Comparing biofuel cropping options by means of sustainability indicators

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Abstract: *A number of biofuel production chains have been assessed by means of sustainability indicators: we considered agricultural production and subsequent industrial conversion of sugar beet and wheat into ethanol and of rapeseed into biodiesel. We used the following set of indicators: greenhouse gas emission reduction; energy output/input ratio, soil degradation, fertilizer use efficiency, pesticide use, water use efficiency, and land use efficiency. Values for these indicators, representative of good agricultural practice in Northwest Europe, have been derived from scientific literature. Sugar beet performed best with respect to the reduction of greenhouse gas emissions, energy output/input ratio, nitrogen use efficiency, pesticide use efficiency, water use efficiency and land use efficiency. Although it is a crop with substantial risk of soil erosion, this risk can be reduced with conservation tillage and winter cover crops. Furthermore, the share of sugar beet in crop rotations is limited by soil borne diseases. Wheat and rapeseed perform better with respect to soil quality indicators and are at present indispensable in first generation biofuel crop rotations. Compared to the current situation, all considered production systems offer several opportunities for improving sustainability.*

Keywords: *biofuels, energy, environment sustainability indicators, sugar beet, rapeseed, wheat*

Introduction

Concerns over climate change and dependency on foreign oil recently spurred governments to set targets for the share of biofuels, or liquid transportation fuels from solid biomass, in their total automotive fuel consumption (European Parliament 2003; U.S. Congress 2005). Attempts to meet these recent targets are creating demand for enormous volumes of biofuels and claim large areas of agricultural land and other resources at the present state of technology. Substantial impacts of such land use changes on the environment, food security and markets for agricultural commodities are to be expected, and to different stakeholders, these may turn out to be either adverse or beneficial.

Increasing concerns over the potential negative impacts of large-scale biomass production has led scientists on both sides of the Atlantic to formulate criteria for assessing the sustainability of biofuel production systems (Cramer et al. 2007; Hanegraaf et al. 1998; Lewandowski and Faaij 2006; Mattsson et al. 2000; Reijnders 2006; Turner et al. 2007). These criteria could enable certification of certain biofuels as 'sustainable', similar to current certification schemes for sustainable timber (e.g. FSC: Lewandowski and Faaij 2006; Turner et al 2007). Introduction of sustainability certificates would potentially give governments and citizens an instrument to influence the characteristics of an emerging biofuel industry: governments could for instance only admit certified biofuels to the market, while citizens could exert a steering influence through their purchasing power.

In order to be certified as 'sustainable', certain sustainability criteria that comprise a certification standard should be met, both during agricultural production and consequential industrial conversion of feedstock into biofuel. Due to the requirement of traceability (Lewandowski and Faaij 2006; Turner et al. 2007), sustainability criteria are in practice applied to concrete situations: e.g. a crop grown by farmer A, which is then transported and converted to biofuel in factory B after which it is shipped to location C for consumption. However, in this work, we will use a set of sustainability criteria for comparing the sustainability of certain biofuel production chains (agricultural production and subsequent industrial conversion) in more general terms: our purpose is not certification, but improving the understanding of the properties of certain crop-climate combinations, which could aid in making better founded crop choices in the future.

Methods

The crops that we are considering are commonly categorized as ‘first generation’ biomass crops: they contain either plant oil that may readily be extracted (and converted into biodiesel) or components (starch, sugar) that can easily be converted into ethanol by fermentation. For this paper, we chose to analyse the production of ethanol from sugar beet and wheat and of biodiesel from rapeseed. These systems are typical for temperate regions; to assess their sustainability, we compiled a list of sustainability criteria from the literature. In some cases, indicators were adapted to better suit our purpose. Sustainability of the concerning biofuel production chains was assessed for best practice production situations in Northwest Europe: values of the indicators were obtained from literature. The criteria can be grouped into the following themes:

