European Commission

JRC SCIENCE AND POLICY REPORTS

Estimates of indirect land use change from biofuels based on historical data

Koen Overmars*

Robert Edwards**

Monica Padella**

Anne Gerdien Prins***

Luisa Marelli**

* Koen Overmars Consultancy

** European Commission, Joint Research Centre, Institute of Energy and Transport, Sustainable Transport Unit

***PBL Netherlands Environmental Assessment Agency

2015

Report EUR 26819 EN

Joint Research Centre

European Commission

Joint Research Centre

Institute for Energy and Transport

Sustainable Transport Unit

Contact information

Luisa Marelli

Address: Joint Research Centre, Via Enrico Fermi 2749, TP 230, 21027 Ispra (VA), Italy

Email: luisa.marelli@jrc.ec.europa.eu

Tel: +39 0332 78 6332

https://ec.europa.eu/jrc

JRC91339

EUR 26819 EN

ISBN 978-92-79-39930-5 (PDF)

ISBN 978-92-79-39931-2 (print)

ISSN 1831-9424 (online)

ISSN 1018-5593 (print)

doi: 10.2790/3647

Luxembourg: Publications Office of the European Union, 2015

Abstract

Indirect land use change (ILUC) emissions from biofuels are commonly estimated with sophisticated economic models of world agriculture. Because these are often complex, the JRC in collaboration with K. Overmars and the Netherlands Environmental Assessment Agency (PBL) has developed an alternative approach based on "historical" data.

This approach gives simple and transparent estimates of ILUC emissions in recent years, even if the method is less rigorous in principle than estimates based on sophisticated economic models. The purpose is to understand how much crop expansion (and hence ILUC) would be attributed to 1 megajoule (MJ) biofuel if the crop had been used for that purpose.

ILUC emissions calculated with this methodology are broadly in line with results from economic models (both in magnitude and in the relative ILUC impact of biofuels from different crops), showing a lower impact of cereals and sugar crops compared to vegetable oils.

Acknowledgments

We thank Dr. Fabien Ramos and Dr. Bettina Baruth for their precious comments and review of this work.

Disclaimer

Table of Contents

Glossary

Arable land

Land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category (FAOstat Glossary[1]).

Cropped area

The sum of areas under arable land and permanent crops.

Cropping intensity

The ratio between harvested area and cropped area.

Harvested area

The area from which a crop is gathered. Therefore, it excludes the area from which, although sown or planted, there was no harvest due to damage, failure, etc. It is usually net for temporary crops and sometimes gross for permanent crops. If the crop under consideration is harvested more than once during the year as a consequence of successive cropping (i.e. the same crop is sown or planted more than once in the same field during the year), the area is counted as many times as harvested. However, area harvested will be recorded only once in the case of successive gathering of the crop during the year from the same standing crops (FAOstat Glossary[1]).

Permanent crops

These crops (such as cocoa, coffee and rubber) are sown or planted once, and then occupy the land for some years and need not be replanted after each annual harvest. The category includes flowering shrubs, fruit trees, nut trees and vines, but excludes trees grown for wood or timber (FAOstat Glossary[1]).

---

[1] http://faostat.fao.org/site/379/DesktopDefault.aspx?PageID=379

Summary

Indirect land use change (ILUC) emissions from biofuels are commonly estimated with sophisticated economic models of world agriculture. Because these are often complex, the JRC has evaluated and developed two alternative approaches. The "historical approach" is one of them, and is presented in this study. The other is presented in the report "Historical deforestation due to expansion of crop demand: implications for biofuels" (JRC, 2014).

This study, made in collaboration with the Netherlands Environmental Assessment Agency (PBL) and K. Overmars, refines the "historical approach" of Overmars et al. (2011), to reduce the range of uncertainty in the results. The approach is transparent and gives simple, clear estimates of ILUC emissions in recent years, even if the method is less rigorous in principle than estimates based on correctly calibrated economic models.

The purpose is not to model the impacts of the EU biofuels policy in 2020, but to understand how much crop expansion (and hence ILUC) would be attributed to 1 megajoule (MJ) of biofuel if the crop had been used for that purpose.

The main assumption of the method is that an increase in crop demand due to biofuels would drive increased yield and crop area in the same proportions as they have increased with time in the past[2]. Thus, historical data are used to assess what proportion of all increase from production came historically from yield growth and what proportion from area growth[3]. Historical data are derived from Food and Agriculture Organization (FAO) statistics for 2004-2012.

The main improvement made in this study with respect to the Overmars et al. (2011) method consists in how estimated ILUC emissions are divided between biofuels and their by-products. We now allocate part of the biofuel ILUC emissions to the by-products (used as animal feed) on the basis of their energy-content compared to biofuels: this is consistent with the methodology set out in Annex V of the Renewable Energy Directive (RED) for the calculations of direct emissions for biofuels production. For comparison, we also implement allocation by 'economic value', which has the advantage of better capturing the capacity for an animal-feed by-product to replace crops. This resulted in moderately different ILUC emission estimates.

---

[2] In fact this may overestimate the contribution of yield increase and therefore underestimate ILUC, because it assumes that yields grow only due to an increase in demand, whereas in fact a large part of the yield increase would happen anyway, due to technical progress. Furthermore, we did not account for additional emissions from the assumed demand-induced yield intensification, as well as the lower yield on new cropland, which also leads to underestimation of ILUC.

[3] For example, suppose making 1 GJ of a particular type of biofuel requires 0.05 ha of cropland, (after allocating half of the total 0.1 ha to by-product). And suppose that 20% of the production growth historically came from area increase for this crop (and 80% from yield increase). Then we only attribute 0.01 ha to crop area expansion due to making 1 GJ biofuel.

ILUC results for a biofuel from a particular feedstock in one region depend on how much one assumes the extra crop demand is provided by changes in imports, rather than local production. Here we present a range of assumptions and a "*best-estimate*".

In order to estimate the greenhouse gas (GHG) emissions resulting from the estimated crop area increases, we apply and compare two independent methods. The first one is the Integrated Model to Assess the Global Environment (IMAGE), developed by the Netherlands Environmental Assessment Agency (PBL), and the second is the Cropland Spatial Allocation Model (CSAM) developed by the JRC. The choice of the method did not much affect the results.

We present the ILUC emission results (Table 18) in terms of gCO_2/MJ of biofuels made from different EU and foreign crops. **Our ILUC emissions are broadly in line with results from economic models, both in magnitude and in the relative ILUC impact of biofuels from different crops.**

Introduction

A set of specific mandatory targets for the EU transport sector aims at achieving the overall objective of a sustainably fuelled European transport system, implying that "alternative" fuels must ultimately come from sustainable renewable sources.

Biofuels are expected to play a crucial role in achieving the mandatory targets set by EU legislation[4]. According to the National Renewable Energy Action Plans (NREAPS) that Member States presented to the European Commission (EC) in 2010, more than 85% of the RED target for transport will be achieved through biofuels; predominantly biodiesel (about 70%) and ethanol (about 30%) in road fuels. Almost all of this would come from "first-generation" biofuels, made from agricultural crops. This raised a worldwide debate about the environmental implications of the policy, because land use change (LUC) is one of the main concerns related to the impact of first-generation (and to a lesser extent of second-generation) biofuels.

If biofuel crops are grown on land that has not previously been arable land, such as pasture or forest, this "*direct* land use change" (DLUC) usually results in an immediate loss of carbon store in above- and below-ground biomass (vegetation), and a more gradual decline of carbon in the soil organic matter (SOM). However, frequently crops for biofuels are diverted from existing food production. Then the "hole" in the food supply is filled partly by the expansion of cropland around the world, and this is likely to lead to carbon emissions from *indirect* land use change (ILUC). EU Directives (Renewable Energy Directive – RED, and Fuel Quality Directive – FQD) set out the rules for the calculation of the GHG savings for individual plants and biofuel pathways. Emissions from cultivation (including DLUC if it occurs) are included in the methodology. However, emissions from ILUC are not included. Both directives mandate the EC to assess the impact of ILUC and to examine regulatory options for addressing it[5].

ILUC cannot be measured directly; it is commonly determined by making use of existing agro-economic models, which seek to look at the **global land use change response** to increased demand for biofuels. Several economic models have been used to evaluate the ILUC effects of biofuels, but they contain many parameters that are determined by econometric fitting to historical statistical data, with significant uncertainties. Wicke et al. (2012) provide an overview of the current status of ILUC modelling approaches highlighting their criticalities and uncertainties.

---

[4] Directive 2009/28/EC on the "Promotion of the Use of Energy from Renewable Sources" (Renewable Energy Directive – RED) set a 10% target for each Member State for the share of renewable energy in transport by 2020. Directive 2009/30/EC (amendment to the Fuel Quality Directive – FQD) sets a target for fuel suppliers to reduce life-cycle GHG emissions from fuel and energy in transport by at least 6% by 2020 compared to the EU average level of fossil fuels in 2010.

[5] This obligation was the object of the Commission proposal COM(2012)595 of October 2012.

Economic models provide estimates of the total change in crop area for a given increase of demand for biofuels in different world regions[6]. Some models also predict the area of land converted from pasture, forest or natural land into cropland within each region, but in most cases they do not specify where in the economic regions the extra production will take place. To calculate carbon stock changes resulting from land conversion, economic models must be combined with biophysical or other land use models. This is the correct scientific approach to an inherently complex problem, but it must rely on hundreds of assumptions and parameters contributing to the model results.

The method developed in this study is a simplified approach aiming at providing an alternative to economic models to estimate the magnitude of ILUC area and emissions.

Unlike the assessments generally carried out through economic models, this "spreadsheet" analysis does not project future impacts of biofuel policies, but works out how much crop expansion (and hence ILUC) would be attributed to the amount of crop needed to make 1 MJ of biofuel.

Spreadsheet estimates of ILUC area present challenges such as:

1. How to deal with by-products?
2. What is the contribution of crop imports?
3. What fraction of extra crops for biofuels would come from extra yield increase?
4. What is the yield on new cropland compared to the average of existing cropland (marginal versus average yield)?
5. The emissions caused by the measures used to increase yield in response to extra demand for biofuels.

