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DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INNOVATION
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Working Party on Biotechnology, Nanotechnology and Converging Technologies

An OECD Biomass Sustainability Platform

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NOTE BY THE SECRETARIAT
This report partially fulfils the requirements of Module 3.1 Bio-production, Theme 3.1.1 Biomass Sustainability, of the Programme of Work and Budget (PWB) of the BNCT for Biennium 2015-2016 (see Figure 1 of [DSTI/STP(2014)39]).

Delegates to the BNCT are requested to:
· Note and comment on the paper at the meetings of the Working Party on BNCT of May 18-20 2015, and;
· Submit written comments by June 15, 2015.

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AN OECD BIOMASS SUSTAINABILITY PLATFORM

Introduction: a pivotal role for the OECD in biomass sustainability assessment

1. In the 1980s, the OECD played an important role in preventing agricultural trade wars by developing standards for agricultural subsidies (OECD, 1983) which are now accepted globally. The OECD is well positioned to perform a similar function today with regard to biomass. There are now large numbers of biomass sustainability schemes that are difficult to compare, leaving both suppliers and consumers confused. This can lead to mistrust and protectionism, which ultimately can lead to international disputes, and a slow-down in the growth of a bio-based economy. As a result, there is need for a new measure or indicator for biomass sustainability, and the OECD could take a leading role.

2. In the previous two biennia the OECD has been conducting work on the sustainability of biomass as there is a growing need for future production to use biomass as a partial substitute for fossil-based production. This creates a competition for land between food and industrial uses. With a growing world population, the number one priority must be ‘food first’, and then industrial use. Many documents agree that by 2050 the population of the planet will be over nine billion. Food production will need to rise by 50-70% (UN FAO, 2009), and agriculture is already appropriating some 70% of all freshwater use (Sophocleous, 2004). Moreover, more crops will need to be grown on less land (intensification): massive cropland expansion is not a viable approach to food security (Burney et al., 2010).

3. But since the 2009 OECD publication on the policy agenda for a bioeconomy (OECD, 2009), many OECD countries have produced bioeconomy strategies. These envisage future bio-based industries that use biomass as a feedstock instead of oil and gas. The philosophy behind this is that biomass as a feedstock is renewable and sustainable. Nevertheless, over-exploitation of biomass could lead to some serious issues of unsustainability e.g. soil erosion and destruction, water shortages, loss of biodiversity (see OECD, 2015).

4. This comes down to how much biomass can be grown sustainably to accommodate both food and industrial use of biomass, both of which occur just now, but both of which would need to be seriously increased, even in the medium term, if we are to maintain current standards of living in the OECD countries, and to improve the economies and standard of living in developing economies. The work of the previous biennium (2013-2014) in this area culminated in an international workshop (OECD, 2014). The primary non-technical conclusion of the workshop was that an international platform is required to share biomass sustainability experiences, which is needed to learn and grow the bioeconomy. Shaping this platform is one focus of the work of the BNCT in the 2015-2016 biennium.

5. The essence of what needs to be done is:

   1. Discover how to measure biomass sustainability, and;

   2. Estimate how much biomass can be grown sustainably (biomass potential).

6. These tasks are inter-dependent and constitute the major focus for a future Biomass Sustainability Platform. To achieve this, the OECD has the following to offer:

- In July 2012, principles for the sustainability of biomass were established at ministerial level;
- In 2013, the OECD published a *Recommendation of the OECD Council on Assessing the Sustainability of Bio-based Products* (OECD, 2013);
- The OECD is now attempting to create a platform for the harmonisation of data and methods to quantify the availability and the sustainability of biomass;
- Data on availability and sustainability of biomass are available in sufficient quality and quantity to allow further development of methods (see Box 1);
- The newly created OECD platform could be leveraged (where necessary) to fill gaps in data and knowledge.

Box 1. Building on work performed at the Wageningen University and Research Centre (WUR)

Wageningen University and Research Centre (WUR) has worked on an index method to measure the sustainability of biomass production based on Total Factor Productivity (TFP). This work took place during 2012-2014 on behalf of the Ministry of Economic Affairs of the Netherlands. WUR determined the relative sustainability of two soy meal chains in Brazil. In one of the two chains genetically modified (GM) seed is used, in the other non-modified (non-GM) seed is used. The following issues were taken into account in the sustainability measurement: profitability, climate change mitigation, eutrophication, toxicity for the living environment, toxicity for labourers, toxicity for consumers, deforestation, and employment.

