1. Introduction

1.1. General introduction

Biofuels have the potential to mitigate climate change by reducing greenhouse gas (GHG) emissions compared to using fossil fuels. Because carbon dioxide is removed from the atmosphere by growing the feedstock used for biofuels, the net carbon balance after consumption is practically zero. However, in addition to the GHGs that are emitted during consumption, GHGs are also emitted while growing and producing biofuel. This means that the GHG balance relative to using fossil fuels results in a reduction of less than 100%.

In recent years, mitigation policies have been promoting biofuels as one of the potential means to reduce GHG emissions (EU, 2009; Pousa et al., 2007; US Congress, 2005). In order for these policies to be effective, they must ensure that GHG emissions are actually reduced, which requires the introduction of sustainability criteria (CARB, 2009; EU, 2009). In the EU, the sustainability criteria thus far have focused mainly on the direct effects of the production chain of bioenergy products. However, in addition to the effects from the production chain, bioenergy may cause significant indirect effects in other systems too (Fargione et al., 2008; Searchinger et al., 2008). Examples of these indirect effects are indirect land use change (ILUC) that leads to GHG emissions and biodiversity loss, and the impact on food prices that determine the availability of food for the poor.

A general feature of the indirect effects is that they work through systems that are larger and more complex than the production chain of biofuel. The effects induced by the biofuel system in these larger systems are intertwined with a variety of other processes in such a way that they are difficult to identify separately. Consequently, monitoring of the indirect effects of individual biofuels directly is impossible, and...
The objective of this paper is to provide a methodology for calculating the CO2 emissions from the ILUC for biofuel production based on historical data from national to global level
and demonstrate this methodology for biofuel consumption in the EU. We acknowledge that biofuel production generates more indirect effects than just the effects of ILUC, and that ILUC has more knock-on effects than just CO₂ emissions. This paper only focuses on the CO₂ emissions from ILUC. As mentioned above, in other studies agro-economic models are often applied to estimate the direct and indirect land use implications of biofuels. These models are complex. Often, some of the assumptions are not explicit and their results show a large variability. Here, we aim to be as simple and transparent as possible.

2. Methodology and data

In this paper, we quantify ILUC for cultivated biofuels consumed in the EU in 2007.³ In this methodology section we provide the data sources, assumptions and the calculation methods. In some cases a range is presented to describe a certain step of the calculation. By combining these values systematically, the range of results gives an indication of the uncertainty of the possible outcome.

We identify six steps in the approach.

1. EU biofuel consumption and share of EU-produced and EU-imported biofuels during 2007
2. Feedstock and origin of the feedstock for the biofuels
3. Energy yields per hectare for the various feedstocks in their region of origin taking the effect of by-products into account
4. ILUC calculation with historical data on land expansion and yield increase
5. Global land use conversions to agricultural land
6. CO₂ emissions from land use conversions

1. EU biofuel consumption and share of EU-produced and EU-imported biofuels during 2007

To determine the biofuel consumption in the European Union, EUROSTAT data on 2007 were used (EUROSTAT, 2009). The data also indicates that the final energy consumption in transport is less than the production and imports of biofuels. The EU both imports and exports biofuels. The assumption on which the biofuels are consumed and which of them are exported influences the calculation because the ILUC impact of imported biofuels may be different from EU-produced biofuels. To define the share of EU-produced and EU-imported biofuels in the final consumption, two opposite assumptions were made: the first is that all imported biofuels are consumed and EU-produced biofuels are exported, and the second is that all EU-produced biofuels are consumed and excess imported biofuels are exported again.

