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Biomass for transport, heat and electricity: scientific challenges

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Abstract

Purpose – The objective of this paper is to discuss some scientific challenges related to the production and use of biomass for transport, heat and electricity.

Design/methodology/approach – Specific attention is paid to the environmental assessment of liquid bio-fuels for transport and to the discussion of causes of uncertainties in the assessment. Three main topics are taken as examples, in order to illustrate the complexity of environmental assessment of bio-fuels and the difficulty in reducing uncertainties: agro-environmental impact of bio-ethanol (from sugar cane) in Brazil and bio-diesel (from palm oil) in Malaysia. These two tropical countries were selected because of their role as leaders at world level and their strong export potential to the European Union), N_2O (Nitrous Oxide) emissions related to crop cultivation for bio-fuels and land use change; and GHG emissions and Life Cycle Assessment (LCA) of bio-diesel from palm oil in Malaysia. These three topics are discussed and complemented by considerations about biomass conversion issues.

Findings – The quantification of the degree of the sustainability of the production and use of bio-fuels for transport is to a large extent related to the choice of farming practices during the feedstock production and their corresponding environmental impact.

Practical implications – Recommendations are formulated so as to reduce scientific uncertainty, for example through the development of internationally-agreed sustainability certification systems with corresponding verification measures, or further research on emissions and indirect land-use change.

Originality/value – The value of the paper on bio-energy research challenges is related to the combined analysis of European and tropical constraints in the field of biomass.

Keywords Assessment, Europe, Brazil, Malaysia

Paper type Research paper

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Introduction

The objective of this paper is to discuss some scientific challenges related to the environmental assessment of bio-energy. This discussion of scientific challenges addresses causes of uncertainties in the agro-environmental assessment of bio-fuels for transport or bio-heat and bio-electricity. The three topics selected because of their importance in order to illustrate the complexity of bio-fuels assessment and the difficulties to reduce uncertainties are:

(1) Agro-environmental impact of bio-ethanol in Brazil and bio-diesel in Malaysia (countries with major export potential).
(2) N_2O (Nitrous oxide) emissions.
(3) Life Cycle Assessment (LCA) of bio-diesel from palm oil.

Issues regarding the water footprint of bio-fuels and the challenges in biomass conversion and bio-refineries are also discussed.

In the context of this paper on bio-energy, biomass is considered to be the organic fraction of agricultural products (including vegetal and animal substances), from silviculture and related industries, as well as the organic part of industrial and municipal waste. This includes, for example, wood, straw, energy crops, agricultural waste, agro-industrial waste, plants and animal waste.

Agriculture contributes to various extents to providing food, but also fibre, fodder and fuel (the 4Fs) and also provides feedstock for green chemistry, or bio-based materials. If the production of bio-fuel or bio-gas by agriculture is often presented as a new option valid for the future, it should be mentioned that in the nineteenth century in Europe, about 20 per cent of agricultural land was used to grow crops for non-food purposes. The land used for energy purposes disappeared with the development of mechanisation and now again the issue of bio-energy is being discussed in some cases for its utility at farm level, but most of the time in order to produce energy for the entire society.

The assessment of biomass resource potential is important at global level due to various factors such as:

- increase of population at global level;
- change in diet, especially in Asia with the increase in meat consumption; and
- competition between biomass uses with the development of new uses of biomass, for example green chemistry.

A few points regarding the production, use of liquid bio-fuels for transport in the European Union and imports

The Directive on the Promotion of the Use of Energy from Renewable Sources (2009/28/EC) has been approved on 23 April 2009. The objective of this directive is to establish a framework for the promotion of energy from renewable sources, with a view to achieving the European Union (EU) target of a 20 per cent share of renewable energies by 2020, indicated in the Renewable Energy Road Map.

EU member states are required to achieve renewable energy production targets by 2020 in electricity, heating and cooling and transport. For pre-2004 member states, these targets are to increase the share of renewable energies in these countries by about 6 to 13 per cent compared to 2005 and, for member states, which joined in 2004 or afterwards, by about 5 to 10 per cent compared to 2005. Intermediate trajectories are also laid down for each country. Moreover, EU member states must ensure at least a 10 per cent share of energy from renewable sources in transport by 2020.

Unlike the other bio-fuel key players, the EU produces more bio-diesel than bio-ethanol. Of transport fuels, 54.6 per cent consumed in the EU are diesel versus 45.4 per cent for gasoline. This proportion is not reflected in the production of bio-fuels: bio-diesel accounts for more than 80 per cent of EU total bio-fuels production. In 2007, the EU major producers of bio-diesel were Germany (50.6 per cent), France (15.3 per cent), and Italy (6.35 per cent) (EBB 2008). The main feedstock for the production of bio-diesel is rapeseed oil, which corresponds approximately to 90 per cent of the EU bio-diesel production. In the EU the expansion of bio-diesel production has put pressure on the rapeseed market. The areas dedicated to the cultivation of rapeseed and sunflower seeds for energy use have increased from 780,000ha in 2004 to 1,634,000ha in 2006, corresponding to 22.5 per cent of the total area dedicated to both crops. This expansion is taking place in areas traditionally dedicated to food crops. Currently, the EU is using about 40 per cent of its rapeseed production and about 62 per cent of its rapeseed oil production for the manufacturing of bio-diesel. The pressure on rapeseed areas is mainly due to the relatively low productivity of this feedstock in terms of litres of bio-diesel per hectare. As a consequence, between 2002-2003 and 2006-2007 rapeseed oil prices have increased by 63 per cent.

Bio-fuel incorporation rates show great variations per EU member state but the total for EU 25 was around 1 per cent in 2005, thus behind the targets set towards the 2010 objective set in Directive 2003/30/EC. Moreover, there has been a bio-diesel yearly growth of only 16.8 per cent in 2007 compared to 54 per cent in 2006 and 65 per cent in 2005 (production increased from 4.9 million tonnes in 2006 to 5.7 million in 2007) (European Bio-diesel Board, 2008, EuR Observer, 2006). According to Jank *et al.* (2007), if the EU decides to limit the oilseed area dedicated to bio-diesel feedstock to 50 per cent of the total oilseed area, the EU will need to import 4.16 million tonnes of vegetable oil or bio-diesel.

