STUDY REPORT ON

REPORTING REQUIREMENTS ON BIOFUELS AND BIOLIQUIDS STEMMING FROM THE DIRECTIVE (EU) 2015/1513

by

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List of Abbreviations

ALCA	Attributional Life Cycle Assessment
CARB	California Air Resources Board
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CLCA	Consequential Life Cycle Assessment
DDGS	Dried Distillers Grains with Solubles, by-product of production of maize and wheat ethanol
DLUC	Direct Land Use Change
EU	European Union
FAO	Food and Agriculture Organization
EPA	United States Environmental Protection Agency
EPFL	Ecole Polytechnique Federale De Lausanne
FAPRI	Food and Agriculture Policy Research Institute
FSU	Former Soviet Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAM	Integrated Assessment Model
ICONE	Institute for International trade Negotiations (Brazil)
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect Land Use Change
IMAGE	Integrated Model to Assess the Global Environment
IMAGE-LPJmL	Lund-Potsdam-Jena model with Managed Land model included in the IMAGE model
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCFS	California Low Carbon Fuel Standard
LEC	Land Extension Coefficients
LIIB	Low Indirect Impact Biofuels
LUC	Land Use Change
MPOC	Malaysian Palm Oil Council
OECD	Organisation for Economic Co-operation and Development
NREAP	National Renewable Energy Action Plans (NREAPs)
OSR	Oilseed Rape
PE	Partial Equilibrium
RED	Renewable Energy Directive
REDD	Reducing Emissions from Deforestation and forest Degradation
RSB	Roundtable on Sustainable Biomass
RFS	Renewable Fuel Standard
SOC	Soil Organic Carbon
SRC	Short Rotation Coppice
UNFCCC	United National Framework Convention on Climate Change
USA	United States of America
USDA	United States Department of Agriculture
WWF	World Wildlife Fund

Executive Summary

This report was commissioned to **gather comprehensive information on,** and to **provide systematic analysis** of the latest available scientific research and the latest available scientific evidence on indirect land use change **(ILUC) greenhouse gas emissions** associated with production of biofuels and bioliquids.

The EU mandatory sustainability criteria for biofuels and bioliquids do not allow the raw material for biofuel production to be obtained from land with high carbon stock or high biodiversity value. However, this does not guarantee that as a consequence of biofuels production such land is not used for production of raw materials for other purposes. If land for biofuels is taken from cropland formerly used for other purposes, or by conversion of grassland in arable land for biofuel production, the former agricultural production on this land has to be grown somewhere else. And if there is no regulation that this must happen sustainably, conversion of land may happen, which is not allowed to be used under the EU sustainability criteria for biofuels. This conversion may take place in other countries than where the biofuel is produced. This is called **indirect land use change (ILUC).**

According to Article 3 of the European Union's **Directive (EU) 2015/1513 of 9 September 2015**, the European Commission has to provide information on, and analysis of the available and the best available scientific research results, scientific evidence regarding ILUC emissions associated to the production of biofuels, and in relation to all production pathways.

Besides, according to Article 23 of the **revised European Union's Directive 2009/28/EC (RES Directive)**, the Commission also has to provide the latest available information with regard to key assumptions influencing the results from modelling ILUC GHG emissions, as well as an assessment of whether the range of uncertainty identified in the analysis underlying the estimations of ILUC emissions can be narrowed down, and if the possible impact of the EU policies, such as environment, climate and agricultural policies, can be factored in. An assessment of a possibility of setting out criteria for the identification and certification of low ILUC-risk biofuels that are produced in accordance with the EU sustainability criteria is also required.

The report describes the selection and the review of the literature, and highlights the development and progress in understanding and quantifying ILUC. The main methods used to quantify ILUC are described, and the most relevant ILUC related studies, which provide detailed qualitative and quantitative results are outlined. ILUC factors found in the literature are presented and related to the quantification methodology applied. The report also provides an in-depth analysis of key assumptions in ILUC research and related uncertainties. Finally, it also analyses the main mitigation options for ILUC, including low ILUC-risk biofuels[1].

Literature review

In order to provide a systematic analysis of the latest available scientific research and the latest available scientific evidence on ILUC GHG emissions associated with the production of biofuels, focus was put on the literature published in 2012-2016 period, and included also the main *landmark studies*[2] on ILUC published before 2012. The **literature review** included **peer reviewed** scientific articles as well as **grey literature** such as reports from influential organisations, working papers and conference proceedings. The **initial search** was not constrained to any geographic scope in order to maximise the number of returned literature. Therefore, worldwide produced research was addressed.

The initial literature search returned 1248 entries. This literature was narrowed down through a **1st preselection** that excluded studies focusing on aspects that were not of direct interest to this study, i.e. literature focusing on biodiversity, water, air quality, (indirect) land use changes from drivers other than biofuels/bioenergy. The first preselection yielded 559 studies. A **2nd preselection** was conducted in order to limit the number of studies to those that would help identifying causes, effects, determinants and mitigation options of ILUC for biofuel/bioenergy production. The 2nd preselection yielded 105 eligible studies providing quantitative information, 166 providing non-quantitative information, as well as 31 pre-2012 landmark studies. All eligible quantitative and landmark literature from the 2nd preselection underwent a **detailed review** in order to extract relevant information for the present report.

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[1] According to the Directive (EU) 2015/1513 low ILUC-risk biofuels and bioliquids can be defined as “biofuels and bioliquids of which the feedstocks were produced within schemes which reduce the displacement of production for purposes other than for making biofuels and bioliquids and which were produced in accordance with the sustainability criteria for biofuels and bioliquids set out in article 17 of Directive 2009/28/EC on promotion of the use of energy from renewable sources”.

[2] Landmark studies are identified as the most cited relevant literature.

ILUC GHG factors for pathways

Analysis of the best available scientific evidence was mainly focused on **30 studies** that reported land use change (LUC) and indirect land use change (ILUC) factors of different biofuels in units that allowed for direct comparison. These studies ranged a number of models and methods. The following methods were adopted by these studies:

- Seventeen studies applied PE-, CGE- or IAM-models
- Six studies used hybrid-LCA techniques
- Five studies were based on empirical approaches analysis
- One study used a Causal Descriptive model
- One study was based on expert opinion

Results of recent ILUC studies are **far from consistent in their approaches and outcomes**. After 2012, **no further convergence in results** is presented in the literature. Besides, studies that show similar levels of ILUC GHG emissions may in fact not imply result robustness. This is because the studies may be displaying completely different situations, arising from differences in parametrization, regional coverage, (potential) land use changes and scenario assumptions.