In principle, economic models can handle all these challenges, even if point 4 is sometimes not considered, and point 5 is almost always neglected.

The issue of by-products might be dealt with by building a spreadsheet calculation based on a train of consequences. However, in practice these consequences are very complex and numerous, and results vary greatly depending on which consequences are selected.

Another approach was the spreadsheet analysis of ILUC based on historical data described by the Netherlands Environmental Assessment Agency (PBL) (Overmars et al., 2011). In this study, simplification was achieved by assuming (for point 3) that increasing demand through biofuels would increase yield and area at the same proportions as happened historically. This may overestimate yield increases, which are

---

[6] The distinction between direct and indirect land use change makes sense only for a particular batch of biofuels, when one knows which field it came from. For a whole policy, or entire production of biofuel, there is just one land use change effect, which is the sum of all the direct and indirect effects of the particular batches. The models do not distinguish which feedstock is grown on "new" or "old" land: they simply look at the consequences of crop demand changes on land area. Thus one can call the effect simply "land use change" (JRC, 2010).

largely a function of technology change in time (progress) and not demand, but it puts a minimum on ILUC emissions.

PBL (Overmars et al., 2011) dealt with challenges 1 and 2 (above) by considering alternative scenarios, which described best- and worst-case assumptions. This provided upper and lower limits for ILUC emissions, but these were very wide apart, making it difficult to draw policy conclusions.

The aim of the present work is to narrow down the range of variation in Overmars et al. (2011), while preserving the transparent and historical basis of the PBL approach. Thus, to answer the challenges 1 to 3 to spreadsheet models (listed above):

1. we use allocation to deal with by-products, in the same way as it is used, for example, for direct-emission calculations in the RED (i.e. emissions are attributed to biofuels and their by-products in proportion to their energy content defined by lower heating value);
2. as well as presenting the possible range of estimates, we make a best-estimate of the share of crop imports by comparing domestic production to the volume of world trade;
3. we retain the simple historical PBL method of estimating the contribution of yield increase, even if this tends to underestimate ILUC.

We do not account for points 4 and 5 above, and acknowledge this means we probably tend to underestimate ILUC.

Finally, we compared the PBL-IMAGE method (PBL, 2012) for converting crop area expansion to ILUC emissions using a completely different approach, which had been independently developed by the JRC (CSAM) (Hiederer et al., 2010).

Considering all the limitations described above, our method is less rigorous than economic models and does not pretend to replace economic models in ILUC estimates. Its aim is to put results in perspective and provide a transparent analysis that can easily be reproduced.

The present report, after a detailed description of the method, provides a set of ILUC estimates for several biofuel pathways, including first- and second-generation biofuels.

1. Method

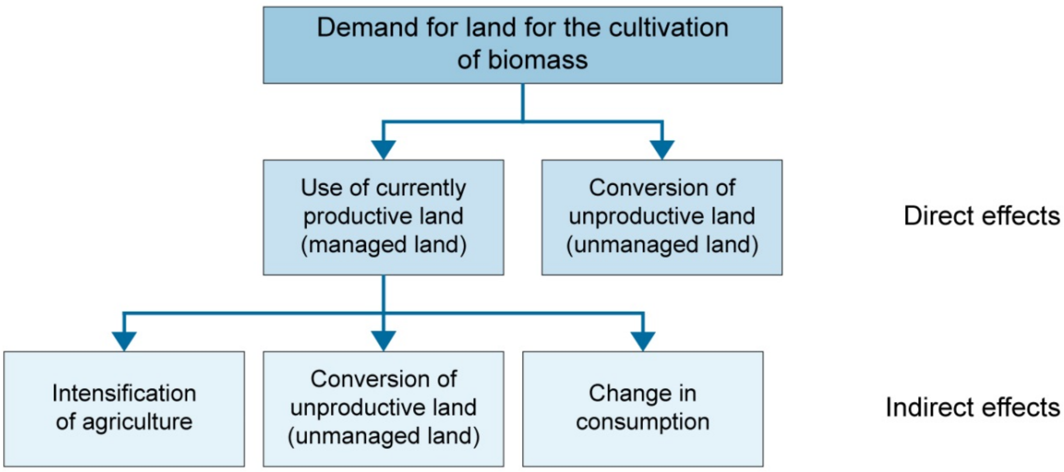
1.1 General description

The main assumption of the method to estimate ILUC from biofuels on the basis of historical data is that increasing crop demand will increase yield and area in the same proportions as happened historically. We look at historical data to estimate how much of the production increase will come from area and how much from yield, assuming that each extra tonne of production increases as a combination of area expansion and increased yield.

Land conversion for biofuels will directly or indirectly lead to conversion of currently unproductive lands (such as natural areas) and/or intensification of agriculture, resulting in higher yields (see Figure 1).

The effects on land expansion and yield increase due to the increased demand for biofuels are considered to be the same as the increase in demand from the other sectors of the economy (food, animal feed and fibre).

Figure 1. Direct land use for bioenergy and its indirect effects.



Source: Overmars et al., 2011.

The part of the production increase associated with biofuel demand caused by land expansion of displaced crops is considered to be the indirect land use change (ILUC).

For each region/country[7], data on harvested area and yields of all agricultural products (aggregated per crop groups[8]) from FAOstat[9] are used to determine the area and yield changes[10].

[7] The regions/countries considered in this report are the ones used by Laborde (2011) (IFPRI, International Food Policy Research Institute) in the MIRAGE (Modeling International Relationships in Applied General

The share of the area expansion that contributes to the production increase is determined as follows:

$$\textit{fraction of prod. increase from area expansion} = \frac{\%\ \textit{area expansion}}{\%\ \textit{area expansion} + \%\ \textit{yield increase}}$$

Equation 1

Choice of time period

The choice of the time period to estimate the % area expansion and yield increase in Equation 1 is critical for the final ILUC results.

On the one hand, we wish to use data that are as recent as possible; on the other, we need to average over many years to minimise annual fluctuations (Figure 2).

Lywood et al. (2009)[11] indicate there is no advantage in using periods of more than four years for cancelling annual variations. The most recent data are for 2012; therefore we chose to average and compare the periods 2004-2008 and 2008-2012.

Equilibrium) model to estimate the ILUC emissions included in the 2012 Commission proposal COM(2012)595. They are: Brazil; CAMCarib (Central America countries and Caribbean countries); China; CIS (Commonwealth of Independent States); European Union (EU); IndoMal (Indonesia and Malaysia); LAC (Other Latin American countries); RoOECD (Rest of OECD countries); SSA (Sub-Saharan Africa); USA; RoW (Rest of the World).

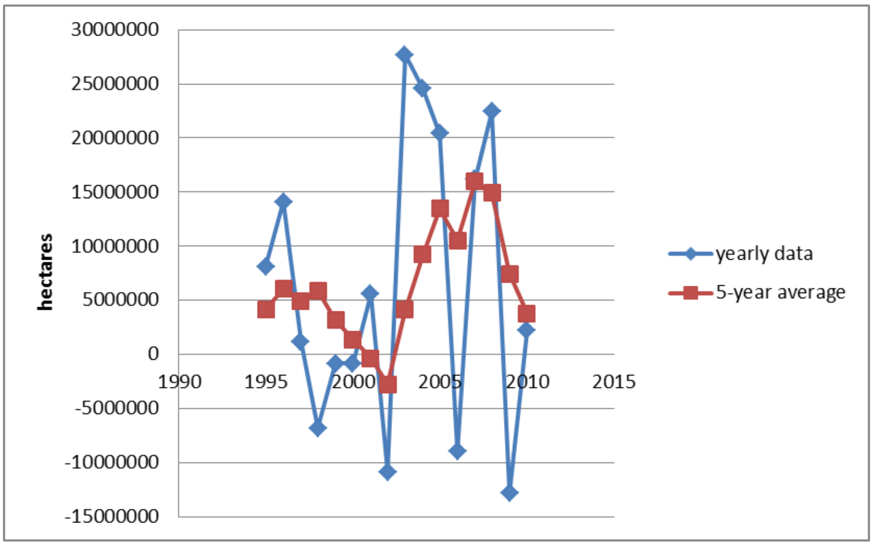
[8] The crop groups included in our calculations are: cereals, citrus fruit, fibre crops (primary), fruit (excluding melons), oilcakes equivalent, pulses, roots and tubers, treenuts, vegetables and melons, and fodder crops when available for the considered time period (excluding pumpkins for fodder which we may suppose is estimated since it remains steady for several years and then jumps), sugar beet and sugar cane.

[9] FAOstat website: http://faostat3.fao.org/download/Q/QC/ accessed 10 November 2014.

[10] The yield increase of the crop groups is weighted according to the harvested area to translate yield increase into land. This assumption holds if the shares of the different crops do not change.

[11] Lywood et al. (2009) show that for the six crops considered in their study, there is a large negative autocorrelation of annual yield changes between one year and the next; this indicates that 1-year yield changes (in part driven by short-term external agronomic factors) are followed by a reversion in yields once the external perturbation ends. When using a time-span of four years the magnitude of autocorrelation is minimised.

Figure 2. Area changes over all crop groups for the world for differences in five-year moving averages and one-year differences.



Source: FAOstat data.

To illustrate how the fraction of production increase from area expansion (calculated by using Equation 1) changed over time, we estimated it over different time periods. Table 1 shows the results comparing:

1. in the second column, the change in harvested area and yield between the five-year averages for 2000-2004 and 2004-2008;
2. in the third column, the change in harvested area and yield between the five-year averages for 2004-2008 and 2008-2012.

So, if the calculation were to be updated with future data as it becomes available, we can expect the results to change again.

