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Agricultural crop-based biofuels – resource efficiency and environmental performance including direct land use changes

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ABSTRACT

This paper analyses biofuels from agricultural crops in northern Europe regarding area and energy efficiency, greenhouse gases and eutrophication. The overall findings are that direct land use changes have a significant impact on GHG balances and eutrophication for all biofuels, the choice of calculation methods when by-products are included affecting the performance of food crop-based biofuels considerably, and the technical design of production systems may in specific cases be of major importance. The presented results are essential knowledge for the development of certification systems. Indirect land use changes are recognised but not included due to current scientific and methodological deficiencies.

1. Introduction

Today, there are strong incentives to encourage an increased use of renewable fuels in the transport sector worldwide. Incentives exist within energy-, climate- and agricultural policies in several countries to promote further progress in the use of biofuels (see e.g. (European Commission, 2007)). Another possibility is to utilise biomass-based liquid and gaseous products as feedstock in the chemical industry, where the current use of renewable feedstock is almost insignificant due to weak political incentives. However, there is an emerging interest also in this industry to replace fossil feedstock by biomass-based raw materials. In the development of the 12 principles of Green Chemistry (Anastas and Warner, 1998), the replacement of fossil feedstock by renewable feedstock represents one important principle.

The benefits of introducing biofuels in the transport sector, or as feedstock in the chemical industry, are widely debated today. Several analyses have been published in recent years often presenting contradictory results, e.g. regarding greenhouse gas (GHG) reductions, energy efficiency, impact on biodiversity, water pollution and water depletion (see e.g. Kendall and Chang, 2009; Hill, 2007; Kim and Dale, 2009; Pimentel and Patzek, 2005; Bridgewater, 2006; Sims et al., 2006; Reijnders and Huijbregts, 2008; Gerbens-Leenes et al., 2009; Searchinger et al., 2008; Fargione et al., 2008; Concawe et al., 2007; Bernesson et al., 2006; Gallagher, 2008; Petersen et al., 2007). Other important sustainability criteria are those related to socio-economic aspects, especially concerning biofuel production in developing countries. Studies including these aspects also often present diverging conclusions, from scenarios in which developing countries gain beneficial opportunities to their being exposed to significant disadvantages (e.g. Gallagher, 2008; Bekunda et al., 2009; Woods, 2006; Hazell and Wood, 2008; Börjesson et al., 2008).

There are several explanations for the contradictory results regarding the sustainability of biofuels. For example, the variations in the GHG performance of biofuels are often due to differences in local conditions and the design of the specific production systems, and/or different calculation methods and systems boundaries. Critical factors in, for instance, grain-based ethanol production are i) what kind of land is used for cultivation and the alternative land use, ii) the efficiency in nitrogen fertilisation and how the fertilisers are produced, iii) whether the biofuel plant uses fossil fuels or biomass, and iv) how efficiently by-products are utilised. Depending on these factors, bioethanol could be everything from good to bad from a GHG point of view (Kendall and Chang, 2009; Börjesson, 2009; Menichetti and Otto, 2009).

Land use change due to biofuel production can occur in two ways, (i) directly, when uncultivated land, pasture etc is converted

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to produce energy crops (e.g. grassland is used instead to cultivate cereals for bioethanol), or (ii) indirectly, through displacement of food and feed crop production to new land areas previously not used for cultivation. From a life cycle assessment (LCA) perspective, direct land use changes is often straightforward and easy to include in the assessment (see e.g. Reijnders and Huijbregts, 2008), although there are often uncertainties in the levels of carbon stock changes due to variations in local conditions and lack of reliable field trial data. Two reviews of previous LCAs of biofuels show that only a few studies have take into account direct land use impacts driven by biofuel crop production and defined an alternative land use reference system (Kendall and Chang, 2009; Menichetti and Otto, 2009). Furthermore, several studies exclude biogenic, soil-derived emissions of nitrous gas (N_2O), induced by nitrogen fertilisation. Depending on which land use reference system is chosen, the emission of biogenic CO_2 and N_2O will have a significant impact on the GHG balances of biofuels.

The issue of nitrous oxide emissions during the cultivation of biofuel feedstock crops has been discussed intensively in the research community over recent years. Today, several methods to calculate biogenic N_2O emissions are available, all giving different results (Kendall and Chang, 2009). One of the most utilised is the method developed by IPCC (2006), which is based on the assumption of a linear relationship between the input of nitrogen and N_2O emissions, also including mineralisation of crop residues and indirect emissions from nitrogen leaching and ammonia losses. However, the level of biogenic N_2O emissions from the soil is inherently uncertain, since these levels are influenced by a large number of local parameters (Bernesson et al., 2006; Bouwman et al., 2002; Nevison et al., 1996). Some models therefore attempted to utilise more local environmental and field management parameters, not utilising a linear emission factor but site-specific factors (Concawe et al., 2007; Kim and Dale, 2005). Contrary to these detailed bottom-up approaches, Crutzen et al. (2007) have suggested a top-down approach which shows much higher biogenic N_2O emissions in the cultivation of biofuel crops, leading to no GHG benefits when fossil vehicle fuels are replaced. However, this top-down calculation method has been seriously questioned and is not regarded as relevant to utilise in LCAs of biofuels (Gallagher, 2008; Rauh, 2007; Ammann et al., 2007).

The importance of indirect land use changes has been investigated in some recent studies (see, Searchinger et al., 2008; Fargione et al., 2008; Gallagher, 2008), which conclude that potential displacement of food and feed production may completely offset the potential reduction of GHG emissions of biofuels. However, assessment of potential indirect land use change and its GHG implications is a very complex and contentious issue (Gallagher, 2008; Ravindranath et al., 2009). Some argue that indirect land use changes should be included in LCAs, which require an extension of the scope including cross-sector issues, whereas others argue that this issue is far too complex, as it includes considerable uncertainties and thus has to be assessed by complementary tools (e.g. global agro-economical models) (Kim and Dale, 2009; Börjesson, 2009). Börjesson et al. (2008) for example, conclude that it is impossible to ascertain the sustainability of biofuels without at the same time taking the scale and pace of growth into consideration. A suitable pace of growth could lead to an increase in biofuel potential and simultaneously have a low risk of negative displacement effects by (i) enhanced agricultural development leading to increased productivity within existing cropland, (ii) increased utilisation of wastes and crop residues (as well as by-products in biofuel production), and (iii) expansion of dedicated energy crop cultivation on unused and new cropland of low competition ("marginal lands" currently producing no or little food, having low biodiversity and low carbon stock but capable of producing abundant crops without representing competition for freshwater in water-scarce areas) (Ravindranath et al., 2009; Bustamante et al., 2009).

Thus, a conclusion is that indirect land use changes have to be recognised in conjunction with the expansion of biofuel production, but there is no reliable, scientific methodology available today to include these aspects in LCAs (see also Kim and Dale, 2009). The increased utilisation of biomass feedstock for the production of biofuels and green chemicals, together with the anticipated increase in the worldwide demand for food and feed, will put pressure on arable land. Consequently, when developing production systems for biofuels and green chemicals it is becoming increasingly important to evaluate factors such as area efficiency, which is the amount of biofuels/feedstock produced from crops harvested from a certain area. This factor could easily be included in LCAs of biofuels and thereby indirectly evaluate the differences between biofuel production systems concerning potential risks of displacement effects.

A study by Rockström et al. (2009) has concluded that the "planetary boundaries" have been exceeded for three of nine "planetary systems". These three systems are i) the rate of biodiversity loss, ii) climate change, and iii) human interference with the nitrogen cycle. Much of the environmental concern related to biofuels focuses on GHG emissions today, but changes in land use and cropping systems may also have serious implications for eutrophication (Simpson et al., 2008, 2009; Donner and Kucharik, 2008). According to Galloway et al. (Galloway et al., 2003), agro-ecosystems receive 75% of the reactive nitrogen created by human activities, leading to benefits such as improved productivity in agriculture, but also to negative effects in the form of eutrophication and global warming. Previous systems analyses of crops used as feedstock for biofuels and green chemicals often conclude that, together with GHG emissions, eutrophication is a critical environmental aspect which should be included when direct land use changes are assessed (Börjesson and Berglund, 2007; Tufvesson and Börjesson, 2008).