2. Feedstock and origin of the feedstock for the biofuels

In order to determine the land area necessary for the production of the consumed biofuels, information is needed about the types of feedstock used and where these are produced. The latter is important since yields of feedstock can vary between countries and regions. The feedstocks of EU-produced bioethanol are cereals (mainly wheat and barley) and sugar beet, which together form the bulk of the feedstock. Wheat and sugar beet are taken into account in the calculations. The main feedstock of EU-produced biodiesel is rapeseed (EU, 2008; FAO, 2008), with an estimated share of approximately 84% (European Biomass Industry Association, 2010) to 90% (EU, 2006). Other biodiesel feedstocks are sunflower oil, recycled oils and animal fats. Only rapeseed is taken into account in the calculations. Country data of imported bioethanol and biodiesel is based on data from the World Ethanol and Biofuels Report (F.O. Licht’s, 2009). The information on feedstocks is based on historical data. Therefore, for this part of the calculation we do not include different assumptions.

3. Energy yields per hectare for the various feedstocks in their region of origin taking the effect of by-products into account

The third step completes the calculation of the net land area necessary to produce the feedstock for the consumed biofuels. In this step we use data on the required hectares to produce a certain quantity of energy to convert the energy consumption per feedstock, which is the result of steps 1 and 2, to hectares. We make use of assumptions on the use of by-products (or co-products) to determine a minimum and maximum net land use to produce the energy. If by-products are not taken into account, the net land use is equal to the actual area that the crop occupies. However, by-products can be used as feed; therefore, part of the land can be attributed to these by-products.

The starting point is the energy crop yields that can be derived from monitoring data. The allocation of part of the land use to by-products is more complicated. If these by-products are applied as a source of energy, as is the case for bagasse, the by-product of cane ethanol, allocation or correction of the greenhouse gas balance is relatively simple, and can be based on the energy content of both products. However, by-products with high protein content are often used as feed. Rapeseed meal and dried distillers’ grain with solubles (DDGS) from wheat are examples. In this case, the protein-rich by-product has to be compared somehow with the biofuel in order to determine which part of the land use can be attributed to each product. A substitution method is used to make this comparison. In Europe, soy meal is an important source of protein in feed. In many cases, substitution of soy meal by biofuel by-products is quite likely. Data on the actual substitution are not available. Therefore, we assume soy meal is replaced and the land use for soy production can be reduced. This land can be subtracted from the direct (gross) land that is used for cropping the biofuel. Data and more details on this method are available in ECOFYS (2009), Eickhout et al. (2008) and JRC/CONCAWE/EUCAR (2007). Actually this can trigger additional effects, since the biofuel by-product will influence the feed market. Because we do not have enough information on the actual use of the by-products and their impact on the feed market we include two levels of substitution which together give an indication of the
uncertainty of these additional effects, including imperfect use of the by-product.

4. ILUC calculation with historical data on land expansion and yield increase

The assumptions on land use are the following:

a. The Renewable Energy Directive (RED) (EU, 2009) identifies certain land use types not permitted to convert to biofuel crops. In our calculation, we assume that these direct conversions do not take place, neither within Europe nor outside of it. Thus, no direct land use change for biofuels occurs on these lands and therefore all land use changes on these lands are ILUC.

b. All former production (tonnes) of the land occupied by biofuel crops is compensated for by either land expansion or increased yields. The change in consumption (Fig. 1) is assumed to be zero.
c. Using set-aside land for bioenergy crops does not result in ILUC. In 2007, it was permitted to grow bioenergy crops on set-aside land. These lands would have been fallow otherwise, so there is no production to replace and therefore no ILUC.

The actual locations of displaced production are determined in step 5.

So, excluding consumption changes, the displaced agricultural production from the net land area will be realised elsewhere by either yield increase (intensification) or land expansion. This may occur directly, for example if wheat is compensated for through a yield increase of wheat or through land expansion for wheat, but it can also result from displacement of other crops that can substitute one another. Since we do not know the actual array of substitutions, we assume that the reallocation of displaced production occurs in the same way as increase in global agricultural production has occurred in the past. The displaced agricultural production is treated as an additional demand, and the way this demand is fulfilled has the same behaviour as observed for agricultural production in the past. We take into account trends of yield increase and land expansion of all major crop types from the past years.