Table 1. Fraction of production increase from area expansion calculated using Equation 1

	2000-2008 (avg 2000-2004 and avg 2004-2008)	**2004-2012** (avg 2004-2008 and avg 2008-2012)
Brazil	0.76	0.30
CAMCarib (Central America countries and Caribbean countries)	0.19*	0.32
China	0.24	0.42
CIS (Commonwealth of Independent States)	0.22	0.20
European Union (EU)	0.26*	0.08*
IndoMal (Indonesia and Malaysia)	0.56	0.64
LAC (Other Latin American countries)	0.61	0.97
RoOECD (Rest of OECD countries)	0.09*	0.08
SSA (Sub-Saharan Africa)	0.59	0.45
USA**	0.03*	0.01
RoW (Rest of the World)	0.53	0.47

* The % change in harvested area is negative (harvested area decreasing).

** For USA, fodder crops are not included in the calculation of harvested area and yield since in FAO databases they show unexplained plateaus and jumps and they come from a mix of different data (unofficial, trend or estimates).

Most regions/countries experienced an increase in harvested area and yield in both periods. If an extra tonne of biofuel feedstock is produced, this increase in production will be covered by a fraction of yield increase and a fraction of land expansion. Among these countries, some (such as Brazil but also CIS, SSA and RoW to a lesser extent) registered a consistent decrease in the fraction of area expansion in the second time period (2004-2012) compared to the previous one; while for others (China, IndoMal and LAC), the fraction of area expansion was bigger in recent years (2004-2012) compared to the previous ones.

Table 1 shows that while a few countries/regions experienced negative changes in area, yield always increased. For the period we used in further calculations (2004-2012), this only happened in the EU. Here we have an anomaly: in this case Equation 1 would predict, incorrectly, that a further increase in demand would see a further reduction in area in the EU. This is explained by the fact that recently abandoned land is easily available for re-conversion to cropland, so that a *reduction* in crop area is also an indicator of the ease of area change. Therefore, in this case, we used the absolute value of the % area expansion in Equation 1.

Cropping intensity

ILUC depends on the expansion of *cropland* area rather than *harvested* area. Therefore, it would be preferable to estimate ILUC starting with data on cropped area (rather than harvested area). However, in FAO databases only *total* cropped area is reported[12], and it is aggregated for all crops. So it is of little use for the purposes of this analysis.

The difference between cropland and harvested area can be explained by the increase in cropping intensity and fallow land (see Appendix 2). Cropping intensity is greater than one if fields are cropped more than once a year, and less than one if the land is defined as cropland but is not actually harvested. As cropping intensity tends to increase with time, using harvested area instead of cropped area tends to overestimate ILUC. However, as we explain in Appendix 1 and 2, the lack of consistent input data makes correction for cropping intensity problematic, resulting in strong inconsistencies in the results for different regions. Therefore, we could not include this correction in the main results. However, as an uncertainties analysis, we show in Appendix 1 the effect on the results of correcting for changes in cropping intensity using the available data.

The advantage of using statistical historical data is that all economic effects on crop area and yield are included, since they are the real-world outcomes. However, this may overestimate the contribution of yield increase, and thus may underestimate ILUC (see discussion in Section 4).

We assume that the extra demand for biofuels does not affect the demand of the crop for other uses. Therefore, unlike all economic models, this methodology does not take into account reductions in food consumption due to increased crop demand for biofuels, and hence does not reduce ILUC emissions as a consequence of food reduction (Laborde, 2011; Searchinger et al., 2015).

1.2 Detailed description

In our analysis we include the following first-generation biofuel feedstocks: wheat, maize, sugar beet, sugar cane, rapeseed, soybean, palm oil and sunflower. Some second-generation feedstocks are also considered for the regions where the production of that specific crop is relevant: wheat straw, willow, miscanthus and jatropha, (Table 2).

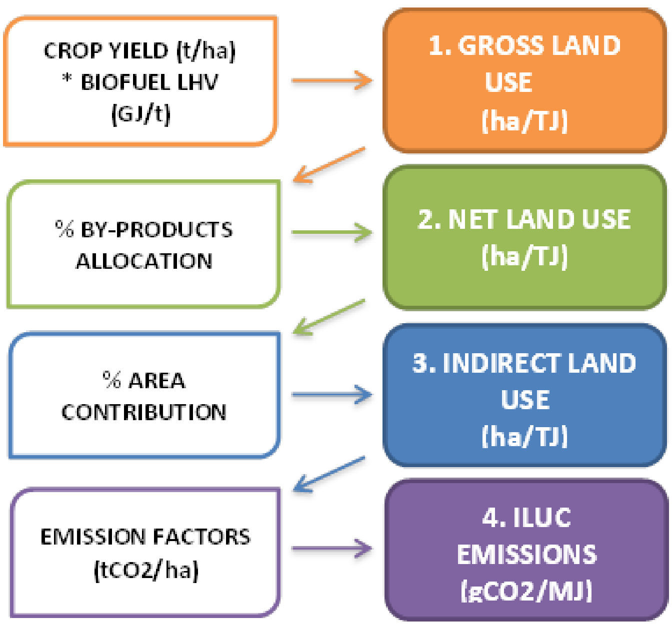
[12] Total arable land plus total land under permanent crops, per region.

Table 2. Feedstocks and countries included in the analysis

Biofuel	Feedstock
Ethanol	EU wheat
	EU sugar beet
	US maize
	Brazil sugar cane
	EU switchgrass or miscanthus
	EU wheat straw
Biodiesel	EU rapeseed
	US soy
	LAC soy
	Indonesia palm oil
	Malaysia palm oil
	EU sunflower
	Jatropha (Africa)
	EU willow or poplar

ILUC area and ILUC emissions have been calculated through the following procedure/steps, shown in Figure 3 and described below:

Figure 3. Procedure/steps to estimate ILUC area and ILUC emissions



STEP 1. Starting from the crop yield (tonne/ha) and the lower heating values (LHV) of biofuels (expressed in gigajoule per tonne of crop - GJ/tonne), we estimate the amount of land necessary to produce 1 GJ of biofuel from a specific crop in a specific region (**gross land use per crop and region**). There is no correction for marginal versus average yield ("challenge 4" described in the Introduction).

STEP 2. After "allocation to by-products", we obtain the fraction of land use attributed only to biofuels (**net land use per crop and region**).

We use two methods to allocate land between biofuels and by-products: one is based on their respective energy content (RED method) and the other is based on the economic value of the two products.

a. By-product allocation by RED method
   This method follows the allocation rules specified in the RED (Annex V) for the calculation of direct GHG emissions from biofuels production. This allocates the emissions from cultivating a crop to the biofuels and by-products according to their energy contents (LHV) except in the case of straw and other low-value residues, which are not allocated emissions. We apply the same methodology to allocate the land use.
b. By-product allocation based on economic value
   Crushing of oilseeds produces crude vegetable oil (an intermediate product that is later refined and transformed to biodiesel) and oilseed meals, which are used for animal feed. We allocate part of the land use change for oilseed cultivation and crushing to the oilseed meal by-product. That is done of the basis of the economic value of the oilseed meal as a fraction of the total value of the oilseed meal plus crude vegetable oil.
   However, in ethanol production, the equivalent of crude vegetable oil is the sieved "wine" before distillation, for which there is no market price. Therefore a different way has to be found. It would be inappropriate to allocate land use using the prices of the DDGS[13] and ethanol, because that of ethanol has a large added value from distillation. Our solution is to allocate to DDGS according to its value compared to the feedstock cost. This makes sense because DDGS is returned to the animal feed sector, where it mitigates the extra crop-land needed for biofuel.

STEP 3. The crop production increase is considered to come partly from area expansion and partly through yield increase, and the fraction from area expansion[14] has been estimated applying Equation 1. We simply consider the % changes in harvested area and

[13] DDGS = distilled dried grains with solubles, the by-product of ethanol-from-cereals production.

[14] We consider the change in harvested area in the rest of the report, and the arable land and cropping intensity in Appendix 1.

yield for all agricultural products between the five-year averages of 2004-2008 and 2008-2012 as explained in Section 1.1. We use two different approaches to calculate the area-contribution-factors; these represent the upper and lower limit of the range of possible values. The reality lies between the two limits.

In the ***local approach*** (local ILUC), we assume that extra crop production takes place in the region where crop is diverted to biofuel. Then the area contribution factor for each region is applied.

In the ***exporting regions*** approach[15], the extra crop production is assumed to occur in the world regions that export that crop group, no matter where the biofuel is actually produced. In this case, the area contribution factor is the average of exporting regions weighted by their share of net exports.

For both approaches, the net land use per crop (expressed as ha/TJ biofuel) are multiplied by the area contribution factors to estimate ILUC area (in ha/TJ biofuel).

Our best-estimate of ILUC area is a weighted average of the regional and exporting regions results, as detailed in the results section.

STEP 4. To estimate the emissions due to cropland expansion from ILUC area results (ha/TJ biofuel), we apply emission factors (tCO_2/ha) given by two methodologies:

- the Integrated Model to Assess the Global Environment (IMAGE) developed by PBL;
- the Cropland Spatial Allocation Model (CSAM) developed by JRC.

Combining the ILUC number with the emission factors, we finally obtain the emissions associated to the ILUC in gCO_2/MJ biofuel.

2. Data

This chapter focuses on the data and data sources used in this study.

Yields

Food-crop yields are the average yields per crop and per region or country from 2004 to 2012 from the FAOstat database[16] (Table 3).

For jatropha, (IFEU, 2011[17]) data based on Reinhardt et al. (2008) have been used, while for willow/poplar, switchgrass/miscanthus, we assume that their dry-matter yields are 1.57 times the EU wheat yield at traded water content (JEC-WTWv2c, WTT, March 2007 report).

---

[15] A yield factor is applied in the exporting regions approach, to account for the difference in yield for the biofuel crop between the region and the world exporters.

[16] FAOstat website: http://faostat3.fao.org/download/Q/QC/ accessed 4 December 2014.

[17] Institut für Energie und Umweltforschung (Institute for Energy and Environmental Research).

