000 tons of CO_2 equivalent a year and 30,000 tons of CO_2e a year, respectively,

The sequestration activities include reduced tillage, cover crops, residue management, mulching, composting, green manure, more targeted application of fertilizers, reduced biomass burning, and agroforestry. The projects use activity-based monitoring. The estimates of carbon sequestration over 20 years are derived from a model known as RothC. The World Bank BioCarbon Fund is purchasing the carbon credits based on a price per ton mutually agreed on by the fund and the project developers, VI-Swedish Cooperative Center and ECOM Agroindustrial Group (coffee). Of the total revenues that the communities receive, 80 percent will go to the community bursars and 20 percent to monitoring and project development.

Two lessons appear to be emerging. First, a good aggregator is essential, especially one that can also advise on agricultural practices. Second, the method for monitoring must be simple but also accessible and transparent to the farmer. In these cases, the farmer can easily consult a table to determine the exact payment he or she will receive for each activity, a system that encourages participation.

Source: Kaonga and Coleman 2008; Woelcke and Tennigkeit 2009.

market. The economies of scale that landscape-level sequestration promises will be more readily accessed if there are no “silos” separating sequestration in agriculture and forestry.

Because carbon sequestration activities tend to have a positive impact on soil and water management as well as on yields,[249] the most important aspect of carbon finance applied to soil management may be to serve as a “lever” to execute the sustainable agricultural practices that have so many other benefits. From 1945 to 1990 soil degradation in Africa reduced agricultural productivity by an estimated 25 percent.[250] And about 86 percent of the land in Sub-Saharan Africa is moisture-stressed.[251] Effective carbon finance mechanisms would help reduce the rate of land degradation? A soil compliance carbon market holds great potential for achieving the necessary balance between intensifying productivity, protecting natural resources, and simultaneously helping rural development in some of the world’s poorest communities. Such a market is not yet ready. Technical issues regarding verification, scale, and time frame remain to be solved. The United Nations Framework Convention on Climate Change proposes a phased approach starting with capacity building and financial support. The first phase would demonstrate techniques, monitoring approaches, and financing mechanisms. In the second phase soil carbon techniques would be incorporated into the broader compliance carbon market.[252]

Redirecting agricultural subsidy systems could be an important mechanism for achieving climate-smart land and water management

The member countries of the Organisation for Economic Co-operation and Development provide $258 billion every year in support to their farmers, which amounts to 23 percent of farm earnings.[253] Of this support 60 percent is based on the quantity of a specific commodity produced and on variable inputs with no constraints attached to their use—2 percent is for noncommodity services (such as creating buffer strips to protect waterways, preserving hedgerows, or protecting endangered species).

The political imperatives of climate change offer an opportunity to reform those subsidy schemes, to focus them more on climate-change mitigation and adaptation measures that would also bring benefits to domestic soil, water, and biodiversity resources as well as increase farm productivity. Allocating resources on that scale would produce direct benefits. It would also demonstrate whether these climate-smart techniques can be applied on a large scale in the developing world and attract entrepreneurial ingenuity and energy to find new ways of solving the technical and monitoring problems that will arise.

The European Union has already reformed its Common Agricultural Policy so that member states can withdraw funds for income support (pillar 1), and rural development (pillar 2).[254] Any income support to farmers is contingent on their meeting good environmental and agricultural standards. The eligible rural development actions include measures to improve competitiveness, manage the environment and the land, improve the quality of life, and increase diversification. Under the rural development pillar, farmers can be compensated if they provide environmental services that go beyond the mandatory standards. This reform is a promising initiative to jump-start climate- and farmer-smart agricultural and natural resource policies, and the European Union could serve as a test bed for technologies that could be applied for sustainable land and water management in the developing world.

To cope with the effects of climate change on natural resources and simultaneously reduce emissions of greenhouse gases, societies need to produce more from land and water and protect their resources better. To produce more, they need to increase investment in agriculture and water management, particularly in developing countries. For agriculture that means investing in roads and research and development as well as adopting better policies and institutions. For water, it means using new decision-making tools and better data, strengthening policies and institutions, and investing in infrastructure. The expected increase in prices of agricultural production will give farmers and other resource users an incentive to innovate and invest. But the increased profitability will also increase incentives to overexploit resources. Protection needs the same increase in effort as production.

A number of tools, techniques, and approaches exist that can help users protect natural resources better. But users often do not have the right incentives to apply them. There are disparities in space and in time. What is best for a farmer isn't best for the whole landscape or watershed. What's optimal over a short time period isn't optimal over decades. Doing things differently also involves asking poor farmers and rural dwellers to take risks they may not be willing to take.

Governments and public organizations can take three types of actions to make the incentives for resource users more climate-smart. First, they can provide information so that people can make informed choices and can enforce cooperative agreements. This can be high-tech-generated information. It can also be information that communities themselves gather. Second, they can set a price for retaining or storing carbon in the soil. Done right, this will reduce the risks to farmers of adopting new practices. It will also help resource users take a longer time horizon in their decisions. Third, they can

> *"Our global is facing environmental problems due to human behavior—cutting down trees, air pollution, use of plastics cannot be reused or recycled, chemical hazards in agriculture. . . . Global warming has affected us greatly by causing tsunamis, El Ninó, cyclones, flood, greenhouse effect, earthquake, and volcano disruption. . . . Tree planting would reduce CO_2. Biking and mass transit would reduce air pollution and energy saving for the better world."*
>
> —Netpakaikarn Netwong, Thailand, age 14

redirect agricultural subsidies, particularly in rich countries, so that they encourage climate-smart rural development practices. These subsidies can be transformed to show how the new techniques can be adopted on a large scale, and they can be used to equalize spatial disparities so that individual actions are a better fit with the needs of the landscape as a whole. Finally, they can attract the ingenuity and creativity needed to achieve the delicate balancing act of feeding the world of nine billion people, reducing greenhouse gas emissions, and protecting the natural resource base.

Notes

1. See for example Lotze-Campen and others 2009.
2. IPCC 2007b.
3. OECD 2008.
4. Burke and Brown 2008; Burke, Brown, and Christidis 2006.
5. Milly and others 2008; Barnett, Adam, and Lettenmaier 2005.
6. de la Torre, Fajnzylber, and Nash 2008.
7. World Water Assessment Programme 2009.
8. Perry and others forthcoming.
9. World Water Assessment Programme 2009.
10. World Bank 2009e.
11. World Bank 2009e.
12. Molden 2007.
13. Milly and others 2008; Ritchie 2008; Young and McColl 2005.
14. As the public trustee of the nation's water resources, the national government, acting through the minister of water affairs, must ensure that water is protected, used, developed, conserved, managed, and controlled in a sustainable and equitable manner, for the benefit of all persons and in accordance with its constitutional mandate. Salman M. A. Salman, World Bank Staff, personal communication, July 2009.
15. Dye and Versfeld 2007.
16. Bates and others 2008.
17. Molle and Berkoff 2007.
18. Molle and Berkoff 2007; OECD 2009.
19. Olmstead, Hanemann, and Stavins 2007.
20. Molle and Berkoff 2007.
21. Asad and others 1999.
22. Bosworth and others 2002.
23. See Murray Darling Basin Agreement Schedule E, http://www.mdbc.gov.au/about/the_mdbc_agreement.
24. Molle and Berkoff 2007.
25. Rosegrant and Binswanger 1994.
26. World Bank 2007b.
27. Bates and others 2008; Molden 2007.
28. Young and McColl 2005.
29. http://www.environment.gov.au/water/mdb/overallocation.html (accessed May 7, 2009).
30. Molden 2007.
31. World Bank 2009b.
32. World Bank 2009b.
33. World Bank 2009b.
34. Bhatia and others 2008.
35. Strzepek and others 2004.
36. World Commission on Dams 2000; For discussion of the impacts of the High Dam at Aswan on soil fertility and coastlines in the Nile Delta, see Ritchie 2008.
37. World Water Assessment Programme 2009.
38. Danfoss Group Global. http://www.danfoss.com/Solutions/Reverse+Osmosis/Case+stories.htm (accessed May 9, 2009).
39. FAO 2004b.
40. Desalination is also viable for high-value agriculture in some parts of the world, such as Spain. Gobierno de Espana 2009.
41. World Water Assessment Programme 2009.
42. Molden 2007.
43. Molden 2007.
44. Molden 2007.
45. Rosegrant, Cai, and Cline 2002.
46. For example, see citation from the *Indian Financial Express* on December 1 2008, cited in Perry and others forthcoming.
47. De Fraiture and Perry 2007; Molden 2007; Ward and Pulido-Velazquez 2008.
48. Perry and others forthcoming.
49. Moller and others 2004; Perry and others forthcoming.
50. Perry and others forthcoming.
51. www.fieldlook.com (accessed May 5, 2009).
52. Perry and others forthcoming.
53. World Bank 2009d.
54. Carbon dioxide is an input in photosynthesis, which uses sunlight to produce carbohydrates. Thus, higher CO_2 concentrations will have a positive effect on many crops, enhancing biomass accumulation and final yield. In addition, higher CO_2 concentrations reduce plant stomatal openings and thus reduce water loss. The so-called C3 crops, such as rice, wheat, soybeans, legumes, and trees, should benefit more than the C4 crops, such as maize, millet, and sorghum. Recent field experiments indicate that past laboratory tests have overstated the effect. One study indicates that at CO_2 concentrations of 550 parts per million, yield increases amounted to 13 percent for wheat, not 31 percent; 14 percent for soybeans, not 32 percent; and 0 percent, not 18 percent, for C4 crops. Cline 2007.
55. Easterling and others 2007.
56. EBRD and FAO 2008.
57. Sutton, Block, and Srivastava 2008.
58. A food production shortfall is a year in which potential production of the most impor-

tant crops in an administrative region is below 50 percent of its average climate-normal production. The greater likelihood of shortfalls occurring in more than one region in a given year may compromise the ability of exports from other regions to compensate for food production deficiencies, thus leading to food security concerns. Alcamo and others 2007.

59. Easterling and others 2007.

60. Cline 2007. The high-emission scenario is the IPCC A2 scenario, which over a range of models, leads to a mean temperature increase of 3.13°C from 2080 to 2099 relative to 1980–99. Meehl and others 2007.

61. Lobell and others 2008.

62. Schmidhuber and Tubiello 2007.

63. Based on five climate models and the high-emission SRES A2 scenario. Fischer and others 2005.

64. Calculation based on FAO 2009c.

65. IPCC 2007a

66. Emissions come from converting unmanaged land to agriculture, and from soil erosion.

67. van der Werf and others 2008.

68. This 18 percent sums the estimated contribution of livestock within several categories, such as land use, land-use change, and foresry, to get the total contribution of livestock. It comprises livestock greenhouse gas emissions from land-use change (36 percent); manure management (31 percent); direct emission by animals (25 percent); feed production (7 percent); and processing and transport (1 percent). Steinfeld and others 2006.

69. IEA 2006. This estimate assumes that current trade restrictions are maintained. If those restrictions change, particularly those that restrict imports of biofuels into the United States, there could be a large regional shift in production.

70. Gurgel, Reilly, and Paltsev 2008.

71. National Research Council of the National Academies 2007; Tilman, Hill, and Lehman 2006

72. Beckett and Oltjen 1993.

73. Hoekstra and Chapagain 2007. Pimentel and others (2004) give an estimate of 43,000 liters per kilogram of beef.

74. Peden, Tadesse, and Mammo 2004. In this system one head of cattle consumes 25 liters of water a day over a two-year period to produce 125 kilograms of dress weight and consumes crop residues for which no additional water input is required.

75. Williams, Audsley, and Sandars 2006. Some sources give higher emission estimates for meat production-up to 30 kilogram of CO_2e per kilogram of beef produced, for example. Carlsson-Kanyama and Gonzales 2009.

76. Randolph and others 2007; Rivera and others 2003.

77. Delgado and others 1999; Rosegrant and others 2001; Rosegrant, Fernandez, and Sinha 2009; Thornton 2009; World Bank 2008e

78. One study projects that total good and prime agricultural land available will remain virtually unchanged at 2.6 billion and 2 billion hectares, respectively, in 2080 compared with the end of the 20th century (based on the Hadley Centre HadCM3 climate model and assuming the very high emission scenario, SRES A1F1 and comparing 1961-90 to 2080. Fischer, Shah, and van Velthuizen 2002; Parry and others 2004.

79. Lotze-Campen and others 2009; Wise and others 2009b.

80. Cassman 1999; Cassman and others 2003.

81. Calculated from FAO 2009c.

82. Diaz and Rosenberg 2008.

83. Schoups and others 2005.

84. Delgado and others 1999.

85. Hazell 2003.

86. Hazell 2003; Rosegrant and Hazell 2000.

87. Pingali and Rosegrant 2001.

88. Reardon and others 1998.

89. Rosegrant and Hazell 2000.

90. Rosegrant and Hazell 2000.

91. One form of specialized agricultural products is known as functional foods. These are products in food or drink form that influence functions in the body and thereby offer benefits for health, well-being, or performance beyond their regular nutritional value. Examples include antioxidant foods, such as guarana and acai berry, vitamin A-rich golden rice and orange-fleshed sweet potato, margarine fortified with plant sterols to improve cholesterol levels, and eggs with increased omega-3 fatty acids for heart health. Kotilainen and others 2006.

92. Kotilainen and others 2006.

93. Ziska 2008.

94. T. Christopher, "Can Weeds Help Solve the Climate Crisis?" *New York Times*, June 29, 2008.

95. Ziska and McClung 2008.

96. UNEP-WCMC 2008. In the oceans the situation is even more paltry. Approximately 2.58 million square kilomaters, or 0.65 percent of the world's oceans and 1.6 percent of the total marine area within Exclusive Economic Zones, are marine protected areas. Laffoley 2008.

97. Gaston and others 2008.

98. Hannah and others 2007.

99. Dudley and Stolton 1999.

100. Struhsaker, Struhsaker, and Siex 2005.

101. Scherr and McNeely 2008; McNeely and Scherr 2003.

102. Van Buskirk and Willi 2004.

103. Scherr and McNeely 2008.

104. McNeely and Scherr 2003.

105. Chan and Daily 2008.

106. Leguminous trees contain symbiotic bacterial nodules that fix atmospheric nitrogen therefore enhancing the nutrients load in the plants and in the soil.

107. McNeely and Scherr 2003.

108. Ricketts and others 2008.

109. Klein and others 2007.

110. Lin, Perfecto, and Vandermeer 2008.

111. World Bank 2008a.

112. World Bank 2008a.

113. Of the $6 billion spent annually on land trusts and conservation easements, a third is in the developing world. Scherr and McNeely 2008.

114. A typical system of zoning for conservation allows development in some areas and limits it in conservation areas. Tradable development rights are an alternative to pure zoning that allows for substitutability between areas in meeting conservation goals and provides incentives for compliance. Some landowners agree to restrict property rights, that is, development, in return for payments. For instance, a government law may prescribe that 20 percent of each private property be maintained as natural forest. Landowners would be permitted to deforest beyond the 20 percent threshold, if they purchase from other landowners, who sell the development rights of "surplus" forest, which is irreversibly placed under forest reserve status. Chomitz 2004.

115. IAASTD 2009.

116. World Bank 2008c.

117. Alston and others 2000; World Bank 2007c.

118. Beintema and Stads 2008.

119. Blaise, Majumdar, and Tekale 2005; Govaerts, Sayre, and Deckers 2005; Kosgei and others 2007; Su and others 2007.

120. Thierfelder, Amezquita, and Stahr 2005; Zhang and others 2007.

121. Franzluebbers 2002.

122. Govaerts and others 2009.

123. Derpsch and Friedrich 2009

124. Derpsch 2007; Hobbs, Sayre, and Gupta 2008.

125. World Bank 2005.

126. Derpsch and Friedrich 2009; Erenstein and Laxmi 2008.

127. Erenstein 2009.

128. Erenstein and others 2008.

129. de la Torre, Fajnzylber, and Nash 2008.

130. Passioura 2006.

131. Yan and others 2009.

132. Thornton 2009.

133. Smith and others 2009.

134. Doraiswamy and others 2007; Perez and others 2007; Singh 2005.

135. Such as the deep placement of urea briquettes or supergranules.

136. Singh 2005.

137. Singh 2005.

138. Poulton, Kydd, and Dorward 2006; Dorward and others 2004; Pender and Mertz 2006.

139. Hofmann and Schellnhuber 2009; Sabine and others 2004.

140. Hansen and others 2005.

141. FAO 2009e.

142. FAO 2009e.

143. Delgado and others 2003.

144. FAO 2009e.

145. Arkema, Abramson, and Dewsbury 2006.

146. Smith, Gilmour, and Heyward 2008.

147. Gordon 2007.

148. Armada, White, and Christie 2009.

149. Pitcher and others 2009.

150. OECD 2008; World Bank 2008d.

151. FAO 2009e.

152. World Bank 2008d.

153. Costello, Gaines, and Lynham 2008; Hardin 1968; Hilborn 2007a; Hilborn 2007b

154. Delgado and others 2003.

155. FAO 2009c. Fish and seafood include both marine and freshwater fish and invertebrates. Total animal protein includes the former, plus all terrestrial meat, milk, and other animal products. The data are for 2003.

156. United Nations 2009.

157. FAO 2009c (2003 data).

158. FAO 2009e.

159. FAO 2009e.

160. World Bank 2006.

161. De Silva and Soto 2009.

162. De Silva and Soto 2009.

163. FAO 2004a.

164. Gyllenhammar and Hakanson 2005.

165. Deutsch and others 2007.

166. Gatlin and others 2007.

167. Tacon, Hasan, and Subasinghe 2006.

168. Tacon, Hasan, and Subasinghe 2006.

169. Naylor and others 2000.

170. Primavera 1997.

171. Tal and others 2009.

172. Naylor and others 2000.

173. FAO 2001; Lightfoot 1990.

174. Delgado and others 2003.

175. FAO 2009b.

176. For example, China and Nepal are not parties to an agreement between Bangladesh and India for the water of the Ganges basin and receive no allocation.

177. Salman 2007.

178. Qaddumi 2008.

179. Kurien 2005.

180. FAO 2009e.

181. Duda and Sherman 2002.

182. FAO 2009d; Sundby and Nakken 2008.

183. Lodge 2007.

184. BCLME Programme 2007.

185. GEF 2009.

186. World Bank 2009c.

187. Fischer and others 2005.

188. Rosegrant, Fernandez, and Sinha 2009.

189. Easterling and others 2007.

190. FAO 2008.

191. Mitchell 2008. Climate shocks have led to restrictive domestic food trade policies and exacerbated price increases in the past as well; for examples, see Battisti and Naylor 2009.

192. "Outsourcing's Third Wave." *Economist,* May 21, 2009.

193. von Braun and Meinzen-Dick 2009.

194. World Bank 2009c.

195. World Bank 2009c.

196. von Braun and others 2008.

197. Bouet and Laborde 2008.

198. Other issues need a case-by-case assessment, such as exemptions from tariff cuts on special products, as sought by developing countries for products specified as important for food security, livelihood security, and rural development. World Bank 2007c.

199. WMO 2000.

200. Xiaofeng 2007.

201. United Nations 2004.

202. Science and Development Network. www.Scidev.net November 7, 2006.

203. WMO 2007.

204. Barnston and others 2005; Mason 2008.

205. Moron and others forthcoming; Moron, Robertson, and Boer 2009; Moron, Robertson, and Ward 2006; Moron, Robertson, and Ward 2007.

206. Sivakumar and Hansen 2007.

207. Patt, Suarez, and Gwata 2005.

208. Two large flood events in July and September 2007 on the Brahmaputra River were forecast with some accuracy 10 days ahead, based on medium-range weather forecasts and fine-tuned hydrological models. For the first time, the country's Disaster Emergency Response Group was planning and evacuating ahead of the flooding. Winston Yu, World Bank, personal communication.

209. Patt, Suarez, and Gwata 2005.

210. Bastiaanssen 1998; Menenti 2000.

212. WaterWatch, www.waterwatch.nl (accessed May 9, 2009).

213. Bastiaansen, W., WaterWatch, personal communication, May 2009.

214. http://www.globalsoilmap.net/ (accessed May 15, 2009).

215. Bindlish, Crow, and Jackson 2009; Frappart and others 2006; Turner and others 2003.

216. Bouma, van der Woerd, and Kulik 2009.

217. UNESCO 2007.

218. World Bank 2008d.

219. Kumar 2004.

220. World Bank 2007a.

221. World Bank 2009b.

222. World Bank 2008b.

223. World Bank 2008b.

224. Mitchell 2008.

225. Zilberman and others 2008.

226. Rosegrant, Fernandez, and Sinha 2009.

227. Parry and others 1999; Parry, Rosenzweig, and Livermore 2005; Rosenzweig and others 2001.

228. Rosenzweig and others 2001.

229. Parry and others 2004.

230. Fischer and others 2005b; Parry and others 1999; Parry and others 2004; Parry 2007; Parry, Rosenzweig, and Livermore 2005; Schmidhuber and Tubiello 2007.

231. Dawe 2008; Robles and Torero forthcoming; Simler 2009.

232. McKinsey Global Institute 2009.

233. Perez and others 2007.

234. Smith and others 2009.

235. The official development assistance flow to Africa from 1996 to 2004 was about $1.30 billion a year: World Bank 2007c.