We include two variants:

1. All displaced agricultural production from the various feedstocks in various regions is reallocated over the world. The fraction production increase that results from intensification and the fraction production increase that results from expansion are determined by the world average.
2. The displaced agricultural production from a certain region is reallocated within the region. The fraction of intensification versus expansion is based on the regional figures.

Global and regional data on land use (agricultural land expansion) and yield increase is obtained from the FAOSTAT database on production (FAO, 2010). For the calculation of the average land expansion the relative land expansion between 1997 and 2007 of the crop groups is used. The yield increase of the crop groups is weighted according to the area harvested to translate yield increase into land (i.e. a crop with a low yield, in tonnes, and a 10% yield increase is weighted relatively the same as a crop with a high yield and a 10% yield increase). This assumption holds if the shares of the different crops do not change. Another assumption that has to be made with this is that the cropping densities do not change. The harvested area is used in the current calculation. Since area can be harvested more than once a year – cropping density higher than one – harvested area is not equal to land area. In the event the shares of the different crops and their cropping intensities do not change, the calculation with harvested area is valid. ILUC values are calculated with the formula below. The result from this formula is used as the percentage of the net land use area of the biofuel crop that is converted somewhere else to accommodate the displaced production that cannot be accommodated by yield increase.

\[
\text{Indirect land use as percentage of direct land use by the biofuel} = \frac{\text{Percentage increase in harvested area}}{\text{percentage increase in yield}} + \text{percentage increase in harvested area}
\]

\(^{4}\)Increase in yield is weighted over the harvested area.

In the first variant, we need an additional yield factor. Net land use is calculated for the world region (for example, the EU or South America) where the feedstock is cropped. Assuming the displaced production is cropped all over the world, this may lead to a somewhat different need for land since the average yield of agricultural crops is higher or lower in the region of the feedstock crop then in the world as a whole where the displaced production is allocated. In the second variant, the displaced production stays in the same region and therefore no yield factor was needed.

5. Global land use conversions to agricultural land

In order to transform ILUCs into emissions it should first be clear which former land cover has changed into the new agricultural land use, i.e. which land use conversions have occurred. For most countries, some information on land use for different years is available on FAOSTAT (resources database). Potentially, this information could be used to estimate land use transitions caused by agriculture. However, the data has a low level of detail on land cover, which is essential to determine the carbon content of vegetation and soils. To determine the land use changes that have occurred in the recent past, we use a global model simulation of the IMAGE model (MNP, 2006), which has been calibrated to FAOSTAT data from 1970 to 2000. IMAGE identifies 20 land-cover types. Land use changes towards 2010 are based on scenario calculations including actual biofuel figures until 2007 (Stehfest et al., in preparation). So, this data set is not purely monitoring but extrapolated (by modelling) data of 1970–2000 and 2007 biofuels data. The results from IMAGE are
maps of 1995 and 2005 land cover. Similar to the analysis in step 4 we calculated an average over all agriculture land and not specifically over the effect caused by biofuels (since we do not have a world without biofuels to compare with). In this conversion analysis based on IMAGE we analyse the conversion into arable lands as well as into cultivated grasslands. This ensures that cases where, for example, forest is converted to pasture and pasture to arable land, the effect of forest conversion is also included in the average. In combination with step 4 we also distinguish a regional and a global variant for this calculation.

6. CO₂ emissions from land use conversions

Land contains carbon stored in vegetation and soil. The amount of carbon depends on the type of vegetation and the type of soil. In general, agricultural land contains less carbon than natural land. We assume that the carbon in the vegetation is emitted into the air as CO₂ at the moment of the conversion. This is an important assumption, which may not necessarily be true, as removed biomass can be used for energy purposes or stored in other ways, for example in timber products. The carbon content in soil slowly changes to a new equilibrium after removing the natural vegetation. This equilibrium can be reached after several decades. While the emissions vary over time; for many biofuel emission calculations these ILUC emissions are calculated as a yearly average over periods of 20–50 years. Possibly, the carbon effect can even be the other way around. For example, if energy crops are grown on degraded land with almost no vegetation and low soil carbon content, then a net uptake of CO₂ might be the result.