In Brazil, sugar cane, and more recently, soybean are the main crops used for energy purposes. Although in 2007 the EU is the world's third largest producer of ethanol (2.1 billion litres, it is far behind the USA (24.6 billion litres) and Brazil (19 billion litres). EU ethanol production increased only by 11 per cent compared to 2006 (in 2006 the increase was 71 per cent compared to 2005, with 1.5 billion litres). The main producers of ethanol in the EU were (2007) France (32.6 per cent), Germany (22.2 per cent), Spain (19.6 per cent) and Poland (8 per cent) (eBio, 2008). Contrary to the situation in Brazil with the development of bio-fuels so far mainly based on a single crop, i.e. sugar cane, ethanol in the EU is produced from a large variety of grain feedstock (wheat, barley, and rye) which account for the major part of the production, followed by sugar beet. Sugar beet is the most efficient crop for bio-ethanol in Europe, with production estimates around 7,250 litres of ethanol per hectare (3,125 for cereals). Since EU ethanol production is much smaller than bio-diesel production, and since it is based on the utilisation of various types of feedstock, of which the EU is a net exporter of some, ethanol has so far had no significant impact on agricultural land availability and commodity prices. On the contrary, it provides a new option to sugar beet producers, after the reform of the sugar Common Market Organisation adopted in February 2006 that reduced the sugar beet price by almost 40 per cent and limited the sugar export opportunities to the World Trade Organization WTO quota. In 2007, Brazil exported more than 887 Million litres of ethanol to the EU (50 per cent of 2007 EU production) (eBio, 2008; MAPA (Ministério da Agricultura, Pecuária e Abastecimento), 2008). In the EU, the main countries of destination were The Netherlands, the UK, and Sweden. In addition, ethanol production might also be considered in the future in some ACP (African, Caribbean and Pacific Group of States) countries.

Production and use of liquid bio-fuels for transport: a controversial issue

In order to reach European targets, there is a consensus on the need for Europe to complement at short- and mid-term bio-fuels produced from European feedstock with imports of bio-fuels from other countries. The amount of bio-fuel imports needed by the EU depends on the scenarios chosen and the sustainability benefits expected or taken into account by various groups. It is clear that in relation to imports from non EU countries, there is a wide variability of dominant trends between the attitudes on this issue of European countries, as different as Sweden (low-agricultural potential, presently importing ethanol from Brazil), The Netherlands (strongly involved in international trade of biomass and bio-fuels, limited-land availability, competitive harbour infrastructure), France, Germany or Poland (all countries with strong agricultural sectors), Cyprus and Malta (limited-land availability).

Bio-fuels for transport are often considered as a tool to mitigate greenhouse gas emissions, reduce climate change, increase energy supply diversity, and security of supply, as well as a new opportunity for agriculture and rural development. Bio-fuels have a domestic economic appeal because locally produced fuel creates jobs and keeps part of the energy bill within the country, the financial fluxes being totally different in the case of bio-energy or use of fossil oil. In the context of a planned increase of oil prices in the long term, the interest in bio-fuels has escalated sharply and the competitiveness of bio-fuels is expected to improve.

On the other hand, bio-fuels are often criticised at various levels, for reports on their low environmental performance, their negative consequences on tropical deforestation and the diversion of land use ("fuel against food"). Bio-fuels policies, especially in Europe and the USA, are not a field of consensus, with very different scientific conclusions presented by different research groups as technical support for decision-making. In addition, the debate on bio-fuels is often made confusing by a lack of agreement, or even preliminary discussion of the policy drivers and their respective weights: climate change, environment, security of supply, employment, transport, agriculture, rural development, international cooperation … The criticism towards bio-fuel development comes to a large extent from the scientific community (Crutzen *et al.*, 2007; Searchinger *et al.*, 2008), from some international organisations (OECD, 2007) and to a large extent from part of the media. Some NGOs are calling for a moratorium on bio-fuels. Another aggravating factor is the lack of consensus on Life Cycle Assessment results in relation to bio-fuels (see for example (Farrell *et al.*, 2006) on the issue of US corn ethanol.

It should be noted that bio-fuel policies are not only a case of disagreement on technical results or governance, but also a field of international dispute: Brazil initiated a WTO case against US ethanol and farm subsidies. The US presently protects its own ethanol producers by a 0.54$ per gallon tariff. This takes place in an ethanol global market still at a very preliminary stage, but characterised by considerable differences in production costs according to the feedstock and the geographic origin. Jank *et al.* (2007) reports production costs (expressed in US$ cents/litre) of 22 for sugar cane ethanol from Brazil (2005), 40 for US corn ethanol, 50-75 for EU ethanol and 44-81 EU bio-diesel (2004).

Bio-fuels in Brazil and Malaysia and associated agro-environmental impact

Bio-ethanol (Brazil)

The Pro Alcool Programme started in Brazil in 1975, after the first oil crisis and mainly for security of supply concerns. Initially benefiting from public-support mechanisms, the activities were liberalised at the end of the 1990s, even if there are still some differential taxation schemes at State level. Information on the use of biomass for bio-energy in Brazil can be found in Focus on Brazil (IEA (International Energy Agency), 2006). From 1983 to 1988, 90 per cent of the 800,000 new cars sold each year, on average were using ethanol. Due to the strong increase in consumption, a severe shortage of ethanol took place at the end of 1989, provoking a loss of consumer trust in the security of ethanol supply and Pro Alcool Programme. Owing to these problems, by the end of the 1990s, the sales of ethanol-fuelled cars amounted to less than 15 per cent of total car sales. In 2003, car manufacturers introduced "flex-fuel" vehicles and it is estimated that "flex-fuel" vehicles correspond now to more than three quarters of new car sales in Brazil. Pure gasoline is no longer sold. The share of bio-fuels in road-transport fuel was estimated at 14 per cent in 2004.

Most of the reduction in the cost of production of ethanol in recent years came from the agricultural part of ethanol production. It is estimated that around 60 to 70 per cent of the final cost of ethanol corresponds to the cost of the sugar cane. Agricultural yield has therefore a strong impact on the final cost of ethanol. Average productivity in Brazil is around 65t/ha, but it can reach 100 to 110t/ha in São Paulo State, which is the main ethanol-producing region. Since the beginning of the Pro Alcool Programme, yields have improved by 33 per cent in São Paulo, thanks to the introduction of new varieties and the improvement of agricultural practices. There has also been a development of mechanisation. In the period 2001-2006, in the mid-west, southeast and southern regions, about 35 per cent of the area planted with sugar cane has been harvested mechanically and the mechanised harvesting rate can reach 90 per cent in some regions.

It should also be noted that there has been historical evolution of Pro Alcool, with a progressive change of technological priorities. This is especially to be taken into account when comparing respective advantages/disadvantages of EU local production or imports. Initially the main focus of the Pro Alcool was put on the increase of equipment productivity. The size of Brazilian mills also increased. The focus then shifted to the improvement of conversion efficiencies. Over the past 15 years, special attention has been paid to a better management of the processing units. As a consequence, presently almost all sugar-cane distilleries in Brazil use bagasse-fired steam turbine systems for providing steam and electricity to cover their site needs. For example, most biomass cogeneration takes place in São Paulo State with 40 sugar mills selling 1.3 GW of surplus power to the electrical grid. Bagasse-based co-generation is developed in order to reduce the country's traditional reliance on hydropower and in addition this improves the competitiveness of Brazilian ethanol.