236. Perez and others 2007.

237. McKinsey Global Institute 2009.

238. Erenstein and others 2008; Hobbs 2007.

239. The sequestration benefits of those activities would be regularly updated based on the state-of-the-art measurement and model-based approaches.

240. West and Post 2002.

241. Rochette and others 2008.

242. Johnston and others 2004.

243. Sullivan and others 2004.

244. In the Conservation Reserve Program, however, landowners bid on the payments and the government accepts or rejects the bids, which is quite different than a carbon emissions trading market.

245. McKinsey Global Institute 2009.

246. Tschakert 2004.

247. Alston and others 2000.

248. Chicago Climate Exchange, http://www.chicagoclimatex.com/index.jsf (accessed February 10, 2009).

249. Lal 2005.

250. UNEP 1990.

251. Swift and Shepherd 2007.

252. FAO 2009a.

253. OECD 2008.

254. http://ec.europa.eu/agriculture/capreform/infosheets/crocom_en.pdf (accessed May 12, 2009).

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CHAPTER 4

Energizing Development without Compromising the Climate

With the global economy set to quadruple by midcentury, energy-related carbon dioxide (CO_2) emissions would, on current trends, more than double, putting the world onto a potentially catastrophic trajectory that could lead to temperatures more than 5°C warmer than in preindustrial times. That trajectory is not inevitable. With concerted global action to adopt the right policies and low-carbon technologies, the means exist to shift to a more sustainable trajectory that limits warming to close to 2°C. In the process, there is an opportunity to produce enormous benefits for economic and social development through energy savings, better public health, enhanced energy security, and job creation.

Such a sustainable energy path requires immediate action by all countries to become much more energy efficient and achieve significantly lower carbon intensity. The path requires a dramatic shift in the energy mix from fossil fuels to renewable energy and nuclear power, along with widespread use of carbon capture and storage (CCS). This, in turn, requires major cost reductions in and widespread diffusion of renewable energy technologies, safeguards for containment of nuclear waste and weapons proliferation, and breakthroughs in technologies from batteries to carbon capture and storage. And it also requires fundamental shifts in economic development and lifestyles. If even one of these requirements is not met, keeping temperature increases close to 2°C above preindustrial levels may be impossible.

In order to limit warming to 2°C, global emissions would have to peak no later than 2020 and then decline by 50–80 percent from today's levels by 2050, with further reductions continuing to 2100 and beyond. Delaying actions by 10 years would make it impossible to reach this goal. The inertia in energy capital stocks means that investments over the next decade will largely determine emissions through 2050 and beyond. Delays would lock the world into high-carbon infrastructure, later requiring costly retrofitting and premature scrapping of existing capital stocks.

Governments should not use the current financial crisis as an excuse to delay climate change actions, because the future climate crisis is likely to be more damaging to the world economy. The economic downturn may delay the business-as-usual growth in emissions by a few years, but it is unlikely to fundamentally change that path over

Key messages

Solving the climate change problem requires immediate action in all countries and a fundamental transformation of energy systems—significant improvement in energy efficiency, a dramatic shift toward renewable energy and possibly nuclear power, and widespread use of advanced technologies to capture and store carbon emissions. Developed countries must lead the way and drastically cut their own emissions by as much as 80 percent by 2050, bring new technologies to market, and help finance developing countries' transition onto clean energy paths. But it is also in developing countries' interests to act now to avoid locking into high-carbon infrastructure. Many changes—such as removing distortionary price signals and increasing energy efficiency—are good both for development and the environment.

the long term. Instead, the downturn offers opportunities for governments to provide stimulus investment in efficient and clean energy to meet the twin goals of revitalizing economic growth and mitigating climate change (box 4.1).

Governments can adopt climate-smart domestic policies now to deploy existing low-carbon technologies while a global climate deal is negotiated. Energy efficiency is the largest and lowest-cost source of emission reductions and is fully justified by development benefits and future energy savings. The potential is huge on both the energy supply side (as in the burning of coal, oil, and gas and the production, transmission, and distribution of electricity) and on the demand side (use of energy in buildings, transport, and manufacturing). But the fact that so much efficiency potential remains untapped suggests that it is not easy to realize. Achieving significant energy savings requires price increases and the removal of fossil-fuel subsidies as well as a concerted strategy to tackle market failures and nonmarket barriers with effective regulations, financial incentives, institutional reforms, and financing mechanisms.

The second-largest source of emission reductions could come from use of low- to zero-emission fuels for power generation—particularly renewable energy. Many of these technologies are commercially available today, have benefits for development, and can be deployed much more widely under the right policy frameworks. Scaling them up requires putting a price on carbon and providing financial incentives to deploy low-carbon technologies. And large-scale deployment will help reduce their costs and make them more competitive.

BOX 4.1 *The financial crisis offers an opportunity for efficient and clean energy*

The financial crisis brings both challenges and opportunities to clean energy. Sharply falling fossil-fuel prices discourage energy conservation and make renewable energy less competitive. The weak macroeconomic environment and tight credit have led to lower demand and declining investment, and renewable energy is hard hit because of its capital-intensive nature (renewable energy is characterized by high up-front capital costs but low operating and fuel costs). By the final quarter of 2008 clean energy investments dropped by more than half from their peak at the end of 2007.[a]

Yet the financial crisis should not be an excuse to delay climate-change action, for it offers opportunities to shift to a low-carbon economy (see chapter 1). First, stimulus investments in energy efficiency, renewable energy, and mass transit can create jobs and build an economy's productive capacity.[b] Second, falling energy prices provide a unique opportunity to implement programs to eliminate fossil-fuel subsidies in emerging economies and adopt fuel taxes in advanced economies in ways that are politically and socially acceptable.

Sources: WDR team based on
a. World Economic Forum 2009.
b. Bowen and others 2009.

But these win-wins, good for both development and climate change, are, on their own, simply not enough to stay on a 2°C trajectory. Not-yet-proven advanced technologies, such as carbon capture and storage, are needed urgently and on a large scale. That will require greatly enhanced research, development, and demonstration as well as technology sharing and transfer to accelerate widespread availability and use.

An economywide, market-based mechanism, such as a carbon cap-and-trade program or a carbon tax (see chapter 6), is essential to unleash robust private sector investment and innovation to achieve deep emission cuts at least cost. Coordinated and integrated government approaches are needed to ensure compatible policies to achieve low-carbon economies while minimizing conflicts and risks of social and economic disruptions.

Developed countries must take the lead in committing to deep emission cuts, pricing carbon, and developing advanced technologies. That is the surest way to trigger development of the needed technologies and ensure their availability at a competitive price. But unless developing countries also start transforming their energy systems as they grow, limiting warming to close to 2°C above preindustrial levels will not be achievable. That transformation requires transfers of substantial financial resources and low-carbon technologies from developed to developing countries.

Energy mitigation paths, and the mix of policies and technologies necessary to reach them, differ among high-, middle-, and low-income countries, depending on their economic structures, resource endowments, and institutional and technical capabilities. A dozen high- and middle-income countries account for two-thirds of global energy-related emissions, and their emission reductions are essential to avoid dangerous climate change. This chapter analyzes the mitigation paths and challenges facing some of these countries. It also presents a portfolio of policy instruments and clean energy technologies that can be used to follow the 2°C trajectory.

Balancing competing objectives

Energy policies have to balance four competing objectives—sustain economic growth, increase energy access for the world's poor, enhance energy security, and improve the environment—tall orders. Fossil-fuel combustion produces around 70 percent of greenhouse gas emissions[1] and is the primary source of harmful local air pollution. Many win-win options can mitigate climate change and abate local air pollution through reducing fossil-fuel combustion (box 4.2), but the tradeoffs need to be weighed. For example, sulfates emitted when coal is burned damage human health and cause acid rain, but they also have local cooling effects that offset warming.

Developing countries need reliable and affordable energy to grow and to extend service to the 1.6 billion people without electricity and the 2.6 billion without clean cooking fuels. Increasing access to electricity services and clean cooking fuels in many low-income developing countries, particularly in South Asia and Sub-Saharan Africa, would add less than 2 percent to global CO_2 emissions.[2] Replacing traditional biomass fuels used for cooking and heating with modern energy supplies can also reduce emissions of black carbon—an important contributor to global warming[3]—improve the health of women and children otherwise exposed to high levels of indoor air pollution from traditional biomass, and reduce deforestation and land degradation (see chapter 7, box 7.10).[4]

Energy supplies also face adaptation challenges. Rising temperatures are likely to increase demand for cooling and reduce demand for heating.[5] Higher demand for cooling strains electricity systems, as in the European heat wave of 2007. Climate extremes accounted for 13 percent of the variation in energy productivity in developing countries in 2005.[6] Unreliable or changing precipitation patterns affect the reliability of hydropower. And droughts and heat waves that affect the availability and temperature of water hamper thermal and nuclear energy production,[7] because the plants require substantial water for cooling—as in the case of power shortages in France during the 2007 heat wave.

The challenge then is to provide reliable and affordable energy services for economic growth and prosperity without compromising the climate. Low-income countries now account for only 3 percent of global energy demand and energy-related emissions. While their energy demand will increase with rising income, their emissions are projected to remain a small share of global emissions in 2050. But middle-income countries, many with expanding economies and a large share of heavy industry, face huge energy needs. And developed countries demand enormous amounts of energy to maintain their current lifestyles.

Low-carbon energy choices can substantially improve energy security by reducing price volatility or exposure to disruptions in energy supplies,[8] but tradeoffs exist. Energy efficiency can reduce energy demand, and renewable energy diversifies the energy mix and reduces exposure to fuel price shocks.[9] But coal, the most carbon-intensive fossil fuel, is abundant near many high-growth areas and provides low-cost and secure energy supplies. Recent oil price swings and uncertainty about gas supplies are leading to increased interest in new coal-fired power plants in many countries (developed and developing). Reducing reliance on oil and gas imports by turning to coal-to-liquid and coal-to-gas production would substantially increase CO_2 emissions. Global coal consumption has grown faster than consumption of any other fuel since 2000, presenting a formidable dilemma among economic growth, energy security, and climate change.

Faced with such challenges and competing objectives, the market alone will not deliver efficient and clean energy in the time and at the scale required to prevent

BOX 4.2 *Efficient and clean energy can be good for development*

Valuing the co-benefits of energy efficiency and clean energy for development—more energy savings, less local air pollution, greater energy security, more employment in local industry, and greater competitiveness from higher productivity—can justify part of the mitigation cost and increase the appeal of green policies. Energy savings could offset a significant share of mitigation costs.[a] The actions needed for the 450 parts per million (ppm) CO_2e concentrations associated with keeping warming at 2°C could reduce local air pollution (sulfur dioxide and nitrogen oxides) by 20–35 percent compared with business as usual in 2030.[b] In 2006 the renewable energy industry created 2.3 million jobs worldwide (directly or indirectly), and energy efficiency added 8 million jobs in the United States.[c] The energy-efficiency and technology-innovation programs in California over the past 35 years have actually increased gross state product.[d]

Many countries, both developed and developing, are setting targets and policies for clean energy technologies (see table). Many of these initiatives are driven by domestic development benefits, but they can also reduce CO_2 emissions substantially. The Chinese government's target of a 20 percent reduction in energy intensity from 2005 to 2010 would reduce annual CO_2 emissions by 1.5 billion tons by 2010, the most aggressive emission reduction target in the world, five times the 300-million-ton reduction of the European Union's Kyoto commitment and eight times the 175-million-ton reduction of the California emission reduction target.[e]

Sources:
a. IEA 2008b; McKinsey Global Institute 2009a.
b. IEA 2008c.
c. EESI 2008;
d. Roland-Holst 2008.
e. Lin 2007.

Many countries have national plans or proposals for energy and climate change

Country	Climate change	Renewable energy	Energy efficiency	Transport
European Union	20 percent emission reduction from 1990 to 2020 (30 percent if other countries commit to substantial reductions); 80 percent reduction from 1990 to 2050	20 percent of primary energy mix by 2020	20 percent energy savings from the reference case by 2020	10 percent transport fuel from biofuel by 2020
United States	Emission reduction to 1990 levels by 2020; 80 percent reduction from 1990 to 2050	25 percent of electricity by 2025		Increase fuel economy standard to 35 miles a gallon by 2016
Canada	20 percent reduction from 2006 to 2020			
Australia	15 percent reduction from 2000 to 2020			
China	National Climate Change Plan and White Paper for Policies and Actions for Climate Change, a leading group on energy conservation and emission reduction established, chaired by the prime minister	15 percent of primary energy by 2020	20 percent reduction in energy intensity from 2005 to 2010	35 miles a gallon fuel economy standard already achieved; plan to be the world leader in electric vehicles; and mass construction of subways under way
India	National Action Plan on Climate Change: per capita emissions not to exceed developed countries, an advisory council on climate change created, chaired by the prime minister	23 gigawatts of renewable capacity by 2012	10 gigawatts of energy savings by 2012	Urban transport policy: increase investment in public transport
South Africa	Long-term mitigation scenario: emissions peak in 2020 to 2025, plateau for a decade, and then decline in absolute terms	4 percent of the power mix by 2013	12 percent energy-efficiency improvement by 2015	Plan to be the world leader in electric vehicles; and expand bus rapid transit
Mexico	50 percent emission reduction from 2002 to 2050; national strategy on climate change: intersecretariat commission on climate change set up for coordination	8 percent of the power mix by 2012	Efficiency standards, cogeneration	Increase investment in public transport
Brazil	National plan on climate change: reducing deforestation 70 percent by 2018	10 percent of the power mix by 2030	103 terawatt hours of energy savings by 2030	World leader in ethanol production

Sources: Government of China 2008; Government of India 2008; Government of Mexico 2008; Brazil Interministerial Committee on Climate Change 2008; Pew Center 2008a; Pew Center 2008b; McKinsey Global Institute 2009d.

Note: Some of the above goals represent formal commitments, while others are still under discussion.

dangerous climate change. Pollution needs to be priced. Achieving the needed progress in energy efficiency requires price incentives, regulations, and institutional reforms. And the risks and scale of the investments in unproven technologies call for substantial public support.

Breaking the high-carbon habit

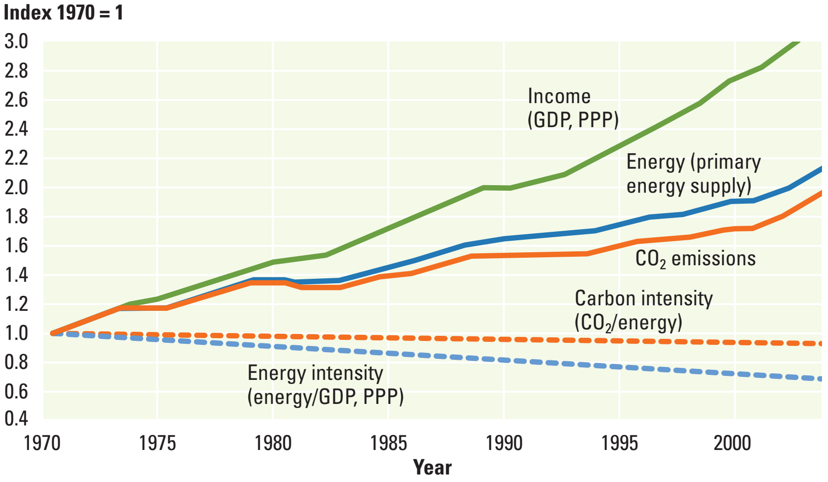
Carbon emissions from energy are determined by the combination of total energy consumption and its carbon intensity (defined as the units of CO_2 produced by a unit of energy consumed). Energy consumption increases with income and population but with sizable variation depending on economic structure (manufacturing and mining are more energy intensive than agriculture and services), climate (which affects the need for heating or cooling), and policies (countries with higher energy prices and more stringent regulations are more energy efficient). Similarly, the carbon intensity of energy varies depending on domestic energy resources (whether a country is rich in coal or hydro potential) and policies. So the policy levers for a low-carbon growth path include reducing energy intensity (defined as energy consumed per dollar of gross domestic product, or GDP) by increasing energy efficiency and shifting to low-energy-consuming lifestyles—and reducing carbon intensity of energy by shifting to low-carbon fuels such as renewable energy.

A doubling of energy consumption since the 1970s combined with near-constant carbon intensity has resulted in a doubling of emissions (figure 4.1). Energy intensity has improved but far too little to offset the tripling in world income. And carbon intensity has remained relatively constant as achievements in producing cleaner energy have been largely offset by a massive increase in the use of fossil fuels.

Fossil fuels dominate global energy supplies, accounting for more than 80 percent of the primary energy mix (figure 4.2). With the global economy set to increase fourfold between now and 2050, energy use and energy-related CO_2 emissions will more than double if the world continues its heavy reliance on fossil fuels.[10]

Developed countries are responsible for about two-thirds of the cumulative energy-related CO_2 now in the atmosphere.[11] They also consume five times more energy per capita, on average, than developing countries. But developing countries already account for 52 percent of annual energy-related emissions, and their energy consumption is increasing rapidly—90 percent of the projected increases in global energy consumption, coal use, and energy-related CO_2 emissions over the next 20 years will likely be in developing countries.[12] Projections suggest that because

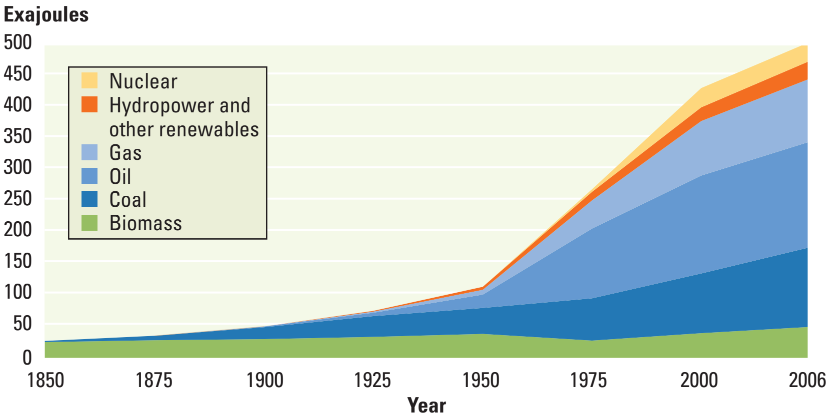
Figure 4.1 The story behind doubling emissions: improvements in energy and carbon intensity have not been enough to offset rising energy demand boosted by rising incomes



Source: IPCC 2007.

Note: GDP is valued using purchasing power parity (PPP) dollars.

Figure 4.2 Primary energy mix 1850–2006. From 1850 to 1950 energy consumption grew 1.5 percent a year, driven mainly by coal. From 1950 to 2006 it grew 2.7 percent a year, driven mainly by oil and natural gas.



Source: WDR team, based on data from Grübler 2008 (data for 1850–2000) and IEA 2008c (data in 2006).

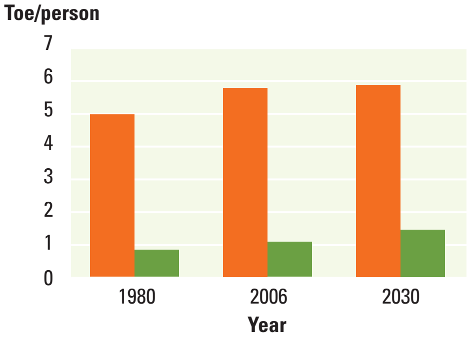
Note: To ensure consistency of the two data sets, the substitution equivalent method is used to convert hydropower to primary energy equivalent—assuming the amount of energy to generate an equal amount of electricity in conventional thermal power plants with an average generating efficiency of 38.6 percent.

such a large share of global population is in developing countries, they will use 70 percent more total energy annually than developed countries by 2030, even though their energy use per capita will remain low (figure 4.3).

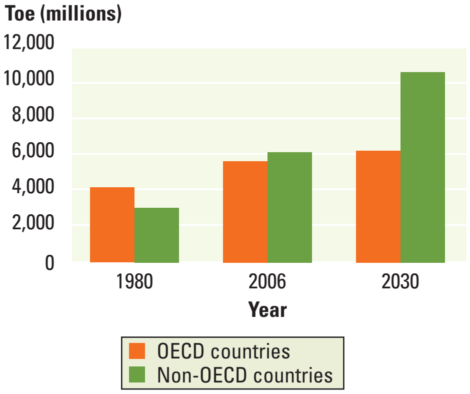
Globally, power is the largest single source of greenhouse gas emissions (26 percent), followed by industry (19 percent), transport (13 percent), and buildings (8 percent),[13] with land-use change, agriculture, and waste accounting for the balance (figure 4.4). The picture varies, however, across income groups. Developed-country emissions are dominated by power and transport, while land-use change and agriculture are the leading emission sources in low-income countries. In middle-income countries, power, industry, and land-use change are the largest contributors—but with land-use change emissions concentrated in a handful of countries (Brazil and Indonesia account for half the global land-use change emissions). Power will most likely continue to be the largest source, but emissions are expected to rise faster in transport and industry.