In this final step, the land conversions from step 5 are converted to CO₂ emissions. The data on the carbon stored in the vegetation and the soils is based on Sabine et al. (2004); WBGU (1988) in IPCC (2001); and Carter and Scholes (2000), De Fries et al. (1999), Roy et al. (2001) in IPCC (2001). This data on global carbon includes information on pools in various biomes and the land area of the biomes. This is transformed into average carbon content per hectare per biome. The minimum and maximum values from the three sources are taken to construct a range. The loss due to conversion to arable land is calculated as the difference between these values and the minimum carbon content of arable land.

Emissions from land use intensification, which is the main contributor to increased agricultural production in the world, are not included in this study. Intensification of agricultural production can add to the emissions of GHGs in agriculture through higher emissions from fertilizer use or machinery use (Smith et al., 1997). We do acknowledge that these emissions can play a significant role, however, in this study we focus on the effects from land expansion and only include the effect of intensification on the total agricultural area.

Overall analysis

In summary, the set up of the overall calculation is as follows. We can identify which part of the energy consumption originates from which crop – measured in terajoules (TJ) – by using the figures on the total EU biofuel consumption, the share of EU-produced and EU-imported biofuels, and the feedstock and origin of the feedstock. Combining this with energy yields per hectare (TJ/ha) for the various feedstocks and the by-products that are produced leads to the net amount of hectares needed for growing these crops. By making assumptions on how the production of this occupied land is produced elsewhere, we determined the percentage of ILUC associated with the feedstock production. Subsequently, we use modelled data on the actual land use conversions to agricultural land that took place (1995–2005). By using data on CO₂ emissions from the different land use conversions we arrive at CO₂ emissions from ILUC caused by biofuel consumption (tonne CO₂/year). By dividing this through the energy consumption we arrive at emissions in gCO₂/MJ.

Energy from a certain feedstock and country (TJ)

\[
\times \text{net land use (ha/ T)} \times \text{ILUC } \% \times \text{yield factor } (-) \\
\times \text{conversion emissions (tonne CO₂/(ha year))}
\]

\[= \text{emission (tonne CO₂/year)} \] (2)

This is summed for all feedstock country combinations occurring in our datasets.

In order to assess the range of possible outcomes of this calculation, we combine the highest and lowest figures – in all possible combinations – for those steps where we included a range. This gives a good estimate of the range of possible outcomes, though not of their likelihood. The steps that have a high and low variant are: imports (step 1), net land use (step 3), ILUC (steps 4 and 5) and conversion emissions (step 6). This analysis results in 16 possible outcomes which together span the potential outcome space. We do provide an average of the ILUC emissions.

3. Results

This section starts with the results of the six separate steps. Subsequently, we describe the result of the final calculation of the emissions from historical biofuel consumption in the EU.

1. EU biofuel consumption and share of EU-produced and EU-imported biofuels during 2007

Final energy consumption of road transport in the EU27 was 49.714 TJ biogasoline and 279.488 TJ biodiesel. Under the assumption that all imported biofuels are consumed and that the excess of EU-produced biofuels is exported, the EU bioethanol consumption consists for 13% of imported bioethanol; and EU biodiesel consumption consists for 17% of imported biodiesel. Under the assumption that all EU-produced biofuels are consumed and that the excess imported biofuels are exported the EU bioethanol consumption includes 2% imported bioethanol and the EU biodiesel consumption 10% imported biodiesel (EUROSTAT, 2009).

2. Feedstock and origin of the feedstock for the biofuels

Table 1 displays the main exporters of biofuels to the EU. In the calculation, all smaller exporters are ignored and the exporters presented are considered to provide 100% of the import to the EU, for example, where Brazil and Pakistan provide 80% and 13% of the bioethanol imports in reality,
respectively, we recalculated this to be 86% and 14%. For biodiesel, the countries included account for 98% of the imports; for bioethanol, it is 93%.