Table 3. Yields of different feedstocks

	Feedstock	Yield (tonne/ha)
First-generation		
	EU wheat	5.28
	EU sugar beet	65.61
	US maize	9.41
	Brazil sugar cane	76.52
	EU rapeseed	3.07
	US soy	2.83
	LAC soy	2.45
	Indonesia palm oil	17.74
	Malaysia palm oil	21.49
	EU sunflower	1.77
Second-generation		
	EU wheat straw	3.36
	Jatropha (Africa)	4.16
	EU willow or poplar*	8.29
	EU switchgrass or miscanthus*	8.29

** Dry-matter yield (otherwise it is the yield at traded water content).*

Biofuel and by-products per tonne of crop

Table 4 shows the energy content, expressed as lower heating value (LHV), of the biofuel obtained from a tonne of the different crops, and the LHV of the related by-products per tonne of the same crop.

The ratio between the biofuels energy content and total energy content (column C) is used to allocate land use to by-products in line with the method prescribed in Annex V of the RED, based on LHV content (except for low-value residues like straw, which are not allocated any emission).

Table 4. Lower heating values (LHV) and ratio

	A. LHV biofuel (GJ/tonne of crop)	B. LHV by-product (GJ/tonne of crop)	C. LHV biofuels ratio A./(A.+B.)
Wheat	8.04	6.20	0.56*
Sugar beet	2.08	0.84	0.71
Maize	8.76	4.92	0.64
Sugar cane	1.84	0.00**	1.00
Rapeseed	15.62	9.22	0.63
Soybean	6.99	12.86	0.35
Palm (fresh fruit bunch)	8.33	0.48	0.95
Sunflower	16.33	8.91	0.65
Wheat straw	7.19		0.00*
Jatropha seed	8.56	13.65	0.39
Willow or poplar	6.17	0.00	1.00
Switchgrass or miscanthus	7.40	0.00	1.00

** No ILUC assigned to straw, in line with RED rules for direct emissions.*

*** There is no by-product from sugar cane ethanol production. Bagasse is used within the process for power and heat. Sometimes electricity is exported but this has no LUC effects.*

Economic values

Table 5 provides the value shares of biofuel for the different oilseeds (first column) and for ethanol crops (second column).

As explained in Step 2 above, for biodiesel we allocate land use (and hence ILUC emissions) to the by-product meals on the basis of the economic value of the oilseed meal as a fraction of the total value of the oilseed meal plus crude vegetable oil:

$$\textit{value share}_{veg\_oil} = \frac{\textit{value of veg oil}}{\textit{value of veg oil} + \textit{value oilseeds meal}}$$

Equation 2

In the case of ethanol production, the allocation to by-products is made instead by comparing the value of the by-products (e.g. DDGS) with the value of the crop. Thus the fraction of ILUC allocated to ethanol is given by:

$$1 - \frac{\textit{value of byproduct from 1 tonne crop}}{\textit{value of 1 tonne of crop}}$$

Equation 3

Table 5. Vegetable oils and ethanol shares based on 'economic value'

Oilseeds	Fraction of LU attributed to biofuel	Ethanol	Fraction of LU attributed to biofuel
Rapeseed oil	0.79	Maize ethanol	0.62
Soybean oil	0.43	Sugar beet ethanol	0.54
Sunflower oil	0.82	Wheat ethanol*	0.56
Palm oil	0.98	Wheat straw ethanol**	0.05
Jatropha	0.80		

** No ILUC assigned to straw.*

*** ILUC assigned to straw.*

Area contribution factors

The fractional contributions of area expansion to the increase in agricultural production for each region are listed in Table 6. These are the same reported in Table 1 in Section 1.1. They are used directly in the ***local approach***.

In Brazil, for example, 30% of the increase in production derived from area expansion[18], while in the US most of the increase is covered by yield increase (only 1% came from land).

[18] Brazil is one country where a notable increase in multiple cropping has taken place in recent years, so this value is probably over-estimated. This is also further discussed in Appendix 1.

Table 6. Area expansion component of production increase (<u>local approach</u>)

Region	Fraction of production increase from area expansion 2004-2012 (avg 2004-2008 and avg 2008-2012)
Brazil	0.30
CAMCarib (Central America countries and Caribbean countries)	0.32
China	0.42
CIS (Commonwealth of Independent States)	0.20
EU27	0.08*
IndoMal (Indonesia and Malaysia)	0.64
LAC (Other Latin American countries)	0.97
RoOECD (Rest of OECD countries)	0.08
SSA (Sub-Saharan Africa)	0.45
USA	0.01
RoW (Rest of the World)	0.47

* The % change in harvested area is negative.

In the ***exporting regions*** approach (Table 7), the area contribution fraction is calculated for the three main crop groups: A_1 cereal, A_2 sugar equivalent (which includes sugar cane and sugar beet), and A_3 vegetable oils.

A weight has been assigned to each region in relation to their share as a net exporter[19] between 2004 and 2011[20] of the three crop groups (A_1, A_2 and A_3).

The area contribution fraction (per crop group) is then given by the sum of the regional area contribution fractions weighted by the net-export-share of the region/country. In formula:

$$\boldsymbol{Cj} = \sum_{\boldsymbol{i}} \boldsymbol{Aji} * \boldsymbol{Bi}$$

Equation 4

Where Cj = area contribution fractions (per crop group j)

Aji = share of region/country i on the total net exports of crop group j

Bi = area contribution fractions (per region i)

For j = 1 to 3 (crop groups)

i = 1 to 11 (regions)

[19] Export and import data for all regions/countries from 2004 to 2011 are downloaded from FAOstat (http://faostat3.fao.org/download/T/TP/E accessed 3 December 2014).

[20] Import and export figures for 2012 were not available in FAOstat at the time of writing the report.

Table 7. Area expansion component of production increase (exporting regions approach)

	Cereals (contribution to export) A_1	Sugar equivalent (contribution to export) A_2	Vegetable oils (contribution to export) A_3	Regional fraction due to area B_i
Brazil	0.001	0.854	0.053	0.30
CAMCarib	0.000	0.130	0.000	0.32
China	0.000	0.000	0.000	0.42
CIS	0.211	0.000	0.026	0.20
EU27	0.054	0.000	0.000	0.08
IndoMal	0.000	0.000	0.768	0.64
LAC	0.106	0.016	0.153	0.97
RoOECD	0.000	0.000	0.000	0.08
RoW	0.000	0.000	0.000	0.47
SSA	0.000	0.000	0.000	0.45
USA	0.627	0.000	0.000	0.01
Fraction due to area, for crop group = C_j	**0.16**	**0.31**	**0.66**	

The net exporting countries/regions are the ones that contribute to the area contribution fractions of the three crop groups. Thus we are assuming that a crop is produced in exporting regions according to their share of net exports.

Yield factor

In the exporting regions approach, the extra production of a specific crop is assumed to occur in the net exporting regions of that crop. Therefore, to account for the difference between the crop yield in a specific region/country and the crop yield in the main exporting regions/countries, we have introduced an additional "yield factor". This is given by the ratio between the crop yield of a specific region and the weighted yields of the net exporting regions.

This adjustment is necessary since the region/country of production of the biofuel crop is different in the exporting regions approach from the place where the displaced crops will be grown. For example, if 1 ha of wheat in Europe (yield = 5 t/ha) is replaced with 1 ha rapeseed, the 5 tonnes of wheat should be replaced. If it was all replaced in Ukraine (yield = 3 t/ha), one might need 1.6 ha to grow 5 tonnes of wheat, since the average yield in the Ukraine is lower than in Europe. This 1.6 is called the yield factor in this report.

Table 8 shows the yield factor specific per crop and region.

Table 8. Yield factors used in the exporting regions approach

Region and feedstock	Yield factor
EU wheat	0.94
EU sugar beet	1.39
US maize	1.25
Brazil sugar cane	1.02
EU rapeseed	0.54
US soy	0.39
LAC soy	0.34
IndoMal palm oil	1.20
EU sunflower	0.31
EU wheat straw	0.94
Jatropha (Africa)	0.65

Emission factors

Table 9 shows the emission factors calculated by IMAGE[21]. The numbers in the table express the loss of carbon due to changes from natural area or grasslands to cropland systems.

IMAGE is an integrated assessment model for the world and was developed by PBL. For this analysis, IMAGE[22] was used to calculate the land use conversions that took place in each region in the period 1995-2005 and the land use emissions that resulted.

IMAGE uses agricultural production per crop/animal type per region as an input to drive the land use changes. IMAGE allocates the agricultural area by considering the potential production for each grid-cell (0.5 by 0.5 degree) that is assigned to a land-cover type, and other allocation rules.

IMAGE has been calibrated for the period until 2005. This means that for each IMAGE region, if we use the FAO production statistics as an input, the resulting estimates of individual crop areas, grazing area and the total agricultural area represent the data in the FAO database within 5%.

[21] For more information on the IMAGE model, see Stehfest et al. (2014).

[22] Version described in PBL (2012).

Table 9. Emission factors in the period 1995-2005 — IMAGE results

	IMAGE tCO_2/ha
Brazil	177
CAMCarib	186
China	276
CIS	2
EU27	93
IndoMal	1188*
LAC	141
RoOECD	15
SSA	241
USA	155
RoW	188

* Including emissions from drainage of peatland for crop expansion.

Emission factors in Table 10 represent the changes in carbon stocks across the different world regions obtained through the application of the Cropland Spatial Allocation Model (CSAM). CSAM is a methodology developed by the JRC for estimating GHG emissions resulting from a change in land use and area of particular crops in particular regions (Hiederer et al., 2010).

The emission factors are calculated using an approach that differs from the IMAGE model. CSAM has been run considering cropland expansion of a *specific* crop in a *specific* region.

CSAM has an algorithm to allocate crop expansion on to different land types in a region into a grid map with 5x5 minimum resolution, using publicly available datasets with a global coverage. For the purpose of this analysis, we have applied CSAM to estimate "regional" emission factors (as CO_2 emissions/ha) for a crop area expansion of 100 kha in each region[23].

In CSAM, the distribution of land demand over the grid cells is driven by initial crop shares and historical trends. The choice of candidate grid cells for cropland expansion is made using filters on land cover, soil type, crop suitability and distance to cropland areas.