Figure 4.3 Despite low energy consumption and emissions per capita, developing countries will dominate much of the future growth in total energy consumption and CO_2 emissions

a. Per capita energy consumption



b. Total energy consumption



Source: WDR team, based on data from IEA 2008c.
Note: Toe = tons of oil equivalent

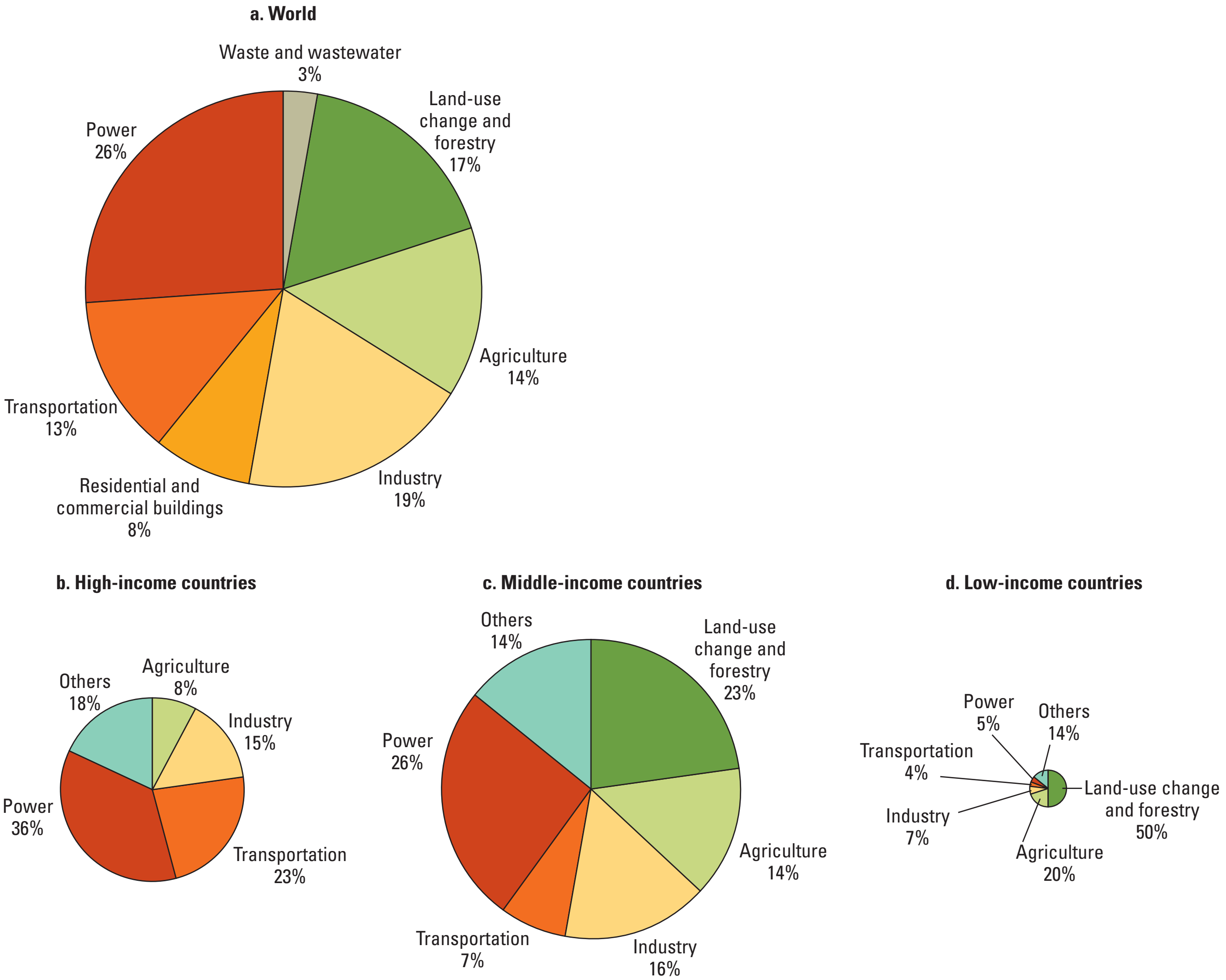
As major centers of production and concentrations of people, the world's cities now consume more than two-thirds of global energy and produce more than 70 percent of CO_2 emissions. The next 20 years will see unprecedented urban growth—from 3 billion people to 5 billion, mostly in the developing world.[14] From now to 2050 building stocks will likely double,[15] with most new construction in developing countries. If cities grow through sprawl rather than densification, demand for travel will increase in ways not easily served by public transport.

Car ownership rates increase rapidly with rising incomes. On current trends 2.3 billion cars will be added between 2005 and 2050, more than 80 percent of them in developing countries.[16] But if the right policies are in place, increased rates of ownership do not have to translate into similar increases in car use (figure 4.5).[17] Because car use drives energy demand and emissions from transport, pricing policies (such as road pricing and high parking fees), public transport infrastructure, and urban form can make a big difference.

Developing countries can learn from Europe and developed Asia to decouple car ownership from car use. European and Japanese drivers travel 30–60 percent fewer vehicle kilometers than drivers in the United States with comparable incomes and car ownership. Hong Kong, China, has one-third the car ownership of New York, the American city with the lowest ratio of cars per capita.[18] How? Through a combination of high urban density, high fuel taxes and road-pricing policies, and well-established public transport infrastructure. Similarly, Europe has four times the public transport routes per 1,000 persons as the United States.[19] But in many developing countries, public transport has not kept up with urban growth, so the move to individual car ownership is causing chronic and increasing problems of congestion.

Transport infrastructure also affects settlement patterns, with a high volume

Figure 4.4 Greenhouse gas emissions by sector: world and high-, middle-, and low-income countries



Source: WDR team, based on data from Barker and others 2007 (figure 4a) and WRI 2008 (figures 4b, c, and d).

Note: The sectoral share of global emissions in figure 4.4a is for 2004. The sectoral share of emissions in high-, middle-, and low-income countries in figures 4.4b, 4.4c, and 4.4d are based on emissions from the energy and agriculture sectors in 2005 and from land-use changes and forestry in 2000. The size of each pie represents contributions of greenhouse gas emissions, including emissions from land-use changes, from high-, middle-, and low-income countries; the respective shares are 35, 58, and 7 percent. Looking only at CO_2 emissions from energy, the respective shares are 49, 49, and 2 percent. In Figure 4.4a, emissions from electricity consumption in buildings are included with those in the power sector. Figure 4.4b does not include emissions from land-use change and forestry, because they were negligible in high-income countries.

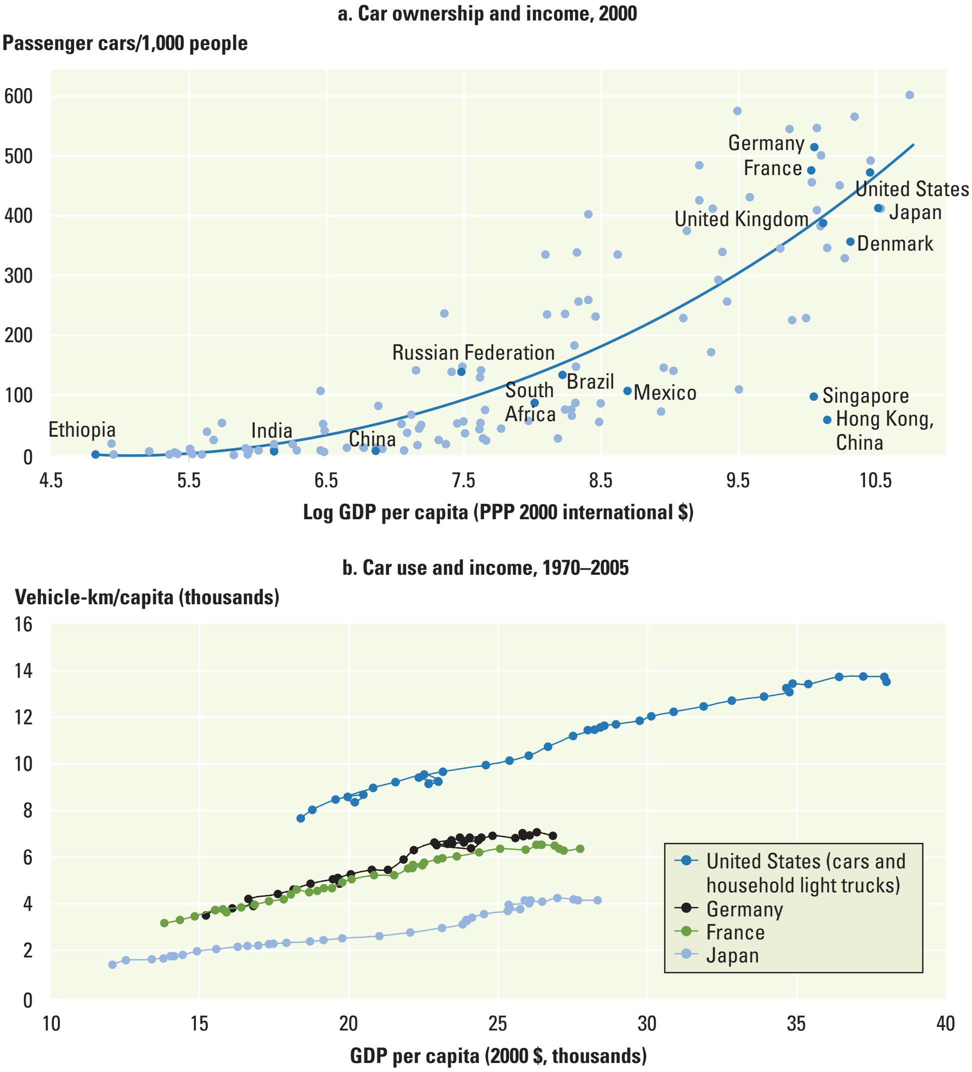
of roads facilitating low-density settlements and an urban form that mass transit systems cannot easily serve. Low-density settlements then make it more difficult to adopt energy-efficient district heating for buildings.[20]

Where the world needs to go: Transformation to a sustainable energy future

Achieving sustainable and equitable growth and prosperity requires that high-income countries significantly reduce their emissions—and their emissions per capita (blue arrows in figure 4.6). It also depends on developing countries avoiding the carbon-intensive path followed by developed countries such as Australia or the United States, taking instead a low-carbon growth path (orange arrow). It thus requires fundamental changes in lifestyles for developed countries and a leapfrogging to new development models for developing countries.

Achieving these goals requires reconciling what is adequate to prevent dangerous climate change with what is technically

Figure 4.5 Car ownership increases with income, but pricing, public transport, urban planning, and urban density can contain car use



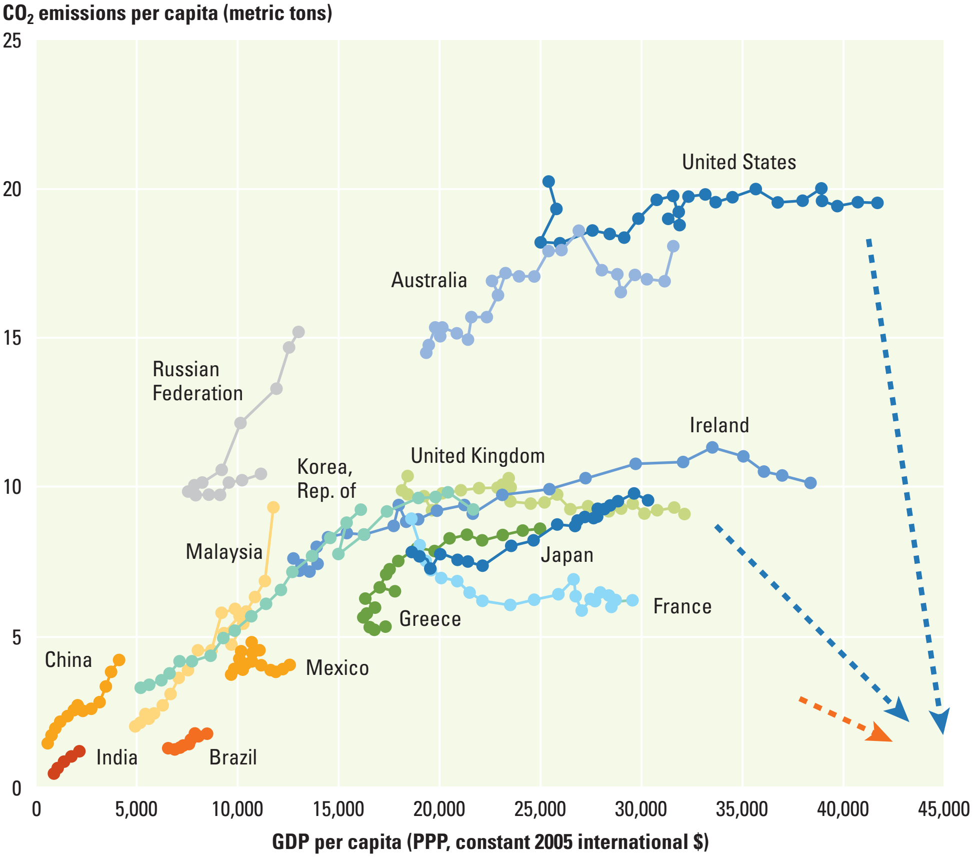
Source: Schipper 2007; World Bank 2009c.

Note: In figure 4.5b, data are from West Germany through 1992 and for all of unified Germany from 1993 onward. Notice the similarity in rates of car ownership among, the United States, Japan, France, and Germany (panel a) but the large variation in distance traveled (panel b).

achievable at acceptable costs. Limiting warming to not much more than 2°C above preindustrial temperatures means that global emissions must peak no later than 2020, then decline by 50–80 percent from current levels by 2050, with perhaps even negative emissions required toward 2100.[21] This is an ambitious undertaking: only about half of the energy models reviewed find it feasible (figure 4.7), and even then most require all countries to start taking action immediately.

More specifically, staying close to a 2°C warming requires greenhouse gas concentrations in the atmosphere to stabilize at no more than 450 parts per million (ppm) CO_2 equivalent (CO_2e).[22] Current greenhouse gas concentrations are already at 387 ppm CO_2e and are rising at about 2 ppm a year.[23] Thus, there is little room for emissions to grow if warming is to stabilize around 2°C. Most models assume that achieving 450 ppm CO_2e will require overshooting that concentration for a few decades and then coming back to 450 ppm CO_2e toward the end of the century (table 4.1). Faster reductions of short-lived greenhouse gas emissions, such as methane and

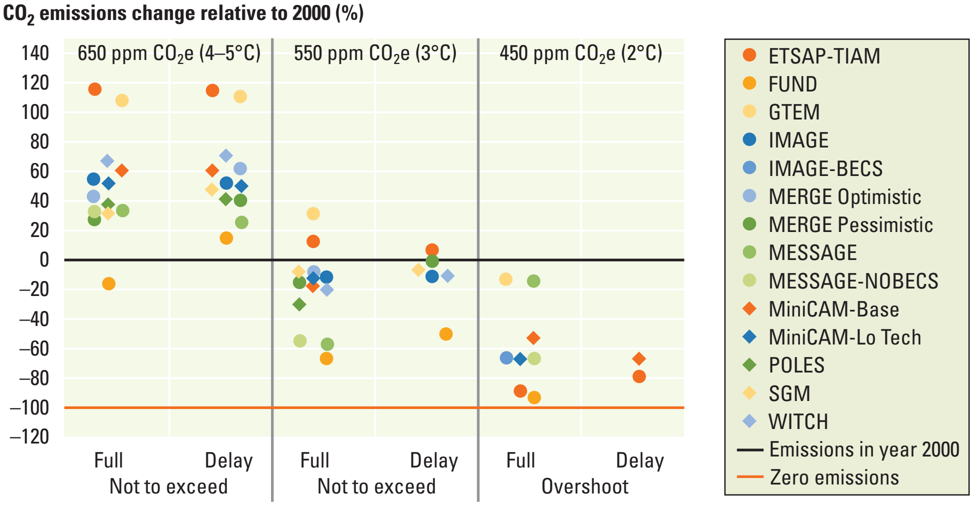
Figure 4.6 **Where the world needs to go: energy-related CO_2 emissions per capita**



Source: Adapted from NRC 2008, based on data from World Bank 2008e.

Note: Emissions and GDP per capita are from 1980 to 2005.

Figure 4.7 **Only half the energy models find it possible to achieve the emission reductions necessary to stay close to 450 ppm CO_2e (2°C)**



Source: Clarke and others forthcoming.

Note: Each dot represents the emissions reduction that a particular model associates with a concentration target—450, 550, 650 parts per million (ppm) of CO_2 equivalent (CO_2e)—in 2050. The number of dots in each column signals how many of the 14 models and model variants were able to find a pathway that would lead to a given concentration outcome. "Overshoot" describes a mitigation path that allows concentrations to exceed their goal before dropping back to their goal by 2100, while "not to exceed" implies the concentration is not to be exceeded at any time. "Full" refers to full participation by all countries, so that emission reductions are achieved wherever and whenever they are most cost-effective. "Delay" means high-income countries start abating in 2012, Brazil, China, India, and the Russian Federation start abating in 2030, and the rest of the world in 2050.

Table 4.1 What it would take to achieve the 450 ppm CO_2e concentration needed to keep warming close to 2°C

	Not-to-exceed	Overshoot
Immediate participation	1) Immediate participation by all regions 2) 70% dramatic emissions reductions by 2020 3) Substantial transformation of the energy system by 2020, including the construction of 500 new nuclear reactors, and the capture of 20 billion tons of CO_2 4) Carbon price of \$100/tCO_2 globally in 2020 5) Tax on land-use emissions beginning in 2020	1) Immediate participation by all regions 2) Construction of 126 new nuclear reactors and the capture of nearly a billion tons of CO_2 in 2020 3) Negative global emissions by the end of the century, and thus requires broad deployment of biomass-based CCS 4) Carbon prices escalate to \$775/tCO_2 in 2095 5) Possible without a tax on land-use emissions, but would result in a tripling of carbon taxes and a substantial increase in the cost of meeting the target.
Delayed participation		1) Dramatic emissions reductions for non-Annex 1 (developing countries) at the time of their participation 2) Negative emissions in Annex 1 (high-income) countries by 2050 and negative global emissions by the end of the century, and thus requires broad deployment of biomass-based CCS 3) Carbon prices begin at \$50/tCO_2, and rise to \$2,000/tCO_2 4) Results in significant carbon leakage, because crop production is outsourced to nonparticipating regions resulting in a substantial increase in land-use change emissions in those regions

Source: Clarke and others forthcoming.

Note: Maintaining emissions at 450 ppm CO_2e or less at all times is almost impossible to attain. If concentrations are allowed to exceed 450 ppm CO_2e before 2100, keeping warming close to 2°C still poses tremendous challenges, as the right-hand column outlines. Annex I countries are the OECD and transition economies committed to reducing emissions under the Kyoto Protocol. The non-Annex I countries did not take on any commitment to reduce emissions.

black carbon, could reduce the overshoot but not avoid it.[24] In addition, 450 ppm CO_2e trajectories rely on biomass-based carbon capture and storage[25] for negative emissions.[26] But given the competition for land and water for food production and carbon storage (see chapter 3), sustainable biomass supplies will be an issue.[27] Limiting warming to 2°C will thus require fundamental changes in the global energy mix (box 4.3 and box 4.4; see endnote 28 for model details).[28]

The mitigation costs of achieving 450 ppm CO_2e are estimated at 0.3–0.8 percent of global GDP in 2030, assuming that all mitigation actions occur whenever and wherever they are cheapest (figure 4.8).[29] This estimate compares to total expenditures in the energy sector of 7.5 percent of GDP today. Moreover, the costs of inaction—from the damages caused by greater warming—may well exceed this mitigation cost (see chapter 1 for a discussion of the cost-benefit analysis of climate policy).

Achieving 450 ppm CO_2e requires the adoption of technologies with marginal costs of \$35 to \$100 for a ton of CO_2 in 2030, for a global annual mitigation investment of \$250 billion to \$1.2 trillion in 2030 (table 4.2).[30] Future energy savings would eventually offset a substantial share of the up-front investment.[31] But much of this investment is needed within the next 10 years in financially constrained developing countries. And removing obstacles to reform and directing capital to low-carbon investments where and when they are needed will be challenging.

A less challenging option would be to aim for a higher concentration—for example, 550 ppm CO_2e. That concentration is associated with a 50-percent chance of warming exceeding 3°C, and a higher risk of damages from climate change impacts, but it allows a little more time for emissions to peak (2030). Emissions would need to fall back to today's levels by 2050 and continue to fall substantially thereafter. Mitigation costs of 550 ppm CO_2e are somewhat lower, at 0.2–0.6 percent of global GDP in 2030 (figure 4.8a), and require adoption of technologies with marginal costs up to \$25 to \$75 a ton of CO_2 in 2030 (figure 4.8b), for average annual additional investments of \$250 billion to \$400 billion a year over the next 20 years.[32] Achieving this more modest goal would still require far-reaching policy reforms.