Regarding processing conditions, on average 5m^3 of water are used for each ton of sugar cane processed, even if values range from 0.7m^3/t to 20m^3/t. According to (de Carvalho Macedo, 2005) the levels of water withdrawal and release for industrial use have substantially decreased over the past years from around 5m^3/t sugar cane collected in 1990 and 1997 to 1.83m^3/t sugar cane in 2004 (sampling in São Paulo State). In the conversion to ethanol, the reduction of water consumption was mainly due to reuses and recycling, process improvements and substitution of wet cane washing with dry-cane washing; in the higher values of water use (5m^3/t) sugar cane washing, evaporation and cooling in condensers and fermentation cooling accounted for 87 per cent of the water use. It seems possible to decrease water collection to 1m^3/t with no release, by optimising both the reuse and use of wastewater for irrigation (Moreira, 2007).

In the past, direct discharge of vinasse (liquid residue from the distillation of ethanol, rich in potassium and organic matter) to water streams was a cause of significant environmental damage. For each litre of ethanol, ten to 15 litres of vinasse are produced. Vinasse began to be recycled to the cane fields in 1978 when the first legislation governing the disposal of vinasse was passed. The current practice is full recycling of vinasse and industrial wastewaters. The application of vinasse is optimised for specific topographic, soil, and environmental conditions. Filter cake, another waste stream is also recycled as a fertiliser. Nutrient recycling in turn has reduced application of fertilisers. The highly intensive production systems for ethanol have been in the past a cause of environmental damage mainly due to the use of fertilisers and pesticides. Sugar cane cropping is also a source of air pollution due to burning prior to manual harvesting. The phase-out of burning is taking place in Brazil with a deadline for complete phase-out in 2022.

According to UNICA (the Brazilian Sugar Cane Industry Association), sugar cane culture in Brazil is considered to have relatively small soil erosion loss compared with soybean and corn for example. This situation keeps improving as harvesting without burning expands and reduced preparation techniques are introduced, thereby reducing losses to very low rates that are comparable to those for direct planting in annual crops.

According to Dufey *et al.* (2006), the main issues of concern related to sugar production development are: natural habitat conversion and species loss, water uptake and reduced water flow, soil erosion and loss of fertility, water pollution, pollution from burning cane fields, air pollution and solid waste from processing cane.

Average ethanol production yields have grown from 3,900 litres per hectare and year (L/(ha*year)) in the early 1980s to 5,600L/(ha*year) in the late 1990s. In the most efficient units, yields are as high as 8,000 to 10,000L/(ha*year). Sugar cane crops are virtually non-irrigated in Brazil, except for some small areas (supplementary irrigation). The annual rainfall in São Paulo State is roughly 1,000-2,500 mm/year.

Regarding the area requirements, in 2007 11.6 per cent of the cultivated area was used for sugar cane, compared with 23.8 per cent for corn and nearly 35 per cent for soybeans (IBGE 2008) (out of presently about 59Mha of arable land (IBGE, 2008) and about 172Mha of pasture land (IBGE, 2006)).

World sugar production in 2007/2008 (October/September) is estimated by FAO to reach 169 million tonnes (raw sugar equivalent), 2.7 per cent more than in the previous year, and about 12 million tonnes higher than the projected world sugar consumption of 157 million tonnes. Virtually all of the growth in output would stem from developing countries. Brazil is set to produce 32.2 million tonnes of sugar in 2007/2008, relatively unchanged from 2006/2007. This is despite a record level cane harvest, following relatively favourable weather conditions, which boosted yields. It is estimated that around 55 per cent of Brazil's 2007/2008 sugar-cane harvest will be converted into ethanol rather than into sugar (FAOSTAT, 2007).

It has been estimated (Earth Policy Institute) that expanding the sugar cane area, from about 6.7 million ha in 2007 to some 8 million ha, would allow Brazil to become self sufficient in automotive fuel within a few years while conserving its sugar production and exports.

According to projections from the sugar/ethanol sector in Brazil, increasing internal and export market demands for sugar and ethanol can easily be met. It is assumed that the industry should be able to produce 33.7 million tonnes of sugar (12.8 million tonnes for internal consumption and 20.9 million tonnes for export) and 26.4 million m^3 of ethanol (of which 4.4 million m^3 for export) by the year 2015. This would mean an increase of about 230 million tonnes of sugarcane in ten years – a doubling in the ethanol production and an increase of 44 per cent in sugar production (Worldwatch Institute, 2007).

Presently, sugar cane (both for food and energy) corresponds to less than 1 per cent of Brazilian territory, soybean 6 per cent and pasture 20 per cent.

Bio-diesel (Malaysia)

The Malaysia National Bio-fuels Policy (Malaysia Energy Centre, 2005) was launched in August 2005. The Government is promoting, among others, the use of bio-diesel in public fleets. The blend is not compulsory yet, but it will be in the next phase of the implementation plan.

For oil palm, the oil extraction rate is 20 per cent and the palm oil yield about 4t/(ha*year). It should be noted that the best fields could produce seven/eight tonnes annually. The planting density ranges from 136-160 palms per hectare. The economic life span is 20-30 years. An oil palm usually bears fruits from 30 months after planting. Malaysia humid tropical climate with a temperature range of 24°C to 32°C throughout the year, an annual rainfall of about 2000 mm evenly distributed, is very adapted to the cultivation of oil palm. According to Oil Worlds 2007, the average oil yield is 3.74t/(ha*year) for oil palm (mesocarp) against 0.38 for soybean, 0.48 for sunflower and 0.67 for rapeseed. The average oil yield from rapeseed in Europe is 1.3t/ha*year.

Malaysia produced 200 million litres of bio-diesel in 2006, consuming 1 per cent of the 15.88 million litres of palm oil produced. In 2007, the production remained almost unchanged and has already totalled 5.3 million litres in January-April 2008 (of the 17 million litres expected for this year) (Department of Statistics Malaysia 2008). In 2006 less than 13 per cent, or 4.17Mha (from 54,000ha in 1960) (Basiron, 2007) of Malaysia's land is planted with oil palm (the bulk of oil palm estates was previously planted with rubber, coconut and cocoa) (with 7.9Mha of land used for agriculture (FAOSTAT, 2005)).

Malaysia is the world's largest exporter of palm oil selling around 13.5 million tonnes with a relatively low domestic consumption. Malaysia's share of global oils and fats trade was 27.9 per cent in 2006 (Oil World). According to MPOB 2008, the EU was, after China, the second destination for Malaysian Palm Oil in 2007 with 2 million tonnes (about 18 per cent against less than 1 per cent to the USA), almost half of the total palm oil imported in EU in 2007.

For the future, improved planting materials and better management techniques are foreseen. Domestic consumption is relatively low and Malaysia exports most of its palm oil and kernel oil.

MPOB is reporting costs of oil production (US $ per ton), of 228 for Malaysia, 400 for soybean (USA), 648 for rapeseed (Canada), 900 for rapeseed (Europe). The palm sector in Malaysia corresponds to the employment of 860,000 persons with 100,000 smallholders with 650.000ha.

The issue of sustainable resource development, specifically of palm tree cultivation, has been discussed for example in Brussels in June 2007 during the Meeting on Sustainable Resources Development organised by the Malaysian Palm Oil Council (MPOC).