Depending on which type of land is used for the production of biofuel crops, the impact on biodiversity could be anything from minor to major. Examples of major effects are when natural forest areas are cleared and utilised for biofuel production (Osvaldo et al., 2009). Considering biofuel production in northern Europe on existing farmland, the cultivation of perennial crops instead of annual crops may potentially lead to some minor local and specific benefits in biodiversity (Börjesson, 1999). However, considering the overall biodiversity in a larger region, including different ecosystems, the impact is often insignificant.

Several biofuel production systems generate by-products and, depending on the methods used in the treatment of these by-products in LCAs, the results may vary significantly (Kendall and Chang, 2009; Bernesson et al., 2004, 2006; Börjesson, 2009; Menichetti and Otto, 2009). The most common methods used in previous LCAs are system expansion, energy allocation and economic allocation (Kendall and Chang, 2009; Menichetti and Otto, 2009). According to the ISO 140 44-standard of LCA (ISO, 2006), by-products should be included by system expansion when possible. System expansion is utilised, for example, in the well-to-wheels study conducted by Concawe et al. (2007), but the method has some limitations (Tillman, 2000; Finnveden and Ekvall, 1998). Examples are when no reliable life cycle inventory data exist for the alternate product, when several potential replacements exist and it is not possible to define the most realistic alternate product, or when the market for the most realistic replacement is restricted. Thus, the calculations using system expansion should be coupled to a specified amount of biofuels produced.

Where allocation cannot be avoided, this should be based on physical or economic criteria (ISO, 2006). An advantage of physical allocation, compared to economic allocation, is that physical allocation is based on data which are constant over time, such as the energy content of the various products. Economic allocation, however, is based on data which change over time, such as the price of by-products for animal feed which follows the world market price of grain and other animal feed components. One advantage of economic allocation, compared to physical allocation, is that the results may be more rational in systems by which large quantities of by-products with low economic value are produced. One example is in ethanol production from grain where the energy yield in the form of straw exceeds the energy yield in the form of ethanol, but where the economic value of straw is estimated to be equivalent to 10–15% of the economic value of ethanol (Börjesson, 2009). To conclude, these different methods of by-product treatment in LCA are more or less relevant for use under specific circumstances, which motivates that all three methods are included in LCA calculations.

In this paper, biofuels (and feedstock for green chemicals) from crops are analysed and compared from a life cycle perspective, including the parameters area and energy efficiency, GHG emissions and eutrophication. The overall aim is to show the importance of (i) including direct land use changes and defining an alternative land use reference system, (ii) defining the technical status and design of the biofuel production systems, and (iii) the choice of calculation methods when by-products generated during cultivation and processing are included. This focus is based on the general findings in the literature referred to above concerning some limitations of previous LCAs and the most critical parameters to be assessed under current conditions.

2. Methodology and assumptions

The crops and conversion routes analysed are shown in Table 1. The production is assumed to take place in northern Europe with current cultivation practices and state-of-the-art technologies concerning biofuel conversion processes. Concerning new conversion technologies for lignocellulosic feedstock, the technical performance is estimated to represent potential commercial plants under current conditions, making the comparison between the first and second generation of biofuels as appropriate as possible. The conversion processes are here considered as single production routes for which the output of the specific biofuel is maximised. Potential multi-output production processes in bio-refineries, for example, are discussed in the sensitivity analysis. The crop yields are based on average yields in southwest Sweden, which are assumed to represent average yields in northern Europe (Ericsson and Nilsson, 2006). Production conditions regarding field management practices, climate, soil properties, precipitation etc are comparable for all crops included in the analysis.

The study follows the principles of the LCA described in the ISO standard 140 44 (ISO, 2006). Two alternative land use reference systems are included in the analysis, (i) unfertilised grassland (representing existing farmland currently not utilised, e.g. fallow land), and (ii) wheat production without straw recovery (representing a common cultivation system today). The cultivation is assumed to take place on mineral soils, but the effects on the GHG balance of direct land use changes on cultivated peat soils is discussed in the sensitivity analysis. Indirect land use changes are not included in the assessment (see the motivation for this exclusion in Section 1). The treatment of by-products includes three different methods, system expansion, energy allocation and economic allocation.

The calculations of energy inputs are based on primary energy inputs; that is, all energy flows are calculated as unconverted and untransformed natural resources. The energy input in cultivation includes diesel fuel, commercial fertilisers, seed, pesticides, the manufacture and maintenance of field machinery, field transport etc. In the conversion processes, the energy input in the form of heat, steam and electricity, as well as all transportation operations concerned with feedstock and by-products, are included. The energy embodied in farm buildings, roads and conversion plants is considered to be negligible compared to the net energy flows in the production systems, and is therefore not included (Berglund and Börjesson, 2006). Based on current commercial practices in Sweden, the primary energy source in biomass conversion plants (generating heat, steam and electricity) is here assumed to be solid biofuels, such as forest fuels or by-products from crop cultivation or conversion processes (e.g. straw, lignin etc). The effects of using fossil fuels instead of biomass is analysed in the sensitivity analysis.

The calculation of life cycle emissions of GHGs includes carbon dioxide (CO_2) of fossil origin (and soil carbon), methane (CH_4) and nitrous oxide (N_2O). The emissions originate from both energy conversion (including spontaneous emissions from conversion processes, e.g. emissions of CH_4 from biogas production and N_2O from fertiliser production plants) and biogenic processes in the soil (causing N_2O and CO_2 emissions). The biogenic emission of N_2O is calculated using the model presented by IPCC (2006). Expressed as global warming potential (GWP), 1 g of CH_4 and 1 g of N_2O is taken to be equivalent to 25 g and 298 g CO_2-equivalents, respectively IPCC (2006).

The contributions to the eutrophication potential (EP) include leaching of nutrients (phosphates, PO_4^{3-}, and nitrate, NO_3^-) to water and emissions of ammonia (NH_3) to the air from cultivation, and emissions of nitrogen oxides (NO_x) from energy conversion.

Table 1
The crops and conversion routes included in the analysis.

No.	Crop	Conversion process	Chemical compound	By-products from	
				cultivation	conversion process
1	Wheat	Fermentation	Ethanol	Straw	Distiller's waste
2		Anaerobic digestion	Methane	Straw	Digestate
3	Sugar beet	Fermentation	Ethanol	Tops and leaves	Pulp
4		Anaerobic digestion	Methane	Tops and leaves	Digestate
5	Rape-seed	Extraction & esterification	Rape methyl ester (RME)	Straw	Rapeseed meal & glycerol
6	Ley crops	Anaerobic digestion	Methane	–	Digestate
7	Maize	Anaerobic digestion	Methane	–	Digestate
8	Willow	Hydrolysis & fermentation	Ethanol	–	Lignin
9		Thermal gasification	Fischer-Tropsch liquids	–	–[a]
10		Thermal gasification	Methanol / Di-methyl ether (DME)	–	–[a]
11		Thermal gasification	Methane	–	–[a]

[a] A small amount of wood ash is produced but is neglected here.

Expressed as EP, 1 g of NO_3^-, 1 g of NH_3 and 1 g of NO_2 are taken to be equivalent to 0.10, 0.35 and 0.13 g PO_4^{3-}-equivalents, respectively (Baumann and Tillman, 2004).

3. Cultivation of crops

3.1. Energy and area efficiency

The energy output:input ratio for the different cultivation systems is estimated to vary between 5 (rapeseed) and 24 (willow) (Table 2).

3.2. Greenhouse gases

The biogenic emissions of GHGs are estimated to be roughly twice as high as the emissions from technical conversion processes concerning annual crops and unfertilised grassland as land use reference, and approximately equal for the case of perennial crops (Table 3). Regarding wheat cultivation as land use reference, perennial crops will have an overall negative GHG balance. The changes in soil carbon content are affected mainly by a combination of the input of crop residues and the frequency of soil tillage, which is obviously significantly reduced when perennial crops are grown. The reduced soil carbon accumulation when crop residues are harvested is counteracted by reduced N_2O emissions from the residues.

