Good or bad bioethanol from a greenhouse gas perspective – What determines this?

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A B S T R A C T
The purpose of this study is to describe how the greenhouse gas (GHG) benefits of ethanol from agricultural crops depend on local conditions and calculation methods. The focus is mainly on the fuels used in the ethanol process and biogenic GHG from the soils cultivated. To ensure that “good” ethanol is produced, with reference to GHG benefits, the following demands must be met: (i) ethanol plants should use biomass and not fossil fuels, (ii) cultivation of annual feedstock crops should be avoided on land rich in carbon (above and below ground), such as peat soils used as permanent grassland, etc., (iii) by-products should be utilised efficiently in order to maximise their energy and GHG benefits and (iv) nitrous oxide emissions should be kept to a minimum by means of efficient fertilisation strategies, and the commercial nitrogen fertiliser utilised should be produced in plants which have nitrous oxide gas cleaning. Several of the current ethanol production systems worldwide fulfill the majority of these demands, whereas some production systems do not. Thus, the findings in this paper helps identifying current “good” systems, how today’s “fairly good” systems could be improved, and which inherent “bad” systems that we should avoid.

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1. Introduction

No-one has been able to avoid the debate raging over the past year in respect of biofuels, discussing whether these should be viewed as a threat or an opportunity. From the situation whereby biofuels were considered to be one of several vital solutions to the climate problem, the view put forward by the media has changed radically: now, the emphasis has been shifted to all the threats that could be posed. So which view is the true one? Well, the simple response is that both views could be true; there are both good and bad systems (see e.g. [1–4]). Biofuels can be produced in so many different ways and in so many different locations in the world, and so conditions vary widely. It is not possible to generalise to the extent that the current media debate is pretending. To bring about a more varied discussion, as well as providing better decision data for various organisations, more knowledge needs to be developed and disseminated, and the various arguments for and against biofuels have to be reviewed critically.

Climate benefits and greenhouse gas (GHG) balances are aspects often discussed in conjunction with sustainability and biofuels. Ethanol is currently the dominant biofuel on both a global and a Swedish national scale, which is why the debate often focuses on ethanol. In Sweden, the use of ethanol has increased over the past few years and now accounts for more than 3% of fuel consumption for transportation by road [5]. Most of this ethanol is imported, mainly from Brazil, while domestic ethanol from grain accounts for barely a fifth. On a global scale, the two dominant ethanol-producing countries today are Brazil and the USA.

The purpose of this study is to describe the GHG benefits of ethanol and how this depends on local conditions and calculation methodology. The emphasis is on Swedish ethanol based on grain, but links are also made to other production systems for ethanol worldwide, such as ethanol from sugarcane in Brazil and maize in the USA, respectively. Aspects such as the influence on biodiversity and other environmental and social parameters fall beyond the scope of this study, thus the definition of “good” and “bad” ethanol is limited here to include just the aspects of climate benefits. The paper starts with a description of the ethanol production system, followed by analyses of the emissions of GHG from the different steps in the production chain aiming at identify the most critical factors from a GHG point of view.

2. Structure of the ethanol production system

The structure of current production systems for grain-based ethanol in Sweden is shown in Fig. 1, expressed as energy flows (GJ/ha) [based on data from [6,7]. 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 (equivalent to about 37% of the total energy input), commercial fertilisers (about 41%), seed, pesticides, the manufacture and maintenance of field machinery, field transport by tractors etc (all together equivalent
Energy output

Seed, agrochemicals, diesel, machinery, etc. → Wheat cultivation (80)

Diesel, vehicles, etc. → Transport (120 - grain)

Wood chips, electricity, etc. → Ethanol production (40)

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Energy input (GJ / hectare)

Wheat – grain 10 9.2 5.7 (1.5) 25 0 25

Emissions of greenhouse gases in the case of grain cultivation, expressed as kg of CO₂-equiv./GJ of harvested grain.a

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3. GHG during cultivation

Greenhouse gas emissions during cultivation are made up of carbon dioxide from tractors, fertiliser manufacture, etc. and nitrous oxide from arable land and from the manufacture of nitrogenous fertiliser. Often emissions of nitrous oxide contribute more than emissions of carbon dioxide (see Table 1), but there is great uncertainty about how much nitrous oxide is emitted by arable land, and such emissions may vary widely depending on local conditions. Here, emissions of nitrous oxide from land are estimated from the latest IPCC model [8]. The issue of nitrous oxide emissions during cultivation of biofuel feedstock crops have been discussed intensively in the research community during the last years (see e.g. [9–11]).