Effects on climate

Reducing the emissions of greenhouse gases (GHGs) is one of the prime goals for producing biofuels. Therefore, the extent to which biofuels reduce GHG emissions, compared with fossil fuels, is an important measure of their sustainability. An inventory of GHG emissions arising from production and combustion of fossil fuels and GHGs emitted during biofuel production[1] is needed to estimate potential reduction (or increase) of GHG emissions. Fossil energy use in crude oil production and transport, refining and distribution, are main sources of GHGs during the production of fossil fuels; with production of biofuels, emissions result among others from the production of fertilizers, pesticides and seeds, from production and combustion of fossil fuels (by e.g. tractors and conversion facilities) and from the production of chemicals needed during the conversion processes. Figures on emissions from production and combustion of fossil fuels (i.e. diesel and gasoline) and from production of biofuels were derived from Ludwig-Bölkow-Systemtechnik GmbH (2002) and Department for Transport (2007), respectively. For comparing GHG emissions from biofuels and fossil fuels, we assumed that a volume of fossil fuel can simply be replaced by a volume of biofuel with equal energetic value[2]. Under this assumption, GHG emissions per unit of energy (e.g. kg CO_2/MJ) for both fuel types may be compared directly.

Fossil fuel depletion

Another main argument for the production of biofuels is reducing the dependency on oil. Therefore, fossil energy used in agricultural production and conversion of biomass crops should be used efficiently. The actual efficiency may become apparent from the energy output/input ratio. Energy in the production of biofuels is generally consumed by the same processes that emit GHGs: those were listed under the previous theme. For estimating the energy output/input ratios of our different biofuel production systems, a number of energy balance and life cycle analyses was reviewed.

The environment

Large-scale production of biomass crops may affect the (agro-) environment in several ways:

Soil erosion

Depending on crop type and previous land use, soil erosion may be aggravated by introducing biofuel crops, especially if perennials or grassland are replaced by annual crops. Apart from harmful downstream effects, erosion leads, *ceteris paribus*, to reduced productivity of crops (Reijnders 2006). The relative intensity of soil erosion under different biomass crops is therefore used as an indicator for sustainability of those crops. Indicative figures for severity of erosion under different crops were derived from literature.

[1] CO_2 emitted during *combustion* of biofuels is not taken into account as this CO_2 had earlier been captured from the atmosphere by photosynthesis during the agricultural production phase.
[2] Since the energy content of one litre of gasoline is 36.12 MJ (Ludwig-Bölkow-Systemtechnik GmbH 2002) and that of one litre of ethanol 21.11 MJ (Elsayed et al. 2003), this assumption implies that for the replacement of one litre of gasoline, (32.40/21.11 =) 1.53 litres of ethanol are needed. A consensus on these numbers has not yet been reached: studies on energy balances use values between 1.54 and 1 (Henke et al , 2005). Currently, further studies are being performed.

Soil organic matter decline

For a soil to function effectively in plant production it must possess substantial water-holding and ion-exchange capacities, good physical structure, and thriving populations of bacteria, fungi, and invertebrates. These attributes are highly correlated with humus substances (and other soil organic matter compounds), which are dark-brown organic macromolecules rich in phenolic compounds and are derived from plant remains and microbial synthesis (Jenny 1980). Furthermore, breakdown of organic matter releases the carbon it contains into the atmosphere, where it contributes to the greenhouse effect. Tillage systems differ in the amount of crop residues that they add to the soil, and in the extent to which they disturb the soil by e.g. ploughing and harvesting of belowground compounds. Soil disturbance stimulates soil organic matter decomposition. For different crops, these two counteracting processes result in different rates of accumulation (or decomposition) of organic matter in the soil. The more organic matter is added to the soil during cultivation of a certain crop (by addition of its residues) and the less soil disturbance, the better the crop scores with respect to our soil organic matter indicator.

Risk of soil borne diseases

The susceptibility of certain biofuel crops to soil borne diseases may reduce the frequency with which they can be grown on a certain field: build-up of pathogens may otherwise render the field more or less useless for cultivating those and other crops. This maximum share of such crops in rotations effectively also puts limits to their acreage. Data on susceptibility of different biofuel crops to soil-borne diseases have been derived from literature.

Eutrophication

Some amount of chemical nutrients (fertilizers) applied in agricultural production drains to aquatic systems, where it may cause excess oxygen demand and damages ecosystems (Turner et al. 2007). If nitrate leaching to groundwater occurs this can cause problems for quality of drinking water. The main fertilizer compounds responsible for these processes are phosphate and nitrate. For this work we decided to focus on nitrate, as it is easier to make general (non location-specific) assumptions on nitrogen applications in a certain crop than on phosphorus applications: the latter are much more dependent on soil type and long-term management. Further, leaching of phosphorus is minimal except in soils where excessive amounts of organic manures are added.