The land-cover change trends within a region are disaggregated in CSAM at country level using historical trends on cropland expansion deduced by the Moderate Resolution Imaging Spectroradiometer (MODIS) time series dataset. It indicates how much of the new cropland is supposed to be taken from other classes such as forest, grassland,

[23] The linearity of CSAM has been also tested by estimating emission factors for increasing sizes of area expansion, showing the "stability" of the model.

savannah or shrubland of the MODIS classification, if the trends between 2001 and 2004 are followed in the future.

The selection of cells in which expansion could occur is based on the suitability of land for agriculture, which can be defined for each crop and gives information on the likelihood of cropland expansion in the different areas according to the type of soil and the climate of the region. Land suitability for agriculture has been obtained from Global Agro-Ecological Zones (GAEZ) data provided by the International Institute for Applied Systems Analysis (IIASA) and FAO.

The grid cells are also ranked according to their proximity to the current cropland areas. The land allocation process gives a priority to the cells close to those areas already devoted to agriculture, but it can also accommodate the emergence of new areas for agriculture (Hiederer et al., 2010).

Table 10. Emissions due to land conversions calculated with CSAM per crop and region

Region and feedstock	tCO_2/ha
EU wheat	70
EU sugar beet	65
US maize	199
Brazil sugar cane	47
EU rapeseed	61
US soy	209
LAC soy	297
IndoMal palm oil	1004*
EU sunflower	62
Jatropha (Africa)	259**
Wheat straw	70
EU willow/poplar	22
EU switchgrass/miscanthus	22

* Including peatland emission.

** Maize in Sub-Saharan Africa (SSA).

In both methods (IMAGE and CSAM), for Indonesia/Malaysia peat emissions have been manually added assuming that 33% of all extra land for oil palm is on peatland, because both methodologies exclude allocation on soils high in organic carbon. Carbon emissions from peat decomposition derive from a recent review by Page et al. (2011), which indicates a value for carbon emissions from peat of 27.3 tC ha-1 yr-1 over the 25-year life of the plantation.

The main assumptions made in CSAM are:

- For Europe, the expansion of cropland into closed forest[24] has been excluded.
- For Brazil, sugar cane expansion into closed forest has been excluded. Moreover, in CSAM sugar cane is considered a semi-perennial crop (JRC, 2011), while in IMAGE it is classified as annual/cultivated crop. IPCC emission factors[25] indicate that perennial crops disturb the soils less and release less carbon than cultivated crops, bringing improvements in the carbon content of the soil. This difference between the two models may explain why the CSAM estimate is so much lower than the IMAGE estimate.
- For jatropha in Africa, which does not appear in the CSAM crop list, it is difficult to find specific (and reliable) emission factors in literature. We have assumed that it would have a similar spatial distribution of land suitability, for a commercial yield as maize (which can thus be displaced by Jatropha plantations). Therefore, it was ascribed the same LUC emission factor per ha as maize.
- For miscanthus and willow/poplar, we used the EU wheat expansion adjusted by a factor of 0.66 tC/ha/year (over 20 years), which is the increase in soil organic carbon (SOC) when annual crops are replaced by miscanthus (Don et al., 2012). We chose wheat as the most pervasive EU crop.

In the ***exporting regions*** approach, we estimate combined emission factors (Table 11), weighting the regional factors by the contribution of the net exporting regions.

Table 11. Emissions due to land conversions per crop group

Crop group	tCO_2/ha	
	IMAGE	**CSAM**
Cereals	102	226
Sugar equivalent	176	83
Vegetable oils	921	823

[24] Closed forest is a forest with more than 30% of canopy.

[25] Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines for National Greenhouse Gas Inventories. Eggelstone, S., L. Buemdia, K. Miwa, T. Ngara and K. Tanabe (Eds.). IPCC/OECD/IEA/IGES, Hayama, Japan.

3. Results

In this section, Subsection 3.1 provides estimates of the ILUC in hectares per TJ of incremental annual biofuels production from the two different approaches ("local" and "exporting regions") and the final weighted estimates of the ILUC area. Subsection 3.2 shows the resulting "historical" ILUC emissions.

3.1 ILUC area

Following allocation of part of the land use to by-products according to the methodologies explained in previous sections, we obtain the net area required to produce biofuel from a specific crop (net ***direct*** land use).

The outcomes for the two by-product allocation methods (the RED method and the 'economic value' method) are shown in Table 12 below.

Table 12. Net direct land use: by-product allocation by RED and 'economic value' method

		by RED method		by 'economic value' method	
Feedstock	**Gross land use ha/TJ biofuel**	**Ratio biofuel by-product**	**Net direct land use ha/TJ biofuel**	**Ratio biofuel by-product**	**Net direct land use ha/TJ biofuel**
EU wheat	23.57	0.56	**13.30**	0.56	**13.28**
EU sugar beet	7.32	0.71	**5.22**	0.54	**3.97**
US maize	12.12	0.64	**7.76**	0.62	**7.50**
Brazil sugar cane	7.12	1.00	**7.12**	1.00	**7.12**
EU rapeseed	20.84	0.63	**13.11**	0.79	**16.56**
US soy	50.54	0.35	**17.80**	0.43	**21.94**
LAC soy	58.30	0.35	**20.54**	0.43	**25.31**
Indonesia palm oil	6.77	0.95	**6.40**	0.98	**6.62**
Malaysia palm oil	5.58	0.95	**5.28**	0.98	**5.46**
EU sunflower	34.59	0.65	**22.38**	0.82	**28.40**
EU wheat straw	41.37	0	**0**	0.05	**2.15**
Jatropha (Africa)	28.10	0.39	**10.82**	0.80	**22.49**
EU willow or poplar	19.56	1.00	**19.56**	1.00	**19.56**
EU switchgrass or miscanthus	16.30	1.00	**16.30**	1.00	**16.30**

Combining the net direct land use (which is the extra crop area if all extra crop came from area expansion) with the fraction of the extra crop production estimated to come from area expansion, we obtain two estimates of the *indirect* land use change. The first, based on the local approach, is the result of the assumption that all the production increase occurs in the region where the biofuel feedstock is produced (Table 13).

Table 13. Net indirect land use change results using the *local approach*, in ha/TJ

Feedstock	Net direct land use ha/TJ biofuel		Fraction due to area	ILUC ha/TJ biofuel	
	by RED method	by 'economic value' method		by RED method	by 'economic value' method
EU wheat	13.30	13.28	0.08	1.09	1.09
EU sugar beet	5.22	3.97	0.08	0.43	0.32
US maize	7.76	7.50	0.01	0.06	0.06
Brazil sugar cane	7.12	7.12	0.30	2.11	2.11
EU rapeseed	13.11	16.56	0.08	1.07	1.35
US soy	17.80	21.94	0.01	0.15	0.18
LAC soy	20.54	25.31	0.97	19.86	24.48
Indonesia palm oil	6.40	6.62	0.64	4.10	4.24
Malaysia palm oil	5.28	5.46	0.64	3.38	3.50
EU sunflower	22.38	28.40	0.08	1.83	2.32
EU wheat straw	0	2.15	0.08	0	0.18
Jatropha (Africa)	10.82	22.49	0.45	4.84	10.06
EU willow or poplar	19.56	19.56	0.08	1.60	1.60
EU switchgrass or miscanthus	16.30	16.30	0.08	1.33	1.33

The second, based on the exporting regions approach, is the result of the assumption that the increase in production occurs in the net exporting regions in proportion to their export shares (Table 14).

Table 14. Net indirect land use change results using the *exporting regions* approach, in ha/TJ

Feedstock	Net direct land use ha/TJ biofuel		Area contrib.	Yield factor	ILUC ha/TJ biofuel	
	by RED method	by 'economic value' method			by RED method	by 'economic value' method
EU wheat	13.30	13.28	0.16	0.94	1.94	1.94
EU sugar beet	5.22	3.97	0.31	1.39	2.26	1.72
US maize	7.76	7.50	0.16	1.25	1.51	1.46
Brazil sugar cane	7.12	7.12	0.66	1.02	2.26	2.26
EU rapeseed	13.11	16.56	0.66	0.54	4.64	5.87
US soy	17.80	21.94	0.66	0.39	4.64	5.72
LAC soy	20.54	25.31	0.66	0.34	4.64	5.72
Indonesia palm oil	6.40	6.62	0.66	1.20	5.08	5.25
Malaysia palm oil	5.28	5.46	0.66	1.20	4.19	4.33
EU sunflower	22.38	28.40	0.66	0.31	4.64	5.89
EU wheat straw	0	2.15	0.16	0.94	0	0.31
Jatropha (Africa)	10.82	22.49	0.66	0.65	4.64	9.65
EU Willow or poplar	19.56	19.56				
EU switchgrass or miscanthus	16.30	16.30				

The actual value of the ILUC area lies between these two values. Our best-estimate is a weighted average of the results of the two approaches:

Best-estimate ILUC = (*local-approach* ILUC) x **L** + (*exporting-regions* ILUC) x (1-**L**)

where the weighting factor **L** is specific to each crop group:

$$\boldsymbol{L} = \frac{\boldsymbol{change\ in\ regional\ production}}{\boldsymbol{change\ in\ production\ in\ world\ regions\ with\ net\ exports}}$$

Equation 5

The "change in production" refers to the difference between average 2004-2008 and average 2008-2012 production, consistent with the calculation of the area expansion component.

In this way, for a major and expanding world producer of a particular crop (e.g. sugar in Brazil) the regional result dominates, whereas for a small producing region, or one where production is rather fixed, the exporting regions result predominates.

Table 15 shows the weighted ILUC for the two by-product allocation methods.

We assume no trade for second-generation /energy crops or jatropha, so in these cases the weighted ILUC estimate corresponds to the regional numbers.