A second element of the feedstock analysis is the share of the former set-aside area that is used for the production of biofuels. Since this land had no production before biofuels were cropped, this feedstock production does not induce indirect land use change. In 2007, the percentage of EU produced biofuel feedstock on set-aside land was 25% for wheat, 14% for sugar beet and 28% for rapeseed (EU, 2008).

Combining this information with Table 1 results in the figures in Table 2. Since 2009 the set-aside policy is abolished. For the calculation of current biofuel emission this means that all feedstocks in Europe should be treated similarly. This will cause the calculated emissions to increase.

3. Energy yields per hectare for the various feedstocks in their region of origin taking the effect of by-products into account

Table 3 presents the results of the calculations of energy yields per hectare for the various feedstocks in their region of origin. Note that inclusion or exclusion of by-products creates large differences (up to a factor five in case of soy).

In the calculation, we do not use the two extremes of Table 3, but a combination of both. For rapeseed, wheat and sugar beet, we assume that only 50% (lower assumption) or 90% (higher assumption) of the by-products is effectively used. The inefficiency of 50% or respectively 10% is considered to stem from unused by-products, inefficient use of by-products and a possible consumption effect that occurs due to higher levels of feed supply. For soy, we assumed variants of 90% and 100% efficiency because soy is mainly cultivated for the soy meal production. For palm oil and sugar cane, we assumed a 0% and a 100% variant. The by-products for these feedstocks are a relatively small part of the production; consequently, results are hardly influenced by these contrasting assumptions.

4. ILUC calculation with historical data on land expansion and yield increase

The model variant in which all displaced agricultural production is reallocated over the world produces just one global figure for ILUC, which is 32%. So, for each hectare of biofuel on land that is currently agricultural somewhere in the world, 0.32 hectares are converted to arable land. This assumes that agricultural production increase is developing according to the trend of the past ten years.

Table 4 presents the results for the regional approach of the ILUC calculation. In order to calculate the ILUC in the regional approach the same formula (1) was used for each region. A few exceptions were made on this method. First, set-aside area did not have production prior to the cultivation of biofuels, so no production is substituted on set-aside area and subsequently the ILUC is zero. Second, the FAO data for North America indicated that total agricultural production had increased over the period with less land. Therefore, we assumed that no extra land was converted to arable land. Here the question remains as to whether or not production was moved to

### Table 1 - Sources of biofuel imports to the EU.

<table>
<thead>
<tr>
<th>Biofuel</th>
<th>Exporter to EU</th>
<th>Feedstock</th>
<th>Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioethanol</td>
<td>Brazil</td>
<td>Sugar cane</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>Pakistan</td>
<td>Sugar cane</td>
<td>13%</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>USA</td>
<td>Soy</td>
<td>82%</td>
</tr>
<tr>
<td></td>
<td>Argentina</td>
<td>Soy</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Indonesia</td>
<td>Palm</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Malaysia</td>
<td>Palm</td>
<td>2%</td>
</tr>
</tbody>
</table>

Authors’ calculations based on F.O. Licht’s, 2009.

### Table 2 - Origin of feedstock (percentage).

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Import assumption 1</th>
<th>Import assumption 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bioethanol</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>13.0 14.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>38.9 44.3</td>
<td></td>
</tr>
<tr>
<td>Sugar beet</td>
<td>4.9 5.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29.7 33.7</td>
<td></td>
</tr>
<tr>
<td>Sugar cane</td>
<td>11.6 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.9 0.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100 100</td>
<td></td>
</tr>
</tbody>
</table>

| **Biodiesel** |       |       |
| Rapeseed     | 23.0 24.7 |       |
|              | 60.3 64.9 |       |
| Soy          | 13.9 8.7  |       |
| United states of America | 0.8 0.5 |       |
| Argentina    | 1.6 1.0  |       |
| Malaysia     | 0.4 0.2  |       |
| Total        | 100 100  |       |