In 2006, the palm oil plantations had the following distribution in Malaysia: 2.34 million ha (56 per cent) in Peninsular Malaysia, 0.59 million ha (14 per cent) in Sarawak and 1.24 million ha (30 per cent) in Sabah. If there are clear advantages of oil palm in relation to other options, concern has been expressed especially by NGOs about the impact of oil palm plantations development on tropical deforestation. According to FAO 2007, based on country reporting, the total forest area in Malaysia (in thousands of ha) was 20,890, i.e. 63.6 per cent of the land and the forest plantation area 1,573. The annual change (in thousands of ha) 1990-2000 was -78 (-0.4 per cent) and -140 (-0.7 per cent) for the period 2000-2005.

According to Stibig *et al.* (2007), based on TREES (Tropical Ecosystem Environment Observations by Satellites) Project activities, since the mid-1990s Malaysia's and Indonesia's oil palm plantation area has grown from 2.4 to 4 million ha and from 1.7 to 6 million ha respectively: in Indonesia almost three times as much has been cleared for expansion and further huge expansion is foreseen. However, it should be stressed that not all oil palm development on Borneo or Sumatra will lead to forest conversion. In Peninsular Malaysia the conversion of State land forest to oil palm plantation is of limited extent.

Concerning the use of peatlands in South East Asia, an assessment of CO_2 emissions from drained peatlands in SE Asia has been performed in the PEAT-CO_2 project (Hooijer *et al.* 2006). In this study, present and future emissions from drained peatlands were quantified using available data on peat extent and depth, present and projected land use and water management practices, decomposition rates and fire emissions. This study estimated that the current likely CO_2 emissions caused by decomposition of drained peatlands amount to 632Mt/y (between 355 and 874 Mt/y). For comparison, the agricultural sector for EU27 is estimated to emit about 430 Mt CO_{2eq} (EEA, 2008). The authors consider that these emissions will increase in coming decades unless land management practices and peatland development are changed. In addition, over 1997-2006, an estimated average of 1,400 Mt/y in CO_2 emissions, was caused by peatland fires, also associated with drainage, and degradation. The current total peatland CO_2 emission of 2000 Mt/y equals almost 8 per cent of global emissions from fossil fuel burning. These emissions have been rapidly increasing since 1985. Over 90 per cent of this emission originates from Indonesia. Nevertheless, there is a large variability of CO_2 emission assessments due to the type of peat soil considered, the drainage depth and the land use (Hooijer *et al.*, 2006; Melling *et al.*, 2005a, b; Melling *et al.*, 2007; Verwer *et al.*, 2008) and the authors discuss the following uncertainty sources: Input data (peat thickness, extent and distribution of peat-lands, carbon content of SE Asian peat, carbon storage, land-use/land-cover, per cent of peat-land drained, drainage depth). Other uncertainty sources mentioned by the authors were emission relations (relation between drainage depth and CO_2 emissions, CH_4 emissions, peat fires) and uncertainties in the projections (deforestation trend assessment, drainage trend assessment, land use projections).

Further, is should be mentioned that Hooijer *et al.*(2006) estimated that 25 per cent of plantations in Malaysia and Indonesia are on peat (present + future plantations), while MPOB reports only 6 per cent of existing plantations in Malaysia on peat-land.

N_2O emissions and related uncertainties

N_2O emissions and the uncertainty of bio-fuel-GHG budgets

For the GHG balance of bio-fuels, the emissions occurring during cultivation are an important element and they are one of the most important sources of uncertainty (see, e.g. Adler *et al.*, 2007; Porder *et al.*, 2009; Scharlemann and Laurance, 2008; Smeets *et al.*, 2009). If only the direct land-use effects are considered, it is fair to say that most of this uncertainty derives from the difficulty to accurately estimate the emissions of N_2O that go ahead with all soil cultivations. The reason is that nitrogen, once it enters the system as "reactive" nitrogen (all forms of N with the exception of the inert molecular nitrogen, N_2), undergoes several steps of transformations until it is eventually transformed back as N_2 (this is referred to as the "nitrogen cascade", Galloway *et al.*, 2003). The processes of nitrification (converting ammonia to nitrate) and denitrification (converting nitrate back to molecular nitrogen), which both release traces of N_2O in varying quantities, have particular importance.

The resulting high variability of N_2O fluxes in space and in time, and the equally high variability in indirect emissions pathways is one of the largest sources of uncertainty for estimating N_2O emissions from agricultural soils. In field studies for direct N_2O fluxes, coefficients of variation up to 200 per cent have been observed and the part of the variability in fluxes can be explained with the major soil parameters, such as soil organic carbon, pH, and soil drainage texture determining soil moisture and redox-potential (e.g. Dobbie and Smith, 2001; Granli and Bøckman, 1994; Yanai *et al.*, 2003). Further soil compaction influencing (e.g. Sitaula *et al.*, 2000; Van Groenigen *et al.*, 2005), and tillage methods (Skiba and Smith, 2000) are both influencing water- and oxygen status in the soil and thus determine whether the aerobic process of nitrification or the anaerobic process of denitrification, both potential sources for N_2O, can take place.

Also year-to-year variability is very high and is mainly driven by the weather (e.g. Baggs *et al.*, 2003). Within a year, high N_2O emissions are frequently observed following the application of fertilizer nitrogen, but can also be related to springtime freezing/thawing events (e.g. Flessa *et al.*, 1995; Maljanen *et al.*, 2004). These emissions are typically very large and can represent about half of the annual total emissions. They are mainly explained by the increased availability of organic material due to the death of microorganisms combined with anaerobic conditions. A similar effect is given for cycles of wetting and drying (e.g. Davidson, 1991; Zheng *et al.*, 2004).

The resulting variability is overlaid with effects that are active at a larger scale, such as climatic differences, management systems, variations in soil type and landscape morphology at a medium to large scale. So far, however, it was not possible to explain large-scale variations by large-scale drivers and most assessments rely on the up-scaling of small-scale estimates. The difficulty here is to assure that these are effectively representing the larger scale (see, e.g. Leip, 2007).

Approaches to estimate N_2O fluxes vary from very simple to very complex
There are various options to estimate N_2O fluxes associated with the cultivation of crops. These methodologies are differing by the complexity, of the calculation method and number of variables that are taken into account – from single-input global values (Crutzen *et al.*, 2007) to data-hungry methods that are applicable at a high resolution (Leip *et al.*, 2008).

Even though there is little doubt about the high degree of variability in measured data, the most widely used method is the IPCC emission factor of 1.25 per cent of N-input (IPCC, 2001) or the – recently updated – factor of 1.0 per cent (IPCC, 2006). Both factors have thus as their only parameter the input of nitrogen (as fertilizer, organic nitrogen, or crop residue). Next to the factor to estimate direct N_2O emissions occurring on the field, the IPCC provides also a method to estimate the so-called indirect N_2O emissions, which occur further down in the "Nitrogen cascade". Even though many experts are aware that the average N_2O emissions in their country might be different from the IPCC estimates, the default factors are nevertheless used in most national GHG inventories because robust data to estimate country-specific factors are not available (Leip *et al.*, 2005).