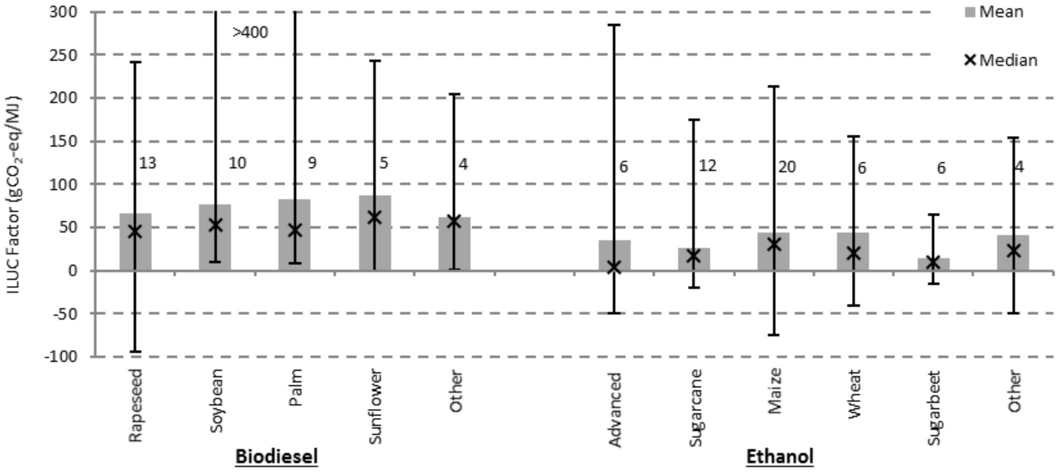

Figure 1 Summary of ILUC factors found in literature for biodiesel and ethanol. Grey bars: Mean, Black crosses: Median, Whiskers: Maximum-Minimum, number of studies quantifying ILUC factors written above each column. All ILUC factors have been harmonized to represent a 20 year amortization period. Note: a given study may include multiple scenarios or feedstocks. **Source:** Own work.

Concerning the modelling studies, results further vary because of **differences in data sets, parameter choices, scenarios**, etc. On average[3] the highest ILUC factors in the assessed quantitative studies carried out in the time period 2009 - 2015, are related to the production of **biodiesel** (median 52 gCO_{2-}eq/MJ), with palm showing the highest variation in results in available research. Estimates of ILUC factors for palm oil biodiesel tend to be higher (median 216 gCO_{2-}eq/MJ) than other vegetable oils in studies (such as Overmars 2015 and Valin 2015) that take into account the increased emission from, and uncertainty of, peatland conversion. First generation **ethanol** presents a median ILUC factor of 21 gCO_{2-eq}/MJ, with sugar crops (sugarcane and sugarbeet) showing the lowest ILUC factors, while maize has the highest numbers.

Advanced biofuels, present a median ILUC factor of 5 gCO_2-eq/MJ. It is important to stress though that unlike other feedstocks where there are multiple studies (18 for biodiesel and 24 for 1st generation), there are only six studies presenting results on advanced biofuels. Among these studies, there is significant disagreement and differences in methodological approaches as the types of lands assumed to be used for dedicated cropping with woody and perennial crops are defined differently in terms of current use status.

A number of points have to be raised in order to help with the interpretation of the above results. These (I)LUC factors are based on studies whose **scenarios are not consistent**, and thus, the **level of biofuel demand is not harmonised**. These factors are **not linear** and would, thus, **vary with changing levels of biofuel demand**. Additional to this, increasing demands, may lead to **different marginal feedstocks being used**, further complicating the predictability of these ILUC factors.

It is important to note that seven of the studies quoted in the above results, covering all feedstocks, explicitly calculate total LUC emissions, a combination of indirect and direct LUC (see Table 9 for details). Since these studies fall within the ranges presented in Figure 1, omitting them does not affect the median or mean values.

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[3] All number quoted below assume a harmonized amortization period (20 years).

Decomposition method for comparison of studies

In order to understand uncertainty of GHG emissions due to ILUC, it is important to understand the main steps (components) in the analysis **of indirect land use change** as well as the availability of scientific evidence for these components. Insight in the main components is also required for understanding outcomes of different studies, even though most studies do not present their results in a manner enabling precise decomposition.

Decomposition approach

Based on **decompositions** accomplished in some relevant ILUC studies such as Valin et al. (2015), Laborde (2011), Searchinger et al. (2015) and Malins et al. (2014), an attempt has been made to integrate these into one framework. The main purpose is to compare the most important studies and to make clear where the main causes of uncertainty come from.

The basic idea of this approach is a **stepwise decomposition** of the biofuel feedstock land use by starting with a gross feedstock area per GJ and resulting in the net land use change after taking into account the following impacts:

- Gross land use of the biofuel feedstock
- Reduced area because of co-production of by-products
- Reduced area because of reduced demand for non-biofuel crops
- Reduced area because of increase in yields of both biofuel feedstocks and other agricultural commodities
- Relocation of production to areas or crops with different yields

Some studies only focus on the change in crop area, while other studies also include permanent grassland or managed forest area[4] explicitly in their analysis. In order to come from net cropland expansion towards GHG emissions from ILUC, it must also be determined which types of land are converted to cropland, and to have knowledge of carbon stock and carbon sequestration potential for all land use types.

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[4] This is a land use category defined in the GTAP-AEZ database (CARB 2009) that is for example used in the general equilibrium model MIRAGE (Laborde et al. 2014).

Uncertainty analysis/ quantification

Empirical information of these 5 most relevant components for ILUC quantification is **limited**.

Uncertainty about the yield trend has relatively small consequences for ILUC compared with the other factors. ILUC is more or less proportional to the area of the biofuel crops per GJ of biofuel.

Reduced area because of increase in yields of both biofuel feedstocks and other agricultural commodities is challenging to estimate. Econometric estimates based on sound instrumental variable econometric techniques suggest small yield elasticities compared with area elasticities and therefore a small area reduction because of yields. However, these econometric estimates provide short-term effects, while most economic models assume that long-term effects are much larger.

Reduced demand for non-biofuel crops can reduce ILUC in one third or a half. However, studies like Searchinger et al. (2015) and Malins et al. (2014) doubt if the impact of reduced non-biofuel demand should be allocated to ILUC reduction for biofuels because the reduction in GHG emissions is the consequence of reduced consumption of non-biofuels such as food and feed while others bear the cost of creating this GHG benefit. According to them, it should at least be made explicit what share of ILUC reduction is caused by reduced consumption of non-biofuels. Furthermore, Schmidt et al. (2015) suggest that the consumption effect should not be included because in the long term agricultural supply is almost perfectly elastic.

Persson (2016) suggests that there is still considerable uncertainty around how **prices are affected by biofuel demand**. In order to predict in a better way both current and future impacts of biofuel demand, improvement of models and data, improved understanding, and empirical evidence for price elasticities is necessary. In addition, mechanisms for price transmission in international markets, and better capture of forces (including policies) that shape the future expansion of cropland should be understood better.[5]

Furthermore, a lot of uncertainty exists related to the **type of land converted by agricultural expansion** and its GHG emissions (including how much carbon is

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[5] There is also an extensive literature on food security consequences of biofuels, but not in the context of ILUC analysis.

emitted with land clearance, or the amount of carbon emissions because of peatland development). However, some researchers, especially Plevin et al. (2015), suggest that this uncertainty is less than the economic effects incorporated in the by-product, yield and consumption effect.

Uncertainty related to relocation of production to areas or crops with different yields has not been analysed in detail, and is in most cases only implicit in the reporting of ILUC results.

Nine studies include detailed ILUC GHG uncertainty analyses. Most studies apply **Monte Carlo** analyses by varying systematically a number of parameters in the model, and the outcome is in most cases that the spread is very large. Most authors conclude that it is **not** plausible that uncertainty will be **narrowed down** in the near future.