The most important outcome of the work is that the TFP method was shown to be usable for this practical case (Gaitán-Cremaschi et al., 2014). This work was presented in June 2014 at the OECD international workshop on biomass sustainability (OECD, 2014) where it was received positively. It remains to be proven that the necessary data can be acquired in sufficient quality and quantity to make the approach more generally useful.

Next steps

7. A project to develop the TFP approach further could be executed within the frame of the new OECD platform, especially with respect to the boundaries that are imposed on the economy by the planet (Rockström et al., 2009; Steffen et al., 2014). The degree to which these boundaries are approached (or exceeded) is of the utmost importance for sustainability. Current methods to calculate the shadow prices which are needed for some forms of TFP do not explicitly take the planetary boundaries into account. One of the topics to be investigated in this project is whether the “vertical demand curve”[1] method of Hueting (1980) can be used to determine shadow prices that take planetary boundaries into account.

8. Sugar could be taken as an example. Sugar is not only relevant as a food but also as a raw material for the bioeconomy, and sugar cane is the most sustainable form of biomass in common use. Sugar-yielding crops include sugar cane in South America, Australia and Asia; sugar beet in Europe; and maize in North America. The global reach of sugar would increase the relevance of the results of the project.

1 Hueting defines the concept of shadow price of environmental functions whose availability has decreased as a result of qualitative competition. Use is made of the defined concepts of elimination, compensation and financial damage. By comparing the cost curve of measures of elimination with the cost curve of measures of compensation and financial damage, a first approach to the shadow price is obtained.

9. Further, this project could contribute to political consensus with respect to promoting sustainable agricultural (or otherwise) production, by quantifying and comparing the sustainability of products. This would be tackled by developing cases or practical examples from a variety of sectors. Specific, “difficult” cases would be used to test and, where necessary, to extend the frontiers of the method.

10. The cases would also be used to engage with stakeholders from the political arena and elsewhere, to inform them about the TFP method, to evaluate the method, and to obtain input as to which issues require further research and/or (political) consensus building. It is expected that several rounds of consultation will be needed to reach consensus on the use of the TFP method to measure sustainability in production and trade of agricultural biomass.

Deliverables

11. The specific first deliverables of the platform would be:

- An improved TFP method for biomass sustainability assessment;
- Workshops with stakeholders and experts, and;
- A report (at least one ‘green paper’[2]).

Biomass sustainability and certification: many issues for the policy maker

12. The concept of sustainable development has been defined rather simply as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”[3]. Such a simple definition, however, lends itself to almost infinite malleability. Biomass sustainability alone is a tangled web of interlinking research, business, logistics, environmental and social issues. It is to be expected, then, that the policy issues and mix are rather complex. More fundamentally, however, biomass sustainability has already entered policy before we even know how to measure it.

13. This situation can have consequences. At present there are large numbers of biomass sustainability schemes. They are difficult to compare and both suppliers and consumers can be left confused. The cost of sustainability assessment, for example, at Rotterdam port, is high. This can lead to mistrust and protectionism, which ultimately can lead to international disputes. All this can hamper production and trading in biomass and thus delay a transition to a global bioeconomy.

14. On the other hand, agreed, standardised measurement of sustainability can allow the following:

- Farmers and agri-businesses can optimise their processes within a number of constraints,
- Consumers can express their preference for products with the smallest negative impact on the environment, and;
- Policy makers can create a regulatory framework to help ensure that the increasing production of food and biomass will be compatible with a world characterised by population increase, globalisation, and a healthy living environment.

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2 A discussion and consultation document produced by a government, used by a government department when it is considering introducing a new law.

3 www.un-documents.net/our-common-future.pdf

Measuring biomass sustainability

15. Generating a quantitative (numerical) or semi-quantitative scale of sustainability is beguiling, as it implies uniform comparability that would lend itself to certification and international harmonisation. Certification is the process whereby an independent third party assesses the quality of data in relation to a set of predetermined standards. These are mostly formulated as criteria that have to be fulfilled for the certification of a product or process.

16. Critical to generating the criteria are the quality and quantity of indicators that are used in their derivation. The Global Reporting Initiative[4] (GRI) cites 36 indicators that seem to be related to sustainability. For efforts in international harmonisation, however, a small number of critical indicators is necessary, or the task becomes unwieldy.

17. International harmonisation requires not only robust analysis, but consensus, and the latter is often more difficult to achieve. The experience of van Dam and Junginger (2011) is illustrative. Based on responses to a questionnaire sent to international stakeholders from 25 European and 9 non-European countries, the respondents rated the following three sustainability criteria with the highest scores in terms of relevance to include in a biomass and bioenergy certification system:

1. Minimisation of GHG emissions (87% of respondents);
2. Optimisation of energy balance (81%);
3. Protection of water quality and quantity (76%).