A compilation of all studies giving annual estimates of N_2O fluxes and sufficient ancillary information is provided by (Stehfest and Bouwman, 2006), improving on earlier work of (Bouwman *et al.*, 2002). The authors develop a statistical method on the basis of these data including N application rate and type, crop type, soil and climate information and the length of the experiment in the analysis. Crop type, fertilizer type and N application rate are significant management-related factors for N_2O emissions. Applying this model globally, (Stehfest and Bouwman, 2006) find an average fertilizer-induced emission factor of 0.9 per cent of the N-input, but obviously regional differences are high. However, using this method to assess the contribution of N_2O to the GHG balance of first-generation bio-fuels, (Smeets *et al.*, 2009) conclude that the statistical model remains to be among the largest contributors of uncertainty changing the overall GHG saving by potentially more than 100 per cent points. More detailed statistical analyses become possible for smaller regions. Particularly in Europe, the density of N_2O measurements is relatively high so that the application of a method based on ecosystemic stratification might become possible (Jungkunst and Freibauer, 2005), which can be seen as a further development of regression-approach developed by (Freibauer, 2003). Still, even in Europe, the number of measurements is scarce and process-based models are seen as the only possibility to extrapolate into "unexplored" conditions and thus give a truly complete picture of larger regions (see for example, Adler *et al.*, 2007; Leip *et al.*, 2008; Werner *et al.*, 2007).

Example one: global approach by Crutzen et al. *(2007)*
Crutzen *et al.* (2007) propose a global emission factor for N_2O emissions of 3-5 per cent of nitrogen needed to grow (bio-fuel) crops. This emission factor stems from a global analysis of the increase of atmospheric N_2O concentration and the anthropogenic

generation of "new" nitrogen. This approach is very attractive as it comprehensively includes both direct and indirect emissions of N_2O, without the need to "track the fate of nitrogen" as this is done in the IPCC methodology. Accordingly, the Crutzen-emission factor can be regarded as much more robust than any of the emission factors contained in the IPCC guidelines. On the other hand, there is the risk of double counting in the case that a significant part of the nitrogen taken up by the crops is not "new" (i.e. obtained through the input of synthetic fertilizer, bio-logical nitrogen fixation or also by draining the nitrogen pool in soils) but stems from the application of manure or from atmospheric deposition (Leip, 2007). Being robust at the global level, however, implies also that the emission factor cannot be used to estimate local or even regional N_2O fluxes. As soon as a "subsample" of global N generation is evaluated, the Crutzen emission factor becomes much more uncertain and should be corroborated (or substituted) by a more flexible approach.

Example two: detailed approach by Leip et al. *(2008)*

Through the combination of an economic model, a downscaling procedure of the most important anthropogenic drivers (geo-referencing of land use activities and quantification of farm input) and a mechanistic bio-geochemistry model, (Leip *et al.*, 2008) established a framework that allows the evaluation of GHG fluxes from agricultural soils using a state-of-the art mechanistic model (Li, 2000). This is embedded into a realistic setting, including the most likely environmental conditions of cultivation of crops and regionally estimated farm input consistent with the economic environment (for example livestock number, feed and fertilizer import, etc.). The possibility to simulate a large number of spatial units allows the assessment of the spatial variability. A disadvantage of this methodology is that it has been set-up for Europe and cannot easily be implemented in other parts of the world. Where the validity of the mechanistic model can be shown on the basis of experimental data (which are scarce in large areas of the world (see Stehfest and Bouwman, 2006), appropriate environmental datasets, in combination with estimates of farm management, might become a significant hurdle. A first application of the method to rapeseed cultivation in Europe, combining simulated emission fluxes by the bio-geochemistry model with literature data (including also CO_2 fluxes occurring during farming-energy consumption), for example, that this occurs on soils characterised by relatively high N_2O flux rates offsetting a large part of the GHG savings when using the crops as feedstock for bio-fuels (Erisman *et al.*, 2010). Using sugar beet leads to a better overall GHG balance due to the lower N-input needed.

Discussion

- The evaluation of the best method is not only a scientific problem, but must be seen in the framework of the policy framework.
- For example, if thresholds for minimum GHG savings are set, then the decision to use a global approach excludes N_2O emissions from distinctions of bio-fuel feedstock with respect to their origin, however the selection of the emissions factor could well influence the "ranking" of bio-fuel crops.
- In the case that GHG certificates are issued for crops cultivated for the production of bio-fuels only, and not for those that enter the feed, food or fibre

industry, the use of a detailed methodology might lead to a shift between land used for bio-fuel production or other uses, without any real impact on total GHG fluxes.

- Consequently, detailed methodologies can only pay off if thresholds for GHG emissions from the field are applied to the whole production of a crop in a country. This could be the average CO_{2eq} emissions over the country, or to assure environmental integrity, the demand that a minimum share of the production be sustainable with regard to the threshold. Only in this case, the application of detailed models, which take into consideration the local environmental conditions (soil, climate, etc.) in combination with a realistic estimate of the spatial distribution of the cultivated areas, would be important. In the case that such a model could be properly be set up, which requires high quality environmental datasets and realistic estimates for farm-input, the use of aggregated emission indicators would also lead to a minimum uncertainty in the estimate of the GHG balance of the bio-fuel.
- It is of utmost importance to improve our knowledge of these indirect land use emissions and our capabilities to accurately predict the GHG impact of bio-fuel (targets) comprehensively (Porder *et al.*, 2009).

Life cycle assessment of bio-fuels

Bio-fuels for transport are generally considered to be environmentally friendly since they save non-renewable energy resources, are bio-degradable and – at least at first glance – CO_2 neutral. The latter is of course only true for the direct combustion of bio-fuels which releases the same amount of CO_2 into the atmosphere that earlier has been taken up by the plants. However, when looking at the entire life cycle of bio-fuels – from biomass cultivation (including the input of fertilizers, pesticides, etc.) through conversion into bio-fuels and their energetic use – substantial amounts of (non-renewable) energy resources are used which in turn cause greenhouse gas (GHG) emissions. Thus, bio-fuels are not CO_2 neutral from a life-cycle point of view. The same holds true for other potential environmental impacts: the use of bio-fuels is not implicitly environmentally friendly simply because the feedstock – biomass – is a renewable resource.

In the 1990s, a method has been developed which addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle: Life Cycle Assessment (LCA). The method is internationally standardised (ISO standards 14040 and 14044) and considers the input and output flows (raw and other materials, energy and wastes, waste-water, emissions, etc.) and potential environmental impacts (e.g. greenhouse effect, acidification etc.) of the considered product system (product or service) along its entire life cycle ("cradle-to-grave", from raw material acquisition through production and final disposal).