More fuel-efficient tractors, more efficient cultivation and manufacture of fertilisers, etc. can somewhat reduce emissions of carbon dioxide per tonne of biomass, maybe by up to 20%. In addition, nitrous oxide emissions may be reduced during the manufacture of nitrogenous fertiliser thanks to catalytic nitrous oxide gas cleaning, which is starting to be implemented in western Europe at the moment. Nitrous oxide emissions are being reduced by approximately 75% in this way [8]. More efficient nitrogen utilisation during cultivation can also reduce the risk of nitrous oxide formation in the ground. The amount of nitrogen available for nitrous oxide formation will be reduced by improved fertilisation strategies, such as more precise nitrogen application during the cropping season in relation to the variations in the actual need by the crop.

Another factor which may be of great significance for the GHG balance is if cultivation involves a change in the use of land, directly or indirectly, which in turn leads to losses of land-based carbon (see e.g. [1,2]). Examples of direct effects are, for example, when straw is harvested which slightly reduces the content of soil carbon (approximately 150 kg C/ha and year), or when grain starts to be cultivated on former grassland leading to even higher losses of soil carbon (approximately 500 kg C/ha and year) [6]. In certain special cases, the losses of land-based carbon may greatly exceed other emissions of GHG, for example if grain starts to be cultivated on peat land which was previously used for cultivation of grassland. In these cases, the losses of soil carbon may amount to 7 tonnes C/ha and year (see Table 1).

Examples of indirect land-use changes are when an expanded production of biofuels leads to displacement of food and feed production into new cropping land previously not cultivated (e.g. natural pasture land, natural forests, etc.), which could lead to even higher losses of carbon than direct land-use changes [1,2]. Such indirect land-use changes are not included in this analysis but discussed further in Section 7. Regarding both direct and indirect land-use impacts, changes to the land’s carbon stock in mineral soils are reduced over time, and after approximately 30–50 years a new state of equilibrium can often be attained. How long emissions of carbon dioxide take place from peat land depends on – among other things – the thickness of the peat layer.

4. GHG during ethanol production

How great emissions of GHG are from ethanol plants depend largely on what fuel is used to produce the heat, steam and electricity required for the manufacture of ethanol. In – for example

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Table 1

Emissions of greenhouse gases in the case of grain cultivation, expressed as kg of CO₂-equiv./GJ of harvested grain.a

<table>
<thead>
<tr>
<th>Cultivation system</th>
<th>CO₂ fossil fuel</th>
<th>N₂O land</th>
<th>N₂O N fertiliser</th>
<th>Total</th>
<th>CO₂ change of land-use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat – grain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- cultivation on “normal” arable land</td>
<td>10</td>
<td>9.2</td>
<td>5.7 (1.5)</td>
<td>25</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>- cultivation on grass-covered mineral soil</td>
<td>25</td>
<td>11</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- cultivation on grass-covered peat soil</td>
<td>25</td>
<td>210</td>
<td>230</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Average for northern Europe, which corresponds to cultivation in southern Sweden [6]. Excluding straw harvest.

b Emissions from tractors, manufacture of fertilisers, etc. Including a small quantity of methane emissions.

c Biogenic emissions from land based on the IPCC model [8].

d Based on [12,13]. Values in brackets relate to emissions from manufacture with catalytic nitrous oxide gas cleaning.

e In the case of straw harvest, the binding of land-based carbon is assumed to fall by 150 kg C/ha and year, and in the case of cultivation of annual crops on grass-covered mineral soil and peat soil, the losses of soil carbon are estimated to amount to 500 kg C/ha and 7000 kg C/ha and year, respectively [14].
– Swedish and Brazilian ethanol production, biomass are used, so giving very low emissions of GHG, while in American and other European ethanol plants fossil fuels such as natural gas and coal are often used. Table 2 describes how great emissions of GHG from ethanol plants are depending on whether biomass, natural gas or coal is used. As can be seen in Table 2, emissions from ethanol production account for less than 10% of total emissions when biomass is used in ethanol plants. When natural gas and coal are used, this amount increases to approximately 40% and just below 60%, respectively.

Apart from selecting biomass instead of fossil fuels for ethanol production, streamlining can also lead to improved energy efficiency and reductions in emissions of GHG. For example, it is thought that more adapted integration between a power and heating plant and an ethanol plant could provide energy savings by allowing more optimal steam pressure to be utilised for the relevant processes and generation of electricity, better heat exchange and recovery of waste heat, along with integration of drying processes, etc. A cautious assessment is that it should be possible for the energy used in a developed ethanol plant to be 15% lower than at present [7]. Another type of streamlining involves increasing the exchange of ethanol per kg of grain by means of refinement. At present, the starch content is often around 70% of the dry matter content, but with new ethanol wheat varieties this may be increased to up to about 75%, which may increase the exchange of ethanol from 55% up to approximately 58% [7]. At the same time, the exchange of the by-product draff will be reduced slightly.