3.3. Eutrophication

The contributions to the EP are completely dominated by biogenic emissions when unfertilised grassland is used as land use reference (Table 4). Harvesting tops and leaves in sugar beet cultivation is estimated to reduce the risk of nutrient leaching, due to the high content of nitrogen in this crop residue (Börjesson and Berglund, 2007). Harvesting straw in cereal and oil seed cultivation, however, is estimated to have an insignificant overall impact on the nutrient leaching. The harvest of straw leads to a minor output of nitrogen, leading to a somewhat reduced risk of nitrogen leaching, but this is counteracted by the output of potential soil carbon from the straw which could help to bind the nitrogen released in microbiological processes and soil biomass.

4. Conversion into chemical compounds

4.1. Energy performance

The conversion efficiency, expressed as the energy content of the biofuel produced divided by the initial energy content of the biomass of the feedstock crop, is here estimated to vary from 36% (ethanol from willow) up to 72% (biogas from sugar beet) (Table 5). The input of external energy into the conversion processes, expressed as a percentage of the biofuel output, varies between 2% (liquid fuels from willow by thermal gasification) and 54% (ethanol from wheat).

4.2. Environmental impact

Carbon dioxide is the dominating GHG in the conversion processes, with the exception of the case for biogas in which methane is estimated to be of equal importance (Table 6). Uncontrolled losses of methane from the production, upgrading and pressurisation of biogas may, however, differ significantly due to variations in the technology used (Börjesson and Berglund, 2006), which is discussed in the sensitivity analysis.

4.3. Generation of by-products

In Table 7, data on the physical and economic allocation used in this analysis are shown. When system expansion is applied, the by-products in the production of ethanol from grain, i.e. DDGS

Table 2
Biomass yields and energy inputs for different crop cultivation systems.

Crop	Biomass yield[a]		Energy input[b] (GJ ha^{-1}, yr^{-1})				Energy balance
	Ton dry matter ha^{-1}, yr^{-1}	GJ ha^{-1}, yr^{-1}	Diesel fuel	Fertilisers	Other	Total	Energy output/input ratio
Wheat	6.4 (4.2–8.6)	120	3.9	7.4	3.9	15.2	7.7
Wheat incl. straw[c]	10.7 (7.0–14.4)	200	5.6	7.4	4.2	17.2	11.3
Sugar beet	11.0 (7.2–14.9)	190	12.8	6.1	1.9	20.8	9.3
Sugar beet incl. tops & leaves[c]	13.5 (8.8–18.2)	240	14.3	6.1	2.1	22.5	10.5
Rapeseed	2.8 (1.8–3.8)	80	4.4	7.2	2.8	14.4	5.4
Rapeseed incl. straw[c]	6.1 (4.0–8.3)	140	5.9	7.2	3.0	16.1	8.7
Ley crops[d]	7.5 (4.9–10.1)	130	5.2	4.0	1.5	10.7	12.3
Maize (whole crop)[e]	9.5 (6.2–12.8)	170	5.9	7.8	1.9	15.6	10.7
Willow[f]	9.5 (6.2–12.8)	180	2.9	4.0	0.6	7.5	24.0

[a] Biomass yields of conventional food and feed crops are based on official statistics (Börjesson, 2007), and of willow on Ericsson and Nilsson (2006). Harvest yields of crop residues are based on Börjesson (2007). The estimated interval of average biomass yields in northern Europe is given within parentheses (approximately +/−35%, based on Ericsson and Nilsson (2006)). The higher heating values, expressed as GJ per tonne dry matter, is for wheat, 18.4; sugar beet, 17.6; rapeseed, 27.7; ley crops and maize (whole crop), 17.6; willow, 18.7; straw (wheat and rapeseed), 17.9; tops and leaves (sugar beet), 17.6.

[b] Expressed as primary energy. Direct use of diesel fuels in field and transportation operations (the harvested biomass is assumed to be transported by truck 50 km from the farm gate to a conversion plant) is based on updated data from Börjesson (1996a), including energy efficiency improvements of, on average, 15% over the past decade, based on Cederberg and Flysjö (2008), Schmidt (2008), Törner (2008). One litre of diesel corresponds to 42.6 MJ primary energy (Berglund and Börjesson, 2006). Energy input in the production of commercial fertilisers in the form of N, P and K, expressed as MJ/kg, is 45, 25, and 5, respectively (Börjesson, 1996a; Davis and Haglund, 1999; Jenssen and Kongshaug, 2003). The amount of fertilisers supplied, expressed as kg N–P–K/ha and yr, is for wheat, 150–25–10; sugar beet, 120–20–40; rapeseed, 145–25–10 (including preceding crop value) (Cederberg and Flysjö, 2008); ley crops, 70–30–40; maize, 140–25–180; and willow 80–10–30 (Börjesson, 1996a; Johnsson and Mårtensson, 2002; Statistics Sweden, 2004). Other energy inputs include the production of seeds, pesticides, machinery and transportation vehicles, based on updated data from Börjesson (1996b), including energy efficiency improvements of, on average, 15% over the past decade. External drying of wheat and rapeseed is also included, based on Mårtensson and Svensson (2009).

[c] About 60% of the total amount of straw is harvested in wheat and rapeseed cultivation, and 50% of the tops and leaves in sugar beet cultivation, based on ecological considerations (maintaining the soil carbon content) and practical aspects (harvest losses).

[d] Clover-grass ley.

[e] Whole-crop harvest.

[f] Short-rotation coppice (Salix), harvested every 4 years, over a total duration of, on average, 24 years.

Table 3
Emissions of greenhouse gases from different crop cultivation systems, expressed as kg CO_2-equivalents per GJ harvested biomass (excluding crop residues).

Crop	Biomass yield excl. crop residues ($GJ\ ha^{-1}, yr^{-1}$)	CO_2 – fossil fuels[a]	N_2O – fert. prod.[b]	Reference – unfertilised grassland		Reference – wheat cultivation		Total	
				N_2O – bio-genic[c]	CO_2 – bio-genic[d]	N_2O – bio-genic[c]	CO_2 – bio-genic[d]	Ref. grass-land	Ref. wheat cult.
Wheat	120	9.7	3.4 (1.1)	7.7	11	0	0	32	13
Wheat incl. straw		11		6.2	15	−0.9	2.8	36	16
Sugar beet	190	8.2	1.7 (0.6)	3.7	6.5	−1.0	0	20	8.9
Sugar beet incl. tops & leaves		8.8		2.5	7.4	−1.8	0.8	20	9.5
Rapeseed	80	14	5.0 (1.7)	10	16	−1.6	0	45	17
Rapeseed incl. straw		16		9.0	21	−1	2.6	51	22
Ley crops	130	6.4	1.4 (0.5)	4.6	0	−2.3	−9.5	12	−4.0
Maize (whole crop)	170	7.2	2.2 (0.7)	5.8	7.5	0.3	0	23	9.7
Willow	180	3.2	1.2 (0.4)	2.6	0	−2.5	−7.0	7.0	−5.1

[a] Life cycle emissions of CO_2 from fossil fuels used in field and transportation operations (Börjesson and Berglund, 2006; Hansson et al., 1998), in fertiliser production (Davis and Haglund, 1999; Jenssen and Kongshaug, 2003), in the production of seeds, pesticides, machinery and transportation vehicles (Börjesson and Berglund, 2006; Börjesson, 1996b), and in external drying of wheat and rapeseed (Mårtensson and Svensson, 2009)).Including a minor amount of CH_4 and N_2O emissions.

[b] Based on current fertiliser production in western Europe where approximately 50% of the plants have installed catalytic N_2O cleaning (Mårtensson and Svensson, 2009). Average emissions of N_2O with and without catalytic cleaning are equivalent to 3 and 15 g N_2O per kg N, respectively (Davis and Haglund, 1999; Jenssen and Kongshaug, 2003), giving an overall average of 9 g N_2O used in the calculations here. Figures within parentheses represent the average of N_2O emissions when all fertiliser plants have installed catalytic cleaning.