By-products accounting in ILUC

All studies take **by-products** into account. Most non-economic approaches distribute land use of the feedstock area over biofuels and by-products (with feed being the main by-product) based on **weight or energy share**, but in more complex economic models **substitution** between by-products (i.e. rapeseed cakes, DDGS) and alternative animal feed are explicitly modelled.

In economic models the production of by-products may generate very complicated substitution processes, where for example production of rapeseed oil in the EU may result in reduction of soy cakes (by-product of soybean oil production) and consequently in reduction of soybean production in Brazil. Reduction of soybean oil production leads to expansion of palm oil production in Malaysia and Indonesia as palm oil is the cheapest substitute of soybean oil. These results depend fundamentally on assumptions about substitution possibilities between different types of animal feed and between different types of vegetable oil. In most economic model studies, there is not an explicit comparison of results with and without biofuel by-products. Also, Lywood (2013) uses a complex substitution approach for by-products. Compared with the economic studies, it shows a different perspective on the substitution process in animal feeding and the consequence of reducing soy vegetable oil production. As a result, it comes to findings that are more positive on the consequences of rapeseed biodiesel production for GHG emissions.

Detailed assessments (based on hybrid-LCAs or bottom-up calculations) highlight that different by-product accounting methods lead to very different ILUC factors.

Some researchers suggest that ambiguities and different interpretations of calculation procedures in existing legislative frameworks, may lead to widely ranging ILUC factors.

Factoring in the impacts of non-biofuel policies

In general, in ILUC studies **little or no information is available about the consequences of other EU-policies on ILUC GHG emissions**. Global environmental policies like deforestation and peatland drainage prevention policies are sometimes modelled by reducing the amount of high carbon land available for conversion into agriculture or a general tax on emissions from land conversion. These type of studies show significant reductions of ILUC GHG emissions because no or less high carbon land is converted for non-biofuel uses, including agriculture. One study (Valin et al., 2015) refers to the "Common Agricultural Policy" (CAP) and its impact on the carbon stock on abandoned agricultural land, but without being it factored in.

ILUC from dedicated energy crops

Studies that evaluate the ILUC effects of **advanced biofuels** are rare, but the available studies overall show **lower ILUC factors** than other biofuels. Advanced biofuels, have a median ILUC factor of 5 gCO_2-eq/MJ. Besides one study, they show the lowest variation in results. **Negative emissions** are generated if **marginal areas**[6]**,** in which the above and belowground carbon content is increased by perennial crops, are used. However, the way "marginal lands" are defined is different per study[7] and this makes drawing general conclusions on negative emissions for dedicated cropping in marginal lands impossible. One study highlights that negative emissions could also be achieved if corn stover is used. Due to the limited number of studies and methodologies assessing advanced feedstocks, and the diversity of lands included in the "marginal land" group, it is not possible to make statements on the robustness of the results.

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[6] FAO definition for marginal land: Land having limitations which in aggregate are severe for sustained application of a given use. Increased inputs to maintain productivity or benefits will be only marginally justified. Limited options for diversification without the use of inputs. With inappropriate management, risks of irreversible degradation.

[7] Many different names are used to designate lands in terms of their production capacity - favoured, fertile, marginal, low potential, resource poor, high potential, fragile, vulnerable or degraded. Terms which relate to "marginal" areas are frequently used interchangeably and often without definition. The difficulty in formulating a clear definition stems from the fact that "productivity" varies according to the type of land use. (FAO)

The **main feedstocks studied reporting ILUC GHG emissions** include:

- **Forest residues**: Valin et al. (2015) report 17 gCO_2-eq/MJ biofuel, these emissions are the result of a lower build-up of soil organic carbon.
- **Straw and stover**: Overmars et al. (2015) report 2-3 gCO_2-eq/MJ biofuel ILUC emissions; Valin et al. (2015) report 0-16 gCO_2-eq/MJ biofuel ILUC emissions for cereal straw. Taheripour and Tyner (2013) present negative ILUC emissions for corn stover ethanol using the GTAP-BIO model with different emission factor databases (-0.9 to -1.6 gCO_2-eq/MJ).
- **Switchgrass & miscanthus**: Valin et al. (2015) report -12 gCO_2-eq/MJ biofuel if grown on abandoned crop lands, negative emission caused by net carbon increase in above and below ground carbon compensating for the foregone carbon sequestration on abandoned lands. Taheripour & Tyner (2013) present ILUC emissions ranging from 5.8-74, depending on emission factor database. Mullins et al. (2011) reports a range of -10-155 gCO_2-eq/MJ based on the 95% confidence interval of a Monte Carlo analysis of different parameters. Melillo et al. (2009), using the EPPA CGE model, reports very high values for ILUC emissions (275-285 gCO_2-eq/MJ) for an aggregate of eucalyptus, switchgrass and poplar).
- **Short rotation plantations**: Valin et al. (2015) report -29 gCO_2-eq/MJ biofuel if grown on abandoned crop land. The negative emission is caused by net carbon increase in above and below ground carbon compensating for the foregone carbon sequestration on abandoned lands. Fritsche et al. (2010) provides a range of 38-75 gCO_2-eq/MJ based on different assumptions of ILUC prevalence.

Other indirect effects of EU biofuels policy

The literature review described in this report focuses primarily on GHG emissions due to ILUC. Nonetheless, during the review, a number of studies pointed out other important indirect effects of biofuel production. Those are mainly focused on **environmental impacts**, especially on biodiversity, and social impacts of increased prices of agricultural commodities. Furthermore, concerns have been raised related to indirect nitrous oxide emission impacts (i.e. for production of fertilisers due to increased removal of agriculture residues), which may be higher than those from carbon loss.

Low-ILUC certification and ILUC mitigation options

In order to prevent ILUC effects, different **mitigation** options have been discussed in the literature. The starting point for the inventory of low ILUC-risk biofuels is the definition in the ILUC Directive (EU) 2015/1513 that defines the concept as "biofuels, the feedstock of which were produced within schemes which reduce the displacement of production for purposes other than for making biofuels". In other words, it concerns measures that reduce displacement, but not necessarily mitigate it completely. Following, a summary overview of approaches that help to bring ILUC impacts down is given, and their effectiveness is discussed:

- Prioritize **the use of residues and by-products such as** agricultural residues (i.e. straw, stover, manure), forestry residues (i.e. branches, stumps), by-products of the food processing industry (i.e. animal fats, peels, husks, molasses, etc.) and of the wood processing industries (i.e. bark, sawdust, cut-offs, etc.) or other types of waste and residues (i.e. demolition wood, organic fraction of municipal solid waste). As far as these by-products are unused by-products and their use does not lead to a reduction in carbon stock or loss of soil fertility, they can be regarded as low ILUC-risk. Several studies indicate however, that when removal rates of primary residues exceed sustainable potentials, the resulting losses in soil organic carbon and fertility need to be compensated by increased use of fertilisers to prevent lower crop yields. Fact that can potentially result in higher GHG emissions (i.e. Taheripour et al. 2013; Valin et al. 2015). Secondly, several economic oriented studies consider that harvesting of residues generates extra income and consequently may create an incentive to expand the production of main products, either through area expansion and/or yield increases, and this may have possible additional ILUC effects (Dunn et al. 2013; Pratt and et al. 2014; Taheripour and Tyner 2015; Thompson and Tyner 2014).
- Prioritize the use of feedstock produced on **abandoned**[8] **, unused, marginal, fallow, under-utilised or polluted lands.** In most studies, these lands are not clearly defined and this explains why these 5 terms are used here.