### Table 3 - Average land demands per unit of energy accounting for the use of by-products.

<table>
<thead>
<tr>
<th></th>
<th>ha/TJ</th>
<th>ha/TJ</th>
<th>GJ/ha</th>
<th>GJ/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excl. by-products</td>
<td>Incl. by-products</td>
<td>Excl. by-products</td>
<td>Incl. by-products</td>
</tr>
<tr>
<td><strong>Bioethanol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cereals (EU-produced)</td>
<td>14.7</td>
<td>4.3</td>
<td>68</td>
<td>232</td>
</tr>
<tr>
<td>Sugar beet (EU-produced)</td>
<td>11.3</td>
<td>5.9</td>
<td>88</td>
<td>170</td>
</tr>
<tr>
<td>Sugar cane (import)</td>
<td>7.2</td>
<td>6.9</td>
<td>139</td>
<td>144</td>
</tr>
<tr>
<td><strong>Biodiesel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapeseed (EU-produced)</td>
<td>17.7</td>
<td>6.8</td>
<td>56</td>
<td>147</td>
</tr>
<tr>
<td>Soy (import)</td>
<td>54.1</td>
<td>10.8</td>
<td>18</td>
<td>92</td>
</tr>
<tr>
<td>Palm oil (import)</td>
<td>5.9</td>
<td>5.7</td>
<td>168</td>
<td>176</td>
</tr>
</tbody>
</table>
somewhere else. The regional approach assumes that this is not the case. Another exception is Europe. Total production in Europe has decreased, which is evidence that replaced production could not have been produced in Europe. Therefore, the assumption of regional replacement was not valid for Europe. Here we used the figure for the world outside Europe, which is nearly the same as the world average: 32%.

5. Global land use conversions to agricultural land

Table 5 displays the land use conversions in the world in total, as calculated by the IMAGE model. For the regional approach, this was further subdivided per world region.

<table>
<thead>
<tr>
<th>Biofuel feedstock</th>
<th>ILUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioethanol</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
</tr>
<tr>
<td>EU set-aside land</td>
<td>0%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>EU non set-aside</td>
<td>32%</td>
</tr>
<tr>
<td>Sugar beet</td>
<td></td>
</tr>
<tr>
<td>EU set-aside land</td>
<td>0%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>EU non set-aside</td>
<td>32%</td>
</tr>
<tr>
<td>Sugar cane</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>49%</td>
</tr>
<tr>
<td>Pakistan</td>
<td>19%</td>
</tr>
<tr>
<td>Biodiesel</td>
<td></td>
</tr>
<tr>
<td>Rapeseed</td>
<td></td>
</tr>
<tr>
<td>EU set-aside land</td>
<td>0%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>EU non set-aside</td>
<td>32%</td>
</tr>
<tr>
<td>Soy</td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>0%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Argentina</td>
<td>49%</td>
</tr>
<tr>
<td>Palm oil</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>48%</td>
</tr>
<tr>
<td>Malaysia</td>
<td>48%</td>
</tr>
</tbody>
</table>

<sup>a</sup> No production is substituted on set-aside area.

<sup>b</sup> In the period under analysis agricultural production in the US is increasing with decreasing agricultural land use.

6. CO₂ emissions from land use conversions

The minimum and maximum carbon pools according to the literature used in the various biomes were translated into CO₂ equivalents. The difference of these values and the carbon content of arable land are reported in Table 6.