[c] Soil emissions induced by nitrogen fertilisation, nitrogen in crop residues, ammonia emissions and nitrogen leaching, calculated by the method developed by IPCC (2006). The gross N_2O emissions, expressed as kg N_2O /ha and yr, are for the cultivation of wheat, 3.6 (3.0 incl. straw harvest); sugar beet, 3.0 (2.1 incl. harvest of tops and leaves); rapeseed, 3.1 (2.8 incl. straw harvest); ley crops, 2.5; maize, 3.7; and willow 2.1. Background emissions from unfertilised grassland is estimated to be, on average, 0.5 kg N_2O /ha and yr (Ahlgren et al., 2009).

[d] Cultivation takes place on mineral soils. The net losses of soil carbon, compared with unfertilised grassland, are estimated to be, expressed as kg C /ha and yr: for cultivation of wheat, 350 (500 incl. straw harvest); sugar beet, 350 (450 incl. harvest of tops and leaves); rapeseed, 350 (450 incl. straw harvest); ley crops, 0; maize, 350; and willow 0, based on (Börjesson, 1999). These changes are estimated to continue over a period of about 30–50 years, after which the soil carbon level will have reached a new steady state.

(Distiller's Dried Grain with Solubles), and from sugar beet, i.e. beet pulp, and from RME production, i.e. rapeseed meal, are assumed to be used as animal feed, replacing imported soy bean meal and grain, based on the current situation (Börjesson, 2007; Emanuelsson et al., 2006). Previous estimates show that ethanol from grain equivalent to about 5–10% of the current use of petrol for road transport in Sweden and in EU could be produced before the protein feed market is saturated by DDGS (Concawe et al., 2007; Börjesson, 2007).

Based on the protein content of the by-products and their relevance as food components, 1 kg dry DDGS is estimated to be equivalent to 0.6 kg dry soy bean meal and 0.4 kg dry barley (Concawe et al., 2007; Bertilsson, 2008). One kg dry sugar beet pulp is estimated to correspond to 1 kg dry barley (Concawe et al., 2007), and 1 kg dry rapeseed meal to 0.85 kg dry soy bean meal and 0.15 kg dry barley (Cederberg and Flysjö, 2008; Emanuelsson et al., 2006; Bertilsson, 2008). One kg dry soy meal is estimated to correspond to 9.3 MJ energy input, 980 g CO_2-equivalents, and 5.8 g PO_4^{3-} equivalents (Flysjö et al., 2008).

The glycerine generated in RME production (equivalent to less than one tenth of the amount of rapeseed meal produced, Bernesson et al., 2004), is assumed to be used in the chemical industry, replacing both fossil and renewable feedstock in equal parts. This assumption is based on the current situation with a partial overproduction of bio-based glycerine, due to the global increase of RME production (Mårtensson and Svensson, 2009).

Table 4
Emissions of compounds contributing to the eutrophication potential from different crop cultivation systems, expressed as g PO_4^{3-}-equivalents per GJ harvested wheat biomass (excluding crop residues).

Crop	Biomass yield excl. crop residues ($GJ\ ha^{-1}, yr^{-1}$)	NO_x emissions – fossil fuels[a]	NO_3^- leaching[b]		PO_4^{3-} leaching[c]		Total	
			Ref. grass-land	Ref. wheat cult.	Ref. grass-land	Ref. wheat cult.	Ref. grass-land	Ref. wheat cult.
Wheat	*120*	5.7	110	0	10	0	130	5.7
Wheat incl. straw		7.2	110	0	10	0	130	7.2
Sugar beet	*190*	8.0	46	−23	6.3	0	60	−15
Sugar beet incl. tops & leaves		8.8	23	−46	6.3	0	38	−37
Rapeseed	*80*	9.1	230	57	16	0	260	66
Rapeseed incl. straw		11.1	230	57	16	0	260	68
Ley crops	*130*	5.4	17	−83	4.6	−5	27	−83
Maize (whole crop)	*170*	5.4	66	−13	7.3	0	79	−7.6
Willow	*180*	2.4	25	−50	3.4	−3	31	−51

[a] Life cycle missions of NO_x from fossil fuels used in field and transportation operations (Börjesson and Berglund, 2006; Hansson et al., 1998), in fertiliser production (Davis and Haglund, 1999), in the production of seeds, pesticides, machinery and transportation vehicles (Börjesson and Berglund, 2006), and in external drying of wheat and rapeseed (Mårtensson and Svensson, 2009).

[b] The gross nitrogen leaching is estimated to be, expressed as kg N per hectare per year, as follows: wheat (with and without straw harvest), 40; sugar beet, 30 (20 including harvest of tops and leaves); rapeseed (with and without straw recovery), 50; ley crops, 15; maize, 35; willow, 20. The gross nitrogen leaching from unfertilised grassland is estimated to be 10 kg N per hectare and year. Based on data from Börjesson and Berglund (2007), Börjesson (1999), Johnsson and Mårtensson (2002).

[c] The gross leaching of phosphorus is estimated to be, on average, 0.5 kg P per hectare and year in the cultivation of annual crops (Flysjö et al., 2008). The corresponding figure for perennial crops is here estimated to be, on average, 0.3 kg P per hectare and year, since the risk of soil erosion (and thereby P leaching) is lower in the cultivation of perennial crops than in the cultivation of annual crops (Börjesson, 1999). Gross leaching from unfertilised grassland is estimated to be 0.1 kg P per hectare and year.

Table 5
Estimated efficiency in the conversion of various biomass feedstock crops into chemical compounds, and the external energy needed in the processes.[a]

Crop	Chemical compound produced	Conversion efficiency[b] Energy output of biofuel/energy content in feedstock, in per cent		Input of external energy[c] Per cent of the energy output of biofuel	
		Best estimate	Interval	Best estimate	Interval
Wheat (grain)	Ethanol[d]	55	52–55	54 (13)	49–61
	Biogas[e]	68	65–70	23 (16)	20–25
Sugar beet	Ethanol[f]	55	53–55	41 (10)	36–53
	Biogas[f]	72	70–75	28 (20)	25–30
Rapeseed	RME[g]	60	41–64	15 (6)	8–22
Ley crops	Biogas[h]	62	46–72	25 (18)	20–33
Maize	Biogas[h]	68	52–78	27 (20)	25–38
Willow	Ethanol[i]	36	30–40	13 (13)	10–25
	FT-diesel[j]	45	30–46	2 (2)	1–3
	Methanol/DME[j]	58	46–59	2 (2)	1–3
	Methane[k]	65	55–70	4 (4)	2–6

[a] The "best estimate" represents the data used in the following calculations and the "interval" indicates the variation in the data found in the literature.
[b] Calculated as the energy content of the chemical compound produced divided by the initial energy content of the biomass feedstock crop (excluding crop residues in cultivation), expressed as per cent. Refers to single production routes where the output of each biofuel is maximised. The energy content, expressed as MJ per litre, is for ethanol, 21.3; RME, 33.1; FT-diesel, 34.3; methanol, 15.8 and DME, 19.0. The energy content in methane, including upgraded biogas, is 35.3 MJ/Nm^3.
[c] Calculated as the total external energy input in the conversion processes (heat, steam and/or electricity recalculated to primary energy) divided by the energy content of the chemical compound produced, expressed as per cent. Figures within parentheses represent input of electricity. Biogas production includes the refining and upgrading of the gas into natural gas quality and the energy needed to transport and spread the digestion residues.
[d] Data from Concawe et al. (2007), Bernesson et al. (2006), Mårtensson and Svensson (2009), Börjesson (2004), Fredriksson et al. (2006), Paulsson (2007). Including drying of distillers wastes and use of additives.
[e] Data from Börjesson (2004), Paulsson (2007), Edström and Nordberg (2001).
[f] Data from Concawe et al. (2007), Björnsson (2008), Linné et al. (2005). Including drying of pulp and use of additives.
[g] Data from Concawe et al. (2007), Bernesson et al. (2004), Cederberg and Flysjö (2008), Schmidt (2008), Mårtensson and Svensson (2009), Fredriksson et al. (2006). Including use of methanol in the RME process and of other additives.
[h] Data from Berglund and Börjesson (2006), Börjesson (2004), Fredriksson et al. (2006), Karpenstein Machan (2005).
[i] Data from Concawe et al. (2007), Goldschmidt (2005), Hamelinck et al. (2005), Zacchi (2008), Blinge et al. (1997). Including drying of excess lignin into fuel pellets.
[j] Data from Concawe et al. (2007), Goldschmidt (2005), Blinge et al. (1997), Hamelinck and Faaij (2002, 2006).
[k] Data from Linné et al. (2005) and Karlsson and Malm (2005).