18. However, there was much disagreement e.g. optimisation of energy balance was not a high priority in some European and non-European countries. Instead, minimisation of deforestation was given very high priority in these countries. There was only agreement amongst the respondents that a criterion on the minimisation of GHG emissions should be included, and that the other two above were considered “highly relevant”. Moreover, social criteria are sometimes regarded as being low in reliability and practicability, and tend therefore to be assigned a low ranking.

19. The most common tool for sustainability measurements is Life Cycle Analysis (LCA). LCA is not relevant to financial and social criteria, however, and is therefore sub-optimal for measuring biomass sustainability. Conversely, when other tools such as Living Planet Index (LPI), City Development Index (CDI), Human Development Index (HDI), and Environmental Performance Index (EPI) are applied, they often fail to meet scientific criteria.

TFP and its strengths

20. An alternative, more efficient approach may be to apply a market solution (Box 2). One of its particular strengths is it has been used routinely in agriculture so is already familiar. As it has been used routinely in assessing agricultural economic productivity, it may be possible, by incorporating environmental (Glendining et al., 2009) and social criteria, to make a single index of sustainability of commodities based on price-related productivity measures.

4 www.globalreporting.org/

Box 2. What is Total Factor Productivity in this context?

This is an index approach for sustainable benchmarking of biomass production chains based on the concept of Total Factor Productivity (TFP) which has been routinely used in agriculture (Lynam and Herdt, 1989; Ehui and Spencer, 1992; Chung et al., 1997; Glendining et al., 2009; Gaitán-Cremaschi et al., 2015). The general idea of TFP is that it reflects the rate of transformation of inputs (capital, labour, materials, energy and services) into outputs (biomass stock), where negative social and ecological externalities associated to different sustainability issues are included in terms of “bad” outputs. Brandt et al. (2014) suggested that the adjustment of the traditional productivity growth measure for bad outputs is small. This implies that the acceleration in productivity growth that would help to substantially reduce bad outputs, without reducing output growth, should be possible to achieve.

For example, the outputs of a soy production system may include soy oil and soy meal and the inputs of the same soy system may consist of land, seed, labour, pesticides and fossil fuel. The use of fossil fuel emits greenhouse gases to the atmosphere contributing to climate change (this last output is a “bad” output of soy production). The quantification of outputs and inputs needed for the index may partly be obtained from an LCA analysis. The TFP index takes the analysis one step further in that it incorporates the several sustainability issues into *a* ***single measure of sustainability***. Hence, the index facilitates the integration and comparison of sustainability issues affecting human well-being at different temporal and spatial scales. Thus, a biomass chain with the best sustainability performance, i.e. the highest TFP score, is the one that produces the highest ratio of output to input where the “bads” are output penalties that lower the sustainability performance. Multiple chains with different sets of outputs and inputs can be compared using the TFP index.

In order to use the TFP index, the multiple input-output variables must be expressed using a common denominator. One solution is to use prices that reflect the relative importance of input and output variables towards sustainability. In this solution, observed prices can be used for the marketable inputs and outputs and shadow prices need to be estimated for externalities that are non-tradable in conventional markets, and therefore, related price information does not exist. (Shadow prices of pollutants are rarely available and need to be estimated separately or proxied with observed prices, for example resulting from policies such as environmental taxes (Albrizio et al., 2014)). TFP indexes using (shadow) prices reveal the relative performance of a biomass production chain reflected in the form of price signals. A second solution for aggregating multiple inputs and outputs into a single index is the use of distance functions. This solution is based on input and output quantity information (including “bads”) as the way to identify a sustainable frontier of the production possibilities set. Please see Annex 1.

How much biomass can actually be grown sustainably?

21. Several studies have tried to estimate the available amount of biomass in Europe and worldwide, now and into the future. All these studies show large uncertainties. Europe is an interesting case as it has limited land availability for growing biomass, and ambitious bioeconomy plans. The total supply of sustainable biomass in 2030 may be enough to fulfil the demand of a 10% bio-based economy (PBL Netherlands Environmental Assessment Agency, 2012).

22. The United States position is more favourable for a bio-based economy. A US Department of Energy report (US Department of Energy, 2011) demonstrates the feasibility of scenario assumptions for a US billion ton biomass resource, capable of displacing 30% of the nation’s petroleum consumption. Several important assumptions are required, however, and they would require strong policy support.