5. Calculation methodology for allocation to by-products

Apart from the fact that the structure of the production system has a great influence on the GHG performance of the ethanol, the choice of calculation methodology also influences the results. As ethanol from – for example – grain and wood raw materials generates by-products, these also have to be taken into account when calculating the emissions of GHG in order to give fair results. The ISO standard for life cycle assessment (ISO 14044) describes various calculation methods for dealing with situations when a production system generates several products [15]. These methods are physical allocation, economic allocation and system expansion.

The allocation of the emissions between the main products and the by-products could be done by using energy characteristics (physical allocation), or economic characteristics (economic allocation). To avoid allocation, the system boundaries could be expanded to take into account the production of the alternative product and its environmental impact that will be replaced by the by-product generated. Since these methods are more or less relevant for use under specific circumstances, all three methods can be motivated in life cycle assessments of biofuels.

In Table 3, data on the energy and economic allocation used in this analysis are shown. An advantage of energy allocation, compared to economic allocation, is that energy 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 are changing 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 way to handle this uncertainty is by using a data interval reflecting potential variations in prices. In the case of ethanol, draff and straw, however, it appears that the price levels for these three products have been linked relatively well over the past few years, which means that the basis for economic allocation has not altered to any great extent [6].

One advantage of economic allocation, compared to energy 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 ethanol production from grain where the energy yield in the form of straw exceeds the energy yield in the form of ethanol (see Fig. 1), but where the economic value of straw is estimated to be equivalent to 10–15% of the economic value of ethanol. In earlier life cycle analyses of biofuels, both economic and energy allocation is often used to show the impact on the results depending on which method that is used (see e.g. [16,17]). It is here argued, that economic allocation gives more fair results than energy allocation regarding biofuel systems generating large amount of low value by-products, based on the arguments specified above. However, when calculating “defaults” for biofuels, as they are known, in the EU’s fuel directive [18] it is suggested that energy allocation be used, but to “counteract” results that are too positive for grain-based ethanol, for example, by-products from cultivation (straw) are not included. According to the ISO standard, we should use both allocation methods if there is any doubt and show clearly how the choice of allocation method affects the result.

According the ISO standard of life cycle assessment [15], allocation should be avoided where possible by expanding the system boundaries. System expansion is utilised, for example, in the European well-to-wheels study conducted by Concawe et al. [3], but the method has some limitations [19,20]. Examples are when no reliable life cycle inventory data exist on the alternative product, when several potential replacements exist and it is not possible to define the most realistic alternative product, or when the market of the most realistic replacement is restricted. Thus, the calculations with system expansion should be coupled to a specified amount of biofuels produced. For example, previous estimations show that ethanol from grain equivalent to about 5–10% of the current use of petrol for road transport in Sweden and EU could be produced before the protein feed market is saturated by draft [3,7].

When system expansion is applied in this analysis, draft is assumed to replace imported soy bean meal from Brazil and straw is assumed to replace forest chips as fuel. Dried draff is currently used as protein feed in primarily milk production which is normally using soy protein feed and the potential market of draft as feed is estimated to be about five to ten times higher than current production in domestic grain-based ethanol production [7]. This replacement is estimated to result in a GHG reduction equivalent to approximately 430 kg CO2-equiv./GJ ethanol [6,21].

As far as system expansion for the by-product straw is assessed, forest chips are thought to be the most realistic substitute fuel in several countries in northern Europe, such as Sweden, as there is an unutilised potential for an increase in the extraction of forest fuels [6]. However, in other countries fossil fuels such as coal and natural gas may be the most realistic alternative fuels, which mean considerably greater benefits from a climate viewpoint. There is also logic in assuming that mainly forest chips will be replaced with straw in Sweden, as we use forest chips as a fuel in current

<table>
<thead>
<tr>
<th>Fuel in ethanol plant</th>
<th>Cultivation2</th>
<th>Ethanol production3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest chips</td>
<td>45</td>
<td>3.1</td>
<td>48</td>
</tr>
<tr>
<td>Natural gas</td>
<td>45</td>
<td>31</td>
<td>76</td>
</tr>
<tr>
<td>Coal</td>
<td>45</td>
<td>58</td>
<td>103</td>
</tr>
</tbody>
</table>

1 Based on [6].
2 Excluding straw harvest, the by-product draft and any changes of land-based carbon, i.e. all emissions of GHG load the ethanol alone (equivalent to 25 kg CO2-equiv./GJ wheat grain according to Table 1, which – including transport – gives 45 kg CO2-equiv./GJ of ethanol at an ethanol exchange of 55%).
3 The requirement for electricity and heat is met by means of power and heat production from the relevant fuel.
ethanol production but we could just as well use straw from the cultivation of grain for ethanol. Thus, the GHG benefit of using straw instead of forest fuels is limited to approximately 20 kg CO₂-eq./GJ ethanol [6].