Straw is assumed to be used for energy purposes to replace forest fuels, which are estimated to be the most realistic alternative fuel in northern Europe today (Ericsson and Nilsson, 2006). Tops and leaves from sugar beet are assumed to be used for biogas production. The by-product in ethanol production from lignocellulose (willow), i.e. lignin, is assumed to be dried and used as fuel pellets, replacing wood pellets produced from fresh woody biomass. Today, dry by-products from saw mills (sawdust etc) are fully utilised for pellet production and other applications, thus an expanded pellet production normally requires new, undried biomass resources (Börjesson, 2007). All of these by-products used for energy purposes are estimated to have a significant potential for increase before the markets are saturated (Börjesson, 2007).

One MJ of forest fuels and wood pellets is assumed to correspond to 0.04 and 0.15 MJ energy input, 3.5 and 5.0 g CO_2-equivalents, and 11 and 13 mg PO_4^{3-}-equivalents, respectively (Börjesson

Table 6
Emissions from biofuel production processes using biomass in the biofuel plant[a].

Crop	Chemical compound produced	CO_2 emissions (kg GJ^{-1})	CH_4 emissions (kg CO_2-eq. GJ^{-1})	Total greenhouse gas emissions (kg CO_2-eq. GJ^{-1})	NOx emissions (g PO_4^{3-}-eq. GJ^{-1})
Wheat (grain)	Ethanol	2.0	0.07	2.1	7.3
	Biogas[b]	4.1	5.0	9.1	7.2
Sugar beet	Ethanol	1.6	0.05	1.6	5.6
	Biogas[b]	5.0	5.0	10	8.7
Rapeseed	RME[c]	5.7	0.02	5.7	2.5
Ley crops	Biogas[b]	4.5	5.0	9.5	7.8
Maize	Biogas[b]	4.8	5.0	9.8	8.4
Willow	Ethanol	0.62	0.02	0.64	1.9
	FT-diesel	0.07	0.003	0.07	0.26
	Methanol/DME	0.07	0.003	0.07	0.26
	Methane	0.13	0.005	0.14	0.52

[a] Refers to biomass-based electricity and heat produced from solid lignocellulosic fuels in combined heat and power production plants (CHP). The CHP plant has an overall conversion efficiency of 90% and an alpha-value of 0.5 using steam turbines, and the fuel-cycle emissions are based on Börjesson and Berglund (2007). The primary energy input producing 1 MJ of heat and electricity is assumed to correspond to, on average, 1.17 MJ.
[b] Emissions from biogas production include the transport and spreading of digestion residues, and uncontrolled losses of methane from the production and upgrading of the biogas equivalent to 1% of the biogas produced, based on current Swedish conditions (Börjesson and Berglund, 2006; Lantz et al., 2009).
[c] Emissions from RME production include CO_2 from natural-gas based methanol used in the process, equivalent to 4.8 kg CO_2/GJ (Bernesson et al., 2004; Mårtensson and Svensson, 2009).

Table 7
Data for the energy and economic allocation.

Crop	Products	Energy yield[a] GJ ha^{-1}, yr^{-1}	Energy allocation[a] %	Economic allocation[b]	
				Interval (biofuel) %	Best estimate %
Wheat	Ethanol/DDGS	65/42	61/39	81/19	74-87
	Ethanol/DDGS/straw	65/42/77	35/23/42	73/17/10	63-80
	Biogas/straw	80/77	51/49	84/16	80-86
Sugar beet	Ethanol/pulp	105/57	65/35	84/16	75-88
	Ethanol/pulp/tops and leaves	105/57/44	51/28/21	82/15/3	72-85
Rapeseed	RME/rapeseed meal/glycerol	47/28/2	61/36/3	72/25/3	70-91
	RME/rapeseedmeal/glycerol/straw	47/28/2/59	35/21/1/43	65/23/3/9	55-78
Willow	Ethanol/lignin pellets	64/59	52/48	79/21	68-87

[a] 2.1 kg dry wheat generates 1 l of ethanol and 0.8 kg distiller's dried grain with solubles (DDGS); 2.2 kg dry sugar beet generates 1 l of ethanol and 0.68 kg dry pulp; 2.0 kg dry rapeseed generates 1 l of RME, 1.3 kg dry rapeseed meal and 0.1 kg glycerol; 3.15 kg dry willow generates 1 l of ethanol and 0.8 kg dry lignin pellets. The energy content, expressed as MJ/kg dry matter, is for DDGS, 17.3; dry sugar beet pulp, 16.8; rapeseed meal, 15.3; lignin pellets, 24. Energy allocation is based on adapted data from Concawe et al. (2007), Bernesson et al. (2004, 2006); Börjesson and Berglund (2006), Schmidt (2008), Törner (2008), Davis and Haglund (1999), Börjesson (1996b), Hamelinck and Faaij (2002), Official Report from the Swedish Government (2007).

[b] The "best estimate" is based on estimated average prices for 2008, and the "interval" in estimated price variations for the period 2004–2008. The estimated prices were as follows: 0.62 €/l ethanol (0.46–0.69); 0.017€/MJ upgraded biogas (0.015–0.018); 0.88 €/l RME (0.58–0.93); 0.18 €/kg dry DDGS (0.13–0.21); 0.17 €/kg dry sugar beet pulp (0.12–0.19); 0.24 €/kg dry rapeseed meal (0.18–0.26); 0.36 €/kg glycerol (0.18–0.54); 0.21 €/kg dry lignin pellets (0.13–0.27); 0.06 €/kg dry straw (0.05–0.08); 0.05 €/kg tops and leaves (no interval). Economic allocation is based on data adapted from Concawe et al. (2007), Bernesson et al. (2004, 2006), Schmidt (2008), Davis and Haglund (1999), Ericsson and Börjesson (2008). 1 € = 10 SEK.

and Berglund, 2007; Gustavsson and Karlsson, 2002). Digestion residues from biogas production are assumed to be used as fertiliser, replacing commercial fertiliser. The amount of nutrients that can be recycled to the cultivation of the crop via the digestion residues has been estimated to correspond to 70% of the requirement of nitrogen, and 100% of the requirement of the phosphorus and potassium (Börjesson and Berglund, 2007; Berglund and Börjesson, 2006; Johnsson and Mårtensson, 2002). An additional effect is that digestion residues are estimated to increase the soil carbon content by, on average, 80 kg C/ha per yr when commercial fertilisers are replaced (Lantz et al., 2009).

5. Results

5.1. Energy and area efficiency

The energy output of biofuels per hectare per year varies significantly among the various feasible production systems (Fig. 1). For example, the output of biogas from sugar beet (including tops and leaves) is about 3 times higher than the output of RME from rapeseed, expressed in energy terms. However, the production of RME will also generate by-products which in energy terms exceed the output of RME, and will thus compensate for the relatively low energy output of RME. Regarding the other production systems, the energy output of biofuel varies by +/−30%. The negative bars in the figure show the total external energy input needed in the complete production chain. These energy inputs vary by a factor of 6, expressed per hectare per year, where biofuels based on energy forests (willow) are those requiring the lowest energy input. Concerning biogas systems, the negative bars are somewhat reduced by the energy credit represented by the digestate when commercial fertilisers are replaced.

The energy balance of the various biofuel production systems, expressed as the energy output/input ratio, is here estimated to vary from 1.3 (ethanol from grain) up to 11 (methanol/DME from willow), when no allocation is applied (Table 8). However, the energy balance of the production systems generating by-products may vary significantly depending on how the energy input is allocated between the biofuel and the by-products. Normally, energy allocation gives the highest energy balances, followed by system expansion and economic allocation. Another important factor is whether or not straw is included as a by-product, in biofuel production systems based on grain and oil seed.