23. Therefore bioeconomies will either grow unevenly across the globe, or biomass will be traded internationally. The European Union is one region which will probably depend on the world market to supply its bioeconomy with biomass in the future.

Other economic and societal challenges

24. *Financial*. Energy infrastructure investment decisions are expected to total over USD 20 trillion (Pachauri and Reisinger, 2007) between 2005 and 2030, and these will have long-term impacts on GHG emissions, because of the long lifetimes of energy plants and other infrastructure capital stock. More

recently the IEA (2014) estimated that, over the period to 2035, the cumulative global investment in energy will amount to USD 48 trillion, consisting of around USD 40 trillion in energy supply and the remainder in energy efficiency. Biofuels are attractive in that the resulting changes to the global energy infrastructure would be less than for other new forms of energy. However, the strain on biomass availability in a bioeconomy would be greatest by using biofuels as road transport fuels.

25. *Land use changes*. The Intergovernmental Panel on Climate Change (IPCC) reported that current agricultural land use and land conversion contributions to GHG emissions (CO_2, CH_4 and N_2O) are globally estimated to be at least 2.5 times greater than the total emissions from global transport (Smith et al., 2007). Quantifying these emissions, especially from indirect land use change (ILUC) remains a great challenge and it is therefore difficult to include these into sustainable criteria. A conclusion from the OECD workshop on biomass sustainability is that the current state of ILUC knowledge means that it is in no state to enter policy.

Biomass disputes and their settlement

26. Biomass sustainability disputes have already begun appearing, and are predicted to increase in the future as pressure on fertile land increases. The situation is serious enough to have warranted exploration of the feasibility of setting up an international biomass dispute settlement facility (The Hague Institute for Global Justice, 2012). Biomass disputes relate to human rights issues (land rights, worker's rights, local economies), environmental issues (effects on soil, land, air, biodiversity and climate) and economic issues (international trade, market distortions, property rights and business-to-business conflicts). The global sustainable biomass governance system is currently a patchwork of a large number of voluntary standards and regulations, and it is thought that a dispute settlement facility would lend it credibility and legitimacy.

Background: Drivers for biomass sustainability

27. Humanity is entering a period of extreme difficulty, characterised by so-called 'grand challenges'. An added level of complexity is that some of these grand challenges interact with each other in that, trying to solve one may create issues in another. For example, attempting to use bio-based production to address both climate change (through CO_2 emissions reductions) and energy security may bring agriculture into conflict with industrial production, effectively making a competition for land. This assumes the character of an ecosystem, termed a "grand challenges ecosystem" by the OECD (2015).

Population and demographics

28. Ultimately, there is huge uncertainty about what the eventual equilibrium number of people alive will be, and when it will occur. It is expected that there will be over 9 billion people living on the planet by 2050. The population of the more developed regions is actually expected to change minimally, passing from 1.24 billion in 2011 to 1.34 billion in 2100, but with the population inexorably ageing. Between 2010 and 2060, the OECD's population is expected to increase by 17%, but the working age population (age 15-74 years) may fall by 7% (Braconier et al., 2014).

29. OECD nations are also challenge to remain competitive in key sectors, such as chemicals, long a cornerstone of many OECD economies, unless they can harness their strengths in innovation to make greater efficiencies and move to higher value activities. Most OECD nations will likely become importers of biomass, just as they are currently importers of fossil fuels. One source has predicted that Europe will be importing 80 million tonnes of solid biomass per annum by 2020 (Cocci et al., 2011).

Energy security and resource depletion

30. Modern societies have come to rely so heavily on crude oil for fuels, chemicals and materials that we practically cannot live without it. It is clear that crude oil reserves, no matter how many more are discovered, are ultimately finite. Many publications support the contention held by many independent institutions that conventional oil production may soon go into decline (Owen et al., 2010). Moreover, the cost of finding new sources will escalate as more extreme environments will be more dangerous to explore. Meanwhile, several publications suggest that much of the current inventory of hydrocarbons should remain untouched to reduce GHG emissions (e.g. Friedlingstein et al., 2014).

31. As some countries are struggling to meet their emissions reduction obligations, it is puzzling that the chemical sector has been relatively ignored in this respect compared to fuels and electricity. The sector is the largest industrial energy user, accounting for about 10% of the global final energy use (Broeren et al., 2014), and the third largest industrial source of emissions after the iron and steel and cement sectors (IEA, 2012). Energy costs on average account for 50–85% of the production costs of bulk chemicals (UNIDO, 2011). This is particular pertinent to OECD countries as energy costs can be up to seven times higher in fuel importing nations compared to fuel producing nations.