The use of nitrogen actually impacts several of our sustainability themes. After application, it contributes substantially to the emission of GHGs into the atmosphere: emissions are roughly proportional to the quantity of N applied (IPCC 2006) and comprise of N_2O, a GHG which is 296 times more active than CO_2 (Houghton 2001). Nitrogen may be applied in synthetic forms or in animal manure. Production of synthetic nitrogen fertilizer is an energy intensive process (see e.g. Kongshaug 1998) which claims a substantial part of the (fossil) energy required for the production of biofuels. Large quantities of GHGs are also emitted during production. Nitrogen application here serves as a combined indicator for the risk of eutrophication, acidification and global warming, although the latter aspects have been covered more extensively under themes *a.* and *b.* Comparing different crops is facilitated by introducing a nitrogen use efficiency, which we define as the amount of fertilizer (kg N) required to producing a volume of biofuel with an net energy content[1] of 1 GJ.

Pesticide usage

Similar to N application, we included pesticide use as an indicator for the hazard of emissions to the environment. A particular biomass crops is considered less sustainable than other biomass crops if its production entails comparatively large quantities of pesticides. Data on pesticide usage in the different biofuel crops under consideration were obtained from literature. Similar to our definition of nitrogen use efficiency, we introduce a ‘pesticide use efficiency’ to be able to compare different biofuel crops. It is expressed as kg active ingredient per GJ of net energy.

Water use

Worldwide, agriculture is the main consumer of freshwater: it accounts for about 75% of current water use (Reijnders 2006). Even without additional, large-scale production of biomass crops, shortages of fresh water may become harsh reality for 2.5-6.5 billion people by 2050 (Reijnders 2006). Therefore, water-efficient fuel crops are to be preferred above species that use ample water. Chapagain and

[1] We define net energy content as the total energy in the produced biofuel, minus the energy used during production of that quantity of energy

Hoekstra (2004) introduced the *virtual water content* of a crop product: the volume of water used to produce the product, measured at the place where it was actually produced. Crops with lower virtual water content are considered more sustainable. We used virtual water content data from Chapagain and Hoekstra (2004) to calculate water use efficiencies (WUE) which, for our purpose, we define as the energy content of the biofuel that could be produced with 1 m^3 of water.

Land use

Use of agricultural lands for production of biomass crops could compete with their use for traditional food and fibre production. The result might be decreased food and fibre production (Marland 2001); increased prices might endanger food security of the urban poor and export earnings from agriculture may decline. If less land is occupied by biomass crop production, more land remains available for the essential production of food feed and fibre crops but also for nature. Biomass crops that efficiently use the land may therefore be considered more sustainable. As a measure of this efficiency we define 'land use efficiency' as the net energy content of the biofuel that can be produced from one hectare of land, which is in fact similar to net energy yield.

Results

Climate

GHG emission figures for several biofuel production systems from Dept. of Transport (2007) are compared with emissions from their fossil counterparts: results are displayed in Figure 1. Figures for wheat are averages over average over France, Germany and the UK; those for sugarbeet apply to the UK, while for rapeseed, average values over France, Germany, the UK and Poland are shown.

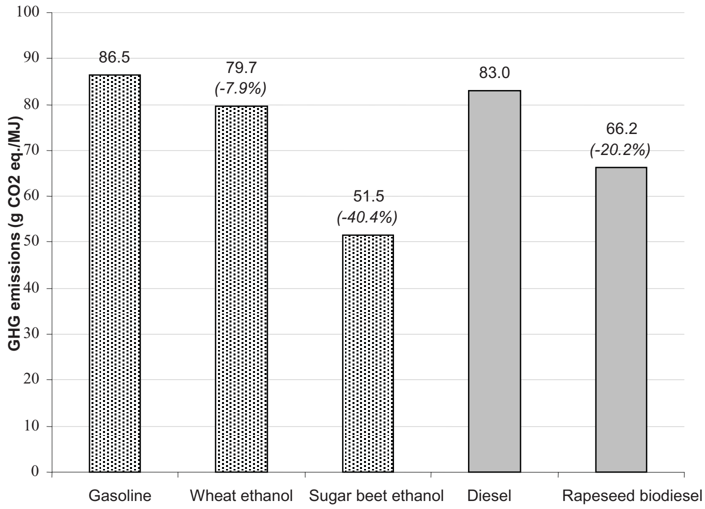

Figure 1. GHG emissions of the biofuels considered in this paper compared to those of the fossil fuel which they may replace