Action—immediate and global

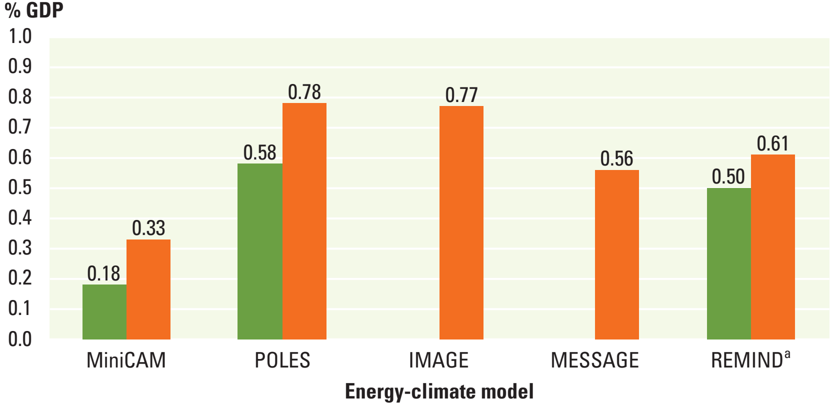
Delaying global actions for 10 years makes stabilization at 450 ppm CO_2e impossible.[33] There is little flexibility on the time when emissions peak. To achieve 450 ppm CO_2e, global energy-related CO_2 emissions will need to peak at 28–32 gigatons in 2020 from 26 gigatons in 2005, and then fall to 12–15 gigatons by 2050.[34] This trajectory requires a 2–3 percent cut in emissions each year from 2020 onward. If emissions increase for 10 years beyond 2020, emissions would have to be *reduced* at 4–5 percent a year. In contrast, emissions *increased* 3 percent a year from 2000 to 2006, so most countries are on their way to a high-carbon path, with total global CO_2 emissions outpacing the worst-case scenario projected by the Intergovernmental Panel on Climate Change (IPCC).[35]

New additions of power plants, buildings, roads, and railroads over the next decade will lock in technology and largely determine emissions through 2050 and beyond. Why? Because the energy capital stock has a long life—it can take decades to turn over power plants, a century to turn over urban infrastructure.[36] Delaying action would substantially increase future mitigation costs, effectively locking the world into carbon-intensive infrastructure for decades to come. Even existing low-cost clean energy technologies will take decades to fully penetrate the energy sector. And given the long lead times for new technology development, deploying advanced technologies on a large scale beginning in 2030 requires aggressive action today.

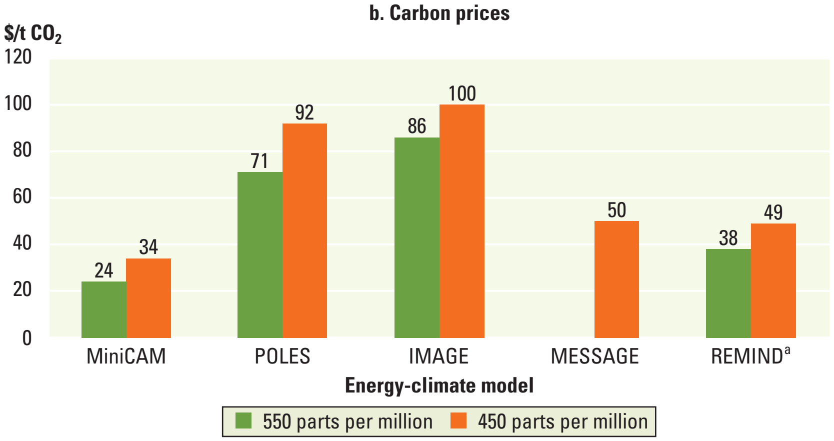
Delaying action would, in addition, lead to costly retrofitting and early retirement of energy infrastructure. Building to current standards and then retrofitting existing capacity, whether power plants or buildings, would be far more costly than building new, efficient, and low-carbon infrastructure in the first place. The same is true for the forced early retirement of inefficient energy capital. Energy savings often justify the higher up-front investments in new capital, but they are less likely to cover premature replacement of capital stock. Even a high CO_2 price may be insufficient to change this picture.[37]

Figure 4.8 Estimates of global mitigation costs and carbon prices for 450 and 550 ppm CO_2e (2°C and 3°C) in 2030 from five models

a. Global mitigation costs



b. Carbon prices



Source: WDR team, based on data from Knopf and others forthcoming; Rao and others 2008; Calvin and others forthcoming.

Note: This graphic compares mitigation costs and carbon prices from five global energy-climate models—MiniCAM, IMAGE, MESSAGE, POLES, and REMIND (see box 4.3 for model assumptions and methodology). MiniCAM, POLES, IMAGE, and MESSAGE report abatement costs for the transformation of energy systems relative to the baseline as a percent of GDP in 2030, where GDP is exogenous.

a. The mitigation costs from REMIND are given as macroeconomic costs expressed in GDP losses in 2030 relative to baseline, where GDP is endogenous.

Table 4.2 Additional annual investment to limit warming to 2°C (450 ppm CO_2e) in 2030 ($ billions)

Region	IEA	REMIND	MESSAGE	McKinsey	MiniCAM[a]
Global	900	375	310	1,215	257
Developing countries	600		137	675	170
North America			53	210	23
European Union			60	155	27
China			12	315	89
India			19	90	28

Sources: IEA 2008b; Knopf and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; McKinsey Global Institute 2009a with further data breakdown provided for WDR 2010 team.

Note: Mitigation investments from IEA, REMIND, MESSAGE, and McKinsey are capital investment costs only.

a. Values from MiniCAM represent total costs and include capital, operation and maintenance, and fuel costs. See Box 4.3 for a discussion of these models and their assumptions.

BOX 4.3 *Global energy mixes and paths for a 450 ppm CO_2e (2°C warmer) world*

For this Report the team examined five global energy-climate models that differ in methodology, assumptions of baseline, technology status, learning rates, costs, and inclusion of greenhouse gases (in addition to CO_2). Attainability of a 450 ppm CO_2e trajectory is dependent on the characteristics of the baseline. Some integrated assessment models can not reach a 450 ppm CO_2e trajectory from a fossil-fuel-intensive and high-energy-growth baseline.

A number of models can achieve 450 ppm CO_2e at moderate costs, but each follows different emissions pathways and energy mitigation strategies.[a] Different emission pathways present a tradeoff between emission reductions in the short to medium term (2005–2050) and the long term (2050–2100). A modest emission reduction before 2050 requires dramatically deeper emission cuts over the long term through widespread use of biomass-based carbon capture and storage.[b] These differences in model methodologies and assumptions also result in varying investment needs in the short term (2030), as shown in table 4.2. The models also vary significantly on the energy mix from now to 2050 (see the figure on the facing page), although the stark conclusion does not vary. The policy implication is that a mix of technology options that varies by country and over time is needed—the least-cost strategies all rely on a broad portfolio of energy technologies.

Global energy mix for 450 ppm CO_2e

The 450 ppm CO_2e trajectory requires a global energy revolution—large reductions in total energy demand and major changes in the energy mix. To achieve this, global climate-energy models call for aggressive energy-efficiency measures that dramatically reduce global energy demand from around 900 exajoules by 2050 under a business-as-usual scenario to 650–750 exajoules—a 17–28 percent cut.

Most models project that fossil fuels would need to drop from 80 percent of energy supply today to 50–60 percent by 2050. The future use of fossil fuels (particularly coal and gas) in a carbon-constrained world depends on widespread use of carbon capture and storage (CCS), which would have to be installed in 80–90 percent of coal plants by 2050, assuming that capture-and-storage technology becomes technically and economically feasible for large-scale applications in the next decade or two (table below).[c]

This significant reduction in fossil-fuel use would need to be offset by renewables and nuclear energy. The largest increase would be in renewable energy, which would jump from 13 percent today (mainly traditional biomass fuel and hydropower) to around 30–40 percent by 2050, dominated by modern biomass with and without carbon capture and storage, with the remainder from solar, wind, hydropower, and geothermal (see the figure). Nuclear would also need a boost—from 5 percent today to around 8–15 percent by 2050.[d] The magnitude of the required effort is substantial: it amounts to an additional 17,000 wind turbines (producing 4 megawatts each), 215 million square meters of solar photovoltaic panels, 80 concentrated solar power plants (producing 250 megawatts each), and 32 nuclear plants (producing 1,000 megawatts each) per year over the next 40 years compared to the baseline.[e] The power sector would need to be virtually decarbonized, followed by the industrial and building sectors (table above).

Cutting energy-related emissions in half by 2050 requires deep decarbonization of the power sector

Sector	Estimated % of carbon that must be removed by sector, 2005–2050	
	IEA	MiniCAM
Power	–71	–87
Building	–41	–50
Transport	–30	+47
Industry	–21	–71
Total	–50	–50

Sources: WDR team based on data from IEA 2008b; Calvin and others forthcoming.

The energy mix to achieve 450 ppm CO_2e can vary, but we must make use of all options

	Current energy mix	Energy mix in 2050				
	Global	Global	United States	European Union	China	India
Energy type	% of total					
Coal without CCS	26	1–2	0–1	0–2	3–5	2–3
Coal with CCS	0	1–13	1–12	2–9	0–25	3–26
Oil	34	16–21	20–26	11–23	18–20	18–19
Gas without CCS	21	19–21	20–21	20–22	9–13	5–9
Gas with CCS	0	8–16	6–21	7–31	1–29	3–8
Nuclear	6	8	8–10	10–11	8–12	9–11
Biomass without CCS	10	12–21	10–18	10–11	9–14	16–30
Biomass with CCS	0	2–8	1–7	3–9	1–12	2–12
Non-biomass renewables	3	8-14	7–12	7–12	10–13	5–19
Total (exajoules a year)	493	665–775	87–121	70–80	130–139	66–68

Sources: WDR team, based on data from Riahi, Grubler, and Nakićenović 2007; IIASA 2009; Calvin and others forthcoming; IEA 2008b.

Sources:

a. Knopf and others forthcoming; Rao and others 2008.

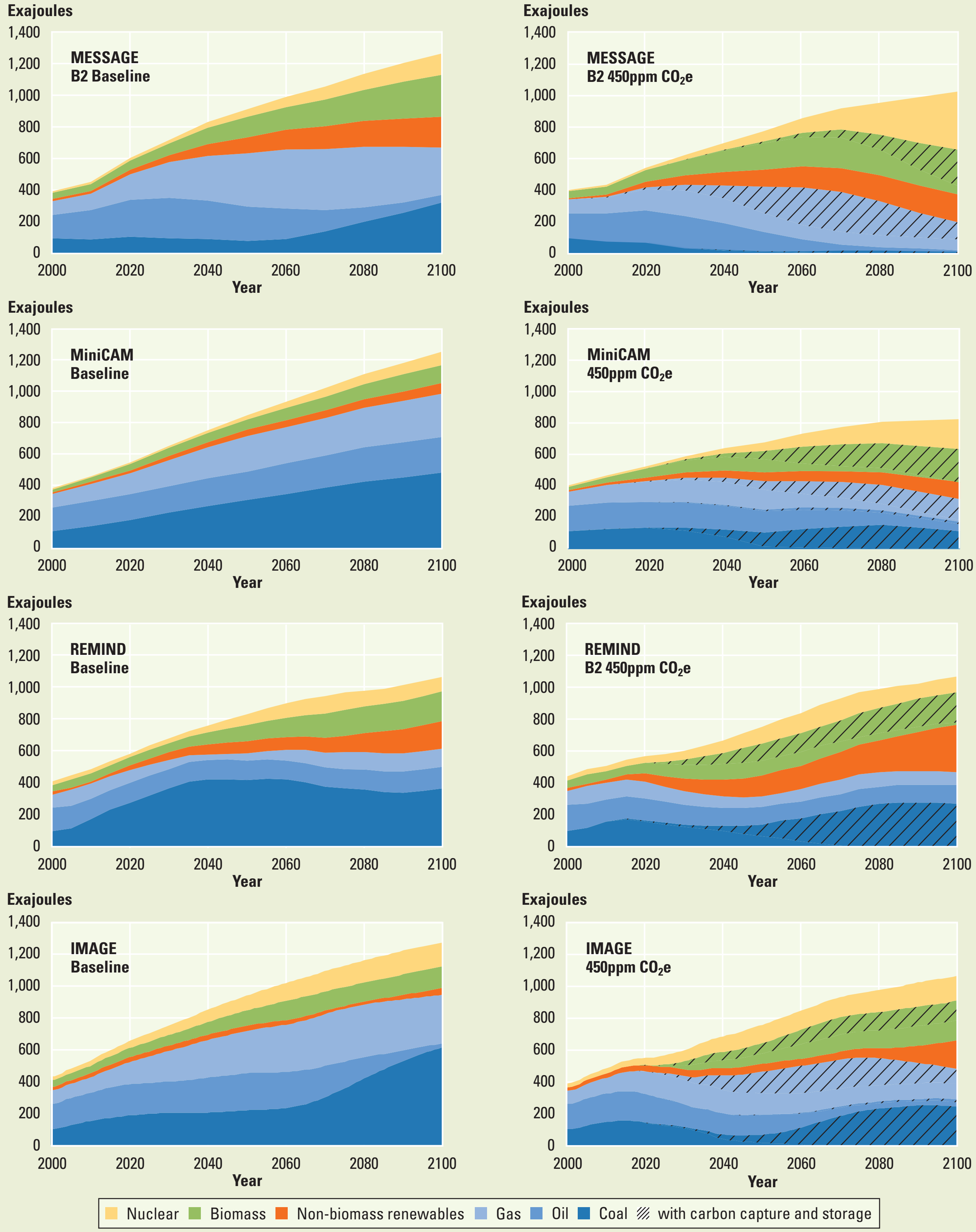
b. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

c. IEA 2008b; Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; van Vuuren and others forthcoming; Weyant and others 2009.

d. IEA 2008b; Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; van Vuuren and others forthcoming.

e. IEA 2008b.

450 ppm CO_2e requires a fundamental change in the global primary energy mix



BOX 4.4 *Regional energy mix for 450 ppm CO_2e (to limit warming to 2°C)*

It is important for national policy makers to understand the implications of a 450 ppm CO_2e trajectory for their energy systems. Most integrated assessment models follow a "least-cost" approach, where emission reductions occur wherever and whenever they are cheapest in all sectors and in all countries.[a] But the country or sector in which mitigation measures are taken is not necessarily the one that bears the costs (see chapter 6). It is not the purpose of this chapter to advocate any particular approach to burden sharing or to allocate emission reductions among countries; that is a matter for negotiation.

The United States, the European Union, and China now account for nearly 60 percent of the world's total emissions. India currently contributes only 4 percent of global emissions despite representing 18 percent of the world's population, but its share is projected to increase to 12 percent by 2050 in the absence of mitigation policy. So, these countries' contributions to global emission reductions will be essential to stabilize the climate.

United States and European Union

Energy efficiency could reduce total energy demand in developed countries by 20 percent in 2050 relative to business as usual. This would require an annual decline in energy intensity of 1.5–2 percent over the next four decades, continuing the current trend of the past two decades. To achieve 450 ppm CO_2e the United States and the European Union would need to cut oil consumption significantly by 2050, a substantial challenge because they now consume almost half of global oil production. They would also need to dramatically reduce coal use—a daunting task for the United States, the world's second-largest coal producer and consumer—and widely deploy carbon capture and storage.

The United States and the European Union have the resources to realize these measures and overcome the challenges. Both have abundant renewable energy potential. Some models project that carbon capture and storage would have to be installed for 80–90 percent of coal and gas plants and 40 percent of biomass plants in the United States by 2050 (see lower table of box 4.3). This is potentially feasible given the estimated CO_2 storage capacity. But doubling the share of natural gas in the European primary energy mix from 24 percent today to 50 percent by 2050, assumed by some 450 ppm CO_2e scenarios, may pose energy security risks, particularly given the recent disruption of gas supplies to Europe. The 450 ppm CO_2e scenario requires an additional annual investment of $50 billion to $200 billion for the United States (0.2–1 percent of GDP) and $60 billion to $150 billion for the European Union (0.4–1 percent of GDP) in 2030 (see table 4.2).

China

Significantly reducing emissions below current levels is a formidable goal for China, the world's largest coal producer and consumer. China, relies on coal to meet 70 percent of its commercial energy needs (compared with 24 percent in the United States and 16 percent in Europe). To meet 450 ppm CO_2e, total primary energy demand would have to be 20–30 percent below the projected business-as-usual level by 2050. Energy intensity would have to decline by 3.1 percent a year over the next four decades.

Impressively, Chinese GDP quadrupled from 1980 to 2000 while energy consumption only doubled. After 2000, however, the trend reversed, even though energy intensity continues to fall within industrial subsectors. The main reason: a sharp rise in the share of heavy industry, driven by strong demand from domestic and export production.[b] China produces 35 percent of the world's steel, 50 percent of its cement, and 28 percent of its aluminum. This development stage, when energy-intensive industries dominate the economy, presents great challenges to decoupling emissions from growth.

China has increased the average efficiency of coal-fired power plants by 15 percent over the last decade to an average of 34 percent.A policy that requires closing small-scale coal-fired power plants and substituting large-scale efficient ones over the last two years reduces annual CO_2 emissions by 60 million tons. A majority of new coal-fired plants are equipped with state-of-the-art supercritical and ultrasupercritical technologies.[c]

Despite these advances, China would still have to reduce the share of coal in the primary energy mix dramatically to achieve 450 ppm CO_2e (see the lower table of box 4.3). Renewable energy could meet up to 40 percent of total energy demand in 2050. Several scenarios have extremely ambitious nuclear programs, in which China would build nuclear power plants three times faster than France ever achieved, and nuclear capacity in 2050 would reach seven times France's current nuclear capacity. Given China's limited gas reserves, increasing the percentage of gas in the primary energy mix from the current 2.5 percent to 40 percent by 2050, as assumed by some models, is problematic.

Given the large domestic reserves, coal will likely remain an important energy source in China for decades. Carbon capture and storage is essential for China's economic growth in a carbon-constrained world. Some 450 ppm CO_2e scenarios project that carbon capture and storage would have to be installed for 85–95 percent of coal plants in China by 2050—more than can be accommodated by the current projections of economically available CO_2 storage capacity of 3 gigatons a year within 100 kilometers of the emission sources. But further site assessment, technology breakthrough, and future carbon pricing could change this situation. The 450 ppm CO_2e scenario requires an additional annual investment for China of $15 billion to $300 billion (0.1–2.6 percent of GDP) by 2030.

India and other developing countries

India faces tremendous challenges in substantially altering its emissions path given its limited potential for alternative energy resources and for carbon storage sites. Like China, India heavily relies on coal (which accounts for 53 percent of its commercial energy demand). Achieving 450 ppm CO_2e would require a veritable energy revolution in India. Total primary energy demand would have to decline relative to the business-as-usual projections by around 15–20 percent by 2050 and energy intensity by 2.5 percent a year from now to 2050, doubling the efforts of the past decade. A large potential exists, however, for improving energy efficiency and reducing the 29 percent losses in transmission and distribution, to a level closer to the world average of 9 percent. And while the efficiency of coal-fired power plants in India has improved in

(*continued*)

recent years, the average efficiency is still low at 29 percent, and nearly all the coal-fired plants are subcritical.

As in China, coal's share in India's primary energy mix would have to be reduced dramatically to achieve 450 ppm CO_2e. The potential for hydropower (150 gigawatts) and onshore wind power (65 gigawatts) is large in absolute terms but small in relation to future energy needs (12 percent in the power mix by 2050 in the 450 ppm CO_2e scenario). Considerable untapped possibilities exist for importing natural gas and hydropower from neighboring countries, but difficulties remain in establishing transboundary energy trade agreements. For solar to play a large role, costs would have to come down significantly. Some models suggest that India would need to rely on biomass to supply 30 percent of its primary energy by 2050 under the 450 ppm CO_2e scenario. But this may exceed India's sustainable biomass potential because biomass production competes with agriculture and forests for land and water.

India has limited economically available carbon storage sites, with a total storage capacity of less than 5 gigatons of CO_2, enough to store only three years of carbon if 90 percent of coal plants were equipped with carbon capture and storage by 2050, as some 450 ppm CO_2e scenarios project. Additional site assessments and technology breakthroughs could change this. The 450 ppm CO_2e scenario requires an additional annual investment of $20 billion to $90 billion for India (0.6–2.7 percent of GDP) in 2030.

Sub-Saharan Africa (excluding South Africa) contributes 1.5 percent of global annual energy-related CO_2 emissions today, an amount projected to grow to only 2–3 percent by 2050. Providing basic modern energy services to the poor should be the top priority and will only slightly increase global greenhouse gas emissions. But a global clean energy revolution is relevant to the low-income countries, which may be able to leapfrog to the next generation of technologies. Clean energy can play a large role in increasing access to energy, and pursuing energy efficiency is a cost-effective short-term solution to power outages.

According to climate-energy models, under the 450 ppm CO_2e scenarios, most developing countries would need to boost their production of renewable energy. Africa, Latin America, and Asia could contribute by switching to modern biomass. And Latin America and Africa have substantial untapped hydropower, although the amount could be affected by a less reliable hydrological cycle resulting from climate change. These countries would also need a major boost in natural gas.

Sources: Calvin and others forthcoming; Chikkatur 2008; Dahowski and others 2008; de la Torre, Fajnzylber, and Nash 2008; Dooley and others 2006; German Advisory Council on Global Change 2008; Government of India Planning Commission 2006; Holloway and others 2008; IEA 2008b; IEA 2008c; IIASA 2009; Lin and others 2006; World Bank 2008c; Zhang 2008.

a. They are based on an integrated global carbon market and do not consider any explicit burden sharing between countries. In reality, this is unlikely. Burden sharing is discussed in chapter 1, and the implication of delayed participation by non-Annex 1 countries is discussed in chapter 6. We also reviewed models from developing countries (China and India), but no public information is available for 450 ppm CO_2e scenarios.

b. Lin and others 2006. Production of exports accounted for around one-third of China's emissions in 2005 (Weber and others 2008).