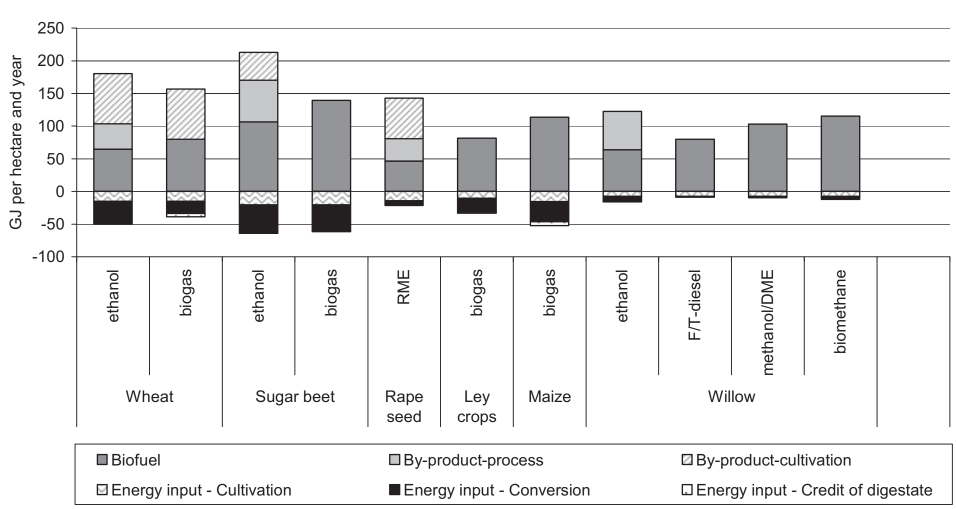

Fig. 1. The output of biofuels and by-products, and input of external energy, expressed as GJ per hectare and year, for the various biofuel production systems.

Table 8
Energy balance, expressed as the ratio of energy output to input, of different biofuel production systems including different allocation methods and system expansions (see text).

Crop	Chemical compound	No allocation	Energy allocation	Economic allocation	System expansion
Wheat	Ethanol	1.29	2.07	1.57	1.87
	Biogas	2.38	2.38	2.38	2.79
Wheat & straw	Ethanol	1.24	3.46	1.68	1.93
	Biogas	2.25	6.27	3.04	2.90
Sugar beet	Ethanol	1.65	2.64	2.00	2.06
	Biogas	2.33	2.33	2.33	2.50
Sugar beet & tops, leaves	Ethanol	1.61	3.22	2.01	2.06
	Biogas	2.43	2.43	2.43	2.57
Rapeseed	RME	2.18	3.77	3.14	4.98
Rapeseed & straw	RME	2.02	6.19	3.25	5.36
Ley crops	Biogas	2.63	2.63	2.63	2.87
Maize	Biogas	2.46	2.46	2.46	2.78
Willow	Ethanol	4.04	7.90	5.10	8.80
	F/T-diesel	8.79	8.79	8.79	8.79
	Methanol/DME	10.8	10.8	10.8	10.8
	Biomethane	9.53	9.53	9.53	9.53

The credit gained by using digestate instead of commercial fertilisers, representing system expansions in biogas systems, is somewhat reduced by the increased input of energy in the fertilisation operations (mainly diesel fuels for trucks and tractors). However, if the digestate is transported in pipes instead of trucks, and spread by new, energy-efficient field equipment instead of tractors, then the energy benefits of using digestate will increase more (Lantz et al., 2009; Johansson and Nilsson, 2006).

5.2. Greenhouse gases

The importance of defining an alternative land use reference system in the LCA of biofuels is clearly shown in Fig. 2. The contribution to the GWP is, on average, twice as high when the reference land use is unfertilised grassland compared to wheat cultivation. Concerning unfertilised grassland as reference, the reduction of GHG is approximately 80–85% when biofuels from lingocellulose (willow) replace fossil vehicle fuels, whereas this reduction could exceed 100% when the reference land use system is wheat cultivation. Fig. 2 also reveals the significance of which method is used in the treatment of by-products. The GHG reduction achieved by ethanol, biogas and RME from conventional crops varies between 35% and 75%, depending on treatment method of the by-products, when unfertilised grassland is used as the land use reference. The corresponding reduction when wheat cultivation is used as reference is between 65% and 110%.

5.3. Eutrophication

The contribution to the EP is roughly 2–3 times lower from biofuels based on sugar beet, ley crops and willow, compared to biofuels based on wheat, when unfertilised grassland is used as land use reference (Fig. 3). RME makes the highest contribution, approximately 50% higher than wheat-based biofuels. When wheat cultivation is used as land use reference, biofuels from perennial crops (ley crops and willow), as well as food crop-based biofuels regarding systems expansion of by-products, will result in a significant benefit by a reduced contribution to the EP.

6. Sensitivity analysis

6.1. Biomass yields

The assessments illustrated in Table 2 show that country-wide average biomass yields may vary by +/−35% among the countries in north-western Europe. An increase in biomass yield will normally lead to an improved energy balance for the cropping systems as the energy input is not directly proportional to the energy output. For example, the requirement of soil tillage, sowing operations, weed control etc. are similar independent of the biomass yield. A rough estimate shows that a biomass harvest increased by 35% leads to an improved energy balance by, on average, 10%. This will simultaneously lead to a somewhat reduced contribution to the GWP and EP per GJ of biomass.

6.2. Biofuel conversion efficiency

The literature review shows a variation in the efficiency of the biomass conversion technologies included in this analysis, which is typically +/− a few per cent for ethanol and RME production, +/−10–15% for chemical compounds produced by thermal gasification of lignocellulosic biomass, and +/−15–25% for biogas production from ley crops and maize (see Table 5). A change in conversion efficiency is directly proportional to the energy and environmental performance of the biofuel (when potential by-products are excluded).

According to the data found in the literature, the energy input in the conversion processes may also vary (Table 5). If the energy input in a conversion process is significant in absolute terms, e.g. in ethanol production from grain and sugar beet including drying of the by-products to animal feed, then a relatively small change in the energy efficiency of the process may affect the results appreciably.

Data on the conversion efficiency and energy input are here based on the assumption that the production of the specific biofuel is maximised (base case). However, several different ways to co-produce two or more biofuels in biorefinery concepts exist. One example is the combined production of ethanol and biogas from cereals or sugar beets, where the distiller's waste or the pulp is not dried to animal feed but used for biogas production. In the case of ethanol from wheat, an additional 35–40% of biofuel could then be produced in the form of biogas, at the same time as the external energy input is reduced by about 15–20% (Börjesson and Mattiasson, 2008). Concerning biofuels from lingocellulose, these could be produced together with electricity and heat for external use, e.g. in district heating systems. Such biorefineries often have a higher total energy efficiency than stand-alone biofuel production plants, but the output of the biofuel is normally somewhat reduced in biorefineries (Goldschmidt, 2005; Hamelinck et al., 2005; Hamelinck and Faaij, 2002, 2006; Ericsson and Börjesson, 2008).