Fossil fuel depletion

Energy output/input ratios for the three biofuel production chains have been calculated based on a number of energy balance and life cycle analyses for Germany and the UK[1]. Results are shown in Figure 2; for added clarity, energy balances are included in Figure 3. All values are averaged over

[1] The reviewed references were Tzilivakis (2005b), Kuesters (1999), Malca (2006), Richards (2000), Punter (2004), Scharmer (2001). Crop yields were derived from FAO (2007). Conversion efficiency of wheat grain into ethanol was assumed 276 kg ethanol/ton fresh grain and that of sugarbeet to ethanol 100 l ethanol/ton fresh beets (Kavalov 2004). Lower heating values of ethanol (26.72 MJ/kg) and biodiesel (39.20 MJ/kg) were derived from Elsayed (2003).

both study countries. For wheat, the energy balance was negative, hence the energy ratio was less than than one. For converting wheat into ethanol, Malça and Freire (2006) and Richards (2000) assumed an energy consumption of some 20.5 GJ/ton ethanol. However, according to (Punter et al. 2004), there is consensus among several studies that for a new plant, only 10.7 GJ/t EtOH is needed. Under the former assumption, production of wheat ethanol result in a net energy loss while with more modern facilities, production of ethanol from wheat is energetically worthwhile. The latter case is considered in the remainder of our analyses.

The (agro-) environment

Soil erosion

Sugar beet production can lead to soil erosion, especially if the crop is grown on lighter soils (Edwards et al. 2007), mainly because of the fact that it takes a relatively long period to give adequate soil cover (Riksen and De Graaff 2001). Furthermore, row crops are considered to be crops of high erosion potential unless grown using soil conservation techniques (Fiene and Auerswald 2007) and in wet areas, the heavy machinery used for harvesting sugar beet can cause soil compaction (Edwards et al. 2007). In certain countries, conservation tillage seems to gain ground as a method to control erosion: currently it is applied to about 25% of the German sugar beet area (Märländer et al. 2003). This practice is characterized by among others precision drilling of the seed, which circumvents the need for ploughing, and by covering the soil surface with mulch (Märländer et al. 2003). However, during harvest, soil disturbance remains inevitable. After harvest, generally, the planting of winter cover crops is another option for reducing erosion after sugar beet..

Compared with row crops, soil under small grain crops is considered to be less prone to erosion (Fiene and Auerswald 2007). However, under winter wheat, soil cover is incomplete during a relatively long period, subjecting the soil to the impact of rainfall. As with the other crops discussed here, conservation tillage may contribute to reduction of erosion rates under wheat.

Rapeseed, especially winter rapeseed, keeps the soil covered for more than 11 months per year, preventing nutrients from being washed away and improving the condition of the ground (Scharmer 2001). Members of the Brassicaceae, including yellow and white mustards (e.g. *Sinapis alba* L.), canola (*Brassica napus* L.) and rapeseed (also *B. napus* L.), are used increasingly as cover crops in temperate regions of North America (Haramoto and Gallandt 2004): winter varieties of rapeseed and canola can provide more than 80% ground cover during the winter, an important consideration for erosion control (Haramoto and Gallandt 2004).

Soil organic matter

Sugar beet leaves are often left on the field; a rough estimate is that under good production practices in Western Europe up to 5 ton dry matter/ha may be produced. Due to their relatively high nitrogen content, sugar beet leaves decompose easily; decomposition rates of beet tops are generally slower. Beet tops possess much higher C/N ratios than leaves and are therefore even capable of immobilizing nitrogen from the soil (De Ruijter and Smit 2007). They are normally left in the field due to their negative effect on sugar extraction efficiency. (De Ruijter and Smit 2007) estimated the quantity of effective organic matter from sugar beet residues to be 960 kg/ha. The balance between addition and decomposition of organic matter is strongly influenced by cultivation practices: in sugarbeet, conservation tillage is an option for enhancing soil structure and the build-up of organic matter.