32. Biomass is the fourth largest global energy source after coal, oil and natural gas. Bioenergy is the most important renewable energy option at present (Ladanai and Vinterbäck, 2009). But the use of biomass for bio-based production in ambitious bioeconomy plans is fraught with the risk of unsustainable, over-exploitation of natural resources.

33. Running a future planet without a bioeconomy would be challenging, however. It is often overlooked that 96% of all manufactured goods contain at least one chemical (Milken Institute, 2013). Very many of these chemicals are organic chemicals i.e. they contain carbon e.g. paints and other coatings, detergents, lubricants, textiles, plastics. It is difficult to imagine the replacement of organic chemicals with others. Therefore the need for future chemicals is a given: they will have to come from some source of carbon, either fossil or bio-based resources. (Realistically it will be a mixture for at least several decades).

Climate change and global warming

34. Anthropogenic greenhouse gas (GHG) emissions are now considered to be inextricably linked to climate change and global warming. Quantitatively, the most important of these is CO_2 (Pachauri and Reisinger, 2007). Over 100 countries have signed up to trying to limit the average temperature rise to 2°C or below (relative to pre-industrial levels) (Meinshausen et al., 2009). Drastic reductions in GHG emissions are required: developed countries as a group would need to reduce their emissions by 40% to 95% compared to 1990 levels by 2050, even if developing countries also make significant contributions. Friedlingstein et al. (2014) contend that two thirds of the CO_2 emission quota consistent with a 2°C temperature limit has already been used, and the total quota will likely be exhausted in a further 30 years at the 2014 emissions rates. By century end, the IPCC (2014)[5] has warned that GHG emissions need to be close to zero to achieve the 2°C obligation. The implications are clear: if climate change legislation comes into effect, much of the oil, gas and coal in known reserves will have to remain in the ground.

5 IPCC (Intergovernmental Panel on Climate Change) (2014), "IPCC: GHG emissions accelerate despite reduction efforts", Press Release, 14 April, 2014. http://www.ipcc.ch/pdf/ar5/pr_wg3/20140413_pr_pc_wg3_en.pdf

Soil and water security

35. Often overlooked in policy making, soil is the ultimate genetic resource; soils are the critical life-support surface on which all terrestrial biodiversity depends. The vast majority of all food and feed is derived from cropland (Gore, 2013). In the bioeconomy and sustainability context, soil accounts for some 20% of the capture of human CO_2 emissions (European Commission, 2007). But soil is being destroyed at unprecedented rates. About 2.5% of arable land in China is too contaminated for agricultural use (Chen and Ye, 2014). Therefore soil should be treated as a non-renewable resource.

36. The overall message is clear – our society is utterly dependent on maintaining the global stock of healthy soil. Any plans for a future bioeconomy dare not ignore this. In the face of soil destruction, more crops will have to be grown more efficiently, while methods should also be explored to halt or limit soil destruction. A future expansion of the use of biomass has to be cognisant of these risks.

37. As many as two billion people rely directly on aquifers for drinking water, and 40% of the food in the world is produced by irrigated agriculture that relies largely on groundwater. Globally, 70% of all freshwater use is for agriculture (Sophocleous, 2004). Vast territories of Asia rely on groundwater for 50-100% of the total drinking water (UNEP, 2003). But groundwater depletion is accelerating worldwide. In a global bioeconomy it can be expected that some critical Asian nations will be exporters of biomass, while many OECD countries will be net importers. This could create conditions for unsustainable use of soil and water, and emphasises that biomass sustainability is a global need.

Conclusions

38. The logical way to build on the achievements made so far in the OECD work in this area is to continue the earlier work on how to measure biomass sustainability and to the test the robustness of the methodology. This requires case studies and data from OECD and non-OECD states as most OECD countries will be, or are already, importers of biomass, and some critical developing economies will be exporters. This is why a platform within the OECD is recommended. This would be the first such forum for discussion of biomass sustainability in any international organisation, and the history of the OECD in agricultural subsidies lends it great credibility. It is for the BNCT to define what this platform might consist of e.g. minimally a website, perhaps a dedicated workstream, or more substantively a forum for discussion.