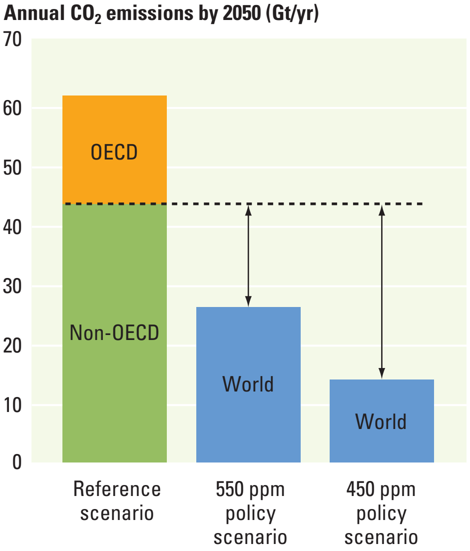
c. Supercritical and ultrasupercritical plants use higher steam temperatures and pressures to achieve higher efficiency of 38–40 percent and 40–42 percent respectively, compared with large subcritical power plants with an average efficiency of 35–38 percent.

To avoid such lock-ins, the scale and rate of urbanization present an unrivaled opportunity, particularly for developing countries, to make major decisions today about building low-carbon cities with compact urban designs, good public transport, efficient buildings, and clean vehicles.

One beneficial feature of the inertia in energy infrastructure is that introducing efficient low-carbon technologies into new infrastructure offers an opportunity to lock in a low-carbon path. Developing countries will install at least half the long-lived energy capital stocks built between now and 2020.[38] For example, half of China's building stock in 2015 will have been built between 2000 and 2015.[39] There are fewer opportunities in developed countries, where residential buildings tend to have slow retirements—60 percent of France's expected residential building stock in 2050 has already been built. This fact constrains the potential for reductions in heating and cooling demand, which requires retrofitting and replacing building shells. But there are abundant opportunities over the next decade in both developed and developing countries to build new power plants with clean energy technologies, thereby avoiding further lock in to carbon-intensive fuels.

For the reasons outlined in the Bali Action Plan, which is shaping the current negotiations under the United Nations Framework Convention on Climate Change, developed countries must take the lead in cutting emissions (see chapter 5). But developed countries alone could not put the world onto a 2°C trajectory, even if they were able to reduce their emissions to zero (figure 4.9). By 2050, 8 billion of the world's 9 billion people will live in today's developing countries, producing 70 percent of projected global emissions.[40] Developed countries can, however, provide financial assistance and

Figure 4.9 Global actions are essential to limit warming to 2°C (450 ppm) or 3°C (550 ppm). Developed countries alone could not put the world onto a 2°C or 3°C trajectory, even if they were to reduce emissions to zero by 2050.



Sources: Adapted from IEA 2008b; Calvin and others forthcoming.

Note: If energy-related emissions from developed countries (orange) were to reduce to zero, emissions from developing countries (green) under business as usual would still exceed global emission levels required to achieve 550 ppm CO_2e and 450 ppm CO_2e scenarios (blue) by 2050.

Table 4.3 Different country circumstances require tailored approaches

Countries	Low-carbon technologies and policies
Low-income countries	Expand energy access through grid and off-grid options Deploy energy efficiency and renewable energy whenever they are the least cost Remove fossil-fuel subsidies Adopt cost-recovery pricing Leapfrog to distributed generation, where grid infrastructure does not exist
Middle-income countries	Scale up energy efficiency and renewable energy Integrate urban and transport approaches to low carbon use Remove fossil-fuel subsidies Adopt cost-recovery pricing including local externalities Conduct research, development, and demonstration in new technologies
High-income countries	Undertake deep emission cuts at home Put a price on carbon: cap-and-trade or carbon tax Remove fossil-fuel subsidies Increase research, development, and demonstration in new technologies Change high-energy-consuming lifestyle Provide financing and low-carbon technologies to developing countries

Source: WDR team.

low-carbon technology transfers to developing countries, while pursuing advanced low-carbon technologies and demonstrating that low-carbon growth is feasible (table 4.3).

Acting on all technical and policy fronts

What fundamental changes need to be made in the energy system to narrow the gap between where the world is headed and where it needs to go? The answer lies in a portfolio of efficient and clean energy technologies to reduce energy intensity and shift to low-carbon fuels. On current trends, global energy-related CO_2 emissions will increase from 26 gigatons in 2005 to 43–62 gigatons by 2050.[41] But a 450 ppm CO_2e trajectory requires that energy emissions be reduced to 12–15 gigatons, a 28–48 gigaton mitigation gap by 2050 (figure 4.10). Four technologies are key to closing this gap—energy efficiency (the largest wedge), followed by renewable energy, carbon capture and storage, and nuclear.[42]

A portfolio of these technologies can achieve the deep emission cuts required by the 450 ppm CO_2e trajectory at least cost, because each has physical and economic constraints that vary by country. Energy efficiency faces barriers and market failures. Wind, hydropower, and geothermal power are limited by availability of suitable sites; biomass is constrained by competition for land and water from food and forests (see chapter 3); and solar is still costly (box 4.5). Nuclear power raises concerns about weapons proliferation, waste management, and reactor safety. Carbon capture and storage technologies for power plants are not yet commercially proven, have high costs, and may be limited by the availability of storage sites in some countries.

Sensitivity analysis incorporating these technology constraints suggests that 450 ppm CO_2e is not achievable without large-scale deployment of energy efficiency, renewable energy, and carbon capture and storage;[43] and that reducing the role of nuclear would require substantial increases of fossil-based carbon capture and storage and renewables.[44] Critical uncertainties include the availability of carbon capture and storage and the development of second-generation biofuels. With today's known

BOX 4.5 *Renewable energy technologies have huge potential but face constraints*

Biomass

Modern biomass as fuel for power, heat, and transport has the highest mitigation potential of all renewable sources.[a] It comes from agriculture and forest residues as well as from energy crops. The biggest challenge in using biomass residues is a long-term reliable supply delivered to the power plant at reasonable costs; the key problems are logistical constraints and the costs of fuel collection. Energy crops, if not managed properly, compete with food production and may have undesirable impacts on food prices (see chapter 3). Biomass production is also sensitive to the physical impacts of a changing climate.

Projections of the future role of biomass are probably overestimated, given the limits to the sustainable biomass supply, unless breakthrough technologies substantially increase productivity. Climate-energy models project that biomass use could increase nearly fourfold to around 150–200 exajoules, almost a quarter of world primary energy in 2050.[b] However, the maximum sustainable technical potential of biomass resources (both residues and energy crops) without disruption of food and forest resources ranges from 80–170 exajoules a year by 2050,[c] and only part of this is realistically and economically feasible. In addition, some climate models rely on biomass-based carbon capture and storage, an unproven technology, to achieve negative emissions and to buy some time during the first half of the century.[d]

Some liquid biofuels such as corn-based ethanol, mainly for transport, may aggravate rather than ameliorate carbon emissions on a life-cycle basis. Second-generation biofuels, based on lignocellulosic feedstocks—such as straw, bagasse, vegetative grass, and wood—hold the promise of sustainable production that is high-yielding and emits low levels of greenhouse gas, but they are still in the R&D stage.

Solar

Solar power, the most abundant energy source on Earth, is the fastest-growing renewable energy industry. Solar power has two major technologies—solar photovoltaic systems and concentrated solar power. Solar photovoltaic systems convert solar energy directly into electricity. Concentrated solar power uses mirrors to focus sunlight on a transfer fluid that generates steam to drive a conventional turbine. Concentrated solar power is much cheaper and offers the greatest potential to produce base-load, large-scale power to replace fossil power plants. But this technology requires water to cool the turbine—a constraint in the desert, where solar plants tend to be installed. So expansion is limited by geography (because concentrated solar power can only use direct beam sunlight) as well as by the lack of transmission infrastructure and large financing requirements. Solar photovoltaics are less location-sensitive, quicker to build, and suitable for both distributed generation and off-grid applications. Solar water heaters can substantially reduce the use of gas or electricity to heat water in buildings. China dominates the global market of solar water heaters, producing more than 60 percent of global capacity.

At current costs, concentrated solar would become cost competitive with coal at a price of \$60 to \$90 a ton of CO_2.[e] But with learning and economies of scale, concentrated solar power could become cost competitive with coal in less than 10 years, and the global installed capacity could rise to 45–50 gigawatts by 2020.[f] Similarly, solar photovoltaics have a learning rate of 15–20 percent cost reduction with each doubling of installed capacity.[g] Because global capacity is still small, potential cost reductions through learning are substantial.

Wind, hydro, and geothermal

Wind, hydro, and geothermal power are all limited by resources and suitable sites. Wind power has grown at 25 percent a year over the past five years, with installed capacity of 120 gigawatts in 2008. In Europe more wind power was installed in 2008 than any other type of electricity-generating technology. But climate change could affect wind resources, with higher wind speeds but more variable wind patterns.[h]

Hydropower is the leading renewable source of electricity worldwide, accounting for 16 percent of global power. Its potential is limited by availability of suitable sites (global economically exploitable potential of 6 million gigawatt-hours a year),[i] large capital requirements, long lead times to develop, concerns over social and environmental impacts, and climate variability (notably water resources). More than 90 percent of the unexploited economically feasible potential is in developing countries, primarily in Sub-Saharan Africa, South and East Asia, and Latin America.[j] Africa exploits only 8 percent of its hydropower potential.

For many countries in Africa and South Asia, regional hydropower trade could provide the least-cost energy supply with zero carbon emissions. But the lack of political will and trust and concerns about energy security constrain such trade. And greater climate variability will affect the hydrological cycle. Drought or glacial melting could make hydropower supplies unreliable in some regions. Nevertheless, after two decades of stagnation, hydropower is expanding, particularly in Asia. But the current financial crisis makes it more difficult to raise financing to meet the large capital requirements.

Geothermal can provide power, heating, and cooling. It meets 26 percent of Iceland's electricity needs and 87 percent of its building heating demand. But this power source requires major financial commitments in up-front geological investigations and expensive drilling of geothermal wells.

Smart grids and meters

With two-way digital communications between power plants and users, smart grids can balance supply and demand in real time, smooth demand peaks, and make consumers active participants in the production and consumption of electricity. As the share of generation from variable renewable resources such as wind and solar increases, a smart grid can better handle fluctuations in power.[k] It can allow electric vehicles to store power when needed or to sell it back to the grid. Smart meters can communicate with customers, who can then reduce costs by changing appliances or times of use.

Sources:

a. IEA 2008b.

b. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Knopf and others forthcoming.

c. German Advisory Council on Global Change 2008; Rokityanskiy and others 2006; Wise and others 2009.

d. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

e. IEA 2008b; Yates, Heller, and Yeung 2009.

f. Yates, Heller, and Yeung 2009.

g. Neij 2007.

h. Pryor, Barthelmie, and Kjellstrom 2005.

i. IEA 2008b.

j. World Bank 2008b.

k. Worldwatch Institute 2009.

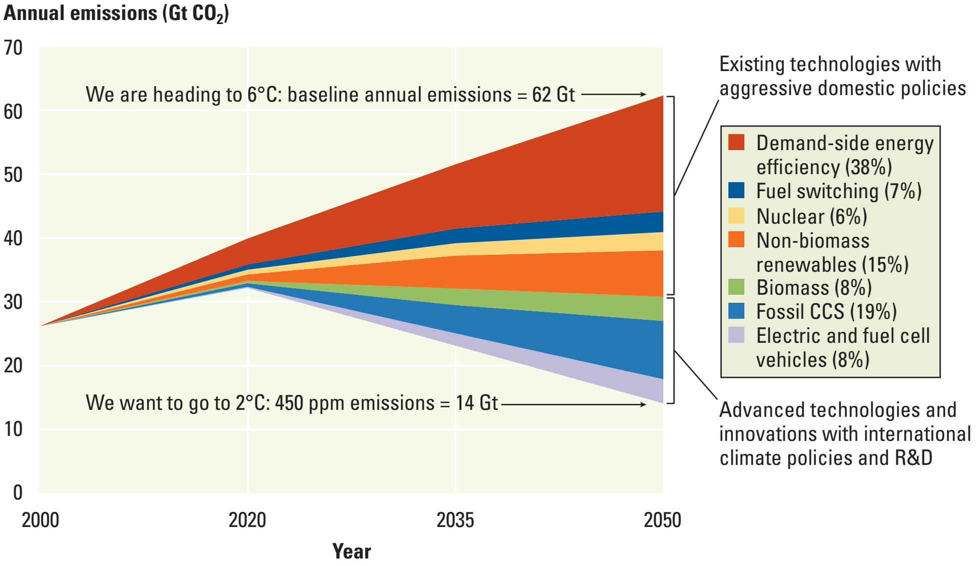
technologies, there is limited room for flexibility in the technology portfolio.

Historically, however, innovation and technology breakthroughs have reduced the costs of overcoming formidable technical barriers, given effective and timely policy action—a key challenge facing the world today. Acid rain and stratospheric ozone depletion are two of many examples demonstrating that estimates of environmental protection costs based on technology extant before regulation are dramatically overstated.[45]

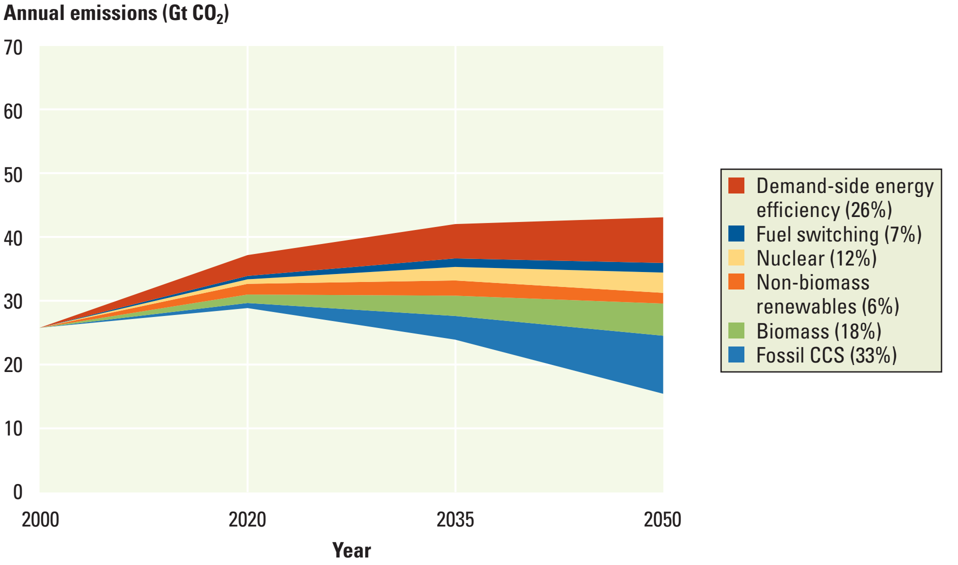
Climate-smart development policies need to be tailored to the maturity of each technology and the national context and can accelerate the development and deployment of these technologies (figure 4.11 and table 4.4).

Figure 4.10 The emissions gap between where the world is headed and where it needs to go is huge, but a portfolio of clean energy technologies can help the world stay at 450 ppm CO_2e (2°C)

a. CO_2 emissions from the energy sector: wedge analysis for IEA Blue Scenario (450 ppm CO_2e)



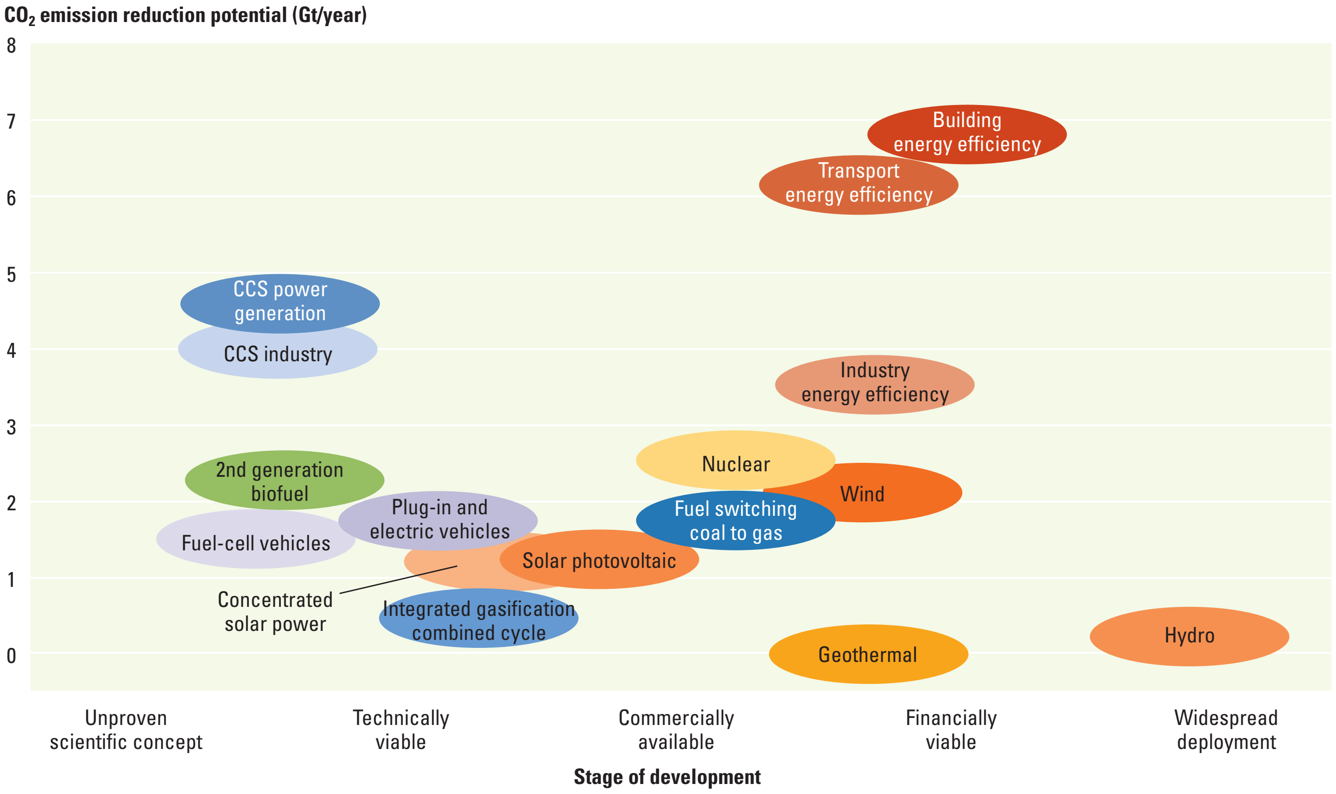
b. CO_2 emissions from the energy sector: wedge analysis for MESSAGE B2 (450 ppm CO_2e)



Sources: WDR team, based on data from Riahi, Grübler, and Nakićenović 2007; IIASA 2009; IEA 2008b.

Note: Fuel switching is changing from coal to gas. Non-biomass renewables include solar, wind, hydropower, and geothermal. Fossil CCS is fossil fuels with carbon capture and storage. While the exact mitigation potential of each wedge may vary under different models depending on the baseline, the overall conclusions remain the same.

Figure 4.11 The goal is to push low-carbon technologies from unproven concept to widespread deployment and to higher emission reductions



Source: WDR team, based on data from World Bank 2008a and IEA 2008a (mitigation potential from IEA Blue Scenario in 2050).

Note: See table 4.4 for detailed definitions of technology development stage. A given technology group can be progressing through different stages at the same time but in different country settings and at different scales. Wind, for example, is already cost competitive with gas-fired power plants in most of the United States (Wiser and Bolinger 2008). But in China and India wind may be economically but not financially viable against coal-fired power plants. So for clean technologies to be adopted in more places and at larger scales, they must move from the top to bottom in table 4.4.

Table 4.4 Policy instruments tailored to the maturity of technologies

Maturity level	Status	Issues to address to move to next stage	Policy support
Technically viable	The basic science is proven and tested in the lab or on a limited scale. Some technical and cost barriers remain.	Development and demonstration to prove operational viability at scale and to minimize costs. Internalize global externalities.	Technology development policies: Substantial public and private R&D, and large-scale demonstration. Internalize global externalities through carbon tax or cap-and-trade. Technology transfer.
Commercially available and economically viable	The technology is available from commercial vendors. Projected costs are well understood. Technology is economically viable, justified by country's development benefits. But it cannot yet compete against fossil fuels without subsidy and/or internalization of local externality.	Leveling the playing field between clean energy and fossil fuels.	Domestic policies to provide a level playing field: Remove fossil-fuel subsidies and internalize local externalities. Provide financial incentives for clean energy technologies.
Financially viable	Technology is financially viable for project investors—cost competitive with fossil fuels, or has high financial returns and short payback period for demand options.	Market failures and barriers hamper accelerating adoption through the market.	Regulations, with financial incentives to remove market failures and barriers. Support for delivery mechanisms and financing programs to expand adoption. Consumer education.
Widespread	Technology is being adopted widely through market operation.		

Source: WDR team.

Energy efficiency. In the short term the largest and cheapest source of emission reductions is increased energy efficiency on both the supply and demand side in power, industry, buildings, and transport. Well-established technologies offer near-term reductions in greenhouse gas emissions by capturing methane emissions[46] from coal mines, municipal solid wastes, and gas flaring and by reducing black carbon emissions from traditional biomass fuels. These technologies can also enhance coal mine safety and improve public health by reducing air pollution.[47] Many energy-efficiency measures are financially viable for investors but are not fully realized. Realizing these low-cost savings requires regulations such as efficiency standards and codes—combined with financial incentives, institutional reforms, financing mechanisms, and consumer education—to correct market failures and barriers.