With a yield of some 8 tons of fresh wheat grain per hectare, a similar quantity of straw is produced[1] which, depending on the circumstances can be left in the field and ploughed back or be used either for various agricultural purposes or as a source of energy (Punter et al. 2004). The increasing importance of the biofuel industry may increase the value of straw, especially for use as fuel for boilers in conversion facilities. According to (Richards 2000) straw represents a useful energy source when produced within a 50 km radius of a heat or electricity plant[2]. The value of straw as a soil improving agent should not be neglected however: assessing maximum quantities of straw that may be removed while still maintaining soil quality may contribute to the sustainability of biofuel production chains, see e.g. Lal (2005). Reduced tillage may further contribute to maintenance of sufficiently high levels of soil organic matter.

[1] Assuming a harvest index of 0.50
[2] With the present oil prices, this distance has probably increased

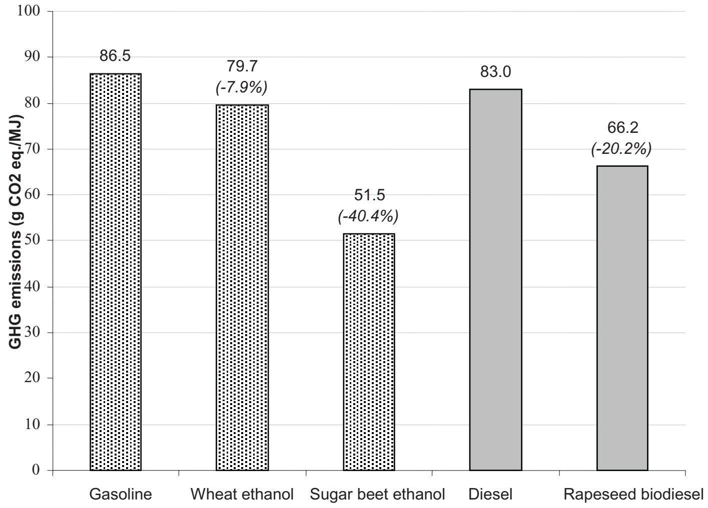

Figure 1. GHG emissions of the biofuels considered in this paper compared to those of the fossil fuel which they may replace

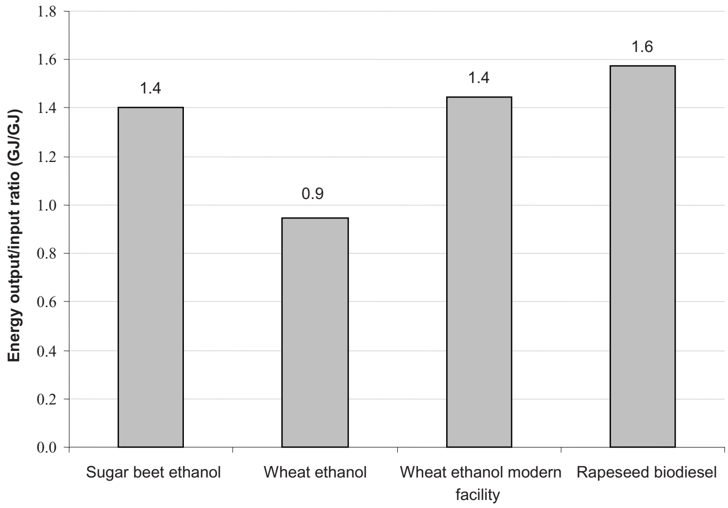

Figure 2. Energy output/input ratios for the biofuel production systems under consideration