39. In the bioeconomy everything is new. The number of countries publishing bioeconomy strategies is increasing, and this includes many OECD countries (if the EU bioeconomy strategy is included). However, it is not clear at this point how progress is being made against the ambitions of these bioeconomy strategies. The published literature on the use of biomass in bioenergy, biofuels and bio-based materials (chemicals, plastics, textiles) is now vast. Significantly, most of it is at the laboratory or field experimental stage. Countries are using bio-based electricity generation to meet their emissions reduction targets. Bio-ethanol is fulfilling an essential role in gasoline, both as a fuel and an oxygenate. However, the vast majority of the applications in materials, with the highest value-added and employment prospects, are yet to be realised.

40. In other words, the foundations of a bioeconomy are still very much in their early stages. Taking the successes to date beyond the laboratory into the real economy depends entirely on the sustainable use of biomass and the gradual replacement of fossil resources. However, although there is no shortage of oil, gas or coal, a new imperative may necessitate a quickening of bioeconomy development if climate change legislation dictates it. Therefore the measurement of biomass sustainability should be regarded as a top priority for the bioeconomy.

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ANNEX 1. FIRST RESULTS OF WAGENINGEN RESEARCH PROJECT ON MEASURING SUSTAINABILITY BY MEANS OF AN INDICATOR BASED-APPROACH

Benchmarking the sustainability performance of the Brazilian non-GM and GM soybean meal chains: An indicator based-approach

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ABSTRACT
A commonly accepted approach for measuring the sustainability of agricultural products is the first step towards treating traded products differentially according to their sustainability. If we were able to measure sustainability, business stakeholders could optimize food production chains, consumers could demand products based on reduced environmental and social impacts, and policy makers could intervene to meet the growing demand for food in a context of environmental conservation, population growth, and globalization. We proposed to measure profitability adjusted for the negative externalities of food production as a single metric for benchmarking products in terms of their sustainability. In addition, the adjusted profits differences between different products are then be assessed by means of the Bennet price and quantity indicator to highlight areas for potential sustainability improvement. To illustrate the usefulness of the approach, we assessed the relative sustainability of two Brazilian conventional soybean meal chains, non-genetically modified (non-GM) and genetically modified (GM) chains. Based on the results, we indicated potential areas for sustainability improvement. Sustainability issues included in the assessment were profitability, global warming potential, eutrophication potential, environmental toxicity, farmworker toxicity, consumer toxicity, deforestation, and loss of employment. Results showed that the non-GM soybean meal chain is slightly more sustainable than the GM chain. However, both chains require joint efforts to address their economic, environmental, and social deficiencies. These efforts should focus on providing technical and high quality assistance to reduce biocide use, and improving transportation. The analysis in this study could be extended by undertaking a comparative assessment of the sustainability performance of major soybean meal producers, i.e. United States, Argentina, China, and Brazil.

The proposed approach proved to be a promising benchmarking tool for agricultural trade flows. It allows an integrated assessment of the dimensions of sustainability along food chains that is sufficiently flexible to compare the sustainability level of various biomass stocks that are produced in different locations and in a variety of environmental and socio-economic contexts. Nevertheless, it requires consensus on which components of sustainability are to be assessed.

1. Data and Methods
1.1 Indicator based-approach

The Brazilian soybean meal chain, for both non-GM and GM, is defined in this study as a set of four product life cycle stages integrated in an input-output system: agricultural, processing, transport to port, and transoceanic transportation. The chain is modelled up to the destination port (Rotterdam Port). At each stage, multiple inputs, denoted by vector x, are transformed into multiple outputs, denoted by vector y. As side effects of production, multiple environmental and social externalities are produced, expressed by vector b, such as waste, pollution and loss of biodiversity. The social or adjusted profit (SP) of the soybean meal chain is defined as the difference between the value of the aggregated good outputs and the aggregated inputs and externalities:

$$SP = p'y - r'b - w'x \quad \text{(Eq. 1)}$$

where *p, r* and *w,* are vectors of (shadow) prices of outputs, inputs and externalities, respectively (prime indicating the transpose of the vector).
To assess the relative sustainability performance, the Bennet quantity indicator and the Bennet price indicator are computed:

$$B_{1,2} = \left[\frac{1}{2}(p'_2 + p'_1)(y_2 - y_1)\right] - \left[\frac{1}{2}(w'_2 + w'_1)(x_2 - x_1)\right] - \left[\frac{1}{2}(r'_2 + r'_1)(b_2 - b_1)\right]$$
$$+ \left[\frac{1}{2}(y_2 + y_1)(p'_2 - p'_1)\right] - \left[\frac{1}{2}(x_2 + x_1)(w'_2 - w'_1)\right] - \left[\frac{1}{2}(b_2 + b_1)(r'_2 - r'_1)\right] \qquad \text{(Eq. 2)}$$