Existing supply-side low-carbon technologies. In the short to medium term, low- or zero-emission fuels for the power sector—renewable energy and nuclear power—are commercially available and could be deployed much more widely under the right policy and regulatory frameworks. Smart and robust grids can enhance the reliability of electric networks when incorporating variable renewable energy and distributed generation (see box 4.5). Fuel switching from coal to natural gas also has great mitigation potential but increases the energy security risks for gas-importing countries. Most renewable energy technologies are economically viable but not yet financially viable, so some form of subsidy (to internalize the externalities) is needed to make them cost competitive with fossil fuels. Adopting these technologies on a larger scale will require that fossil-fuel prices reflect the full cost of production and externalities, plus financial incentives to adopt low-carbon technologies.

Advanced technologies. While commercially available technologies can provide a substantial share of the abatement needed in the short to medium term,[48] limiting warming to 2°C requires developing and deploying advanced technologies (carbon capture and storage in power and industry, second-generation biofuels, and electric vehicles) at unprecedented scale and speed (box 4.6). Policies that put an adequate price on carbon are essential, as are international efforts to transfer low-carbon technologies to developing countries. Given the long lead time for technology development and the early emission peaking date required to limit temperature increases to 2°C, governments need to ramp up research, development, and demonstration efforts now to accelerate the innovation and deployment of advanced technologies. Developed countries will need to take the lead in making these technologies a reality.

An integrated systems approach is needed to ensure compatible policies for sector-wide and economywide emission reductions. Market-based mechanisms, such as a carbon cap-and-trade system or a carbon tax (see chapter 6), encourage the private sector to invest in least-cost, low-carbon technologies to achieve deep emission cuts.

Integrated urban and transport approaches combine urban planning, public transport, energy-efficient buildings, distributed generation from renewable sources, and clean vehicles (box 4.7). Latin America's pioneering experiences with rapid bus transit—dedicated bus lanes, prepayment of bus fares, and efficient intermodal connections—are examples of a broader urban transformation.[49] Modal shifts to mass transit have large development co-benefits of time savings in traffic, less congestion, and better public health from reduced local air pollution.

Changing behaviors and lifestyles to achieve low-carbon societies will take a concerted educational effort over many years. But by reducing travel, heating, cooling, and appliance use and by shifting to mass transit, lifestyle changes could reduce annual CO_2 emissions by 3.5–5.0 gigatons by 2030—8 percent of the reduction needed (see chapter 8).[50]

Governments do not have to wait for a global climate deal—they can adopt domestic efficient and clean energy policies now, justified by development and financial co-benefits. Such domestic win-win measures

BOX 4.6 *Advanced technologies*

Carbon capture and storage (CCS) could reduce emissions from fossil fuels by 85–95 percent and is critical in sustaining an important role for fossil fuels in a carbon-constrained world. It involves three main steps:

- CO_2 capture from large stationary sources, such as power plants or other industrial processes, before or after combustion.
- Transport to storage sites by pipelines.
- Storage through injection of CO_2 into geological sites, including: depleted oil and gas fields to enhance oil and gas recovery, coal beds to enhance coal bed methane recovery, deep saline formations, and oceans.

Currently, CCS is competitive with conventional coal only at a price of $50 to $90 a ton of CO_2.[a] Still at the R&D stage, it is technologically immature. The number of economically available geological sites close to carbon emission sources varies widely from country to country. Early opportunities to lower costs are at depleted oil fields and enhanced oil recovery sites, but storage in deep saline aquifers would also be required for deep emission cuts. CCS also significantly reduces efficiency of power plants and has the potential for leakage.

The near-term priority should be spurring large-scale demonstration projects to reduce costs and improve reliability. Four large-scale commercial CCS demonstration projects are in operation—in Sleipner (Norway); Weyburn (Canada-United States); Salah (Algeria); and Snohvit (Norway)—mostly from gas or coal gasification. Together these projects capture 4 million tons of CO_2 per year. A 450 ppm CO_2e trajectory requires 30 large-scale demonstration plants by 2020.[b] Capturing CO_2 from low-efficiency power plants is not economically viable, so new power plants should be built with highly efficient technologies for retrofitting with CCS later. Legal and regulatory frameworks must be established for CO_2 injection and to address long-term liabilities. The European Union has adopted a directive on the geological storage of CO_2, and the United States has proposed CCS rules. Detailed assessments of potential carbon storage sites are also needed, particularly in developing countries. Without a massive international effort, resolving the entire chain of technical, legal, institutional, financial, and environmental issues could require a decade or more before applications go to scale.

Plug-in hybrids offer a potential near-term option as a means of transition to full electric vehicles.[c] They combine batteries with smaller internal combustion engines, which allow them to travel part-time on electricity provided by the grid through recharging at night. When running on electricity generated from renewable energy, they emit 65 percent less CO_2 than a gasoline-powered car.[d] However, they increase electricity consumption, and the net emission reductions depend on the electricity source. Significant improvements and cost reductions in energy storage technology are required. Electric vehicles are solely battery-powered, but they require much greater battery capacity than plug-in hybrids and are more expensive.

Sources:
a. IEA 2008b.
b. IEA 2008b.
c. IEA 2008b.
d. NRDC 2007.

can go a long way to close the mitigation gap,[51] but they must be supplemented with international climate agreements to bridge the remaining gap.

Realizing the savings from energy efficiency

Globally an additional dollar invested in energy efficiency avoids more than two dollars in investment on the supply side, and the payoffs are even higher in developing countries.[52] So energy efficiency (*nega*watts) should be considered on a par with traditional supply-side measures (megawatts) in energy resource planning. Energy efficiency reduces energy bills for consumers, increases the competitiveness of industries, and creates jobs. Energy efficiency is essential for the 2°C trajectory, because it buys time by delaying the need to build additional capacity while advanced clean energy technologies are being developed and brought to market.

Buildings consume nearly 40 percent of the world's final energy,[53] about half for heating space and water, and the rest for running electric appliances, including lighting, air conditioning, and refrigeration.[54] Opportunities to improve energy efficiency lie in the building envelope (roof, walls, windows, doors, and insulation), in space and water heating, and in appliances. Buildings present one of the most cost-effective mitigation options, with more than 90 percent of potential mitigation achievable with a CO_2 price of less than $20 a ton.[55] Studies find that existing energy-efficiency technologies can cost-effectively save 30 to 40 percent of energy use in new buildings, when evaluated on a life-cycle basis.[56]

While most of these studies are based on high-income country data, the potential for energy-efficiency savings in developing countries can be larger because of the low baseline. For example, the current space-

BOX 4.7 *The role for urban policy in achieving mitigation and development co-benefits*

Urbanization is often cited as a major driver of global emissions growth[a] but is better understood as a major driver of development.[b] It is therefore a crucial nexus of climate and development policy making. Most emissions occur in cities precisely because that is where most production and consumption occur. And the high concentration of population and economic activity in cities can actually increase efficiency—if the right policies are in place. A number of factors call for an urban climate agenda.

First, denser cities are more energy and emission efficient (for example, in the transport sector; see the figure below), and local policies are essential for encouraging densification. Second, the strong and persistent influence of infrastructure on long-term residential and commercial citing decisions reduces the responsiveness of emissions to price signals. Complementary regulation and land-use planning are therefore needed. Third, the interdependence of the systems that constitute the urban form—roads and public transit lines; water, wastewater, and power services; and residential, commercial, and industrial buildings—and that are not easily changed once the initial patterns are set, increases the urgency of designing low-emissions cities in rapidly urbanizing countries.

As discussed in chapter 8, cities have already become a source of political momentum and will advance mitigation actions on the international stage even as they pursue their own initiatives at home. Contrary to a general presumption that local decision making focuses on local issues, more than 900 U.S. cities have signed on to meet or exceed Kyoto Protocol targets to reduce greenhouse gas emissions,[c] while the C40 Cities Climate Leadership Group that aims to promote action to combat climate change includes major cities on all continents.[d]

Cities have the unique ability to respond to a global issue like climate change at a tangible local level. Many cities have legislated to limit the use of plastic bags, disposable cups, or bottled water. These initiatives may be important for social messaging, but their environmental impact has so far been minimal. Deeper, higher-impact efforts—such as congestion charging, green building incentives, support for urban design requiring less automobile dependence, and incorporation of carbon pricing in land taxes and development rights—will ultimately require a more comprehensive cultural momentum to overcome entrenched (or aspirational) high-carbon lifestyle preferences. Fortunately, many city-led measures needed for mitigation have benefits for adaptation to climate change, which will reduce tradeoffs.

Sources: WDR team based on World Bank 2009b.

a. Dodman 2009.

b. World Bank 2008f.

c. U.S. Conference of Mayors Climate Change Protection Agreement.

d. See http://www.c40cities.org/. In addition, the United Cities and Local Governments and International Council for Local Environmental Initiatives have a joint resolution requesting a greater voice for cities in the UNFCCC negotiating process.

Emissions from transport are much lower in denser cities

Source: World Bank 2009b.
Note: The figure does not correct for income because a regression of transport emissions on density and income reveals that density, not income, is a key factor. Data are for 1995.

heating technology used in Chinese buildings consumes 50 to 100 percent more energy than that used in Western Europe. Making buildings in China more energy efficient would add 10 percent to construction costs but would save more than 50 percent on energy costs.[57] Technology innovations such as advanced building materials can further increase the potential energy savings (see chapter 7). Integrated zero-emission building designs, combining energy-efficiency measures with on-site power and heat from solar and biomass, are technically and economically feasible—and the costs are falling.[58]

Manufacturing accounts for one-third of global energy use, and the potential for energy savings in industry is particularly large in developing countries. Key opportunities include improving the efficiency of energy-intensive equipment such as motors and boilers and of energy-intensive industries such as iron, steel, cement, chemicals, and petrochemicals. One of the most cost-effective measures is combined heat and power. Existing technologies and best practices could reduce energy consumption in the industrial sector by 20–25 percent, helping reduce carbon footprints without sacrificing growth.[59] In Mexico cogeneration in the refineries of Pemex, the large state-owned petroleum company, could provide more than 6 percent of the country's installed power capacity at a negative mitigation cost (meaning that the sale of previously wasted electricity and heat would generate sufficient revenue to more than offset the required investments).[60]

Improving vehicle fuel efficiency, for example by shifting to hybrid cars, is the most cost-effective means of cutting emissions in the transport sector in the near to medium term. In addition, improving power-train systems (for example, by downsizing conventional internal combustion engines) and making other design changes, such as lower vehicle weight, optimized transmissions, and start-stop systems with regenerative braking, can also improve fuel efficiency.

In addition, smart urban planning—denser, more spatially compact, and with mixed-use urban design that allows growth near city centers and transit corridors to prevent urban sprawl—can substantially reduce energy demand and CO_2 emissions. It reduces the vehicle kilometers traveled and makes it possible to rely on district and integrated energy systems for heating.[61] In Mexico, for example, dense urban development is expected to reduce total emissions by 117 million tons of CO_2e from 2009 to 2030, with additional social and environmental benefits.[62]

Market and nonmarket barriers and failures

The large untapped potential for greater energy efficiency demonstrates that low-cost energy savings are not easy. Small-scale, fragmented energy-efficiency measures, involving multiple stakeholders and tens of millions of individual decision makers, are fundamentally more complex than large-scale, supply-side options. Energy-efficiency investments need cash up front, but future savings are less tangible, making such investment risky compared with asset-based energy-supply deals. Many market failures and barriers, as well as nonmarket barriers, to energy efficiency exist and tackling them requires policies and interventions that entail additional costs (box 4.8). Another concern is the rebound effect: acquiring efficient equipment lowers energy bills, so consumers tend to increase energy consumption, eroding some of the energy reductions. But empirically the rebound is small to moderate, with long-run effects of 10–30 percent for personal transport and space heating and cooling,[63] and these can be mitigated with price signals.

Price should reflect true cost

Many countries channel public subsidies, implicit and explicit, to fossil fuels, distorting investment decisions for clean energy. Energy subsidies in the 20 highest-subsidizing developing countries are estimated at around $310 billion a year, or around 0.7 percent of world GDP in 2007.[64] The lion's share of the subsidies artificially lowers the prices of fossil fuels, providing disincentives to save energy and making clean energy less attractive financially.[65]

Removing fossil-fuel subsidies would reduce energy demand, encourage the supply of clean energy, and lower CO_2 emissions.

BOX 4.8 *Energy efficiency faces many market and nonmaraket barriers and failures*

- *Low or underpriced energy*. Low energy prices undermine incentives to save energy.
- *Regulatory failures*. Consumers who receive unmetered heat lack the incentive to adjust temperatures, and utility rate-setting can reward inefficiency.
- *A lack of institutional champion and weak institutional capacity*. Energy-efficiency measures are fragmented. Without an institutional champion to coordinate and promote energy efficiency, it becomes nobody's priority. Moreover, there are few energy-efficiency service providers, and their capacity will not be established overnight.
- *Absent or misplaced incentives*. Utilities make a profit by generating and selling more electricity, not by saving energy. For most consumers, the cost of energy is small relative to other expenditures. Because tenants typically pay energy bills, landlords have little or no incentive to spend on efficient appliances or insulation.
- *Consumer preferences*. Consumer decisions to purchase vehicles are usually based on size, speed, and appearance rather than on efficiency.
- *Higher up-front costs*. Many efficient products have higher up-front costs. Individual consumers usually demand very short payback times and are unwilling to pay higher up-front costs. Preferences aside, low-income customers may not be able to afford efficient products.
- *Financing barriers and high transaction costs*. Many energy-efficiency projects have difficulty obtaining financing. Financial institutions usually are not familiar with or interested in energy efficiency, because of the small size of the deal, high transaction costs, and high perceived risks. Many energy service companies lack collateral.
- *Products unavailable*. Some efficient equipment is readily available in high- and middle-income countries but not in low-income countries, where high import tariffs reduce affordability.
- *Limited awareness and information*. Consumers have limited information on energy-efficiency costs, benefits, and technologies. Firms are unwilling to pay for energy audits that would inform them of potential savings.

Source: WDR team.

Ample evidence shows that higher energy prices induce substantially lower demand.[66] If Europe had followed the U.S. policy of low fuel taxes, its fuel consumption would be twice as large as it is now.[67] Removing fossil-fuel subsidies in power and industry could reduce global CO_2 emissions by as much as 6 percent a year and add to global GDP.[68]

But removing those subsidies is no simple matter—it requires strong political will. Fuel subsidies are often justified as protecting poor people, even though most of the subsidies go to better-off consumers. As chapters 1 and 2 discuss, effective social protection targeted at low-income groups, in conjunction with the phased removal of fossil-fuel subsidies, can make reform politically viable and socially acceptable. It is also important to increase transparency in the energy sector by requiring service companies to share key information, so that the governments and other stakeholders can make better-informed decisions and assessments about removing subsidies.

Energy prices should reflect the cost of production and incorporate local and global environmental externalities. Urban air pollution from fossil-fuel combustion increases health risks and causes premature deaths. Lower-respiratory disease resulting from air pollution is a top cause of mortality in low-income countries and a burden of disease in the world.[69] A 15 percent greenhouse gas reduction below business as usual by 2020 in China would result in 125,000–185,000 fewer premature deaths annually from pollution emitted by power generation and household energy use.[70] Pricing local air pollution can be very effective in reducing the related health costs.

Pricing carbon, through a carbon tax or cap-and-trade system (see chapter 6), is fundamental to scaling up advanced clean energy technologies and leveling the playing field with fossil fuels.[71] It provides incentives and reduces risks for private investments and innovations in efficient and clean energy technologies on a large scale (see chapter 7).[72] Developed countries should take the lead in pricing carbon. Legitimate concerns include protecting the poor from high energy prices and compensating the losing industries, particularly in developing countries. Social safety nets and nondistortionary income support, possibly from revenues generated by the carbon tax or permit auction, can help (see chapters 1 and 2).

Pricing policy alone is not enough; energy-efficiency policies are also critical

Carbon-pricing policies alone will not be enough to ensure large-scale development and deployment of energy efficiency and low-carbon technologies (box 4.9). Energy efficiency faces distinct barriers in different sectors. For power, where a small number of decision makers determine whether energy-efficiency measures are adopted, financial incentives are likely to be effective. For transport, buildings, and industry—where adoption is a function of the preferences of, and requires action by, many decentralized individuals—energy demand is less responsive to price signals, and regulations tend to be more effective. A suite of policy instruments can replicate proven successes in removing barriers to energy efficiency.

BOX 4.9 *Carbon pricing alone is not enough*

Carbon pricing alone cannot guarantee large-scale deployment of efficient and clean energy, because it cannot fully overcome the market failures and nonmarket barriers to the innovation and diffusion of low-carbon technologies.[a]

First, price addresses only one of many barriers. Others, such as a lack of institutional capacity and financing, block the provision of energy-saving services.

Second, while the price elasticity of energy demand is high over the long term, it is generally quite inelastic in the short term, because people have few short-run options for reducing their transport needs and household energy use in response to fuel price changes. Automobile fuel prices have an historical short-term elasticity ranging from only −0.2 to −0.4,[b] with a much smaller response of −0.03 to −0.08 in recent years,[c] but a long-term elasticity ranging between −0.6 and −1.1.

Third, the low price elasticity of adoptiing many energy-efficiency measures may also be a result of high opportunity costs in rapidly growing developing countries like China. A return of 20 percent for an efficiency measure is attractive, but investors may not invest in efficiency if other investments with equivalent risks have higher returns.

So, strong pricing policies are important but not enough. They need to be combined with regulations to correct market failures, remove market and nonmarket barriers, and foster clean technology development.

Sources:

a. ETAAC 2008.

b. Chamon, Mauro, and Okawa 2008.

c. Hughes, Knittel, and Sperling 2008.

Regulations. Economywide energy-intensity targets, appliance standards, building codes, industry performance targets (energy consumption per unit of output), and fuel-efficiency standards are among the most cost-effective measures. More than 35 countries have national energy-efficiency targets. France and the United Kingdom have gone a step further in energy-efficiency obligations by mandating that energy companies meet energy-saving quotas. In Japan energy-efficiency performance standards require utilities to achieve electricity savings equal to a set percentage of their baseline sales or load.[73] Brazil, China, and India have energy-efficiency laws, but as in all contexts, effectiveness depends on enforcement. Other options include the mandatory phasing out of incandescent lights.

Complying with efficiency standards can avoid or postpone adding new power plant capacity and reduce consumer prices. And industrial energy performance targets can spur innovation and increase competitiveness. For new buildings in Europe the cumulative energy savings from building codes is about 60 percent over those built before the first oil shock in the 1970s.[74] Refrigerator efficiency standards in the United States have saved 150 gigawatts in peak power demand over the past 30 years, more than the installed capacity of the entire U.S. nuclear program.[75] Efficiency standards and labeling programs cost about 1.5 cents a kilowatt-hour, much cheaper than any electricity supply option.[76] The average price of refrigerators in America has fallen by more than half since the 1970s, even as their efficiency has increased by three-quarters.[77]

Financial incentives. In many developing countries weak enforcement of regulations is a concern. Regulations need to be supplemented with financial incentives for consumers and producers. Low-income consumers are most sensitive to the higher up-front costs of efficient products. Financial incentives to offset these up-front costs, such as consumer rebates and energy-efficient mortgages,[78] can change consumer behavior, increase affordability, and overcome barriers to market entry by new, efficient producers. In addition, regulations are also vulnerable to rebound effects, so pricing policies are needed to discourage consumption. Fuel taxes have proved one of the most cost-effective ways to reduce transport energy demand, along with congestion charges and insurance or tax levies on vehicles based on kilometers traveled, and higher taxes on light trucks and sports utility vehicles (table 4.5).

Utility demand-side management has produced large energy savings. Key to success is decoupling utility profits from electricity sales to give utilities incentives to save. Regulators forecast demand and allow utilities to charge a price that would recoup their costs and earn a fixed return based on that forecast. If demand turns out to be lower than expected, the regulator lets prices rise so that the utility can make the mandated profit; if it is higher, the regulator cuts prices to return the excess to customers (box 4.10).

Institutional reform. An institutional champion, such as a dedicated energy-efficiency agency, is essential to coordinate multiple stakeholders and promote and manage energy-efficiency programs. More than 50 countries, developed and developing, have a national energy-efficiency agency. It can be a government agency with a focus on clean energy or energy efficiency (the most common), such as the Department of Alternative Energy Development and Efficiency in Thailand, or an independent corporation or authority, such as the Korea Energy Management Corporation. To achieve successful results, they require adequate resources, the ability to engage multiple stakeholders, independence in decision making, and credible monitoring of results.[79]

Energy service companies (ESCOs) provide energy-efficiency services such as

Table 4.5 Policy interventions for energy efficiency, renewable energy, and transport

Policy area	Energy efficiency and demand-side management interventions	Renewable energy interventions	Barriers addressed
Economywide	Removal of fossil-fuel subsidies Tax (fuel or carbon tax) Quantitative limits (cap-and-trade)		Environmental externalities not included in the price Regressive or demand-augmenting distortions from subsidies for fossil fuels
Regulations	Economywide energy-efficiency targets Energy-efficiency obligations Appliance standards Building codes Industry energy-performance targets Fuel economy standards	Mandatory purchase, open and fair grid access Renewable portfolio standards Low-carbon fuel standards Technology standards Interconnection regulations	Lack of legal framework for renewable independent power producers Lack of transmission access by renewable energy Lack of incentives and misplaced incentives to save Supply-driven mentality Unclear interconnection requirements
Financial incentives	Tax credits Capital subsidies Profits decoupled from sales Consumer rebates Time-of-use tariffs Fuel taxes Congestion tolls Taxes based on engine size Insurance or tax levies on vehicle miles traveled Taxes on light trucks, SUVs	Feed-in tariff, net metering Green certificates Real-time pricing Tax credits Capital subsidies	High capital costs Unfavorable pricing rules Lack of incentives for utilities and consumers to save
Institutional arrangements	Utility Dedicated energy-efficiency agencies Independent corporation or authority Energy service companies (ESCOs)	Utility Independent power producers	Too many decentralized players
Financing mechanisms	Loan financing and partial loan guarantees ESCOs Utility energy-efficiency, demand-side management program, including system benefit fund	System benefit fund Risk management and long-term financing Concessional loans	High capital cost, and mismatch with short-term loans ESCOs' lack of collateral and small deal size Perceived high risks High transaction costs Lack of experience and knowledge
Promotion and education	Labeling Installing meters Consumer education	Education about renewable energy benefits	Lack of information and awareness Loss of amenities

Source: WDR team.