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[8] Land that was previously used to produce economic output (agricultural production, houses for residential purposes, industrial production, etc.) and that is no longer used for that purpose. Abandoned land is land in a not productive state, which can be reclaimed back to the original use or possibly converted to other uses, in case demand for such uses be. (Perpina-Castillo et al., 2015).

The key assumption in all studies evaluated (Valin et al. 2015; Plevin et al. 2013; Overmars et al. 2015; van der Laan, Wicke, and Faaij 2015; Elbersen et al. 2013; Nsanganwimana et al. 2014; Frank et al. 2013) is that lands are used for the production of biomass for biofuels that would otherwise remain unused for the production of food, feed or biomass for non-energy purposes. In all studies evaluated addressing biofuel feedstock use from these lands, it is assumed that when promoting the production of many woody or grassy energy crops, these can be grown in areas that are not suitable for conventional crops, livestock, and forestry, and therefore do not compete with other land uses (marginal land). These crops include perennial grasses, such as switchgrass, miscanthus, mixed prairie grasses or short rotation coppices, such as eucalyptus or poplar. When carbon sequestration by the biofuel crop is larger than the carbon sequestration on the abandoned and/or unused degraded land, ILUC effects may even be negative. Whether the different types of lands that can be used for biomass crops are really unused and suitable for biomass production (and no food crops) is simply assumed in all studies evaluated on this issue (Valin et al., 2015; Plevin, 2013; Frank et al., 2013; Elbersen et al., 2013; van Laan, 2015). Furthermore, if the study predicts ILUC emissions to be 0 or negative it implies that it is assumed that the carbon value of the biofuel feedstock is higher than the carbon value in the original (natural) vegetation on the “unused” lands. This again is more based on assumptions than on real empirical evidence, since the exact vegetation status and carbon build up is not well studied for lands that are expected to be unused.

- To **increase agricultural yields, since improving the efficiency of agriculture** will avoid conversions of natural vegetation and associated undesirable effects on biodiversity and GHG emissions from land use change. As far as the yield increase is on the area of biofuels, this is included in LCA analysis, but if it is on crops for other purposes, it is not, even though it is relevant for the calculation of net GHG emissions, and thus for the ILUC effect allocated to biofuel pathways. Furthermore, increased demand for biofuel feedstock may lead to higher prices that may also stimulate overall yield increases in agricultural lands. It can therefore be concluded that yield increases should not be focussed on biofuel crops only, both in allocating GHG mitigation and emissions.

Furthermore, policies will be more effective in bringing down land use conversions when applied to the whole agricultural sector and not the biofuel sector alone.

- To **protect areas** with high carbon stock and/or high biodiversity values. The benefits of protection of natural vegetation and lower ILUC emissions from food and biofuels production cannot be allocated to the production of biofuels only, unless these policies are implemented as part of the policies that stimulate the sustainable production and use of biofuels. Moreover, the protection of natural vegetation may limit the ILUC emissions of biofuels, but this may also lead indirectly to a trade-off with higher food prices and impact on food consumption.

Conclusions

ILUC factors identified in the literature vary significantly across biofuel pathways, studies, or even within studies. Studies that have investigated parametric uncertainty conclude that parametric uncertainty has a significant effect on the outcomes. As a consequence of all the **uncertainties** in the components of ILUC emissions, it is very **difficult to narrow them down**.

Low ILUC-risk feedstocks, especially **residues** from forestry or agriculture as well as **dedicated energy crops** may be relatively promising, but it has to be taken into account that sustainable supply potential may be limited for the use of residues due to impacts to other uses of the residues or indirect carbon loss in agricultural or forestland. As for dedicated cropping on unused lands, it is important that a further evaluation is done about the extension and status of lands that can potentially be regarded as "unused, abandoned, marginal or polluted". The studies that evaluate the ILUC effects of these options (Valin et al., 2015; Plevin et al., 2013; van der Laan, Wicke, and Faaij, 2015; Mullins, Griffin, and Matthews, 2011; Overmars et al., 2015; Fritsche, Hennenberg, and Hünecke, 2010) are mostly based on assumptions regarding status, extension and the current natural vegetation present on these areas, rather than on empirical evidence. Uncertainty about how much land can eventually be converted to cropland is also confirmed by a study by Eitelberg, van Vliet, and Verburg (2015).

In general, it can be concluded that the **certification of low ILUC-risk** biofuels, as defined in the Directive (EU) 2015/1513[9] is possible as there are indeed, several options for using feedstock for biofuels that have low displacement effects as compared to most conventionally used cropped feedstocks used for current 1st generation biofuels. However, the evaluation of low ILUC-risk biofuel related studies also indicates that it is unlikely to be able to prevent all negative indirect effects through low ILUC-risk biofuels certification. On the other hand a ban on unsustainable land conversion for biofuel production, results in extra pressure on land for other purposes, and therefore, also in extra unsustainable land conversion for these other purposes.

Additional measures beyond the scope of certification, continue to be needed, such as integrated land use planning, including protection of natural vegetation.

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[9] In Directive (EU) 2015/1513 low ILUC risk biofuels and bioliquids are defined as "biofuels and bioliquids of which the feedstocks were produced within schemes which reduce the displacement of production for purposes other than for making biofuels and bioliquids and which were produced in accordance with the sustainability criteria for biofuels and bioliquids set out in article 17 of Directive 2009/28/EC on promotion of the use of energy from renewable sources.

1. Introduction

The European Union (EU) developed a renewable energy policy in order to fulfil its commitment to mitigate GHG emissions, as well as to promote security of energy supply, technological development and innovation, opportunities for employment and regional development, especially in rural and isolated areas or regions with low population density.

The **Renewable Energy Directive (RED)** sets a target of 10% renewable energy in transport by 2020, the majority of contribution for reaching this target is coming from biofuels. The EU mandatory sustainability criteria for biofuels and bioliquids do not allow the raw material for biofuel production to be obtained from land with high carbon stock or high biodiversity. However, this does not guarantee that as a consequence of biofuels production such land is not used for production of raw materials for other purposes.

If land for biofuels is taken from cropland formerly used for other purposes or by conversion of grassland in arable land for biofuel production, the former agricultural production on this land has to be grown somewhere else. And if there is no regulation that this must happen sustainably, land conversion of land for production may happen on land which is not allowed to be used under the EU sustainability criteria for biofuels. This conversion may take place in other countries than where the biofuel is produced. This is called **indirect land use change (ILUC).** In 2015, it was decided that measures to reduce ILUC will also be included in the RED, although the ILUC factors are included only for reporting requirement.

This report will provide inputs for the reporting requirements under Article 3 of the European Union's **Directive (EU) 2015/1513 of 9 September 2015** by summarizing and interpreting the available and best available scientific evidence on ILUC GHG emissions associated with the production of biofuels and bioliquids and the latest available information with regard to key assumptions influencing the results from modelling of the ILUC GHG emissions associated with the production of biofuels and bioliquids. It will also analyse the scientific evidence on measures (introduced in the directive or not) to limit indirect land-use emissions, either through promotion of low ILUC-risk biofuels or more general measures.