Overall analysis

Overall, the analysis has produced 16 calculations with possible outcomes of the ILUC emissions of 2007 biofuel use in the EU. A summary of these calculations is given in Table 7. The first part of this table shows that the ILUC emissions are substantial compared to the emissions of a traditional fossil fuel, which is approximately 84 g CO₂ equiv/MJ: for bioethanol ILUC emissions are 26–154 g CO₂/MJ and for biodiesel 30–204 g CO₂/MJ when the conversion emissions, which are produced mostly during conversion itself, are spread over 20 years. These figures are 2.5 times smaller when spread over 50 years. A calculation that does not need a range of time to spread the emissions out is the carbon breakeven point, or payback time. This is the actual time it takes the biofuel system to actually start reducing carbon emissions. On average, these terms are 35 years for bioethanol and 50 years for biodiesel.

The differences in the results (Fig. 2) are caused by the ranges in assumptions and data that were used in several steps of the calculation. The largest differences were caused by the assumptions on conversion emissions (tonne CO₂/ha*year, step 6) and on net land use (ha/TJ, step 3) of produced biofuel. The remaining variation is due to
4. Discussion and conclusions

4.1. Uncertainties

As illustrated in the results section, the carbon emission from land use conversion is the factor that causes most variability in the results. In modelling studies with similar objectives, the uncertainty of conversion emissions is often not included (e.g. Burney et al., 2010; Searchinger et al., 2008). Searchinger et al. (2008) use an average conversion emission of 351 tonne CO₂ e-quiv/ha for all land conversions in the world. Using this figure in this analysis would obviously result in less variable results: ILUC emissions for bioethanol would be 34–56 g CO₂/MJ and for biodiesel 39–76 g CO₂/MJ (assuming an annualization period of 20 years). These figures are within the range of the calculations in this study. On average they are lower than the average of our calculations.

The second largest source of variability lies in the assumptions on the use of by-products that are included in the calculation of the net land use of biofuel cropping. The figures presented in the results section are estimates of the authors. This uncertainty can be reduced by collecting empirical data on the use of by-products of biofuel feedstocks.

The different assumptions regarding imports and the regional or global approach towards the location of the ILUC effects add little to the variability caused by the other two elements (Fig. 2). The latter is mainly caused by the assumption that European production was not replaced within Europe. Therefore, the majority of the biofuel production was treated similarly in both approaches.

Compared to modelling studies, as for example reported by JRC (JRC-IE, 2010), the values have a similar range. The JRC study reports feedstock specific values for biodiesel ranging from 14 to 337 g CO₂/MJ and for bioethanol of 19 to 151 g CO₂/MJ. Figures from an IFPRI study (Al-Riffai et al., 2010) fall completely in the feedstock specific ranges of this study, except for sugar cane in Brazil where we found higher emissions. Using the conversion emission used by Searchinger as shown above we would arrive at somewhat lower averages, which are close to the IFPRI study.

4.2. Methodology

Accuracy and reproducibility are of great importance in order for the methods to be adopted by policy makers. It is important to have the most recent information for accurate monitoring. However, fluctuations between years can be substantial; in which case a trend based on several years can be more useful for policy making. The time lag is longer using a longer period to determine the trend. In the present study, we used a period of ten years: 1997–2007. This is a relatively short period in terms of development in agriculture. However, this is quite a long period in the current developments of biofuel production. So far, the biofuel production is relatively small compared to overall production and production increase, which justifies the time period of ten years.

The approach in this study is based on the assumption that agricultural production and land use is a regional or global system. Direct land use for cultivating feedstocks was calculated in a regional to country specific way, but we assume that the ILUC will spread regionally or globally. This may not be the case under all circumstances. Some countries will claim that they can control the indirect effects of land use change and that policies should acknowledge that. We think that for many commodities, the assumption of a regional or global market will hold.

The way biofuels are accommodated (by intensification or expansion) is derived from the aggregation over all agricultural crops. This is different from analysing the difference between a scenario with and a scenario without biofuels. In that case the effect of biofuels would be judged by taking in use the extra amount of hectares that may be less productive and cause biofuels to be more negatively evaluated. In this study expansion and intensification due to biofuels is treated similar as for food and feed.