6.3. Type of fuel used in biofuel plants

If natural gas or coal is used instead of biomass in biofuel plants, the contribution to the GWP will increase significantly (see e.g. Concawe et al., 2007). For example, if ethanol plants processing cereals use natural gas or coal instead of biomass, then the life cycle emissions of GHGs will increase by, on average, 50% and 100%, respectively, when energy allocation is applied and unfertilised grassland is used as land use reference (excluding straw recovery) (Fig. 4). Compared with fossil vehicle fuels, the GHG reduction will then be approximately 30% and 5%, respectively. Biofuels from lignocellulose produced by thermal gasification require a low input of external energy (in the form of electricity). Thus, the

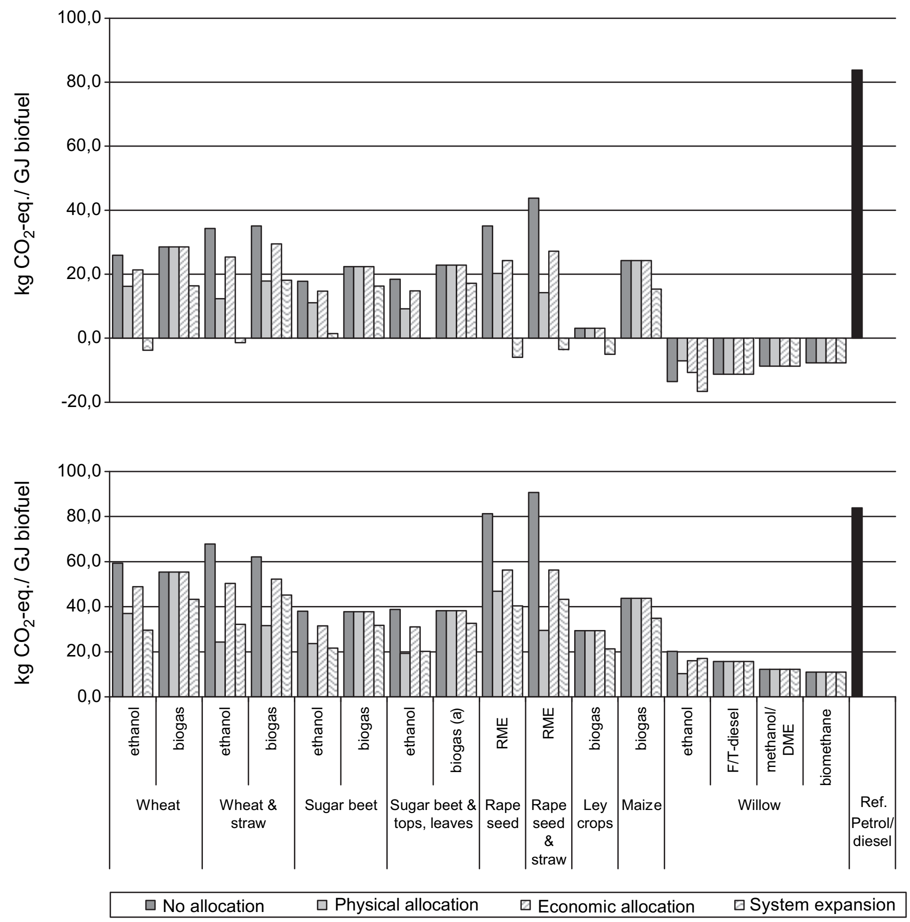

Fig. 2. Contribution to the global warming potential, expressed as kg CO_2-equivalents per GJ biofuel, of different biofuel production systems, including different allocation methods and system expansions, and when the alternative land use reference system is wheat cultivation (above) and unfertilised grassland (below). For comparison, the fuel cycle emissions of GHGs of fossil vehicle fuels are also shown.

environmental performance of these production systems is almost unaffected by changes in the primary sources of the external energy needed.

6.4. Uncontrolled losses of methane from biogas plants

An additional factor of significant importance concerning the life cycle emissions of biogas is uncontrolled losses of methane during production, cleaning and pressurisation of the biogas. Previous calculations are based on the assumption that uncontrolled losses of methane are equivalent to, on average, 1% of the biogas produced (base case, see Table 6). However, such losses could be lower in well-functioning biogas plants, but could also be higher when defective technology is utilised. If, for example, losses of methane amount to 10% of the biogas produced, the contribution to the GWP could be more than doubled depending on how the biogas systems are designed and whether system expansion is applied (see Fig. 2). An extensive analysis of the impact of uncontrolled losses of methane and the contribution to the GWP from various biogas systems is given in Börjesson and Berglund (2006).

6.5. Nitrous oxide emissions from nitrogen fertiliser plants

The emissions of N_2O from an average fertiliser plant in western Europe have been reduced from, on average, 18 g to 15 g N_2O per kg N over the past decade and are currently even lower due to the implementation of catalytic N_2O cleaning equipment (Davis and Haglund, 1999; Jenssen and Kongshaug, 2003). Today, approximately half of the nitrogen fertiliser plants in Western Europe have installed catalytic cleaning equipment, reducing the N_2O emissions by some 80% (Jenssen and Kongshaug, 2003; Mårtensson and Svensson, 2009). In a few years, all plants are expected to have catalytic N_2O cleaning, leading to, on average, 3 g N_2O per kg N, compared with the estimated average today of 9 g N_2O (see Table 3). This will reduce the contribution to the GWP from biofuels based on annual crops (such as wheat, sugar beet, rapeseed and maize requiring large amounts of commercial nitrogen fertilisers, see Table 2) by approximately 5–7% and 12–20%, when unfertilised grassland and wheat cultivation are the land use reference, respectively.

6.6. Biogenic nitrous oxide emissions from cropping

The level of biogenic N_2O emissions from the soil is inherently uncertain, since these levels are influenced by a large number of local parameters (Bernesson et al., 2006; Bouwman et al., 2002; Nevison et al., 1996). Thus, the calculated N_2O emissions should be seen as rough estimates based on "average" conditions (IPCC, 2006). However, one crucial parameter of significant importance is the amount of nitrogen available in the soil. Thus, an improved efficiency in the uptake of nitrogen by the crop and more efficient fertilisation strategies will lead to a decreased risk of N_2O emissions (Reijnders and Huijbregts, 2008; Tufvesson and Börjesson, 2008). A reduction of biogenic N_2O emissions by 20% will reduce the life

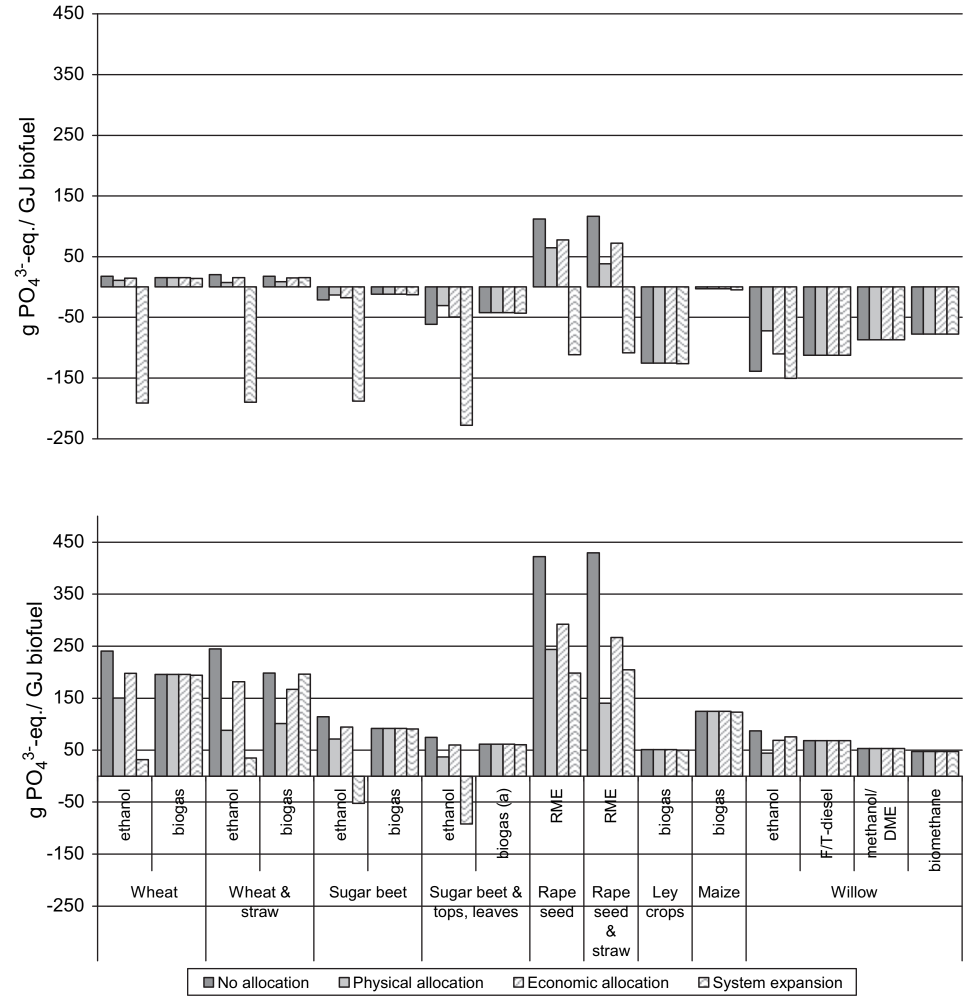

Fig. 3. Contribution to the eutrophication potential, expressed as g PO_4^{3-}-equivalents per GJ biofuel, of different biofuel production systems, including different allocation methods and system expansion, and when the alternative land use reference system is wheat cultivation (above) and unfertilised grassland (below).

cycle emissions of GHGs from annual crop-based biofuels by about 5% based on unfertilised grassland as land use reference, and 10% based on to wheat cultivation as reference.