Life cycle assessments usually address a number of environmental impact categories, such as use of resources, greenhouse effect, acidification, eutrophication, stratospheric ozone depletion, summer smog (photo-oxidant formation), human toxicity and ecotoxicity. In recent years, however, the scope of many studies was restricted to two of them: the use of non-renewable energy resources and greenhouse effect. In this case, the LCA methodology is used to obtain so-called energy and greenhouse gas balances.

The following sub-chapters will only focus on GHG balances of bio-fuels. Using the example of palm oil bio-diesel, the main reasons for variations in the results will be identified.

Greenhouse gas balances of bio-fuels

One of the commonly cited collections of energy and greenhouse gas (GHG) balances of bio-fuels is the JEC Well-to-Wheels study (JEC (European Commission Joint Research Centre-EUCAR-CONCAWE), 2007). It gives ranges of GHG emissions in grams CO_2 equivalents per kilometre (g CO_{2eq}/km), e.g. for bio-ethanol used as neat fuel: 58 to 130 for bio-ethanol from sugar beet, 32 to 209 for wheat, 19 to 22 for wheat straw and 21 to 25 for sugar cane. As for bio-diesel, the values are 83 to 100 for rapeseed, 46 to 60 for sunflower and 14 to 17 for farmed wood. These ranges are due to the different pathways studied in the report (for example concerning the use of by-products). As an order of magnitude the following GHG savings could be found in the same report (JEC (European Commission Joint Research Centre-EUCAR-CONCAWE), 2007) in terms of kg CO_{2eq}/(ha*year): 660 for wheat and 4,429 for sugar beet for ethanol production; 1,505 for rapeseed, 1,545 for sunflower and 4,806 for farmed wood for bio-diesel production.

IFEU (Institut für Energie- und Umweltforschung Heidelberg GmbH) (2004) also gives ranges of GHG savings in terms of kg CO_{2eq}/(ha*year): 800 to 3,700 for bio-ethanol from wheat, 3,000 to 11,000 for bio-ethanol from sugar beet, 500 to 2,800 for bio-diesel from rapeseed, and 1,500 to 4,000 for bio-diesel from sunflower.

According to Jank *et al.* (2007), the greenhouse gas balance of bio-ethanol in tonnes of CO_2 equivalents per tonne of oil equivalent (t CO_{2eq}/toe) is 2.17 for sugar beet, 1.85 for wheat, 0.41 for sugar cane and 0.33 for straw. In the case of bio-diesel production, it is 2.6 for soy, 1.73 for palm and 0.27 for wood.

According to the Worldwatch Institute (2007), "the vast majority of studies have found that, even when all fossil fuels throughout the life cycle are accounted for, producing and using bio-fuels made from current feedstocks result in substantial reductions in GHG emissions relative to petrol fuels". Several studies have assessed the net emission reductions resulting from sugar cane ethanol in Brazil, and all have concluded that the benefits far exceed those from grain-based ethanol produced in Europe and the US. The lower life cycle climate impacts of Brazilian sugar cane ethanol are related to two main factors: high cane yields and use of bagasse for energy or cogeneration.

GHG emissions related to land-use change

Most of the previously mentioned studies, however, do not take into account GHG emissions from land-cover and/or land-use changes. While land cover generally refers to the physical and biological cover of the land surface, land use is rather connected to human activities such as agriculture and forestry and defined in a broader way. A distinction is made between direct and indirect land-use change.

Direct land-use changes (dLUC) occur, if natural ecosystems (e.g. forest land) are converted into agricultural land (e.g. an oil palm plantation). Indirect land-use changes (iLUC) or "leakages" arise if agricultural land currently used for food or feed production is used for bio-energy crop cultivation and the food and feed production is displaced to another area where again unfavourable (direct) land-use changes might occur.

Both dLUC and iLUC can be dealt with in life cycle assessments, as Reinhardt (1993) and Jungk and Reinhardt (2000) have shown for dLUC and iLUC, respectively, although referring to it as the "agricultural reference system" at the time. In the 1990s, set-aside land was readily available for bio-energy crop cultivation in the EU, so, there was no need to use the basic agricultural land (i.e. where food and feed production took place), nor to convert natural ecosystems, such as forests, into agricultural land. In other words, land use was only changed from fallow to bio-energy crops.

This situation changed in the twenty-first century with bio-fuel mandates increasing the pressure on both agricultural land in Europe and natural ecosystems elsewhere on the globe. The first GHG balance studies to account for GHG emissions due to (direct) land-use change from natural forest to oil palm plantation were published by WWF (World Wildlife Fund) (2007) and Reinhardt (2007) showing that GHG balances of palm oil bio-diesel could even turn out negative, i.e. that the use of palm-oil bio-diesel could cause higher life cycle GHG emissions than the use of conventional diesel fuel.

Another way to express the global warming impact of bio-fuels is to quantify how many years it takes for the bio-fuel carbon savings from avoided fossil fuel combustion to offset the losses in ecosystem carbon from clearing land to grow new feedstocks (or Ecosystem Carbon Payback Time, ECPT). Fargione *et al.* (2008) estimated that converting rainforests, peatlands, savannas or grasslands to produce food-crop based bio-fuels in Brazil, Southeast Asia and the USA creates a "bio-fuel carbon debt" by releasing 17 to 420 times more CO_2 than the annual greenhouse gas reductions that these bio-fuels would provide by displacing fossil fuels. On the other hand, it was considered that bio-fuels made from waste biomass or from biomass grown on degraded or abandoned agricultural lands planted with perennials are associated to a small or no carbon debt and can provide immediate GHG advantages. Gibbs *et al.* (2008) concluded that clearing tropical forests and grasslands to produce bio-fuels leads to long-term carbon debt, while only converting degraded lands will provide carbon savings (even if the highest yielding bio-fuel crops from clearing forests are taken into account). It should be noted that growing crops on marginal lands may require significantly more land area than other regions, due to relatively lower yields, and will likely require more energy-intensive management such as fertilizer application or irrigation to remain productive. This will affect the ECPT value.

Indirect land-use change, however, is much more difficult to quantify. The topic of indirect land-use changes caused by bio-fuels was brought to widespread attention by Searchinger *et al.* (2008) who estimated the indirect or "leakage" land-use impacts of US corn ethanol to double the greenhouse gas emissions per fuel mile compared to conventional gasoline over 30 years. The paper marked the starting point of a controversial debate and was criticized among others by Wang and Haq (2008) as well as Kline and Dale (2008) who suggested that an improved understanding of the forces behind land-use change leads to more favourable conclusions regarding the potential for bio-fuels to reduce greenhouse gas emissions. Despite all criticism, the iLUC concept has recently been implemented in legal documents such as California's Low-Carbon Fuel Standard (LCFS) and US EPA's Renewable Fuel Standard (RFS2). In the case of LCFS, GHG emissions due to iLUC are quantified by the GTAP (Global Trade Analysis Project) model, a computable general equilibrium model. On the contrary, RFS2 prefers a combination of two partial equilibrium models, the FASOM (Forest and Agriculture Sector Optimisation Model) and the FAPRI (Food and Agricultural Policy Research Institute) model. Both approaches have been peer reviewed by several experts (ICF 2009) who conclude that none of them is superior to the other and that the science on indirect land-use change is in its infancy (Sheehan, 2009). Work on iLUC is also performed in the EU in relation with the Renewable Energy Directive (2009/28/EC) implementation.