Table 15. Best-estimate ILUC (ha/TJ biofuel)

Feedstock	**ILUC ha/TJ biofuel**	
	by RED method	**by 'economic value' method**
EU wheat	1.91	1.91
EU sugar beet	2.16	1.64
US maize	1.16	1.12
Brazil sugar cane	2.12	2.12
EU rapeseed	4.25	5.37
US soy	4.54	5.59
LAC soy	5.83	7.19
Indonesia palm oil	4.39	4.54
Malaysia palm oil	3.62	3.74
EU sunflower	4.33	5.50
EU wheat straw	0	0.31
Jatropha (Africa)	4.84	10.06
EU willow or poplar	1.60	1.60
EU switchgrass or miscanthus	1.33	1.33

3.2 ILUC emissions

To calculate the ILUC emissions in gCO_2/MJ biofuels, we applied the emission factors provided by IMAGE and CSAM for the ***regional*** and ***exporting regions*** approaches (Table 16 and Table 17).

Table 16. *Local approach* ILUC emissions (gCO_2/MJ biofuel)

Feedstock	ILUC ha/TJ biofuel		Emission factors tCO_2/ha		gCO_2/MJ biofuel[26]			
	by RED method	by 'econ. value' method			by RED method		by 'econ. value' method	
			IMAGE	CSAM	IMAGE	CSAM	IMAGE	CSAM
EU wheat	1.09	1.09	93	70	**5**	**4**	**5**	**4**
EU sugar beet	0.43	0.32	93	65	**2**	**1**	**2**	**1**
US maize	0.06	0.06	155	199	**0.5**	**1**	**0.5**	**1**
Brazil sugar cane	2.11	2.11	177	47	**19**	**5**	**19**	**5**
EU rapeseed	1.07	1.35	93	61	**5**	**3**	**6**	**4**
US soy	0.15	0.18	155	209	**1**	**2**	**1**	**2**
LAC soy	19.86	24.48	141	297	**140**	**295**	**173**	**363**
Indonesia palm oil	4.10	4.24	1188	1004	**243**	**206**	**252**	**213**
Malaysia palm oil	3.38	3.50	1188	1004	**201**	**170**	**208**	**176**
EU sunflower	1.83	2.32	93	62	**9**	**6**	**11**	**7**
EU wheat straw	0	0.18	93	70	**0**	**0**	**1**	**1**
Jatropha (Africa)	4.84	10.06	241	259	**58**	**63**	**121**	**130**
EU willow or poplar	1.60	1.60	45	22	**4**	**2**	**4**	**2**
EU switchgrass or miscanthus	1.33	1.33	45	22	**3**	**1**	**3**	**1**

[26] These emissions are spread over 20 years, following the Commission's rules for estimating LUC emissions in the RED annex. This provision is in line with the proposition that a batch of biofuel should achieve the claimed emissions savings within 20 years of consumption.

Table 17. *Exporting regions* approach ILUC emissions (gCO_2/MJ biofuel)

Feedstock	ILUC ha/TJ biofuel		Emission factors tCO_2/ha		gCO_2/MJ biofuel			
	by RED method	by econ. method			by RED method		by 'economic value' method	
			IMAGE	CSAM	IMAGE	CSAM	IMAGE	CSAM
EU wheat	1.94	1.94	102	226	**10**	**22**	**10**	**22**
EU sugar beet	2.26	1.72	176	83	**20**	**9**	**15**	**7**
US maize	1.51	1.46	102	226	**8**	**17**	**7**	**17**
Brazil sugar cane	2.26	2.26	176	83	**20**	**9**	**20**	**9**
EU rapeseed	4.64	5.87	921	823	**214**	**191**	**270**	**242**
US soy	4.64	5.72	921	823	**214**	**191**	**263**	**236**
LAC soy	4.64	5.72	921	823	**214**	**191**	**263**	**236**
Indonesia palm oil	5.08	5.25	921	823	**234**	**209**	**242**	**216**
Malaysia palm oil	4.19	4.33	921	823	**193**	**173**	**199**	**178**
EU sunflower	4.64	5.89	921	823	**214**	**191**	**271**	**243**
EU wheat straw	0	0.31	102	226	**0**	**0**	**2**	**4**
Jatropha (Africa)	4.64	9.65						
EU willow or poplar								
EU switchgrass or miscanthus								

Using the weighting factor for our best estimate (as in the area estimate), we get the final results shown in Table 18.

Table 18. Best-estimate ILUC emissions (gCO_2/MJ)

Feedstock	ILUC emissions in gCO_2/MJ over 20 years			
	IMAGE		CSAM	
	by RED method	by 'economic value' method	by RED method	by 'economic value' method
EU wheat	10	10	21	21
EU sugar beet	19	14	9	7
US maize	6	6	13	13
Brazil sugar cane	19	19	5	5
EU rapeseed	191	241	170	215
US soy	209	257	187	230
LAC soy	208	256	199	246
Indonesia palm oil	241	249	207	214
Malaysia palm oil	199	205	171	176
EU sunflower	191	243	171	217
EU wheat straw	0	2	0	3
Jatropha (Africa)	58	121	63	130
EU willow or poplar	4	4	2	2
EU switchgrass or miscanthus	3	3	1	1

The final results obtained with two different sets of emission factors (IMAGE and CSAM) are broadly in agreement, even though their emission factors differ for individual crops and regions.

The different emission factors obtained with the two models are mainly due to the different approaches used by IMAGE and CSAM to estimate emissions. In fact, IMAGE uses land use conversions that took place in each region in the period 1995-2005 and determine land use emissions. These data show cropland expansion at the expense of other land use, but do not specify which crop is responsible. Therefore, the emissions in IMAGE refer to all crops in a given region.

By contrast, the emission factors from CSAM are the result of attributing expansion of a specific crop in a specific region to different land covers, as explained in Section 2. As a consequence, the emissions are crop specific.

The 'economic value' allocation of by-products (value method) gives moderately different estimates of the ILUC emissions compared to the energy allocation method (RED method).

4. Discussion and conclusions

Application of statistical historical data

By using observed statistical historical data in our methodology, many economic processes are included, such as the effect of the increase of demand on yields, and the fraction of different land uses that are changed. We do not attempt to estimate future effects. These would differ from historical trends, especially in the case of a very large and system-disturbing shock in crop demand.

Ideally, we would use data from the most recent years to calculate the ILUC for the coming year. However, due to data availability and fluctuations, it is necessary to use a longer period over which the differences are calculated. In this report we compared the first and second halves of the 2004-2012 period.

Simplifications in the analysis

There are three effects we do not consider:

1. We assumed that, when demand increases, the fraction of extra production coming from increased area (as opposed to increased yield) was the same as given by historical increases in area and yield. However, economists recognise that yields generally increase with time, even if prices are stable or falling, because of learning by farmers. This component of the yield increase that does not vary with price will not change if prices increase due to biofuel. Therefore, yield will contribute less to an increase in production due to price than to an observed increase in production with time. This assumption amplifies the impact of extra biofuel demand on yield increase, so we are systematically underestimating the ILUC area. Maize benefits most from this approximation, as it has shown the greatest yield increase in the considered time-period. Other cereals also benefit in this way.
2. The extra emissions from demand-driven yield increases are not considered. The intensification comes in part from using more fertiliser and other inputs. As there are diminishing returns from using more inputs, the *marginal* emissions per extra tonne of production are likely to be larger per tonne than the *average* direct emissions (for a more detailed analysis, see PBL (2010)). Again, maize especially benefits from this approximation.
3. We make no allowance for lower yield on marginal land in developed countries. Here, the best farmland tends to be already used for arable crops, so expansion of the crop area generally occurs on land with lower yield. This means more land is required to produce a given extra quantity of crop. Furthermore, more direct farming emissions per tonne of crop can be expected where yields are lower[27].

[27] DEFRA (1998) and Love and Foster (1990) both indicate that land put into set-aside schemes by farmers had less than 70% of the average yield. Tyner et al. (2010) modelled the yield of potential new

These three effects would increase our estimates of ILUC. However, if it were possible to include changes in cropping intensity in a consistent way (Appendix 1), the ILUC results would presumably be lower.

The methodology as presented includes a range in the assessment of two of the variables. One is the treatment of by-products and the other is on the assumption where ILUC is taking place.

Treatment of by-products

For the treatment of by-products, we present results of both an energy-based (RED) allocation method and an 'economic value'-based method.

The discussion of how to account for by-products is exactly the same for ILUC as for direct emissions. The method adopted by complex economic models of ILUC is equivalent to the "substitution" or "system expansion" methods in direct emissions life-cycle assessment (LCA) calculations, whereby the substitution of crops with by-products generates an emissions credit that reduces the overall emissions estimate. However, the calculation of this credit is highly complex, requiring a complex economic model to handle the myriad consequential trails.

Using allocation greatly simplifies the calculation, as also explained in the impact assessment that accompanied the RED and FQD[28]. For example, in Annex V of the RED, the direct cultivation emissions from the growing of the crop are simply allocated between biofuel and by-products on the basis of their energy (LHV) contents. In our "allocation by energy" results we apply exactly the same method, to give ILUC emissions results consistent with the direct emissions in Annex V.

Allocation by 'economic value' has the advantage of encompassing the motivation for growing the crop. It takes into account the quality of the animal-feed by-products as well as their quantity.

Assumptions on where ILUC is taking place

Our best-estimate sits between the two extreme cases, in which either all ILUC occurs within the region where a biofuel is produced or is distributed between the countries that export the feedstock. As explained in Section 3.1, the equation used shows a realistic dependence on the importance of the region to the world market. It also gives greater weighting to regions that have historically expanded production the most. This assumes that historical increases in production indicate how much a region's production will respond to a given price increase. There is no rigorous proof of this: for example, historical production may have changed because of government incentives rather than a

---

cropland on individual 2500 km^2 grid-cells in 200 larger regions, and found that it varied between 0% and 57% below the average for the region.

[28] SEC(2008)85 and related annexes.

particularly flexible production system. However, we see no simple way of accounting for other factors.

Summary of the main conclusions

- ILUC emissions calculated by a methodology using historical data are generally in line with those of economic models, showing a lower impact of cereals and sugar crops compared to vegetable oils.
- The method is transparent and reproducible but involves simplifications, most of which would lead to an underestimation of ILUC.
- The results calculated by energy-based allocation to by-products use the method for allocating emissions between biofuel and by-products specified in Annex V of the RED.
- Calculations using an 'economic value' allocation approach are only moderately different but may more accurately reflect the contribution of by-products.
- The choice of method for converting land use changes into emissions only moderately affects the results.