Besides the report will also provide inputs for **Article 23 of the revised European Union's Directive 2009/28/EC (RES Directive)** on the latest available information with regard to key assumptions influencing the results from modelling ILUC GHG emissions, as well as an assessment of whether the range of uncertainty identified in the analysis underlying the estimations of ILUC emissions can be narrowed down, and if the possible impact of the EU policies, such as environment, climate and agricultural policies, can be factored in. An assessment of a possibility of setting out criteria for the identification and certification of low ILUC-risk biofuels that are produced in accordance with the EU sustainability criteria is also required.

What is ILUC?

The cultivation of crops requires land. Production of biofuels increases demand for crops that needs to be satisfied either through intensification of current production or by bringing non-agricultural land into production. When new cropland is created for the production of biofuel feedstock, this land conversion is called **direct land use change**, or DLUC. When existing cropland is used for biofuel feedstock production, forcing food, feed and materials to be produced on new cropland elsewhere, this expansion is called **indirect land use change**, or ILUC.

Direct land use changes can be directly observed and measured, and exclusively linked to the life cycle of the bioenergy product that can be expressed in direct GHG emissions. For biofuels in transport, the most common boundary of the life cycle is from the growth of the biomass to its application as fuel. This well-to-wheel method is applied to determine direct GHG emission and environmental impacts. The EU RED requires that for the calculation of the GHG emissions and GHG emission savings compared to fossil fuels, only the direct land use change emissions need to be included in accordance with the IPCC methodology.

In the situation where the biofuel crop is grown on existing productive lands, it is likely that the original crop (or other productive land use) would (at least partly) have to be produced elsewhere. This is the starting point for the **indirect land use change** effects. Firstly, the new demand displaces existing production which needs to be produced elsewhere. This displacement leads directly or indirectly (through a number of other displacement steps) to conversion of natural (i.e. (tropical rain) forests, savannah and wetlands) and semi-natural lands (i.e. extensively grazed grasslands) into agricultural land[10] for non-biofuel production purposes. Secondly, part of the demand is absorbed through intensification of existing land uses.

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[10] Any area taken up by arable land, permanent grassland or permanent crops (CAP Glossary)

The incremental use of land for agricultural production, whether a result of demand for biofuels, food, feed or other non-food applications, leads directly or indirectly to an increase of GHG emissions and to loss of natural habitats with adverse effects on biodiversity and ecosystem services. Indirect effects of additional bioenergy feedstock demand do not only cover indirect land use changes, but also affect agricultural commodity prices, with potential consequences for food security and demand-induced yield increases – where the additional demand for the feedstock triggers additional yield increases.

2. Scientific ILUC research review. Overview and Methodology

In order to provide a systematic analysis of the latest available scientific research and the latest available scientific evidence on ILUC GHG emissions associated with the production of biofuels, focus was put on the literature published in 2012-2016 period, and included also the main *landmark studies*[11] on ILUC published before 2012.

The **literature review** included **peer reviewed** scientific articles as well as **grey literature** such as reports from influential organisations, working papers and conference proceedings. The search was conducted using academic search engines, google and by reviewing publication lists of important consultancies, international organizations, institutes, NGOs and governmental organizations. In order to ensure that the literature provides insights relevant for potential future biofuel/bioenergy possibilities, no constraints were placed on feedstocks or conversion technologies (1st generation, advanced biofuels, bioliquids for power, heat, etc.). The **initial search** was not constrained to any geographic scope in order to maximise the number of returned literature, however studies focusing on EU biofuel policies were given a priority. Furthermore, authors approached their extensive network of contacts in order to get information on the latest research carried out at national level by EU Member States, as well as other countries. Initially contacts in 25 countries were contacted. However, the response rate was very low. Contacts which did respond highlighted the importance of influential reports and peer reviewed literature which was already included in our literature search. Besides, a survey was launched to the ILUC related scientific community aiming at further complete the scientific literature review. Reports and peer reviewed literature compiled from the survey were included in the database.

The initial literature search returned 1248 entries. This literature was narrowed down through a **1st preselection** which excluded studies focusing on aspects which were not of direct interest to this study, i.e. studies focusing on biodiversity, water, air quality, or (indirect) land use changes from drivers other than biofuels/bioenergy. Furthermore, in order to aid data gathering the 1st preselection divided the eligible literature between studies containing detailed quantitative information (such as GHG emission factors, uncertainty values, etc) and studies that did not. After this 1st preselection, there were 191 documents with detailed quantitative information and 337 other eligible documents.

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[11] Landmark studies are identified as the most cited relevant literature.

Table 1 Summary and figures of ILUC literature search. **Source:** Own elaboration

1st Search	1st Preselection	2nd Preselection
1248	**559**	**302**
Landmark	31	31
Quantitative	191	105
Non- Quantitative	337	166

A 2nd **preselection** was conducted in order to limit the number of studies to those which would help identifying causes, effects, determinants and mitigation of ILUC for biofuel/bioenergy production. This was done to filter out studies that, even though relevant for ILUC science, did not provide enough information in order to allow for the detailed analysis required by the matrix, (see Appendix 1: Matrix details). The 2nd preselection yielded 105 eligible studies providing quantitative information, 166 providing non-quantitative information, as well as 31 pre-2012 landmark studies.

All eligible quantitative and landmark literature from the 2nd preselection underwent a **detailed review** in order to extract relevant information. Data gathered is outlined in Appendix 2: Summary Matrix, and was compiled in a spreadsheet database. The literature identified in the 1st preselection is also included in the Matrix, without however including detailed insights.

Among the studies from the 2nd preselection, the vast majority of ILUC related scientific research are **Peer-Reviewed** papers. The studies primarily focus on **Europe and the United States**, which together account for more than 80% of the output. They are followed by Brazil which is significantly behind at 7%. Within Europe, the **Netherlands and Germany** accumulate most of ILUC research (22% and 20% respectively). These are followed by United Kingdom, Austria, Belgium France and Spain.

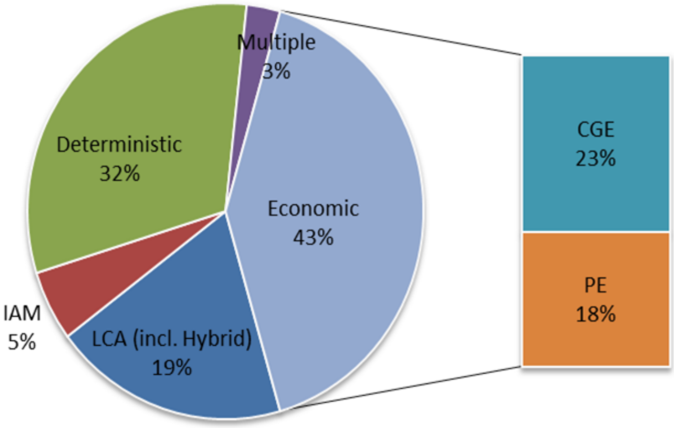

Figure 2 Classification of modelling studies.
Source: Own work.