Greenhouse gas balance of palm oil bio-diesel

Quite a number of greenhouse gas balances for palm oil and downstream products, such as palm oil bio-diesel (palm oil methyl ester, PME) can be found in literature, e.g. Germer and Sauerborn (2008), Reijnders and Huijbregts (2008), Reinhardt (2007), Schmidt (2007), Wicke *et al.* (2007), Wicke *et al.* (2008), WWF (World Wildlife Fund) (2007) and Yusoff and Hansen (2007). The results of these greenhouse-gas (GHG) balances vary quite substantially, mainly depending on whether and how direct land-use changes are considered and to a lesser degree depending on differences in basic data.

GHG emissions related to land-use change

Direct land-use changes (dLUC), i.e. the conversion of natural ecosystems (e.g. forest land) into agricultural land (e.g. an oil palm plantation), induce changes in site quality, e.g. in terms of bio-diversity and carbon stocks. Changes in above ground and below ground carbon stock can lead to high GHG emissions, which have to be included in the GHG balance.

GHG emissions from land-use changes can either result from singular events (e.g. clear-cutting and/or slash-and-burn) – which require an annualisation – or from continuous processes (e.g. peat subsidence) that prevail for many years after land conversion. If fire is used to clear the site (slash-and-burn), emissions of methane and nitrous oxide have to be considered in the GHG balance too. A detailed analysis by Reinhardt (2007) has shown that the two most important influencing factors are connected to singular events:

(1) *Magnitude of carbon stock change*: Depending on the previous land use, the amount of carbon stored in both the above-ground and below-ground vegetation, as well as in the soil differs considerably. Most authors use IPCC (2006) data for carbon stocks of vegetation and mineral soils. Data on the carbon stock of organic soils, however, is rare and depends heavily on soil density, organic matter content and peat thickness. GHG emissions from vegetation fires are only included in Germer and Sauerborn (2008) and Rettenmaier *et al.* (2007), the latter also covering peat fires.

(2) *Annualisation*: GHG emissions resulting from singular events such as clear-cutting of natural forests have to be evenly divided over a certain period of time (i.e. annualised). As the length of this period is not specified by LCA standards, it is up to the user to define an adequate time span. Many opt for 100 years, others for 25 years, which equals one plantation cycle (economic

life span of oil palms) whereas IPCC (2006) and the EU Renewable Energy Directive (2009/28/EC) stipulate an annualisation over 20 years.

The qualitative results of GHG balances, i.e. whether the life cycle GHG emissions are higher or lower than those of conventional fuel, are heavily dependent on these two factors. For example, if undisturbed natural forest on mineral soil is cleared and the resulting GHG emissions are annualised over 100 years, the result of GHG balance is slightly positive. However, if annualisation over 25 years is chosen, the result is negative. In other cases, the results are more uniform: clear-cutting of peat (swamp) forest always leads to negative GHG balances, irrespective of annualisation, whereas establishment of oil palm plantations on degraded land always induces positive GHG balances.

Of course, the establishment of an oil palm plantation does not necessarily lead to a direct land-use change, i.e. the conversion of natural ecosystems into agricultural land. In the 1990s, oil palm plantations were often replacing other plantations like rubber, coconut or cocoa. Assuming a constant demand for the products earlier produced on these plantations, their production is displaced to other areas. The existing agricultural production in those areas might be displaced to a third area and so on. As agricultural land is a finite entity, new land must be reclaimed elsewhere, again leading to unfavourable direct land-use changes. This so-called indirect land-use change (iLUC) or "leakage" is not yet incorporated into LCAs as the underlying mechanisms are not fully understood yet and methods to quantify them are disputed. WWF (World Wildlife Fund) (2007) and Reinhardt (2007) have accounted for the displaced agricultural production by substituting the displaced bio-genic products for conventional products, e.g. natural rubber for synthetic rubber.

Regarding basic data for continuous processes such as CO_2 emissions due to peat subsidence and N_2O volatilisation due to fertilization of organic soils, IPCC (2006) unfortunately does not give clear guidance. For example, if drained peat soils are classified as "drained organic soils in managed forests", CO_2 emissions are as low as 1.36t C/(ha*year). However, if they are classified as "cultivated organic soils" the figure is considerably higher: 20t C/(ha*year). IPCC suggests basing the classification on drainage depth, but gives no threshold values. In the previously mentioned GHG studies, values from 8.6t C/(ha*year) (Germer and Sauerborn, 2008) up to 25t C/(ha*year) (IFEU (Institut für Energie- und Umweltforschung Heidelberg GmbH), 2004) are used, the latter based on an equation by Hooijer *et al.* (2006) and a drainage depth of 1m. Melling *et al.* (2005a) criticize Hooijer's figures, but derive their own ones from disturbed ecosystems (Verwer *et al.*, 2008).

Similar problems arise regarding N_2O emissions from organic soils. In addition to the N_2O emission factor (1 per cent of N input), which was already discussed in part 3 of this paper, IPCC (2006) gives a second emission factor (EF_2) for N application on organic soils. This fixed sum has to be added to the input-dependent term. Again, it is the question whether drained peat soils are classified as "tropical organic forest soils" or as "tropical organic crop and grassland soils", leading to emissions of 8 kg N_2O-N/(ha*year) and 16 kg N_2O-N/(ha*year), respectively. In the previously mentioned GHG studies, values from 4.1 kg N_2O-N / (ha*year) (Germer and Sauerborn, 2008) to 16 kg N_2O-N/(ha*year) (IFEU (Institut für Energie- und Umweltforschung Heidelberg GmbH), 2004, Schmidt, 2007) are used.

In order to obtain more accurate results for the GHG balances, further research is needed, especially regarding GHG emissions from tropical organic soils.

GHG emissions related to palm oil production

Next to land-use change, cultivation and conversion are two critical stages along the life cycle of palm oil bio-diesel, which can be optimised considerably. In order to cover the variability of palm oil production, IFEU (Institut für Energie- und Umweltforschung Heidelberg GmbH) (2004) developed two scenarios: "typical practice" and "good practice". The following parameters differ from each other (for details see Reinhardt (2007); Rettenmaier *et al.* (2007)):

(1) *Cultivation*: By applying good agricultural practices, the yield of an oil-palm plantation can be increased from typically 3.5 tonnes palm oil/(ha*year) to 4.0 tonnes palm oil/(ha*year). "Good practice" includes improved planting material, tailored fertilization and just-in-time harvesting.

(2) *Conversion*: Great optimisation potentials emerge from the energetic utilisation of the entire amount of fibres and shells (50 per cent are required for the internal power supply of the oil mill) and bio-gas, which is produced during the anaerobic digestion of the "palm oil mill effluent" (POME). The surplus power could be fed into the public grid.