Appendix 1

Sensitivity analysis: attempting to include cropping intensity

To account for changes in multiple cropping, it would have been preferable to use the *cropped* area rather than the *harvested* area, but in FAO databases only *total* cropped area is reported[29], aggregated for all crops. Therefore, to see the effect of multiple cropping, the most expedient approach is to examine the overall ratio of harvested/cropped area; this is called “cropping intensity”.

As the harvested area reported by FAO includes the multi-cropped area[30], for those regions where multiple cropping increases, the real crop area increase is lower than the value extracted from the FAO database. Therefore, in an attempt to take into consideration the effect of multiple cropping, we have re-estimated the area component and the final ILUC area and emissions including the cropping intensity.

If we theoretically assume the two areas (harvested area and cropland) are measured in a consistent way (although Appendix 2 indicates that this may not be the case), we could suppose that the historical change in the cropping intensity may give some indication of the maximum contribution of multiple cropping to the crop production increase.

There are two problems with calculating changes in cropping intensity. The first is that the data for cropped area are of much lower quality than those for harvested area per crop (Alexandratos and Bruisma, 2012, p.106). The second problem is that the FAO crop-list is incomplete, so that calculating the sum of the harvested area of all crops gives a figure that is less than the true harvested area. This effect is minimised if we only look at changes in harvested area, but unfortunately the FAO crop-list also expands with time, as explained in Appendix 2.

If we include the cropping intensity as a factor that contributes to the increase in crop production over the same time periods considered before (2004-2008 and 2008-2012), Equation 1 in Section 1.1 will become:

---

[29] Total arable land plus total land under all permanent crops, per region.

[30] In FAO, harvested area is defined as: “if the crop under consideration is harvested more than once during the year as a consequence of successive cropping, the area is counted as many times as harvested.”

$$fraction\ of\ prod.increase\ from\ area\ expansion$$

$$= \frac{\%\ cropped\ area\ increase}{\%\ cropped\ area\ increase + \%\ yield\ increase + F *\ \%\ cropping\ intensity\ increase}$$

Equation 6

Where F = 1 when cropping intensity is considered, and F = 0 when it is not included.

In this appendix, we attempt to estimate the effect of cropping intensity by applying Equation 6 to calculate the fraction of the production increase from area expansion previously defined by Equation 1.

Cropping intensity generally increases with time (Appendix 2), so we might expect that including changes in cropping intensity would decrease the area expansion contribution; and indeed this happens in some of the regions/countries (

Table 19). However, for most regions/countries, the estimated cropped area apparently *decreased* between the considered time periods (see double asterisks). When this happens, the results are not easy to interpret: the fractions including cropping intensity are sometimes even bigger than before, meaning that the area has a larger contribution to the production increase compared to when the cropping intensity was not taken into account (e.g. EU, RoOECD, USA). As this seems unlikely, we decided to consider only the results for those countries where the cropped area is not decreasing so that the fractions given by Equation 6 are at least credible. Consequently, we report only the apparent *regional* ILUC for those regions where the apparent % change in cropped area was positive, which are Brazil, LAC, and IndoMal.

We do not calculate the results for the *exporting country* approach and the *best estimate* of ILUC since we would also need the area contributions of the net exporting countries to get the final results (see Sections 3.1 and 3.2). However, by providing an estimate of the *regional* ILUC for some "key" countries where the area expansion has been particularly relevant in the considered years, we show the apparent contribution of the cropping intensity to lower the *regional* ILUC results.

The apparent area contributions for Brazil, LAC and IndoMal are lower by 54%, 15% and 38% respectively compared to the values where cropping intensity was not included (Table 19).

Table 19. Area expansion component of production increase (local approach)

Region	Fraction of production increase from area expansion without Cropping Intensity (avg 2004-2008 and avg 2008-2012)	Apparent fraction of production increase from area expansion including Cropping Intensity (avg 2004-2008 and avg 2008-2012)
Brazil	0.30	0.14
CAMCarib (Central America countries and Caribbean countries)	0.32	0.06**
China	0.42	0.06**
CIS (Commonwealth of Independent States)	0.20	0.16**
EU27	0.08*	0.26**
IndoMal (Indonesia and Malaysia)	0.64	0.40
LAC (Other Latin American countries)	0.97	0.83
RoOECD (Rest of OECD countries)	0.08	0.18**
SSA (Sub-Saharan Africa)	0.45	0.38
USA	0.01	0.40**
RoW (Rest of the World)	0.47	0.14

* The % change in harvested area is negative.

** The % change in cropped area is negative.

Table 20 and Table 21 show the apparent *regional* ILUC results in terms of area and emissions respectively, for the regions and crops where the fractions were considered credible. The same reductions reported for the area contributions are reflected in the *regiona*l ILUC as shown in the following tables.

We do not calculate the *best estimates* of ILUC because, as explained above, most of the countries showed an apparent reduction in cropped area, which resulted in non-credible fractions of area contributions. We do show that considering the apparent increase in cropping intensity would lower the estimated *regional* ILUC results (see Section 1.2), by between 15% and 54%. However, we stress that these figures are based on estimates of increases in cropping intensity that are poor (see Appendix 2) and probably exaggerated.

Table 20. Apparent benefit of cropping intensity on ILUC area (ha/TJ biofuel), using the *local approach*

Feedstock	ILUC ha/TJ biofuel (including Cropping Intensity)		% change compared to results in Table 13	
	by RED method	by 'economic value' method	by RED method	by 'economic value' method
Brazil sugar cane	0.97	0.97	-54%	-54%
LAC soy	16.95	20.89	-15%	-15%
Indonesia palm oil	2.55	2.64	-38%	-38%
Malaysia palm oil	2.10	2.18	-38%	-38%

Table 21. Apparent benefit of cropping intensity on ILUC emissions (gCO_2/MJ) using the *local approach*

Feedstock	ILUC emissions in gCO_2/MJ over 20 years (including Cropping Intensity)			
	IMAGE		SAM	
	by RED method	by 'economic value' method	by RED method	by 'economic value' method
Brazil sugar cane	9	9	2	2
LAC soy	120	148	251	310
Indonesia palm oil	151	157	128	132
Malaysia palm oil	125	129	106	109

However, there are two main reasons to suppose that our method tends to over-estimate the impact of cropping intensity:

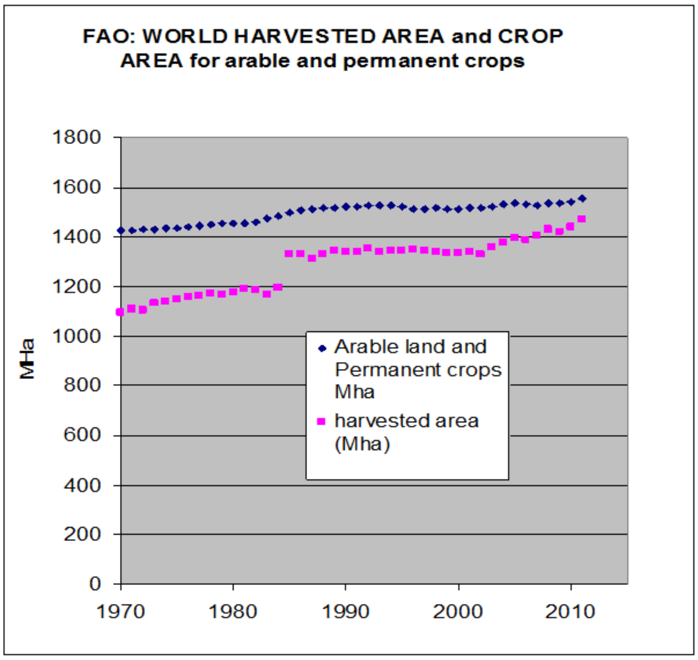
1. Analogously to yields, we assume that the fraction of increased feedstock demand due to increased cropping intensity is the same as the historical fraction. That implies that increase in cropping intensity is entirely driven by increased demand, via crop price. In fact this is unlikely, as real crop prices generally fell during the period considered, so we can suppose that much of the increase in cropping intensity occurred because of historical trends, including learning by farmers.
2. As explained in detail in Appendix 2, increasing cropping intensity by 1% increases output by considerably less than 1%.

Appendix 2

Double cropping and fallow land: interpreting the difference between FAO harvested and cropped area

If more than one crop is harvested on the same area in a year (e.g. in the case of multiple cropping), the harvested area should exceed the cropped area. However, the sum of the harvested area of all crops recorded by FAO is less than the cropped area in FAO data (Figure 4). Therefore, in FAO datasets any effect of multiple cropping is masked by a larger area of land which is counted as “cropped” but is reported as not harvested. Some have assumed that this is all fallow land (Lahl, 2013), which can accommodate new production without land use change emissions. However, this is incorrect, as explained below, and the difference between cropped area and harvested area cannot be explained *only* by fallow land.

Figure 4. Evolution with time of FAO data on total cropped area (“arable land” + “land under permanent crops”), and the sum of the harvested areas of all crops in the FAO crop-list.



Two features stand out in Figure 4.

1. *The large jump in FAO harvested area between 1984 and 1985 (see graph) was merely the effect of FAO adding "pumpkins for fodder" to its crops list.*
2. *There is a plateau in harvested area during the 1990s. During this period the harvested area fell in ex-communist countries, following withdrawal of state production targets and land restitution to disparate private owners. This temporarily countered continued expansion in the rest of the world. The contraction in cropland should theoretically have followed with a lag of five years, as FAO defines cropland as land farmed in the previous five years. However, imprecise national reporting to FAO may have masked this effect.*

App2. 1. Fallow is just one component of "unharvested cropland"

Missing crops

"Harvested area" is the sum of harvested crop area for the crops in the FAOstat crop-list. That does not include all crops, as in the case of "pumpkins for fodder" under point 1 above. Other crops were also added in various years, so some of the convergence in the graph can be explained by the expansion of the FAO crop-list. However, the list still does not include such major and high-yielding crops as hay (16% of US cropland), and improved pasture (e.g. Dutch polders). These lands are not available for cropping without a loss of other production, and are not fallow land.