The sum of the Bennet quantity indicator and the Bennet price indicator reveals in monetary terms the adjusted profit difference of a particular chain relative to the benchmark. The Bennet quantity indicator (first line of equation 2) captures changes in quantities of outputs, inputs and externalities, i.e. the Total Factor Productivity (TFP) component. The Bennet price indicator (second line of equation 2) captures changes in the prices of outputs, inputs, and externalities, the Total Price Recovery (TPR) component. A positive (negative) value of the TFP and TPR components indicate higher (lower) sustainability performance of the assessed observation relative to a benchmark.

1.2. Selection of outputs, inputs, and externalities

To assess the relative sustainability performance of the non-GM and GM soybean meal chains, the main outputs, inputs, and externalities along the product life cycle were selected. The process of selecting the variables consisted of three steps. (i) A generic set of sustainability issues, i.e. topics that are of public concern, such as land use, health, energy, biodiversity, profitability, and water, was provided to a group of stakeholders involved in chain sustainability. Stakeholders were asked to assign a score to each of the issues using a five-point Likert scale, where 1 represented “not at all important” and 5 “extremely important” for the given dimension of sustainability, either economic, environmental, or social. The group of stakeholders consisted of eight academic researchers and eleven practitioners (NGO’s, certifying organizations and firms in the agri-food sector). (ii) Once answers were received, the percentage of participants who gave a score of 4 or 5 was calculated for each issue. The issues for which at least 65% of the participants gave a score of 4 or 5 were selected as being of utmost importance. A total of seven sustainability issues were selected. Four issues were selected for the dimension of environmental sustainability: *water*, *materials*, *atmosphere*, and *biodiversity*. *Economic performance* was selected for the economic dimension, and *labor practices* and *product responsibility* for the social dimension.

For each of the selected issues, data on quantities and (shadow) prices for outputs, inputs and externalities were collected. Prices were expressed in 2011 US dollars (US $). We computed the adjusted profit for each observation to identify the “best” performer from the observed data (in terms of highest adjusted profit). Next, adjusted profit differences and its components (TPR and TFP) were computed.

2. Adjusted profits of the selected non-GM and GM soybean meal chains in Brazil

Table 1 (a-c) shows the adjusted profit estimated for each of the observations of the non-GM and the GM soybean meal chains, as well as the average adjusted profit for the non-GM and the GM soybean meal chains.

Table 1a. Adjusted profit for the observations of the non-GM soybean meal systems in Brazil (US$ per soybean meal ton). In the column headings, y = vector of outputs, x = vector of inputs, b = vector of externalities, p = vector of prices of outputs, w = vector of prices of inputs, r = vector of prices of externalities; thus, ($p'y$) = value of production, ($w'x$) = value of inputs, ($r'b$) = value of externalities, and adjusted profit = $p'y - w'x - r'b$ (consistent with Eq. 1).

	($p'y$)	($w'x$)	($r'b$)	Adjusted profit
Guarapuava	449	262	43	144
Campos Novos	449	276	44	129
Andirá	449	273	50	126
Campo Mourão	449	273	51	125
Londrina	449	280	49	120
Marialva	449	278	50	121
Anahy	449	292	53	104
Arapoti	449	313	40	96
Cafelândia	449	314	55	80
Sorriso	449	342	76	31
Pedro Afonso	449	369	66	14

Table 1b. Adjusted profit for the observations of the GM soybean meal system in Brazil (US$ per soybean meal ton). For explanation of column headings, see above.

	($p'y$)	($w'x$)	($r'b$)	Adjusted profit
Guarapuava	420	258	44	118
Campos Novos	420	277	42	101
Campo Mourão	420	275	52	93
Londrina	420	284	49	87
Marialva	420	287	49	84
Cruz Alta	420	297	44	79
Anahy	420	295	52	73
Passo Fundo	420	305	61	54
Cafelândia	420	314	55	51
Araguari	420	320	53	47
Palmeira das Missões	420	315	60	45

Table 1c. Average adjusted profit for the non-GM and the GM soybean meal systems in Brazil (US$ per soybean meal ton). For explanation of column headings, see above.

	($p'y$)	($w'x$)	($r'b$)	Adjusted profit
Average non-GM chain	449	297	52	99
Average GM chain	420	293	51	76

The highest adjusted profit was calculated for the non-GM observation in the municipality of Guarapuava, equal to $144 per ton of soybean meal. This observation was used as the benchmark observation for the computation of the Bennet quantity indicator and the Bennet price indicator.