Among the main purposes of the available ILUC research, most of the papers aim at addressing ***Policy Impact Forecast***, followed by ***Preventive or Mitigation Measures***. The next most important topic is *Identification of Biofuel Potential*, while *Regulatory issues* are the least addressed. From the latest available research, most of the studies are ***Model Projections*** *(including hybrid LCA)*. *Review Studies, Case Studies* and *Discussion or Methodological Studies* follow, all of which have a very similar proportion. Regarding type of modelling**, *Economic Modelling*** is the most widespread, with a similar proportion of *General Equilibrium* and *Partial Equilibrium* models. Following are *Deterministic* (causal descriptive and empirical) approaches and *LCA*.

Among studies focusing on specific policy targets, these usually evaluate the ***EU-RED*** and ***US-RFS***. However, a very important part of the research does **not indicate** if and which **policy measures** are accounted for. Therefore, it is very risky to extract conclusions on this topic. Regarding the type of biofuels most commonly studied in the most recent ILUC research, those are focused in **1st Generation Biofuels**, or cover **1st and 2nd Generation Biofuels**. In relation to the feedstocks covered, more than half cover the most important 1st generation crops such as **corn, sugarcane, rapeseed, soybean, palm and wheat**. Just over 10% of the reviewed studies cover advanced feedstocks such as SRC, forest residues or miscanthus.

The most common demand regions considered in ILUC research studies are **Global, EU or US demand**. Concerning supply regions, Brazil is usually also included. However, it is important to note that a large portion of the reviewed literature (≈30%) does not state the geographic focus and therefore, it is very hazardous to extract conclusions on this topic.

Although all studies take **by-products** into account, only a minor amount of research clearly indicates the consideration and accounting of by-products. In relation to **uncertainty**, this is explicitly considered in less than half of the reviewed ILUC research. It is addressed by different means such as sensitive analysis, or use of different scenarios.

ILUC quantification methods

ILUC cannot be measured or quantified directly and therefore has to be **modelled**. To quantify GHG emissions from ILUC in models, quantitative relations need to be established between (1) the additional biomass feedstock production and respective conversion of previous land use, and (2) the displaced agricultural production and its direct LUC effects.

Relation (1) can be derived from general or partial equilibrium, **economic models** for agricultural production that simulate the trade relations between countries, commodities, and markets, and can compute changes in land use. It is important to note that these models quantify the total land use changes, not splits between DLUC and ILUC; splits between ILUC and DLUC can only be made when DLUC is quantified by other means. For (2), **biophysical models** are needed to derive direct LUC effects and the respective CO_2 emission balance. Thus, the quantification of GHG emissions from ILUC requires the coupling of very different models and compatible spatial, as well as time, resolutions.

Model projections tend to project different **futures, or scenarios**. These are usually differentiated across *intervention* and *no-intervention* in order to investigate the effect of the said intervention. Interventions include biofuel policies such as EU-RED or US-RFS; land use constraints and policies such as UN REDD Programme (United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries); policies aimed at meeting strict climate goals; availability and improvement of (specific) biofuel technologies; or, combinations of the above.

Besides interventions, it is important to note that the results depend on a number of further **model assumptions**. These include projected trade patterns, substitutability of agricultural products, yield elasticities and consumption elasticity. These are all very **uncertain** and the harmonisation of models and methods, which would allow for a better understanding of “model uncertainty”, is notoriously difficult. As such, each model tells a different story.

The vast majority of studies make projections 5 to 30 years into the future, while studies whose main focus is climate policy tend to have a long term time horizon, mostly 2050 or 2100. Depending on the model and scope of the study, geographic ranges cover country, multi-country (usually having a “demand” country and multiple “supply countries) or global (defined by multiple regions).

Following a **comparative analysis of different approaches and methodologies** to evaluate (I)LUC GHG emissions of biofuels is presented. For each of the methodologies used nowadays, the main **rationale and scientific evidences** behind are compared, followed by the **uncertainties** and **sensitivities** that these present. Finally the main **models** used in each approach, as well as the **geographic scope** are presented. Finally the **range of GHG ILUC results** modelled in each of these approaches are presented.

Table 2 Comparative analysis of different approaches and methodologies to evaluate (I)LUC GHG emissions of biofuels. **Source:** Own elaboration

Methodology[12]	**Scientific Evidence**	**Main sources of uncertainties**	**Main sensitivities**	**Models**	**Geographic Scope**	**Ranges of ILUC results** (gCO_2-eq /MJ) Including outliers[13]	**Key References**
Partial Equilibrium (PE) Models	Based on the concept of "economic equilibrium", i.e. supply and demand are equilibrated through price adjustments. Econometric analysis dictates this behaviour.	The models tend to take a regional or global perspective and suffer from uncertainties arising from aggregation: - Crop yields, particularly marginal crop yields. Indirect effects on food consumption. -Broader indirect effects on the overall economy. Especially food consumption - Land use change emission factors.	Feedstock type. i.e. use of maize leads to higher ILUC effects, compared to other crops.	- CARD-GreenAgSim - FAPRI - FAPRI-CARD - GLOBIOM	Regional or global. Mostly covering the EU and US.	Biodiesel: -10 – 400 1st Gen. bioethanol: -75 – 213 Advanced: -30 – 30	(Dumortier et al., 2011; Edwards, Mulligan, & Marelli, 2010; Mosnier et al., 2013a; Richard J Plevin et al., 2010; T. Searchinger et al., 2008; Valin et al., 2015)
General Equilibrium (CGE) Models	Similar to PEs but accounting for the entire economy. Thus include further economic feedbacks ignored by PEs. These are based on input-output tables (i.e. social accounting matrices) with flows usually measured in monetary terms.	Similar to PEs, except that since CGEs include the broader economy: - Their characterisation of agricultural and energy systems is even more aggregate. - Substitution based on elasticities (CET). - Parameterisation very uncertain. - Land constraints and land aggregation methods.	Parametric uncertainty shows that 90% of results are ±20 gCO_2-eq/MJ from the mean (within a single study).	- MIRAGE - IFPRI MIRAGE - LEITAP - GTAP - GREET-GTAP-BIO-ADV	Regional or global. Mostly covering the EU and US.	Biodiesel: 27 – 107 1st Gen. bioethanol: 1 – 155 Advanced: 272 – 285	(Al-Riffai, Dimaranan, & Laborde, 2010; Edwards et al., 2010; D Laborde, 2011; David Laborde, Padella, Edwards, & Marelli, 2014; Melillo et al., 2009; Moreira, Gurgel, & Seabra, 2014; Richard J Plevin, Beckman, Golub, Witcover, & O'Hare, 2015; Farzad Taheripour & Tyner, 2013; W. Tyner, Taheripour, Zhuang, Bidur, & Baldos, 2010)

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[12] PE and CGE models are also combined with biophysical models which determine changes in carbon stocks based on the land-use changes projected by the economic models.
[13] These values assume a harmonized amortization period of 20 years.