6.7. Carbon dioxide emissions due to land use changes on peat soils

Cultivation of annual crops for biofuels on land which has particularly high soil carbon content, such as peat land normally used as permanent grassland, will lead to a considerable increase in GHG emissions. An estimate is that some 7 Mg C could be lost per hectare and year from cultivated peat soils in northern Europe when these are converted from perennial to annual crop production (Börjesson, 1999). Thus, if wheat for ethanol production is cultivated on peat land previously used as grassland, the contribution to the GWP will be roughly 4 times higher than the contribution from fossil vehicle fuels (Börjesson, 2009). For comparison, Fargione et al. (2008) estimate that carbon losses from tropical peat land may amount to 15 Mg C/ha per yr when these are converted into crop cultivation for biofuel production.

It is important to take the time aspect into consideration when assessing changes in the soil carbon level (Reijnders and Huijbregts, 2008). An estimate is that a change from perennial to annual crops, or vice versa, will influence the soil carbon level in mineral soils over a period of about 30–50 years in northern Europe (Börjesson, 1999). After that, the soil carbon level is assumed to reach a new steady state. The duration of carbon losses from peat soils depends on the thickness of the peat layer. A rough estimate, based on conditions in northern Europe, is that about 1 cm of the peat layer is lost yearly when annual crops are cultivated (Börjesson, 1999). For example, the average thickness of Swedish peat soils used as arable land (which amount to about 7–9% of the total arable land), is estimated to be approximately 0.8 m, thus the GHG emissions from these soils will continue, on average, for 80 years when annual crops are cultivated (Börjesson, 1999). For comparison, Fargione et al. (2008) estimate the average depth of tropical peat soils to be 3 m, and thus carbon losses will continue for about 120 years.

6.8. Nutrient leaching from arable land

The assumptions made about the nutrient leaching from the different cropping systems are uncertain and the actual nitrate leakage can vary greatly depending on location, and reliable input data are limited due to the lack of long-term field trials dedicated to monitor the specific cropping systems analysed here (Börjesson and Berglund, 2007). Depending on type of soil, precipitation, fertilisation strategies etc, the level of nitrate leakage from region to region may be half or twice the level assumed in the base case here

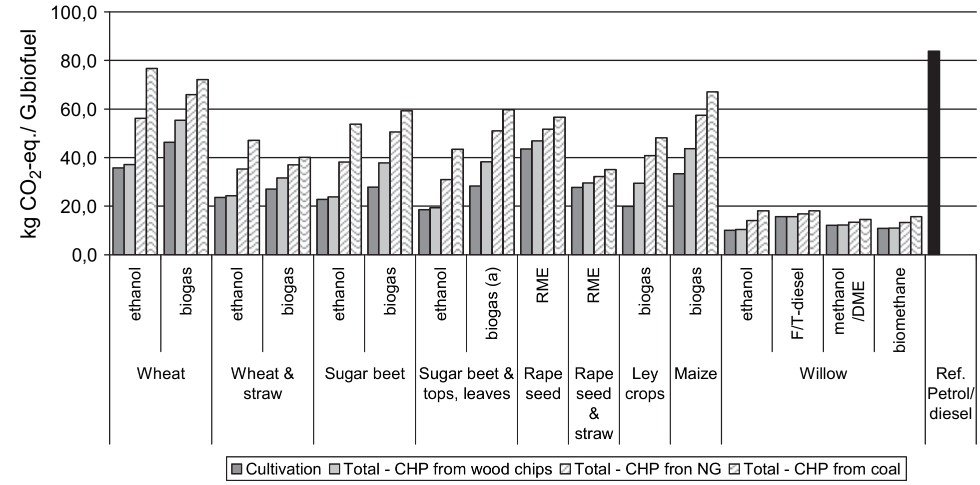

Fig. 4. Changes in the contribution to the GWP when the primary energy source for the production of the electricity and heat needed in the conversion plants is changed from bioenergy (base case) to natural gas or coal. The figure refers to the "energy allocation" case and unfertilised grassland as land use reference.

(Johnsson and Mårtensson, 2002). Thus, the contribution to the EP from biofuels may vary by a factor of almost 2 depending on local conditions, but the relative differences between the different crops are estimated to be more stable (see Fig. 3).

6.9. Economic allocation

As shown in Table 7 (Section 4.3), economic allocation varies over time due to variations in prices. However, analyses conducted here show that the variations in economic allocation concerning ethanol and RME are often smaller than the changes in prices indicate. The reason for this is that the prices of the biofuels are affected by the cereal and oil seed prices, which also influence the prices of the distiller's waste and rapeseed meal used as protein feed in a similar way. Furthermore, an increase in energy prices will increase the price of the biofuels, but also the price of the solid by-products used for energy purposes, such as straw and lignin pellets.

7. Conclusions

This study clearly shows the importance of including direct land use changes in the LCAs of biofuels. Depending on whether traditional cropland or unfertilised grassland is used for the biofuel production, the GHG balance may vary by a factor of two, whereas the variation in the contribution to the eutrophication potential will be even larger. This is due to changes in the biogenic emissions of CO_2 and N_2O from the soils, and leakage of nitrate to water, respectively. If peat soils are utilised, the biogenic emissions of CO_2 may increase 10–20 times. Another parameter of great importance, in conjunction with liquid biofuels from food crops, is how potential by-products are treated. The GHG balance could be considerably improved, in particular when system expansion is applied. The harvest of crop residues will also significantly affect the results by improving the area efficiency, for example. Production of biogas from food and feed crops, and liquid and gaseous fuels from lignocellulosic crops (willow), will be less affected by the choice of allocation method.

The second generation biofuels from lignocellulosic crops, such as willow, have several advantages in the form of high energy efficiency, low emissions of GHG and a low contribution to the eutrophication potential. If the alternative land use reference system is grain cultivation, the contribution to both GWP and eutrophication potential will be negative. The net energy output of biofuels per hectare and year will also be highest for willow-based biofuels produced by thermal gasification, whereas the highest gross biofuel output is for biogas from sugar beet.

The design of the individual production systems may also significantly affect the energy and environmental performance of the biofuels. One factor of particular importance is whether renewable or fossil fuels are used in the conversion processes of ethanol or biogas from traditional crops. Other parameters of significance are whether nitrogen fertiliser is produced in plants which have catalytic N_2O cleaning or not, the magnitude of uncontrolled methane emissions from biogas plants and the efficiency in feedstock conversion into biofuels including various biorefinery concepts.

To summarise, when different production routes of biofuels (and feedstock for the chemical industry) from crops are compared, from a resource- and an environmental perspective, a broad system analytical approach is needed. Systems analyses have to be based on the specific local and/or regional conditions, since every production system is unique in some way. Furthermore, there is no general "right" or "wrong" calculation method for the LCA of biofuels, as different methods may be relevant under specific conditions. However, the most important results of such systems studies may be the identification of crucial parameters which have the highest impact on the energy- and environmental performance of biofuels. This knowledge is crucial in the development of certification systems of biofuels. Thus, setting strong constrictions on the most crucial parameters from an energy- and environmental point-of-view, will ensure that the most sustainable biofuel production systems will be developed in the future. Finally, indirect land use changes must to be recognised in conjunction with the expansion of biofuel production, as in all agriculture and forestry production, but these potential effects should not, or could not be included in the LCA for several reasons (scientific, methodological, practical etc). Thus, to avoid potential negative displacement effects, complementary tools to certification schemes and standardisation are necessary, such as national land use plans and regulations supported by international agreements and cooperation in development at different levels.

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