Table 2. ***Differences in the adjusted profit between observations of the non-GM and GM soybean meal chains and the benchmark at each product life cycle stage, expressed in US $ per soybean meal ton. Stage 1 = agricultural production, stage 2 = processing, stage 3 = transport to port, and stage 4 = transoceanic transportation. The adjusted profit difference is decomposed into TPR and TFP in each of the four stages (consistent with Eq. 2).***

Non-GM chain	**Stage 1**		**Stage 2**		**Stage 3**		**Stage 4**		**Adjusted profit difference**
	TPR	*TFP*	*TPR*	*TFP*	*TPR*	*TFP*	*TPR*	*TFP*	
Guarapuava[a]	0	0	0	0	0	0	0	0	0
Campos Novos	3	-13	0	0	0	-5	0	0	-15
Andirá	0.4	-14	0	0	0	-6	-0.2	0.7	-19
Campo Mourão	-3	-7	0	0	0	-10	0	0	-20
Londrina	-1	-16	0	0	0	-6	0	0	-23
Marialva	3	-19	0	0	0	-7	0	0	-24
Anahy	-3	-21	0	0	0	-15	0	0	-39
Arapoti	-32	-29	0	0	0	12	0	0	-48
Cafelândia	-32	-19	0	0	0	-14	0	0	-64
Sorriso	-18	-14	0	0	0	-82	-0.2	0.7	-113
Pedro Afonso	-34	-57	0	0	0	-40	-0.2	0.7	-130
GM chain	**Stage 1**		**Stage 2**		**Stage 3**		**Stage 4**		**Adjusted profit difference**
	TPR	*TFP*	*TPR*	*TFP*	*TPR*	*TFP*	*TPR*	*TFP*	
Guarapuava	8	-4	-0.7	0	0	-0.4	-29	0	-26
Campos Novos	1	-9	-0.7	0	0	-5	-29	0	-43
Campo Mourão	-4	-7	-0.7	0	0	-10	-29	0	-51
Londrina	-4	-17	-0.7	0	0	-7	-29	0	-57
Marialva	-6	-17	-0.7	0	0	-8	-29	0	-60
Cruz Alta	-12	-15	-0.7	0	0	-6	-29	-2	-64
Anahy	-5	-22	-0.7	0	0	-15	-29	0	-71
Passo Fundo	1	-49	-0.7	0	0	-11	-29	-2	-90
Cafelândia	-31	-18	-0.7	0	0	-14	-29	0	-93
Araguari	-15	-37	-0.7	0	0	-16	-29	1	-97
P. das Missões	-12	-46	-0.7	0	0	-10	-29	-2	-99
GM chain vs. benchmark= non-GM chain	5	-7	-0.7	0	0	6	-29	-0.6	-25

A positive value indicates higher performance relative to the benchmark.
a Benchmarking observation

The decomposition of the aggregate difference in the adjusted profits between the average GM and non-GM soybean meal chains highlights five main differences in price effects (TPR) and quantity effects (TFP) for the inputs, output, and externalities.

3. Conclusions

Our results show that the non-GM soybean meal chain is more sustainable than the GM chain, i.e. it has a higher adjusted profit. Quantity differences (TFP component) include a lower use of biocides, i.e. pesticides, fungicides, and herbicides, in the non-GM chain. The main price difference (TPR component) is associated with the price premium paid per ton of non-GM soybean meal. In contrast, the GM soybean meal chain has a lower emission of GHGs at the transport to port stage due to a lower amount of fossil fuel used in transportation. This is because GM soybean production is mainly found in the southern Brazilian states that are closer to the ports. Our study highlights areas for improving the sustainability of the GM and non-GM chains. Externalities arising from soybean meal production could be reduced by introducing technical assistance in GM soybean production to reduce the application of biocides and by improving the transport infrastructure matrix, especially in remote non-GM soybean production areas of Brazil. These efforts would also reduce production costs.

Although our study focused on the assessment of the relative sustainability performance of the soybean meal chain, the indicator based-approach has a much wider applicability. It is sufficiently flexible to allow aggregation of different sustainability issues and therefore can be used to analyze the sustainability of trade flows at different locations and in a variety of socio-economic contexts. Further development and acceptance of this approach as a benchmarking tool in trade negotiations could assist in the future imposition of trade preferences for sustainable commodities and provide an incentive to switch production towards better economic, environmental, and social practices throughout production chains.