Methodology[14]	**Scientific Evidence**	**Main sources of uncertainties**	**Main sensitivities**	**Models**	**Geographic Scope**	**Ranges of ILUC results** (gCO_2-eq /MJ) Including outliers[15]	**Key References**
Integrated Assessment Models (IAM)	Aim to account for the long term and global interactions between human and natural systems by adopting a systems-dynamic approach combining land-use, energy, nutrient, societal and climate systems. No standard methodology, usually a combination PE, CGE, CD and LCA methods.	- As these models aim to show long-term dynamics, uncertainties include the future development of key drivers (population, economic growth, etc.). - Uncertainties due to increased aggregation.	Future energy and agricultural demand.	- GCAM - GLOBIOM-PRIMES-EPIC-G4M -ReMIND/ MAgPie - IMAGE	Global	Results usually presented in changes in land demand.	(Kraxner et al., 2013; Meller, van Vuuren, & Cabeza, 2015; Popp et al., 2014; Wise, Dooley, Luckow, Calvin, & Kyle, 2014)
Causal Descriptive (CD) Models	Extrapolations of observed trends and assumptions of future trade patterns, displacement ratios and incremental land use. These methods were developed in order to simplify data intense and complex economic models.	Key assumption is that current patterns are an adequate proxy for potential future ILUC. Thus they do not account for economic feedbacks which may arise.	Unclear due to limited number of studies.	Original methods	- EU, Canada, Ukraine. - EU, US, Brazil, Argentina, Indonesia.	Biodiesel: 18 – 101	(Baral & Malins, 2016)

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[14] PE and CGE models are also combined with biophysical models which determine changes in carbon stocks based on the land-use changes projected by the economic models.

[15] These values assume a harmonized amortization period of 20 years.

Methodology[16]	**Scientific Evidence**	**Main sources of uncertainties**	**Main sensitivities**	**Models**	**Geographic Scope**	**Ranges of ILUC results** (gCO_2-eq /MJ) Including outliers[17]	**Key References**
Hybrid Life Cycle Assessment (LCA)	Contains detailed information on techno-economic parameterisation. Limited understanding of land use change dynamics.	Typically, LCAs ignore indirect effects. Some studies overcome this by combining them with economic modelling (Hybrid LCA).	- Results sensitive to allocation of ILUC to all products of a given process, or to biofuel only. - Technological setups and feedstock possibilities.	Consequential LCAs and Hybrid LCA	Multiple, depending on study. Always local.	Biodiesel: 1 – 79 1st Gen. bioethanol: 4-113 Advanced: -23 – 155	(A.A. Acquaye et al., 2011; Adolf A Acquaye et al., 2012; Bento & Klotz, 2014; Boldrin & Astrup, 2015; Mullins et al., 2011; Prapaspongsa & Gheewala, 2016)
Empirical Approaches	Based on case studies and interpreting historical observations.	Counterfactual if biofuels had not been produced. Assumptions are usually based on past behaviour.	Extremely sensitive on assumptions about reduced allocation rules of ILUC factors (similar to LCAs), as well as changes in behaviour, particularly changes in cattle stocking rates and reduced meat consumption.	- IMAGE - In field measurements	Case studies focused in Brazil, Malawi and Germany. IMAGE used in a global study.	Biodiesel: -94-257 1st Gen. bioethanol: 1 – 154 Advanced: 0 - 75	(Dunkelberg, 2014; Fritsche, Hennenberg, et al., 2010; Lywood, 2013; Overmars et al., 2015; Overmars, Stehfest, Ros, & Prins, 2011)

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[16] PE and CGE models are also combined with biophysical models which determine changes in carbon stocks based on the land-use changes projected by the economic models.
[17] These values assume a harmonized amortization period of 20 years.

3. Types of ILUC studies and objectives

3.1. Review Studies

In order to understand and state-of-the art overview of a specific topic, review studies are very useful. Review studies **bring together and analyse writings, knowledge and views on a specific topic. Prior to 2012**, the effects of ILUC were still uncertain. Nevertheless, the existence of the ILUC effects was recognized, as well the need to observe and quantify them. In addition, the necessity for developing and applying harmonized sustainability criteria was acknowledged. As modelling studies were increasingly published, research was done on identifying uncertainties of modelling ILUC.

Since 2012, though ILUC continue to be an important topic of research, progress has been limited: apparently there is still a need to understand and evaluate claims about ILUC, as some studies are focusing on identifying and exploring the key factors which determine the amount of ILUC happening in the real world. Regarding quantifying the GHG of ILUC by modelling it, this area of research has progressed, and the differences in modelling approaches have been described and identified. Nevertheless, it is documented that the ILUC GHG emissions results depend on the model used, where the differences in results range a lot. In this regard, it has been acknowledged that there is still no way to determine which of the many models yields the most reliable overall carbon intensity.

Table 3 . Review studies (Landmark and post-2012) focusing on the calculation and effects of ILUC.
Source: Own elaboration

Study	Aim and main findings
Gibbs et al. (2008)	An analysis of direct carbon impacts of crop based biofuels into tropical ecosystems finding that this expansion will lead to net carbon emissions for decades to centuries.
Cherubini et al. (2009)	Review of bioenergy LCA. Explains ranges in indirect effects with respect methods employed, concluding that the use of advanced feedstocks, as by-products, and higher yields are necessary in order to reduce net emissions.
Liska & Perrin (2009)	Review of ILUC methods, uncertainties and conclusions of the main ILUC research. Points out the necessity for additional and improved research including case studies.
Cherubini & Stromman (2010)	Review of LCA studies, highlighting the lack of ILUC in these analyses.
Fargione et al. (2010)	Review of ecological impacts of biofuels, including ILUC.
Fritsche, Sims, et al. (2010)	Review of current state of GHG emission calculation of bioenergy. Proposes options to reduce LUC and improve its accounting.
Solomon (2010)	Review of biofuels in the context of sustainability science concluding that though biofuels have an important role to play, there is a need for sustainability criteria.
Van Dam et al.	Review the certification of biofuels and bioenergy. Highlights the necessity for

(2010)	increased international harmonisation, monitoring and control.
Gawel & Ludwig (2011)	Covers state of ILUC discussion highlighting the "ILUC" dilemma, i.e. neglect ILUC effects or take them into account despite the lack of a sound methodology. The study suggests to avoid ILUC as much as possible by focusing on the use of, for instance, residues.
Harvey & Pilgrim (2011)	Review of demand drivers for food and fuels, and consequent (I)LUC. Highlights the need for integrated approaches in research and policy making.
Scarlat & Dallemand (2011)	Review of the certification of biofuels and bioenergy. Highlights the requirement for international harmonisation, monitoring and control.
Djomo & Ceulemans (2012)	Reviews models and approaches to quantify (I)LUC, focusing on the variability in results. They highlight that it is unclear which of the results was most appropriate.
Ben Aoun et al. (2013)	Review of methodologies to include LUC effects in LCAs. Finds that LCA should be adapted and combined to other tools in order to provide a more reliable assessment of the biofuels chain.
Broch et al. (2013)	Reviews approaches and databases in order to determine their effects on ILUC variability, highlighting that variability is very high but ILUC values have decreased since Searchinger (2008).
Plevin et al. (2013)	Reviews the ILUC projections of different economic models. Concludes that ILUC can be reduced by limiting competition between bioenergy feedstocks and other high-demand commodities.
Malins et al. (2014a)	Reviews how ILUC factors determined in models are used for regulatory purposes. Reduces ILUC to six key factors: elasticity of food demand to price; elasticity of yield to price; crop choices; co-product use; elasticity of area to price; carbon stock of new lands.

Besides, since 2011 a number of studies have been published **discussing the appropriateness and limits of quantitative methods concerning ILUC calculation.** These studies take the form of methodology comparisons and evaluation of the underlying assumptions, highlighting key uncertainties and knowledge gaps.