The increase in yield, the energetic utilisation of co-products, as well as the retention and utilisation of the bio-gas from POME treatment, improves the greenhouse gas balance of palm oil bio-diesel: the disadvantage (i.e. net GHG emission) accounts for "as little as" 5.9 tonnes of CO_{2eq}/(ha*year) instead of 9.7 tonnes of CO_{2eq}/(ha*year) without optimisation.

A comparison of input data for palm-oil production (Rettenmaier *et al.*, 2007) showed much less variability as compared to the input data for land-use changes. All of them point at a significant potential to optimise both oil-palm cultivation and palm-oil extraction.

Scientific challenges in the field of biomass conversion and bio-refineries

Biomass feedstocks for use in bio-energy processes vary widely in their composition and properties. Work within the European standards organisation, CEN, has almost completed a set of technical specifications for methodologies to determine a wide range of properties of biomass for use as solid bio-fuels, and these technical specifications are being converted to standards for market implementation (CEN/TC335). The properties of biomass have a large impact on what the biomass can be used for and also strongly influence the selection of method of conversion to bio-fuel, heat or electricity. For example, animal slurries and manure contain very high concentrations of water and can only be used as a feedstock in anaerobic digestion (AD) providing a bio-gas that can be used after simple cleaning to produce heat and electricity, or can be upgraded to bio-methane for use as a transport fuel or injected into natural gas grids (Wellinger, 2005). The challenges for more effective and more efficient use of wet agricultural residues include improved methods for accelerating the methanation process using co-digestants containing easily released forms of carbon, overcoming inhibiting effects and maintaining optimum process control. Biogas technology is developed to the stage where a few thousand plants already exist in Europe, but economic viability is not easily achieved without the application of renewable energy subsidies and feed-in tariffs (Weiland, 2008).

Many forms of biomass, including agricultural residues and energy crops such as maize and sugar beet can be used to produce liquid bio-fuels (e.g. bio-ethanol) with existing first generation commercial bio-fuel technologies which make use of simple, easily released sugars from carbohydrates contained in the biomass. The main challenge facing the bio-fuel industry is to convert non-food biomass containing ligno-cellulose to bio-fuel, using so-called second-generation bio-fuel processes. Two main approaches are being addressed. One, a bio-chemical process, involves pre-treatment of ligno-cellulosic biomass by mechanical grinding to increase surface area, followed by steam explosion, sometimes called cavitation, and enzyme treatments and fractionation to isolate sugars and other useful residues. These processes are under intensive development (Kamm *et al.*, 2008). Separation of individual components of the biomass after pre-treatment offers the possibility to obtain additional products by bio-refining. Bio-refineries to produce chemical pre-cursors are the subject of intense research in many countries, the focus of developments devoted to both pre-treatments and synthesis/refinement of chemical products (e.g. BIO-SYNERGY European Project, 2009). The bio-refinery processes under development are in direct competition with hydrocarbon-based production of chemicals and one of the ways to address the high cost element of bio-refineries could be to integrate with fossil refineries. The other approach is to treat the biomass thermally at high temperature using gasification or pyrolysis to produce an intermediate fuel essentially in one process step.

This avoids many steps in the process, but also involves destroying a number of possible useful residues available in bio-chemical processes (e.g. lignin), however providing a very versatile precursor (syngas or bio-oil) that can be readily converted to one of many hydrocarbon products, or even hydrogen. Fischer-Tropsch diesel is the best-known product of gasification of biomass to produce a second-generation bio-fuel. While the F-T diesel process has been proved on pilot scale, the big challenge is to ensure high catalyst performance over long periods of production in large-scale facilities and to prove high-energy conversion efficiency. New catalysts are also sought, while pre-treatment of the woody biomass, mainly to facilitate trouble-free feeding to the thermal process, need to be made less energy consuming.

Direct combustion of biomass or co-firing of biomass in fossil power plants for heat and electricity production is the most widely used technology for producing bio-energy in most European countries. Early trials by the power generators resulted in numerous problems, either during feeding of the biomass into boilers or due to fouling and corrosion after combustion (Tillman, 2000). Pre-treatment by drying and grinding has led to a number of successes, but there remain safety challenges due to the production of biomass dust (fires/explosions) and minimising energy consumption during drying, chipping, and pelleting operations. Torrefaction of woody biomass, which involves removal of moisture and light volatile species, has been tested on a small-scale and needs evaluation at a large scale to establish the costs in terms of energy consumption on the one side, and energy conversion efficiency and reduced corrosion on the other. For direct co-firing of solid biomass with coal, energy efficiency and reliability of a plant using 100 per cent coal are reduced.

Conclusion and recommendations

Even if bio-energy is now operational and not anymore a possible option for a distant future, it is a technological field in evolution and some scientific challenges need to be addressed. In order to reduce uncertainties related to the environmental assessment of bio-fuels and provide options to lower the controversy, especially in Europe and the USA, about the advantages/disadvantages of bio-fuels and bio-energy, the following points can be stated:

(1) The success of the Brazilian experience with ethanol from sugar cane is based on the achievements of a programme started more than 30 years ago, initially with public support, then progressively liberalised. Even if the complex issue of indirect land use change is not quantified, the environmental record of the Brazilian Programme has been improving. In our view, the economic or environmental comparisons between oil-derived fuels on one hand, European, the US and tropical bio-fuels on the other hand are only valid if they take into account externalities, financial fluxes and the difference in maturity between several technology options.

(2) Bio-fuels certification is an opportunity both for exporters from tropical countries and for importers, for example from the European Union. Extreme care must be taken in order to make sure that bio-fuel certification will provide a fair treatment both to European and tropical bio-fuel feedstock productions, and will be acceptable for WTO standards. The implementation of sustainability certification systems and the corresponding verification mechanisms, for example through remote sensing, will allow to reduce some uncertainties.

(3) More research is needed on GHG emission quantification in relation to bio-fuels and bio-energy, especially considering N_2O emissions, the contribution of peat soils to emissions in case of land-use change, indirect effects on tropical deforestation, the price interactions between food/feed and bio-fuel prices. Life cycle assessment of bio-fuels is a useful tool of analysis only if it is transparent but the results are associated to a high level of uncertainty, often due to different methodological choices. The indirect effect (displacement, leakage, …) of EU and US policies on land-use/land-cover in tropical countries is a complex issue, which requires more research using among others global macro-economic models, land use/land cover models and emission models.

(4) Crops must be grown in a sustainable way whatever their final use. All crops have advantages/disadvantages and it is our responsibility that the bio-fuels development based on tropical and other feedstock takes into account "How" (i.e. farming practices including water needs) and not "What" (i.e. this crop is "good" and this one is "bad").

(5) The final decision for a country or group of countries to implement bio-fuel or bio-energy policies should be based on the combination of policies such as: transport, environment, energy, climate change, agriculture, rural development, employment, security of supply, development and aid … Part of the confusion presently observed in the bio-fuels and bio-energy debate is in our view linked to scientific uncertainty mixed with policy-driver confusion and market evolution.

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