Establishment years of permanent crops

In permanent crops, there is always an establishment period when the crop is not harvested. For palm oil that is the first 5-7 years of a 25-30 years cycle (although some of that is in a denser nursery plantation). The fraction of unharvested oil-palm area depends on the age structure of the existing plantations, but Malaysian Palm Oil Board (MPOB) data indicates it was 17% of the harvested area in 2011. More importantly, sugar cane is harvested only five years in a plantation cycle of six years (17% uncropped).

Missing harvests

If the crop fails it is not harvested (or it is harvested for hay instead of grain: see missing crops above) and that land is not included in the harvested area, so it appears as uncropped

US conservation reserve land appears to be considered "fallow"

FAO reported 70 million hectares more unharvested cropland in the US than the fallow land in USDA data[31]. It appears that FAO unharvested cropland includes idled cropland under the Conservation Reserve Programme, and cropland used for pasture. FAO seems to include conservation reserve area in unharvested cropland even though it should be excluded from the FAO definition of cropland, as it has been out of production for more than five years[32].

App2. 2. Yields on unharvested cropland

Arid, marginal, lands

Siebert (2010) showed that a large proportion of unharvested cropland appeared to be in arid regions of Central Asia and Africa (where shifting agriculture may crop one tract of land only once in 10 years or more) or in the western semi-desert regions of the US, where the land is planted with an (unharvested) catch- or cover-crop in preparation for a crop in the subsequent year. Apart from doubts as to whether such land can be farmed more intensively, the yield would be very poor.

Farmers are less likely to crop low-yield fields

If unharvested cropland could support a national-average yield, it would generally already be farmed. Therefore the yield on unharvested cropland is considerably lower than the national average, even if it is in a generally good farming area.

Double cropping does not mean double yield

Increasing cropping intensity by multiple cropping also does not increase production proportionally. The decision to double crop is a marginal one, which considers the reduction in yield-per-harvest. That reduction occurs because the growing season is shortened or crops are pushed out of their natural growing season.

App2. 3. Lost alternative services from unharvested cropland

Foregone production

Even if it is not cropland according to the FAO definition, much unharvested cropland is used for pasture or to grow hay, for which digestible energy yields can even exceed cereals. Unharvested cropland that is actually long-term idled land under conservation

---

[31] http://www.ers.usda.gov/data-products/major-land-uses.aspx#25964.

[32] FAO's cropped-area includes *"land temporarily fallow (less than five years), land temporary meadows for mowing or pasture, land under market and kitchen gardens"* according to the FAO definition.

programmes sequesters carbon at a significant rate. The loss of these services needs to be accounted in ILUC area and emissions.

Foregone soil improvement

In the decision not to crop a field in a particular year, the farmer took into account the soil improvement that would boost the yield of a future crop, for example by ploughing in a legume cover-crop at the end of the season. This yield improvement is foregone if the land is instead cropped every year.

App2. 4. Source of FAO cropland data

The FAO cropland data are based on reporting by national governments. They date back to many years before satellite data became useful, and never showed much correction. The source of the national government data is varied and not reported.

The M3 database of world cropland (Johnston et al., 2009), based on interpretation of satellite data, shows considerably more area of crops in the year 2000 than are reported in FAO harvested area. Most of the difference is supposed to be subsistence agriculture in remote regions, and its effect is so strong that it results in much lower average yields in the M3 database. The question is whether this remote cropland is included in FAO cropland (it is apparently not in the harvested cropland, because FAO yields are much higher).

CONCLUSION

The difference between FAO harvested area and FAO cropland (= unharvested cropland) greatly overestimates the area that could be normally considered as fallow.

The net extra production that could be taken from unharvested cropland would be much less than indicated by the fraction of area, due to low yields and lost benefits.

References

Bouwman, A.F., Kram, T. (2006), 'Integrated modelling of global environmental change: an overview of IMAGE 2.4.'. Netherlands Environmental Assessment Agency (MNP), Bilthoven.

(DEFRA, 1998), 'Evaluation of the impacts of set-aside on UK agriculture'. http://webarchive.nationalarchives.gov.uk/20130123162956/http:/www.defra.gov.uk/evidence/economics/foodfarm/evaluation/setaside/FullRep.pdf/

Don, A., Osborne, B., Hastings, A. et al. (2012), 'Land use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon'. *GCB Bioenergy*, 4, 372–391.

FAOstat, website: http://faostat3.fao.org/home/E.

JEC — Joint Research Centre-EUCAR-CONCAWE collaboration, 'Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context', Version 2c, March (2007), available at: http://iet.jrc.ec.europa.eu/sites/about-jec/files/documents/WTW_Report_010307.pdf.

Johnston, M., Foley J.A., Holloway, T., Kucharik, C.J., and Monfreda C. (2009), 'Resetting global expectations from biofuels'. *Environmental Research Letters* 4:014004: doi: 10.1088/1748-9326/4/1/014004.

(JRC, 2010) Edwards, R., Mulligan, D., Marelli, L. (2010), 'Indirect land use change from increased biofuels demand. Comparison of models and results for marginal biofuels production from different feedstocks'. JRC Scientific and Technical Report (EUR 24485 EN).

(JRC, 2010b) Hiederer, R., Ramos, F., Capitani, C., Koeble, R., Blujdea, V., Mulligan, D., Gomez, O., Marelli, L. (2010), 'Biofuels: a new methodology to Estimate GHG Emissions from Global Land Use Change. A methodology involving spatial allocation of agricultural land demand and estimation of CO2 and N2O emissions'. JRC Scientific and Technical Report (EUR 24483 EN).

(JRC, 2011) Marelli, L., Ramos, F., Hiederer, R., Koeble R. (2011). 'Estimate of GHG emissions from global land use change scenarios'. JRC Technical Notes (EUR24817 EN).

(JRC, 2014) Edwards, R., Padella, M., Vorkapic, V., Marelli, L. (2014), 'Historical deforestation due to expansion of crop demand: implications for biofuels'. JRC Science and Policy Report (EUR 26105 EN).

Lahl, U. (2013), 'Lösungsansätze für die Probleme weltweiter Landnutzungsänderungen'. Festsymposium zum 20-jährigen Bestehen des Beirates für Nachwachsende Rohstoffe, Hannover, 24 Oktober 2013.

Love, H.A., Foster, W.E. (1990), 'Commodity program slippage rates for corn and wheat', *Western Journal of Agricultural economic value's*, 15(2): 272-281.

Lywood, W., Pinkney, J., Cockerill, S. (2009), 'The relative contributions of changes in yield and land area to increasing crop output'. *GCB Bioenergy*, 1, 360-369.

Overmars, K., Stehfest, E., Ros, J.P.M., Gerdien Prins, A. (2011), 'Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data'. *Environmental Science and Policy*, 14, 248–257.

Page, S.E., Morrison, R., Malins, C., Hooijer, A., Rieley, J.O., Jauhiainen, J. (2011), 'Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia'. ICCT White Paper 15, Washington: International Council on Clean Transportation.

(PBL, 2010) 'Indirect effects of biofuels: intensification of agricultural production'. http://www.pbl.nl/sites/default/files/cms/publicaties/500143005.pdf.

(PBL, 2012) 'The IMAGE model suite used for the OECD Environmental Outlook to 2050'. PBL publication number 500113002, The Hague, PBL Netherlands Environmental Assessment Agency.

Reinhardt, G., Becker, K., Chaudary, D.R., Chikara, J., von Falkenstein, E., Francis, G., Gärtner, S., Gandhi, M.R., Ghosh, A., Ghosh, P.K., Makkar, H.P.S., Münch, J., Patolia, J.S., Reddy, M.P., Rettenmaier, N., Upadhyay, S.C. (2008), 'Basic Data for Jatropha Production and Use'. Updated version, Institute for Environmental Research.

Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R., Plevin, R. (2015), 'Are biofuel policies trying to mitigate greenhouse gas emissions by reducing food consumption?' *Science*, 27 March 2015, Vol 347 issue 6229.

Siebert, S., Portmann, F.T., Doll, P. (2010), 'Global Patterns of Cropland Use Intensity'. *Remote Sensing* 2(7), 1625–43.

Stehfest, E., Van Vuuren, D., Kram, T., Bouwman, L. (eds.) (2014), 'Integrated Assessment of Global Environmental Change with IMAGE 3.0'. http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0).

Tyner, W.E., Taheripour, F., Zhuang, Q., Birur, D., Baldos, U. (2010), 'Land use changes and consequent CO2 emissions due to US corn ethanol production: a comprehensive analysis'. Final Report July 2010, Dept. of Agricultural economics, Purdue University, https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3288.

Wicke, B., Verweij, P., van Meijl, H., van Vuuren, D. P., Faaij, A.P.C. (2012), 'Indirect land use change: review of existing models and strategies for mitigation'. *Biofuels* 3(1), 87–100.

European Commission
EUR 26819 EN – Joint Research Centre – Institute for Energy and Transport

Title: **Estimates of indirect land use change from biofuels based on historical data**

Author(s): Koen Overmars, Robert Edwards, Monica Padella, Anne Gerdien Prins, Luisa Marelli

Luxembourg: Publications Office of the European Union

2015– 50 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-39930-5 (PDF)
ISBN 978-92-79-39931-2 (print)

doi: 10.2790/3647

LD-NA-26819-EN-N

JRC Mission

As the Commission's
in-house science service,
the Joint Research Centre's
mission is to provide EU
policies with independent,
evidence-based scientific
and technical support
throughout the whole
policy cycle.

Working in close
cooperation with policy
Directorates-General,
the JRC addresses key
societal challenges while
stimulating innovation
through developing
new methods, tools
and standards, and sharing
its know-how with
the Member States,
the scientific community
and international partners.

Serving society
Stimulating innovation
Supporting legislation

doi: 10.2790/3647

ISBN 978-92-79-39930-5

Publications Office