6. Critical factors: a summary

Fig. 2 sums up the importance of all the different factors presented in previous sections and of significance as to whether ethanol should be considered "good" or "bad". This figure could also be seen as a sensitivity analysis of how the GHG performance of a "rather well defined" biofuel production system, in this case wheat-based ethanol produced in Sweden, could vary depending on systems boundaries, allocation methods, assumed technology, alternative land-use, etc.

Current ethanol production in Sweden can be said to lead to an almost 80% reduction of GHG when biofuels are used in ethanol production and draft is used mainly to replace imported soy meal as a protein feed (column 2). However, there is potential for improvement which, together with straw harvesting, may result in even greater climate benefits compared with petrol (column 1). This improvement include nitrogen fertiliser from more energy efficient plants with nitrous oxide gas cleaning, improved nitrogen fertilisation efficiency, reduced soil tillage, more fuel-efficient tractors, improved ethanol processes and more efficient ethanol plants, increased starch content in grain by plant breeding, etc.

By way of comparison, current Brazilian ethanol from sugarcane is deemed to lead to an 85% reduction when excess electricity from bagasse is included via system expansion [3]. When calculating what are known as "defaults" for biofuels within the EU's fuel directive [18], it is suggested that energy allocation be applied and that by-products from cultivation (such as straw) should not be included. This calculation method brings about a 65% reduction for current ethanol production in Sweden (column 3), which is comparable with current EU proposals stating that biofuels should lead to at least 35% lower emissions of GHG than is the case with fossil fuels.

If both straw and draft are taken into account and economic allocation is applied, the current production of grain-based ethanol will lead to a 60% reduction (column 4). In all of the above examples (columns 1–4), it is assumed that grain cultivation will take place on arable land where mixed plant cultivation takes place. If grain cultivation starts to take place on arable land where grass or grazing have been cultivated for a long time (several decades), current production systems for ethanol would lead to a 55% reduction of GHG (column 5) instead of an 80% reduction (column 2). All of the above examples are also based on the assumption that forest chips are used as fuel in the ethanol plant, but if this fuel is replaced with natural gas, the reduction will be 45% (column 6) instead of 80% (column 2).

When economic allocation of draft is applied instead of system expansion, and cultivation of grain for ethanol takes place on former grassland, the reduction of GHG will be approximately 25% compared with petrol (column 7). If forest fuels are replaced with coal in the ethanol plant and draft is assumed to replace soy meal, the reduction will amount to approximately 15% (column 8). By way of comparison, the average reduction of GHG for American ethanol from maize is deemed to amount to around 20% compared with petrol today, and this relatively limited climate benefit is due mainly to the fact that fossil fuels such as coal and natural gas are used in ethanol plants in the USA [22]. However, there is a major variation from more than a 50% reduction to no reduction at all. Ethanol production from maize also gives a by-product which is used as an animal feed and is included in the above study by means of system expansion [22]. In the European well-to-wheel study discussed previously, ethanol from grain is assessed to lead to a 70% reduction of GHG compared with petrol when straw is used as a fuel in the ethanol plant [3]. When natural gas is used, the reduction amounts to 45%; and if brown coal is used, the emissions increase by approximately 10% (this study also uses system expansion to include by-products).

According to Fig. 2, ethanol production based on coal as a fuel and grain cultivation on former grassland is deemed to give higher emissions of GHG than petrol, irrespective of how the by-products are included (columns 9 and 10). If grass-covered peat land is utilised for cultivation of grain for ethanol, this ethanol production leads to emissions of GHG 4–5 times higher than petrol (column 11). Thus, direct land-use changes could be, in specific situations, the most critical factor regarding the GHG performance of biofuels. This is also the case for indirect land-use changes due to displace-

### Table 3: Distribution of GHG between grain-based ethanol and its by-products in the case of energy and economic allocation, respectively.