BOX 4.10 *California's energy-efficiency and renewable energy programs*

A U.S. leader in energy efficiency, California has kept its electricity consumption per capita flat for the past 30 years, substantially below the U.S. national average (figure, panel a). Appliance standards and building codes, along with financial incentives for utility demand-side management programs, are estimated to be responsible for one-quarter of the difference (figure, panel b). California decoupled utility profits from sales in 1982 and recently went a step further with "decoupling-plus"—utilities earn additional money if they meet or exceed savings goals.

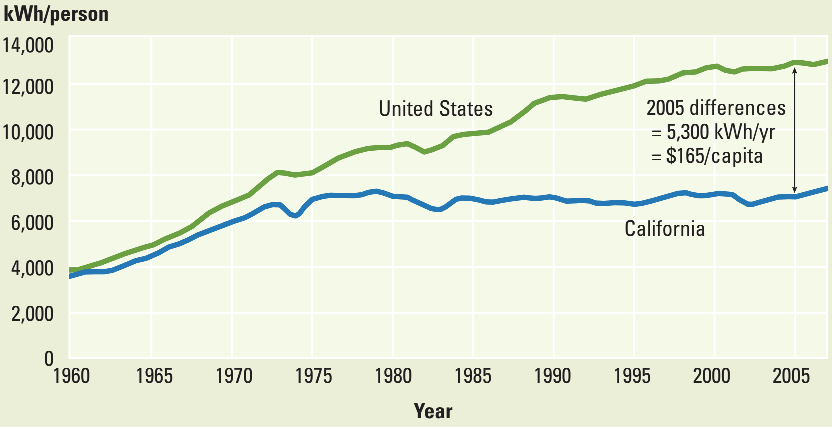
The state's energy-efficiency program has an annual budget of $800 million, collected from tariff surcharges on electricity and used for utility procurements, demand-side management, and research and development. The average cost of the program is about 3 cents per kilowatt-hour, far lower than the cost of supply (figure, panel c). To promote renewable energy, the state is implementing renewable portfolio standards to increase renewable energy's share in power generation to 20 percent by 2010.

In June 2005 California became the first U.S. state to issue an executive order on climate change, setting a target for reducing greenhouse gas emissions to the 2000 level by 2010, to the 1990 level by 2020, and to 80 percent below the 1990 level by 2050. Energy efficiency is projected to contribute about 50 percent of this reduction.

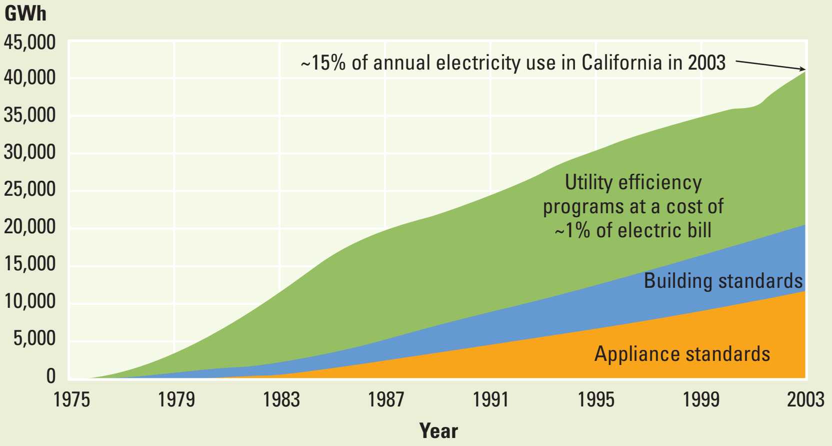
Sources: California Energy Commission 2007a; Rosenfeld 2007; Rogers, Messenger, and Bender 2005; Sudarshan and Sweeney forthcoming.

California's electricity consumption per capita has remained flat over the past 30 years, thanks largely to utility demand-side management and efficiency standards. The cost of energy efficiency is much lower than that of electricity supply

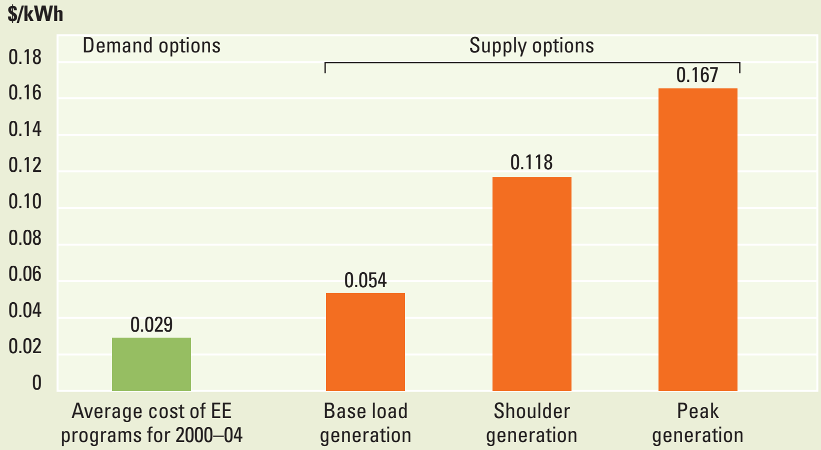
a. Electricity sales per capita



b. Annual energy savings from efficiency programs and standards



c. Comparison of California energy efficiency (EE) program costs to supply generation costs



energy auditing, recommend energy saving measures, and provide financing to clients; they also serve as project aggregators. But they are not a magic bullet. Most ESCOs have had difficulty in obtaining adequate financing from commercial banks because of their weak balance sheets and the perceived higher risks of loans dependent on revenues from energy savings. Policies, financing, and technical support from governments and international development banks can strengthen ESCOs and mainstream their business model. In China, for example, after a decade of capacity building supported by the World Bank, the ESCO industry grew from three companies in 1997 to more than 400, with $1 billion in energy performance contracts in 2007.[80]

Financing mechanisms. Developing and operating energy-efficiency services for investment in energy efficiency are primarily institutional issues. Lack of domestic capital is rarely a problem, but inadequate organizational and institutional systems for developing projects and accessing funds can be barriers to finance. The three main financing mechanisms for energy-efficiency projects are ESCOs, utility demand-management programs, and loan financing and partial loan guarantee schemes operating within commercial banks, as specialized agencies, or as revolving funds.[81]

BOX 4.11 *World Bank Group experience with financing energy efficiency*

The World Bank and the International Finance Corporation (IFC) have financed a series of energy-efficiency financial intermediary projects, mostly in Eastern Europe and East Asia. The IFC pioneered the use of a guarantee mechanism through selected domestic banks with the Hungary Energy Efficiency Guarantee Fund. A Global Environment Facility grant of $17 million was used to guarantee $93 million worth of loans for energy-efficient investments. No guarantee has been called, giving local banks confidence in and familiarity with energy-efficiency lending.

One of the key lessons of the experience is the importance of technical assistance, particularly at the beginning, to raise awareness of energy efficiency, to provide training and advisory services to the banks in developing financial mechanisms, and to build the capacity of project developers. While in Bulgaria the transaction cost of institutional capacity building for both financial institutions and energy service companies—from project concept to financial closure—has been around 10 percent of total project costs at the beginning, it is expected to decline to around 5–6 percent later on.

Sources: WDR team; Taylor and others 2008.

Lending through local commercial banks offers the best prospect for program sustainability and maximum impact. International financial institutions have supported partial-risk-guarantee programs to mitigate the risks of energy-efficiency projects for commercial banks, increasing the banks' confidence in jump-starting energy-efficiency financing (box 4.11). Dedicated revolving funds are another common approach, particularly in countries where investing in energy efficiency is in the early stages and banks are not ready to provide financing.[82] This approach is transitional, and sustainability is a major issue.

Utility demand-side management is usually funded through a system benefit fund (financed by a tariff surcharge on kilowatt-hours to all electricity customers), which is more sustainable than government budgets. Administered by either utilities or dedicated energy-efficiency agencies, the funds cover incremental costs of switching to renewable energy from fossil fuels, consumer rebates, concessional loans, research and development, consumer education, and low-income consumer assistance.

Public procurement. Mass procurement of energy-efficient products can substantially reduce costs, attract larger contracts and bank lending, and lower transaction costs. In Uganda and Vietnam the bulk procurement of 1 million compact fluorescent lamps in each country substantially reduced the cost of the lamps and improved product quality through technical specifications and warranty; once installed, they cut peak demand by 30 megawatts.[83] Public procurement through government agencies, usually one of the biggest energy consumers in an economy, can reduce costs and demonstrate government's commitment and to leadership in energy efficiency. But mandates, incentives, and procurement and budgeting rules have to be in place.[84]

Consumer education. Consumer education can promote lifestyle changes and more informed choices—examples include energy-efficiency labeling and increased use of electricity and heat meters, particularly smart meters. Consumer awareness campaigns are most effective in conjunction with regulations and financial incentives. Based on experience in the public health field, interventions to change behaviors need to occur at multiple levels—policy, physical environment (design of walkable cities and green buildings), sociocultural (media communications), interpersonal (face-to-face contacts), and individual (see chapter 8).[85]

Scaling up existing low-carbon technologies

Renewable energy could contribute around 50 percent to the power mix by 2050.[86] Renewable energy can reduce greenhouse gas emissions and other air pollutants, enhance energy security by diversifying the energy mix and reducing exposure to fossil-fuel price volatility, and stimulate economic development by building local manufacturing industries, creating jobs, and increasing energy access. Adding renewable energy to the utility portfolio can hedge the risks of fossil-fuel price volatility. Renewable energy provides environmentally benign and indigenous energy resources for power generation, for heating and cooling (which make up 40–50 percent of global energy demand),[87] and for transport.

With costs of renewable energy declining over the past two decades, wind, geothermal, and hydro power are already or nearly cost-competitive with fossil fuels.[88] Solar is still costly, but costs are expected to decline rapidly along the learning curve over the next few years (box 4.12). With

BOX 4.12 *Difficulties in comparing energy technology costs: A matter of assumptions*

Comparing costs of different energy technologies is a tricky business. A frequently used approach for comparing electricity generation technologies is based on costs per kilowatt-hour (kWh). A levelized-cost method is commonly used to compare the life-cycle economic costs of energy alternatives that deliver the same energy services. First, capital costs are calculated using a simple capital recovery factor method.[a] This method divides the capital cost into an equal payment series—an annualized capital cost—over the lifetime of the equipment. Then the annualized capital costs are added to the annual operation and maintenance (O&M) costs and the fuel costs to obtain the levelized costs. So capital costs, O&M costs, fuel costs, the discount rate, and a capacity factor are key determinants of levelized costs.

In reality, costs are time and site specific. The costs of renewable energy are closely linked to local resources and sites. Wind costs, for example, vary widely depending on site-specific wind resources. Labor costs and construction time are also key factors, particularly for fossil-fuel and nuclear plants. Chinese coal-fired power plants, for example, cost about one-third to one-half of the international prices for similar plants. The long lead time to construct nuclear power plants contributes to the high costs in the United States.

Second, sensible integrated comparative assessment of different energy technologies compares all the economic attributes along the primary fuel cycle for a unit of energy benefits. Comparing renewable energy costs with fossil fuel and nuclear should take into account the different services they provide (base-load or intermittent energy). On the one hand, solar and wind energy produce variable outputs, although outputs can be enhanced in various ways, usually at an additional cost. On the other hand, solar and wind energy technologies can typically be licensed and built in much less time than large-scale fossil or nuclear plants.

Third, externalities such as environmental costs and portfolio diversification values should be incorporated when comparing fossil-fuel costs and clean energy costs. A carbon price will make a big difference in pushing up the costs of fossil fuels. Fossil-fuel price volatility creates additional negative externalities. Increasing fuel prices by 20 percent increases the costs of generation by 16 percent for gas and 6 percent for coal, while leaving renewable energy practically untouched.[b] Incorporation of the portfolio diversification value of renewable energy, in utility planning can hedge the volatility of fossil-fuel prices and enhance energy security.

When dealing with new technologies, the potential for cost reduction should also be factored in. Dynamic analysis of future costs of new technologies depends on the assumptions made about the learning rate—the cost reductions associated with a doubling of capacity. The cost of wind energy has dropped nearly 80 percent over the past 20 years. Technology breakthroughs and economies of scale can lead to more rapid cost reductions, a phenomenon some experts now expect will lead to dramatic near-term reductions in solar cell prices.[c]

In financial analysis, differences in institutional context (whether public or private financing) and government policies (taxes and regulations) are often the deciding factors. Differences in financing costs are particularly important for the most capital-intensive technologies like wind, solar, and nuclear. A California study shows that the cost of a wind power plant varies much more than the cost of a gas combined cycle plant, with different financing terms for private ("merchant"), investor-owned, and publicly owned utilities.[d]

Sources:

a. The capital recovery factor = $[i(1+i)^n]/[(1+i)^n - 1]$ where i is the discount rate and n is the lifetime or period of capital recovery of the systems.

b. World Economic Forum 2009.

c. Deutsche Bank Advisors 2008 (projected photovoltaic cost reductions).

d. California Energy Commission 2007b.

rising fossil-fuel prices, the cost gap is closing. Biomass, geothermal power, and hydropower can provide base-load power, but solar and wind are intermittent.

A large share of intermittent resources in the grid system may affect reliability, but this can be addressed in a variety of ways—through hydropower or pumped storage, load management, energy storage facilities, interconnection with other countries, and smart grids.[89] Smart grids can enhance reliability of electricity networks when incorporating variable renewable energy and distributed generation. High-voltage, direct-current lines can make long-range transmission possible with low line losses, which reduces the common problem of renewable energy sources located far from consumption centers. And further cost reduction and performance improvement of energy storage will be needed for large-scale deployment of solar and wind power and electric vehicles. So, while the required magnitude of renewable energy is vast, the transformation is achievable. For example, wind already accounts for 20 percent of Danish power production (box 4.13).

Renewable energy policies: financial incentives and regulations

Transparent, competitive, and stable pricing through long-term power purchase agreements has been most effective in attracting investors to renewable energy, and an enabling legal and regulatory framework can ensure fair and open grid access for independent power producers. Two major mandatory policies for renewable power generation are operating worldwide: feed-in laws that mandate a fixed price, and renewable portfolio standards that mandate a set target for the share of renewable energy (box 4.14).[90]

Feed-in laws require mandatory purchases of renewable energy at a fixed price. Feed-in laws such as those in Germany, Spain, Kenya, and South Africa produce the highest market penetration rates in a short period. They are considered most desirable by investors because of their price certainty and administrative simplicity and because they are conducive to creating local manufacturing industries. Three methods are commonly used to set prices for feed-in tariffs—avoided costs of conventional power generation, costs of renewable energy plus reasonable returns, and average retail prices (net metering allows consumers to sell excess electricity generated from their homes or businesses, usually through solar photovoltaics, to the grid at retail market prices). The main risk is in setting prices either too high or low, so feed-in tariffs need periodic adjustment.

Renewable portfolio standards require utilities in a given region to meet a minimum share of power in or level of installed capacity from renewable energy, as in

BOX 4.13 *Denmark sustains economic growth while cutting emissions*

Between 1990 and 2006 Denmark's GDP grew at roughly 2.3 percent a year, more than Europe's average of 2 percent. Denmark also reduced carbon emissions by 5 percent.

Sound policies decoupled emissions from growth. Denmark, along with other Scandinavian countries, implemented the world's first carbon tax on fossil fuels in the early 1990s. At the same time Denmark also adopted a range of policies to promote the use of sustainable energy. Today around 25 percent of Denmark's electricity generation and 15 percent of its primary energy consumption come from renewable energy, mainly wind and biomass, with a goal to raise the use of renewable energy to at least 30 percent by 2025. Membership in the Nordic power pool, with more than 50 percent hydropower, provides the additional flexibility of exporting surplus wind power and importing Norwegian hydropower during periods of low wind resources. Vestas, the major Danish wind company, has 15,000 employees and accounts for a quarter of the global market for wind turbines. In 15 years Danish renewable technology exports have soared to $10.5 billion.

In addition to its low carbon-intensity of energy, Denmark has the lowest energy intensity in Europe, a result of stringent building and appliance codes and voluntary agreements on energy savings in industry. Combined heat- and power-based district heating networks provide 60 percent of the country's winter heating, with over 80 percent of it coming from heat previously wasted in electricity production.

Sources: WDR team based on WRI 2008; Denmark Energy Mix Fact Sheet, http://ec.europa.eu/energy/energy_policy/doc/factsheets/mix/mix_dk_en.pdf (accessed August 27, 2009).

BOX 4.14 *Feed-in laws, concessions, tax credits, and renewable portfolio standards in Germany, China, and the United States*

Developing countries account for 40 percent of global renewable energy capacity. By 2007, 60 countries, including 23 developing countries, had renewable energy policies.[a] The three countries with the largest installed capacity of new renewable energy are Germany, China, and the United States.

Germany's feed-in law

In the early 1990s Germany had virtually no renewable energy industry. Today it has become a global renewable energy leader, with a multibillion-dollar industry and 250,000 new jobs.[b] The government passed the Electricity Feed-in Law in 1990, requiring utilities to purchase the electricity generated from all renewable technologies at a fixed price. In 2000 the German Renewable Energy Act set feed-in tariffs for various renewable energy technologies for 20 years, based on their generation costs and generation capacity. To encourage cost reductions and innovation, prices will decline over time based on a predetermined formula. The law also distributed the incremental costs between wind power and conventional power among all utility customers in the country.[c]

China's renewable energy law and wind concession

China was one of the first developing countries to pass a renewable energy law, and it now has the world's largest renewable energy capacity, accounting for 8 percent of its energy and 17 percent of its electricity.[d] The law set feed-in tariffs for biomass power, but wind power tariffs are established through a concession process. The government introduced wind concessions in 2003 to ramp up wind power capacity and drive down costs. The winning bids for the initial rounds were below average costs and discouraged both wind developers and domestic manufacturers. Improvements in the concession scheme and provincial feed-in tariffs put China at no. 2 in newly installed wind capacity in 2008. The government's target of 30 gigawatts of wind by 2020 will likely be reached ahead of time. The domestic wind manufacturing industry has been boosted by the government's requirement of 70 percent local content and new technology transfer models to hire and acquire international design institutes.

U.S. federal production tax credits and state renewable portfolio standards

A federal tax credit for producing electricity from renewable energy has encouraged significant capacity increases, but the uncertainty of its extension from year to year has led to boom-and-bust cycles in U.S. wind development. And twenty-five states now have renewable portfolio standards. As a result, wind accounted for 35 percent of new generation capacity in 2007, and the United States now has the world's largest installed wind capacity.[e]

Sources:

a. REN 21 2008.
b. Federal Ministry for the Environment 2008.
c. Beck and Martinot 2004.
d. REN 21 2008.
e. Wiser and Bolinger 2008.

many U.S. states, the United Kingdom, and Indian states. The target is met through utilities' own generation, power purchases from other producers, direct sales from third parties to the utility's customers, or purchases of tradable renewable energy certificates. But unless separate technology targets or tenders are in place, renewable portfolio standards lack price certainty and tend to favor established industry players and least-cost technologies.[91] They are also more complex to design and administer than feed-in laws.

An alternative approach for achieving renewable energy targets is competitive tendering, where power producers bid on providing a fixed quantity of renewable power, with the lowest-price bidder winning the contract, as is done in China and Ireland. Tendering is effective at reducing costs, but a main risk has been that some bidders underbid and obligations have not always translated into projects on the ground.

Several financial incentives are available to encourage renewable energy investments: reducing up-front capital costs through subsidies; reducing capital and operating costs through investment or production tax credits; improving revenue streams with carbon credits; and providing financial support through concessional loans and guarantees. Output-based incentives are generally preferable to investment-based incentives for grid-connected renewable energy.[92] Investment incentives per kilowatt of installed capacity do not necessarily provide incentives to generate electricity or maintain the performance of plants. But output incentives per kilowatt-hour of power produced promote the desired outcome—generating electricity from renewable energy. Any incremental costs of renewable energy over fossil fuels can be passed on to consumers or financed through a system benefits charge, a carbon tax on fossil-fuel use, or a dedicated fund from government budgets or donors.