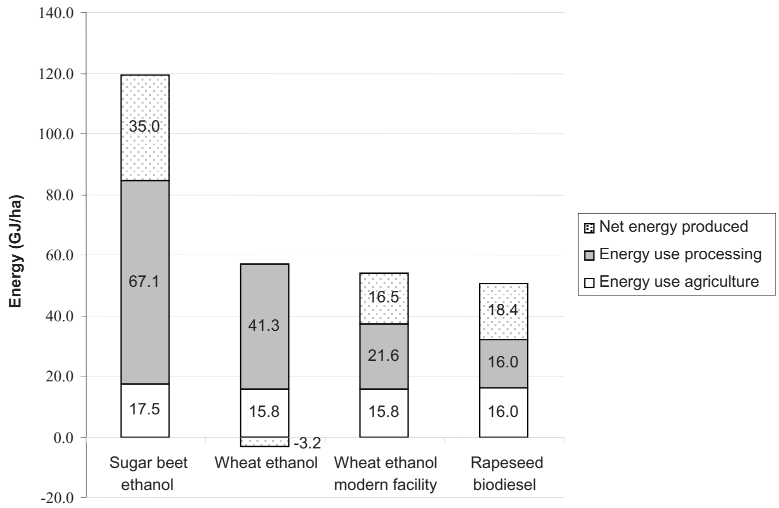

Figure 3. Energy balances for the biofuel production systems under consideration

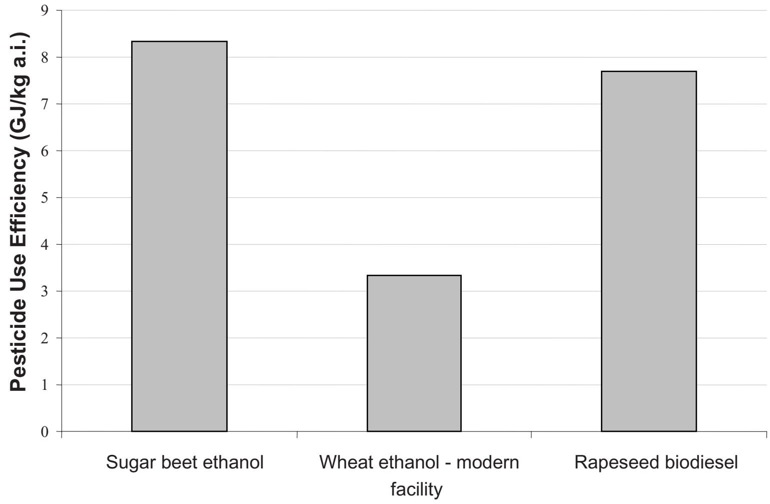

Figure 4. Nitrogen use efficiencies for the biofuel production systems under consideration

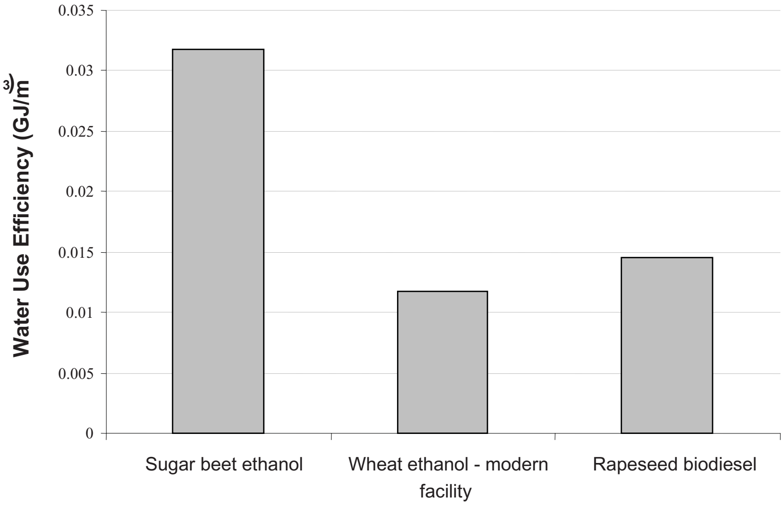

Figure 5 Pesticide use efficiencies for the biofuel production systems under consideration

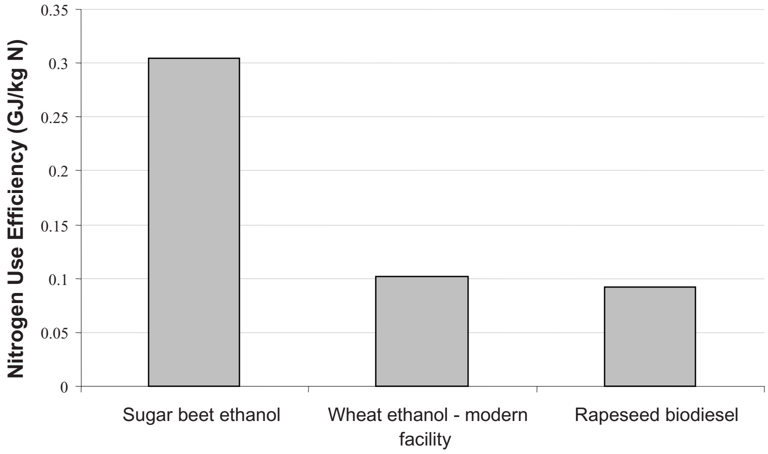

Figure 6. Water use efficiencies for the biofuel production systems under consideration