For the interpretation of the results, it should be clearly noted that this analysis focuses only on indirect effects of land use change and particularly on land expansion. Emission effects from land use intensification are not included. Other indirect effects were assumed to be less relevant for this approach because this analysis is a historical analysis and not

Figure 2 – Variability in ILUC emissions resulting from the different assumptions.
a predictive approach such as many of the modelling approaches. Examples of additional effects that some forward looking modelling approaches incorporate are: changes in consumption due to increased demand for agricultural products and a difference in average yields between the case with and the case without biofuels.

In step 4 the change in consumption (Fig. 1) is assumed to be zero. This is a rather strong assumption. Increasing prices due to biofuels might induce a reduction in consumption of other products. The consumption effect is estimated to be in the range of 0–50% of the produced biofuels (IIASA, 2009; JRC-IE, 2010). However, there are strong arguments to not attribute consumption effects to a more favourable (i.e. smaller) ILUC since this would mean that commodities are diverted from human use. Few policymakers are likely to argue for reduced food consumption, especially because it will affect those that are already malnourished, as a desirable way of reducing greenhouse gases (Searchinger, 2010).

On intensification we assume that the share between expansion and intensification under a biofuels scenario is the same as without biofuels. In general, most other studies would see a slightly higher contribution from expansion to the production of biofuels, than in the counterfactual case, as the long-term yield improvements, which are rather linked to autonomous technological progress than to price effects, are not changed when introducing biofuels. In this study, the changes in yields are incorporated in the observed data. These yield changes are as attributed to the biofuels in the same way as to the other commodities.

Another effect is higher energy consumption due to increased supply of energy by the biofuels. This is not accounted for in this study.

4.3. Monitoring versus modelling in a policy perspective

ILUC and its resulting emissions are an important issue in discussions on the sustainability of biofuels. Discussions focus on how to quantify the effects of ILUC and if this should be incorporated in sustainability criteria; and if so, how. The two main options for quantification of ILUC effects are monitoring and modelling. The most important difference is that most modelling approaches aim to predict future land use under a baseline and a certain policy scenario and a monitoring approach is based on historical data. The approach in this study is an approach in between modelling and monitoring. The approach is partly based on data from past events, for example on actual biofuels consumed, land expansion area and yields, for the remaining part assumptions were made. For the parts based on historical data this approach has less uncertainty compared to modelling approaches. We conclude therefore that in this aspect, the approach has fewer uncertainties and may be easier to be adopted by policy makers. Another advantage of this approach is that it can easily be reproduced, which may add to the acceptability of this method and its results.

4.4. Policy perspectives

This analysis shows that based on ILUC effects alone there is evidence that biofuels do not mitigate emissions. Additionally, the production of biofuels can have additional negative social and ecological effects that are not presented in this study. However, the arguments to promote biofuels are more extensive than emission reductions only, for example energy security. It is a policy decisions how to weigh these arguments.

Policy questions that arise from this kind of analyses are, for example, if biofuels are the best way to mitigate GHG emissions from transport and, if not, what possible alternative ways to mitigate those emissions are. Others perceive the developments in first generation biofuels as an essential step towards second-generation biofuels that may have a better GHG balance. This may also be an argument to continue the promotion of biofuels even though the current contribution to GHG reductions is uncertain.

Policies that are strongly related to the policies aiming at promoting biofuels are the LULUCF (Land Use, Land use Change And Forestry) accounting rules under the Kyoto protocol (Searchinger et al., 2009) and REDD (Miles and Kapos, 2008), which both aim to reduce emissions from land use change. LULUCF accounting rules regulate part of land use change emissions for ANNEX 1 countries and REDD may become part of international agreements in the future. It is evident that accounting for all land use emissions in all countries accurately could ensure a much more logical consideration to cultivate biofuel crops, since emissions from land use changes should be accounted for. However, biofuel policies as implemented currently are mainly unilateral arrangements and have the risk that the land use change leaks towards countries that have fewer obligations to reduce emissions.

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