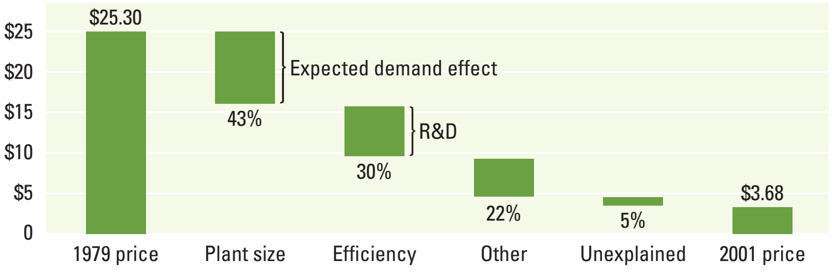
Nuclear power and natural gas

Nuclear power is a viable and significant option for mitigating climate change, but it is limited by four problems: higher costs than coal-fired plants,[93] risks of nuclear weapon proliferation, uncertainties about waste management, and public concerns about reactor safety. Current international safeguards are inadequate to meet the security challenges of expanded nuclear deployment.[94] But studies also demonstrate that the once-through fuel cycle, in which discharged spent fuel is sent directly to disposal, can meet the criteria of low costs and proliferation resistance. The next generation of nuclear reactor designs offer improved safety characteristics and better economics than the reactors currently in operation. Gas-cooled reactors, such as the pebble-bed modular reactor, offer enhanced operational and safety features and are expected to become available in the next decade.

Nuclear power has large requirements for capital and highly trained personnel, with long lead times before it comes on line, thus reducing its potential for reducing carbon emissions in the short term. A 2°C trajectory would require construction of nuclear power plants at twice the historical peak construction rate between 1970 and 1990 (since 1990 there has been very little growth in capacity). But planning, licensing, and constructing a single nuclear plant typically takes a decade or more. And because of the dearth of orders in recent decades, the world has limited capacity to manufacture many of the critical components of nuclear plants, and rebuilding that capacity will take at least a decade.[95]

Figure 4.12 Solar photovoltaic power is getting cheaper over time, thanks to R&D and higher expected demand from larger scale of production

Cost reduction by factor ($/watt)



Source: Adapted from Nemet 2009.

Note: Cost reduction is expressed in 2002 US $. Bars show the portion of the reduction in the cost of solar photovoltaic power, from 1979 to 2001, accounted for by different factors such as plant size (which is determined by expected demand) and improved efficiency (which is driven by innovation from R&D). The "other" category includes reductions in the price of the key input silicon (12 percent) and a number of much smaller factors (including reduced quantities of silicon needed for a given energy output, and lower rates of discarded products due to manufacturing error).

Natural gas is the least carbon-intensive fossil fuel for power generation and for residential and industrial use. There is a large potential to reduce carbon emissions by substituting natural gas for coal in the short term. Some 2°C scenarios project that the share of natural gas in the primary energy mix will increase from 21 percent currently to 27–37 percent by 2050.[96] But the costs of natural gas-fired power depend on gas prices, which have been highly volatile in recent years. And, like oil, more than 70 percent of the world's gas reserves are in the Middle East and Eurasia. Security of gas supply is a concern to gas-importing countries. So energy diversification and supply security concerns could limit the share of natural gas in the global energy mix to less than indicated in some climate-energy models.[97]

Accelerating innovation and advanced technologies

Accelerating innovation and advanced technologies requires adequate carbon pricing; massive investment in research, development and demonstration; and unprecedented global cooperation (see chapter 7). Coupling technology push (by increasing research and development, for example) with demand pull (to increase economies of scale) is critical to substantially reduce the cost of advanced technologies (figure 4.12).

Utility-scale power generation technologies require policies and approaches different from those for small-scale technologies. An international Manhattan Project is likely to be needed to develop the former, such as power-plant-based carbon capture and storage, on a scale large enough to allow substantial cost reductions as the technology moves along the learning curve. Developers—utilities or independent power producers—usually have sufficient resources and capacity. But adequate carbon pricing and investment subsidies are required to overcome the high capital cost barrier. In contrast, decentralized, smaller-scale, clean energy technologies require that "a thousand flowers bloom" to address the needs of many small local players, with seed and venture capital and, in developing countries, business development advisory services.

To achieve the 2°C trajectory, a different technology path is required for developing countries. Energy and emissions growth are projected to come largely from developing countries, but developed countries attract much more investment in clean energy technology. Traditionally, new technologies are produced first in developed economies, followed by commercial roll-outs in developing countries, as has been the case with wind energy.[98] But for emissions to peak in 10 years to stay on the 2°C trajectory, both developed and developing countries would need to introduce large-scale demonstrations of advanced technologies—now and in parallel. This pattern is fortunately emerging with the rapid advent of research and development in Brazil, China, India, and a few other technology leaders in the developing world. The lowest-cost manufacturers of solar cells, efficient lighting, and ethanol are all in developing countries.

One of the major barriers facing developing countries is the high incremental cost of developing and demonstrating advanced clean energy technologies. It is essential that developed countries substantially increase financial assistance and transfers of low-carbon technologies to the developing world through mechanisms such as a global technology fund. Developed countries will also need to take the lead in encouraging technological breakthroughs (see chapter 7). The Mediterranean Solar Plan is an example of cooperation between developed and developing countries on the large-scale demonstration and deployment of concentrated solar power (box 4.15).

Policies have to be integrated

Policy instruments need to be coordinated and integrated to complement each other and reduce conflicts. A reduction of emissions in transport, for example, requires integration of a three-legged approach. In the order of difficulty, they are transforming vehicles (fuel efficient, plug-in hybrid, and electric cars), transforming fuels (ethanol from sugarcane, second generation biofuels, and hydrogen), and transforming mobility (urban planning and mass transit).[99] Biofuel policies need to coordinate energy and transport policies with agriculture, forestry, and land-use policies to manage the competing demands for water and land (see chapter 3). If energy crops take land away from agriculture in poor nations, the "medicine" of the requisite interventions might be worse than the "disease" in the sense that mitigation might increase vulnerability to climate impacts.[100] Large-scale deployment of plug-in hybrid and electric vehicles would substantially increase power demand, threatening the anticipated lower emissions from the technology unless the grid is supplied with an increased share of low-carbon energy sources. Policies to encourage renewable energy, if not designed properly, can discourage efficient heat production for combined heat and power.

Policies, strategies, and institutional arrangements also have to be aligned across sectors. Cross-sectoral initiatives are usually difficult to implement, because of fragmented institutional arrangements and weak incentives. Finding a champion is critical for moving the agenda forward; for example, local governments can be a good entry point for emission reductions in cities, particularly for buildings and modal shifts in transport. It is also important to align policies and strategies in national, provincial, and local governments (see chapter 8).

In conclusion low-carbon technology and policy solutions can put the world onto a 2°C trajectory, but a fundamental transformation is needed to decarbonize the energy sector. This requires immediate action, and global cooperation and commitment from developed and developing countries. There are win-win policies that governments can adopt now, including regulatory and institutional reforms, financial incentives, and financing mechanisms to scale up existing low-carbon technologies, particularly in the areas of energy efficiency and renewable energy.

Adequate carbon pricing and increased technology development are essential

BOX 4.15 *Concentrated solar power in Middle East and North Africa*

The Mediterranean Solar Plan would create 20 gigawatts of concentrated solar power and other renewable energy capacity by 2020 to meet energy needs in the Middle Eastern and North African countries and export power to Europe. This ambitious plan could bring down the costs of concentrated solar power enough to make it competitive with fossil fuels. Concentrated solar power on less than 1 percent of Saharan desert area (see the map below) would meet Europe's entire power needs.

Financing this solar initiative will be a major challenge but offers an excellent opportunity for a partnership between developed and developing countries to scale up renewable energy for the benefit of both Europe and North Africa.

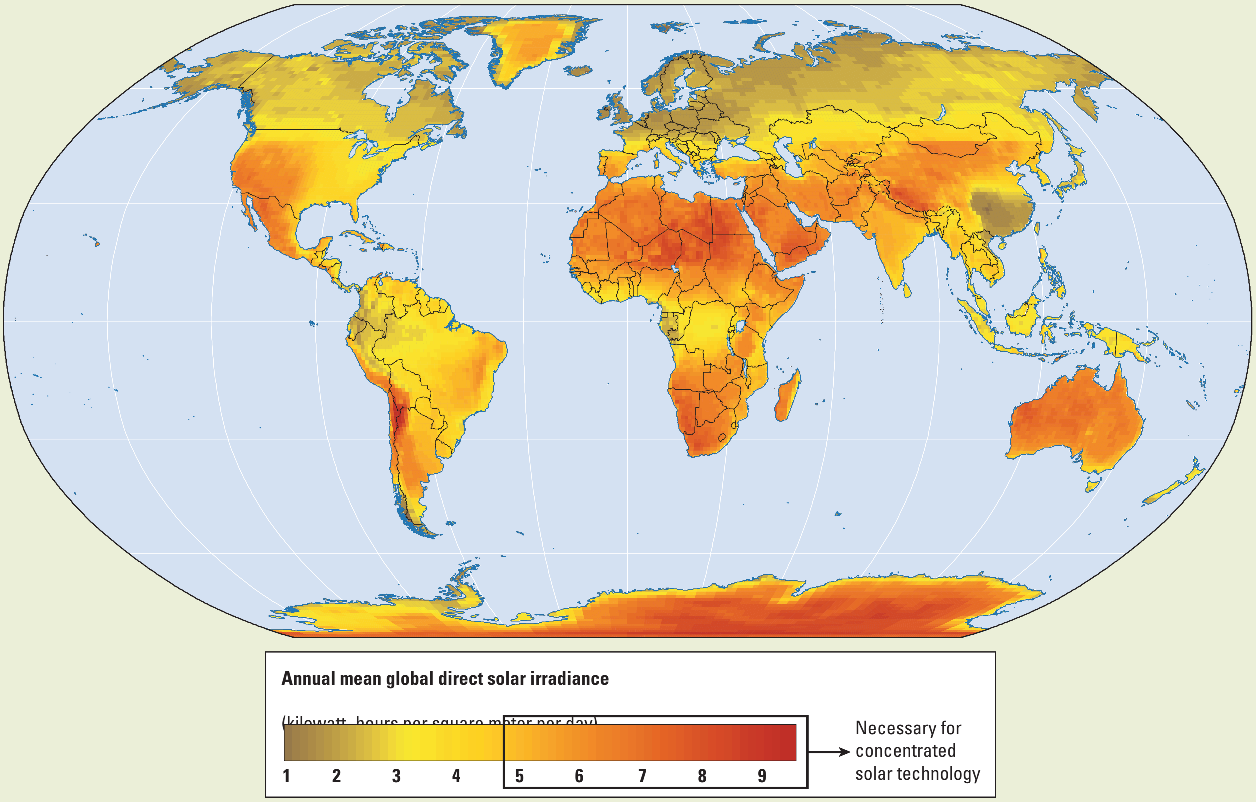
First, the demand for green electricity and the attractive renewable energy feed-in tariffs in Europe can significantly improve the financial viability of concentrated solar power.

Second, bilateral and multilateral funds—such as the Global Environmental Facility, Clean Technology Fund, and carbon financing—would be required for investment subsidies, concessional financing, and revenue enhancement to cover the incremental costs of concentrated solar power, particularly for the portion meeting demand in domestic markets in the Middle East and North Africa.

Third, a successful program also calls for policy actions by the region's governments, creating an enabling environment for renewable energy and removing subsidies to fossil fuels.

Source: WDR team.

Global direct normal solar radiation (kilowatt-hours a square meter a day)



Source: United Nations Environmental Program, Solar and Wind Energy Resource Assessment, http://swera.unep.net/index.php?id=metainfo&rowid=277&metaid=386 (accessed July 21, 2009).

to accelerate development and deployment of advanced low-carbon technologies. Developed countries must take the lead in demonstrating their commitment to significant change at home, while also providing financing and low-carbon technologies to developing countries. Developing countries require paradigm shifts in new climate-smart development models. The technical and economic means exist for these transformative changes, but only strong political will and unprecedented global cooperation will make them happen.

Notes

1. IPCC 2007.

2. Authors' estimates; Socolow 2006. Estimates are based on 100 kilowatt-hours a month electricity consumption for a poor household with an average of seven people, equivalent to 170 kilowatt-hours a person-year. Electricity is provided at the current world average carbon intensity of 590 grams of CO_2 a kilowatt-hour for 1.6 billion people, equivalent to 160 million tons of CO_2. Socolow (2006) assumed providing 35 kilograms of clean cooking fuels (liquefied petroleum gas) for each of the 2.6 billion people would emit 275 million tons of CO_2. So a total of 435 million tons of CO_2 accounts for only 2 percent of current global emissions of 26,000 million tons of CO_2.

3. Black carbon, which is formed through the incomplete combustion of fossil fuels, contributes to global warming by absorbing heat in the atmosphere and, when deposited on snow and ice, by reducing their reflective power and accelerating melting. Unlike CO_2, black carbon remains in the atmosphere for only a few days or weeks, so reducing these emissions will have almost immediate mitigation impacts. In addition, black carbon is a major air pollutant and a leading cause of illness and premature death in many developing countries.

4. SEG 2007.

5. Wilbanks and others 2008.

6. McKinsey Global Institute 2009c.

7. Ebinger and others 2008.

8. The meaning and importance of energy security vary by country depending on its income, energy consumption, energy resources, and trading partners. For many countries dependence on imported oil and natural gas is a source of economic vulnerability and can lead to international tensions. The poorest countries (with per capita income of $300 or less) are particularly vulnerable to fuel price fluctuations, with an average 1.5 percent decrease in GDP associated with every $10 increase in the price of a barrel of oil (World Bank 2009a).

9. Increasing fuel prices by 20 percent increases the costs of generation by 16 percent for gas and 6 percent for coal, while leaving renewable energy practically untouched; see World Economic Forum 2009.

10. IEA 2008b.

11. WRI 2008; see also presentation of historical emissions in the overview.

12. IEA 2008c.

13. IPCC 2007.

14. United Nations 2007.

15. IEA 2008b.

16. Chamon, Mauro, and Okawa 2008.

17. Schipper 2007.

18. Lam and Tam 2002; 2000 U.S. Census, http://en.wikipedia.org/wiki/List_of_U.S._cities_with_most_households_without_a_car (accessed May 2009).

19. Kenworthy 2003.

20. District heating distributes heat for residential and commercial buildings that is supplied in a centralized location by efficient cogeneration plants or large-scale heating boilers.

21. Negative emissions can be achieved by sequestering carbon in terrestrial ecosystems (for example, by planting more forests). It could also be achieved by applying carbon capture and storage to biomass-produced energy.

22. A 450 ppm concentration of greenhouse gases translates into a 40–50 percent chance of temperatures not exceeding 2°C above preindustrial temperatures. Schaeffer and others 2008; Hare and Meinshausen 2006.

23. Tans 2009.

24. Rao and others 2008.

25. Biomass obtained from plants can be a carbon-neutral fuel, because carbon is taken up out of the atmosphere as the plants grow and is then released when the plants are burned as fuel. Biomass-based carbon capture and storage could result in large-scale "negative emissions" by capturing the carbon emitted from biomass combustion.

26. Weyant and others 2009; Knopf and others forthcoming; Rao and others 2008; Calvin and others forthcoming.

27. German Advisory Council on Global Change 2008; Wise and others 2009.

> *"If nothing is done, we shall lose our beloved planet. It is our collective responsibility to find 'unselfish' solutions and fast before it's too late to reverse the damage caused every day."*
>
> —Maria Kassabian, Nigeria, age 10

28. These five models (MESSAGE, MiniCAM, REMIND, IMAGE, and IEA ETP) are the global leading energy-climate models from Europe and the United States, with a balance of top-down and bottom-up approaches and different mitigation pathways. MESSAGE, developed by the International Institute of Applied Systems Analysis (IIASA), adopts the MESSAGE modeling system, which comprises energy systems engineering optimization model MESSAGE and the top-down macroeconomic equilibrium model MACRO, in addition to forest management model DIMA and agricultural modeling framework AEZ-BLS. This analysis considers the B2 scenarios, because they are intermediary between A2 (a high population growth case) and B1 (a plausible "best case" to achieve low emissions in the absence of vigorous climate policies), characterized by "dynamics as usual" rates of change (Riahi, Grübler, and Nakićenović 2007; Rao and others 2008). MiniCAM, developed at the Pacific Northwest National Laboratory, combines a technologically detailed global energy–economy–agricultural-land-use model with a suite of coupled gas-cycle, climate and ice-melt models (Edmonds and others 2008). REMIND, developed by Potsdam Institute for Climate Impact Research, is an optimal growth model that combines a top-down macroeconomic model with a bottom-up energy model, aiming at welfare maximization (Leimbach and others, forthcoming). IMAGE model, developed by the Netherlands Environmental Assessment Agency, is an integrated assessment model including the TIMER 2 energy model coupled with the climate policy model FAIR-SiMCaP (Bouwman, Kram, and Goldewijk 2006). The fifth model is the IEA Energy Technology Perspective, a linear programming optimization model based on the MARKAL energy model (IEA 2008b).

29. Mitigation costs include additional capital investment costs, operation and maintenance costs, and fuel costs, compared to the baseline. Rao and others 2008; Knopf and others forthcoming; Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

30. Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Knopf and others forthcoming; IEA 2008c.

31. IEA 2008b; McKinsey Global Institute 2009a.

32. Knopf and others forthcoming; Calvin and others forthcoming; IEA 2008c.

33. Rao and others 2008; IEA 2008b; Mignone and others 2008. This is true in the absence of effective and acceptable geoengineering technology (see chapter 7 for a discussion).

34. IEA 2008b; IEA 2008c; Riahi, Grübler, and Nakićenović 2007; IIASA 2009; Calvin and others forthcoming.

35. Raupach and others 2007.

36. Shalizi and Lecocq 2008.

37. Philibert 2007.

38. McKinsey Global Institute 2009c.

39. World Bank 2001.

40. IEA 2008b; Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

41. IEA 2008b; Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009. The size of emission reductions required is critically dependent on the baseline scenarios, which vary greatly among different models.

42. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009. It should be noted that land-use changes and methane reductions are also critical measures in nonenergy sectors (see chapter 3) to achieve a 450 ppm CO_2e trajectory, particularly to buy some time in the short term for new technology development.

43. Knopf and others forthcoming; Rao and others 2008.

44. Rao and others 2008; Calvin and others forthcoming; Knopf and others forthcoming.

45. Barrett 2003; Burtraw and others 2005.

46. A molecule of methane, the major component of natural gas, has 21 times more global warming potential than a molecule of CO_2.

47. SEG 2007.

48. IEA 2008b; McKinsey Global Institute 2009b.

49. de la Torre and others 2008.

50. McKinsey Global Institute 2009a.

51. The Mexico Low Carbon Study identified nearly half of the total potential for emissions reduction to be from interventions with positive net benefits (Johnson and others 2008).

52. Bosseboeuf and others 2007.

53. IEA 2008b; Worldwatch Institute 2009.

54. UNEP 2003.

55. IPCC 2007.

56. Brown, Southworth, and Stovall 2005; Burton and others 2008. A comprehensive review of empirical experience based on 146 green buildings in 10 countries concluded that green buildings cost on average about 2 percent more to build than conventional buildings and could reduce energy use by a median of 33 percent (Kats 2008).

57. Shalizi and Lecocq 2008.

58. Brown, Southworth, and Stovall 2005.

59. IEA 2008b.

60. Johnson and others 2008.

61. Brown, Southworth, and Stovall 2005; ETAAC 2008.

62. Johnson and others 2008.

63. Sorrell 2008.

64. IEA 2008c.

65. Stern 2007. A small share of the subsidies supports clean energy technologies, such as the $10 billion a year for renewables.

66. World Bank 2008a.

67. Sterner 2007.

68. UNEP 2008.

69. Ezzati and others 2004.

70. Wang and Smith 1999.

71. A carbon tax of $50 a ton of CO_2 translates to a tax on coal-fired power of 4.5 cents a kilowatt-hour, or a tax on petroleum of 45 cents a gallon (12 cents a liter).

72. Philibert 2007.

73. WBCSD 2008.

74. World Energy Council 2008.

75. Goldstein 2007.

76. Meyers, McMahon, and McNeil 2005.

77. Goldstein 2007.

78. An energy-efficient mortgage allows borrowers to qualify for a larger mortgage by including energy savings gleaned from home energy-efficiency measures.

79. ESMAP 2008.

80. World Bank 2008d.

81. Taylor and others 2008.

82. World Bank 2008b.

83. Each lamp costs about $1 under these bulk procurement programs, instead of $3–$5, plus another dollar of transaction costs for distribution, awareness and promotion, monitoring and verification, and testing.

84. ESMAP 2009.

85. Armel 2008.

86. IEA 2008b; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

87. IEA 2007.

88. The costs of wind, geothermal, and hydro power vary greatly depending on resources and sites.

89. IEA 2008a.

90. ESMAP 2006.

91. For example, renewable portfolio standards tend to favor wind energy but discourage solar energy.

92. World Bank 2006.

93. MIT 2003; Keystone Center 2007.

94. MIT 2003.

95. Worldwatch Institute 2008; IEA 2008b.

96. Calvin and others forthcoming; Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

97. Riahi, Grübler, and Nakićenović 2007; IIASA 2009.

98. Gibbins and Chalmers 2008.

99. Sperling and Gordon 2008.

100. Weyant and others 2009.

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