Mattsson et al. (2000) report that in Sweden, rapeseed cultivation had no discernible effect on soil organic matter. Much depends however on whether conservation tillage practices are used and on the fate of the straw. Richards (2000) mentions that using the straw as fuel improves the energy balance of the rapeseed biofuel production chain without considering its value as a soil improving agent. After extraction of the oil, rapemeal may be used as a fertilizer (Richards 2000): compared with the usage of mineral fertilizers its application will enhance the build-up of organic matter. However, rapemeal is also an economically valuable animal feed. The intense root system of rapeseed plants may be another asset in preserving soil structure and organic matter.

Risk of soil borne diseases

Two important problems of concern for sugarbeet production are the beet cyst nematode (*Heterodera schachtii*) and rhizomania (Märländer et al. 2003). The latter disease results from a pathogen complex consisting of the beet necrotic yellow vein (BNYV) virus and the soil-borne fungus *Polymyxa betae* as a vector; it causes substantial reductions in yield and quality of sugar beet crops. The strong persistence of *Polymyxa betae* is responsible for a long-lasting infectious potential in any infested field. Rhizomania occurs on more than 50 % of the sugar beet area in Germany, and the disease is spreading. Breeding for resistance is the only way to control yield and quality losses caused by rhizomania (Märländer et al. 2003). The beet cyst nematode is common, and populations develop particularly well in crop rotations that include beet at least every third year or more. Other crops such as oilseed rape, fodder beet, and certain weeds are host plants that enable nematode populations to develop rapidly (Märländer et al. 2003). Therefore, oilseed rape is not normally grown in rotation with sugarbeet.

Apart from the abovementioned, rapeseed is also affected by a number of other diseases. The crop is mostly grown in rotation with cereals (Christen et al. 1999); in such rotations, rapeseed has a positive effect due to a break in the disease cycle for a number of cereal pathogens (e.g. *Gaeumannomyces graminis*) and also because of its favorable effect on soil structure (Christen et al. 1999). There are small areas in Schleswig-Holstein as well as in the northern parts of Niedersachsen (Lower Saxonie) with serious rotational problems for oilseed rape production due to occurrence of clubroot (*Plasmodiophora brassicae*). In these areas, oilseed rape has been grown for extended periods every second year or continuously for a number of years. However, pest and disease problems are not regarded as a major constraint on rapeseed production (Christen et al. 1999). Rising demand for biodiesel could evoke increases in the share of rapeseed in crop rotations, potentially creating problems in the future.

Wheat is less prone to soil borne diseases with long-lasting infectious potential than sugar beet or rapeseed. Nevertheless, it is recommended to use crop rotations with a minimum of two years between wheat crops (a 1:3 rotation), mainly to minimize the degree of fungal carryover from one wheat crop to the next.

Eutrophication

Average nitrogen fertilization rates in sugar beet do not differ much across different European countries. Rates range from 105 kg N/ha in Great Britain (Tzilivakis et al. 2005a), to 122 kg N/ha in France (Malça and Freire 2006), with intermediate values of 111 kg N/ha in the Netherlands (De Koeijer et al. 2002) and 120 kg N /ha in Germany (Kuesters and Lammel 1999).

Concerning rapeseed, only winter oilseed rape is considered here. In Germany, common practice is application of 180 kg N/ha (Sauermann and Gronow 2007).

Wheat cultivation in the UK requires some 185 (Punter et al. 2004) to 195 kg N/ha (Richards 2000); Kuesters (1999) mention 160 kg N/ha to be the average amount of N applied in Germany. We assumed application of 180 kg N/ha.

Nitrogen use efficiencies for our three biofuel production systems were calculated on the basis of these fertiliser application figures and earlier calculated net energy production: results are presented in Figure 4.

Pesticide usage

Estimates of pesticide usage in sugar beet cultivation widely differ between the literature sources that we reviewed. We decided to rely on data from two experimental farms of Wageningen University and Research Center (WUR) in the Netherlands (pers. comm.). At these farms good production practices are standard. Averaged over both farms and over the years 2005-2007, pesticide applications were 4.2 kg active ingredient (a.i.) per hectare

For rapeseed, Elsayed (2003) gives a figure for average combined application of herbicides and fungicides in the UK of 2.8 kg/ha. Richards (2000) give a figure of 1.8 kg a.i./ha for UK conditions. We assume an average application of 2.3 kg a.i./ha.