<table>
<thead>
<tr>
<th>Production system</th>
<th>Energy allocation (%)</th>
<th>Economic allocation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol/draft (exc. straw harvest)</td>
<td>62/38</td>
<td>79/21</td>
</tr>
<tr>
<td>Ethanol/draft straw (inc. straw harvest)</td>
<td>36/22/42</td>
<td>70/18/12</td>
</tr>
</tbody>
</table>

* a Based on [6].
* b Based on the energy content of the products.
* c Based on the economic value of the products on the basis of the 2007 price level.

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**Fig. 2.** Emissions of GHG from grain-based ethanol production, taking into account various systems and calculation methods and in comparison with petrol. The various examples may be viewed as an illustration of the scale from "good" ethanol to "bad" ethanol (see the text for more detailed explanations of each column).
ment effects, but such potential effects are much more difficult to include in life cycle assessments of biofuels, which is discussed in the following section.

Thus, a conclusion from the results presented in Fig. 2 is that the biofuel system which is analysed must be clearly defined regarding all the parameters discussed, to make possible the “right” choice of calculation method leading to the most fair and reliable results of the actual system.

7. Conclusions and discussion

The GHG performance of ethanol from an annual feedstock crop, such as wheat, is dependent largely on four factors: (i) cultivation efficiency and its emissions of nitrous oxide, (ii) the fuel used in the ethanol plant, (iii) the efficiency with which by-products are dealt with and (iv) the type of land used for cultivation. Depending on these four factors, production systems for ethanol may mean anything from major climate benefits to increased emissions of GHG compared with petrol.

Current production of Swedish ethanol from wheat can be seen as “good” ethanol, reducing GHG emissions by some 80% compared to petrol. Ethanol based on sugarcane from Brazil leads to a reduction of – on average – 85%, while ethanol from maize in the USA leads to a reduction of only 20% on average. The reason for this is that fossil coal accounts, on average, for 25% of the fuel used in ethanol plants in the US, and natural gas for the remaining 75% [22]. Thus, there is a potential for improvement of current ethanol production systems especially in the US, but also worldwide, leading to increased GHG benefits.

Improved GHG performance of ethanol production systems could, on the other hand, be counteracted by increased carbon losses from new farmland if an expansion of ethanol production leads to displacement of food and feed production. The effects of such indirect land-use changes on the GHG balances of biofuels have been discussed intensively in the past year. Examples are studies by Searchinger et al. [1] and Fargione et al. [2] who have calculated the “payback time” for biofuels to become climate-neutral. The assumption in these studies is that all production of biofuels requires new cultivation of cropland by “displacement effects”, leading to high emissions of carbon dioxide from carbon stored in natural pasture land, natural forests etc. Therefore, losses of carbon bound in biomass above and below ground are by far the largest source of GHG emissions in these calculation models.

However, opinion is divided on when and how indirect displacement effects should be included in a life cycle assessment of biofuels and to what extent clear evidence exists that biofuel production always leads to a change of land-use. In the EU countries, for example, around 10% of the arable land has been taken out of production over the past decade (presently fallow land), due to the low world market prices of food crops. Thus, in a short-term perspective, biofuel production could be expanded in the EU countries, but also in many other countries worldwide, without leading to indirect displacement effects. In a long-term perspective and when prices of food, feed and biofuels increase, the risk of land competition and displacement effects may also be reduced due to development of the agriculture sector leading to increased crop yields on existing farmland. Two crucial factors regarding a potential future risk of displacement effects will then be (i) the expansion rate of the various biofuel systems and (ii) their total production volume.

Only direct land-use changes are included in the analysis in this paper and the reason not to include indirect land-use changes (displacement effects) is the large uncertainties concerning such potential effects. It is almost impossible to present clear evidence that an expansion of a specific biofuel production system leads to a specific indirect land-use change by displacement of food or feed production. Furthermore, if displacement effects occur, these effects should be allocated between all production systems that are expanded, also food and feed production and not only biofuel production. These uncertainties about displacement effects make it necessary to analyse this issue much more extensively and carefully in future.

To summarise: it is not possible to state generally whether ethanol is good or bad as regards the climate, as this is dependent upon the structures of the individual systems. Furthermore, there are various calculation methods which affect the results; i.e. we have to have a critical attitude towards the life cycle assessments being published and which sometimes receive a lot of media attention. However, with our current knowledge we can point out the most important factors for whether or not ethanol production will lead to major climate benefits. This knowledge, together with supplementary knowledge on aspects such as the influence on biodiversity and other environmental and social aspects, is important when structuring – for example – certification schemes for biofuels. Such certification schemes will help us to make the correct demands and develop the good systems while at the same time avoiding the bad ones; i.e. allowing us to promote the development of “good” ethanol and counteract the production of “bad” ethanol.

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