Pesticide usage in wheat in the UK is 5.5 kg a.i./ha on average, according to Richards (2000); Webster (1999) give detailed applications data by type of biocide for the UK from 1982-1996. From their data, we calculate an average over the years 1990-1996 of 4.8 kg a.i./ha. We assume total pesticide applications of 5.2 kg a.i./ha.

Pesticide application data and earlier calculated net energy production were combined to calculate pesticide use efficiencies for our three biofuel production systems: results are presented in Figure 5.

Water use

Virtual water content data have been derived from Chapagain (2004). For sugarbeet, the report lists values of 77 (Germany), 65 (the Netherlands) and 56 m^3/ton product (UK). Assuming a conversion efficiency of 100 litre ethanol per ton of fresh sugar beet (Kavalov 2004) and an LHV of ethanol of 21.1 MJ/l, we found WUE of sugar beet ethanol to range from 0.03 - 0.04 GJ/m^3.

For wheat, virtual water contents are 757 (Germany), 619 (Netherlands) and 501 m^3/ton (UK). With a conversion efficiency of 276 kg ethanol per ton of fresh grain (Richards 2000) and ethanol's lower heating value (LHV) of 26.8 MJ/kg, the WUE of wheat ethanol energy is around 0.01 GJ/m^3.

Rapeseed's virtual water content is 1128 m^3/ton in Germany, 1182 in the Netherlands and 876 for the UK. With an average oil content of 40% (Scharmer 2001) and biodiesel's LHV of 37.3 MJ/kg, the virtual water content of rapeseed biodiesel energy ranges from 0.01 (NL) to 0.02 GJ/m^3 (UK).

Averages of the above calculated upper and lower virtual water content are displayed in Figure 6.

Land use efficiency

Net energy yields for the three biofuel production systems are displayed in Figure 3.

Discussion and conclusion

Since the list of indicators that we employed in this work is not exhaustive, we cannot draw definite conclusions on the comparative sustainability producing biofuels from sugar beet, rapeseed and wheat. However, comparing the three production systems based on a limited set of criteria is possible.

With respect to reducing GHG emissions, sugar beet is the most effective biofuel crop (40% reduction), followed by rapeseed (20%) and wheat (8%). But from the examples that we analyzed, it became apparent that actual GHG reductions strongly depend on locality and state of the technology. Therefore, if one wants to make general assertions on reductions in GHG emissions through different biofuel production chains, data on a sufficiently large and representative sample of production locations should be collected and averaged. The same applies to the calculation of energy balances, or the energy output/input ratio. For this indicator, our results were 1.4, 1.6 and 1.4 for sugar beet, rapeseed and wheat, respectively. This does not correspond very well with figures for reductions in GHG emissions which could be due to the fact that calculations are based on different references. The risk of soil erosion seems at first sight more serious under sugar beet than under wheat and rapeseed. However, due to its growing period, planting a winter cover crop after sugar beet is still possible, while under winter wheat, soil cover remains incomplete during the whole winter period. Erosion risk also depends strongly on topography and cultivation practices. For example, conservation tillage may contribute to the reduction of erosion under all crops discussed here. Without specific data on crop and residue management, it proved difficult to make general remarks on the soil's organic matter balance under the different biofuel crops. Moreover, in practice, much also depends on the other crops in a rotation. All crops analysed probably produce enough residues to maintain an acceptable soil organic matter content, but this also depends on tillage practices and the economic value of the residues. Soil borne diseases are of significant economic importance in sugar beet cultivation. For the other two crops this seems much less the case although rapeseed is more affected than wheat. Nitrogen, pesticides and water are most efficiently employed in sugar beet although for pesticides, the difference with rapeseed is small. Wheat was the worst performing crop with respect to nitrogen and pesticide use efficiency. Pesticide and fertilizer usage in this crop are relatively high, while the net energy per hectare is rather low, even though we assumed conversion into ethanol took place in state-of-the-art facilities. With respect to land use efficiency or net energy yield, sugar beet performed best, followed by wheat. Winter rapeseed did not score well but is a valuable break crop in cereal rotations.

Finally, it became apparent that all considered production systems offer several opportunities for improving sustainability compared to current practices.

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