An over-arching insight from such comparisons is that it is difficult to judge which method/model is most appropriate as results/methods may not be comparable. Key differences in model parameterization (i.e. elasticities) and assumptions (i.e. amortization period, regional/land cover/biofuel definitions) pose further obstacles for comparison. Instead it is more appropriate to highlight **strengths and weaknesses** of different methods.

In partial and general equilibrium models weaknesses arise from the underlying datasets which describe the social accounting matrices (SAM), the elasticities and biophysical properties of newly converted land (yields, carbon contents). Particularly for elasticities, these are usually based on historic data and thus implying that future projections are an extrapolation of observed trends. However, institutional changes such as sustainability criteria and land market regulations will affect the functioning of land markets.

Table 4 . Studies analysing and comparing ILUC study methods. Source: Own elaboration

Study	Aim and main findings
Djomo & Ceulemans (2012)	Reviews models and approaches to quantify (I)LUC, focusing on the variability in results. Highlights that it is unclear which of the results was most appropriate.
Wicke et al. (2012)	Provides an overview of the current status of ILUC modelling approaches highlighting their criticalities and uncertainties. Suggests that despite recent improvements and refinements of the models, large uncertainties still exist.
Kloverpris et al. (2013)	Suggests that estimates of ILUC are heavily influenced by assumptions regarding the production period and ignore key elements.
Gohin (2014)	Quantifies the effect of crop yield elasticities on LUC in the GTAP and FAPRI models. The study shows that across models the sensitivity to yield assumptions are not comparable because land and production elasticities assumptions are not comparable.
Næss-Schmidt & Hansen (2014)	Analyses the amplitude of ranges of results obtained with various models showing that little improvement has been achieved since 2012.
Panichelli & Gnansounou (2015)	Critical comparison of models in order to identify key modelling choices for assessing LUC-GHG emissions. Concludes that a compromise needs to be found between consistency and complexity that simultaneously captures the holistic and complex dependence of LUC-GHG emissions on global market forces and the specificities of local conditions.

3.2. Partial and General Equilibrium models (PE/CGE)

The starting point of economic models is the concept of **economic equilibrium**, i.e. the idea that supply and demand are equilibrated through price adjustment. **Partial equilibrium** (PE) models focus on specific sectors of the economy, which in the context of biofuels are the agricultural sector, the biofuel sector and sometimes also the forestry sector. This allows for a significant level of detail. For example, different management systems for crop production can be considered and explicit restrictions on feed composition for animals can be taken into account. Partial equilibrium models normally make all their calculations on physical quantities.

Computable General equilibrium (CGE) models represent all sectors of the economy, but in order to keep the model manageable the level of detail of the agricultural sector is much lower than in partial equilibrium models. The advantage of the general equilibrium models is that they can take into account the interaction between markets in an economy, such as for example the agricultural market, the fertilizer market, the energy market and the food market, and can also quantify effects on GDP and welfare including their feedback effects.

In contrast with partial equilibrium models, most general equilibrium models are based on input-output tables, i.e. matrices that show for each sector from which sectors they buy inputs and to what sectors they sell their products, where everything is normally measured in monetary terms, implying that it is difficult to take account of physical relationships between quantities. The large number of interdependencies in the input-output tables imply that elasticities of agricultural demand are indirect, i.e. through other sectors like the processing sectors, service sectors, etc.

Most general equilibrium models use so-called constant elasticity of transformation (CET) functions for substitution between different land use types that allows for explicit consideration of price changes on land substitution, but is very coarse in its approach. Some models like MAGNET and MIRAGE (Laborde et al., 2014) include a land supply curve, i.e. a relationship between average land price and agricultural land supply, what can be seen as a substitution elasticity between agricultural land and non-agricultural land according to the CET approach. Recent research (Zhao, Mensbrugghe, & Tyner, 2017) provides an alternative for the CET approach using an additive version of the CET approach that makes the CET function consistent with physical characteristics in contrast with economic characteristics of land.

Table 5 . PE and CGE modelling studies (Landmark and post-2012). Source: Own elaboration

Study	Aim and main findings
Al.-Riffai et al. (2010)	Investigates LUC effects of EU biofuel policies using the MIRAGE model.
Edwards et al. (2010)	Compares PE and CGE models under consistent scenarios, revealing a wide variation in ILUC factors.
Dumortier et al. (2011)	Sensitivity analysis on the CARD model, highlighting that uncertainty makes it difficult to make robust conclusions.
Laborde (2011b)	Quantifies LUC effects of EU biofuel policies using the MIRAGE model.
Djomo & Ceulemans (2012)	Review of models and approaches to quantify (I)LUC, focusing on the variability in results. They highlight that it is unclear which of the results was most appropriate.
Bottcher et al. (2013)	Analyses the effects of different mitigation options on land use, highlighting that targeting deforestation and biodiversity loss directly is most effective.
Malins (2013)	Performs a Monte-Carlo analysis on the MIRAGE model, highlighting that biofuel mandates may not decrease overall carbon emissions.
Mosnier et al. (2013)	Assesses the RFS2 using the GLOBIOM model highlighting that it will substantially increase agricultural land needed for biofuel production.
Nunez et al. (2013)	Quantifies the land use changes in Brazil and the USA, as well as the changes in commodity prices. The study shows that production of biofuel production can increase to 183 billion litres (from 103) with less than 2% increase in total cropland use.
Oladosu & Kline (2013)	Estimate/quantifies global LUC from USA biofuel demand using the GTAP model, showing lower iLUC values than previous studies.
Taheripour & Tyner (2013)	Uses the GTAP-BIO model to investigate the uncertainty of different biofuel production routes given different emission factor databases. Reveals that different databases lead to significant uncertainties for advanced biofuels.
Kavallari et al. (2014)	Evaluates sensitivity of LUC and different assumptions on blending mixes

	between ethanol and biodiesel using the MAGNET model, concluding that the LUC due to RED is limited.
Moreira et al. (2014)	Combines an LCA (CA-GREET) and a CGE model (GTAP) to estimate life cycle emissions of jet fuel, showing that LUC emissions are the main contributor.
Plevin et al. (2015b)	Performs a Monte-Carlo analysis to quantify the parametric uncertainty of the GTAP model, finding that the modelling assumptions with strongest impact on results are the economic model parameters related to crop yield and the productivity of newly converted cropland.
Searchinger et al. (2015a)	Investigates the role of reduced food consumption, yield increases and price-induced yield increases in economic models on GHG emissions, highlighting strong impact of assumptions related to food consumption on modelling results, suggesting that a substantial fraction of crops diverted to biofuels results in food reductions.
Valin et al. (2015)	Quantifies LUC GHG effects of EU biofuel policy per feedstock and different EU and global policy scenarios by using the GLOBIOM model. Results show huge ranges in LUC factors with advanced feedstocks having potentially negative LUC factors.
Kristkova et al. (2016)	Analyses the R&D budget needed to increase agricultural yields using the MAGNET model, showing it to be a significant fraction of the price of biomass.
Smeets et al. (2016)	Assesses land use effects of the use of residues and waste for energy production, highlighting that they may contribute to food security.
Verstegen, van der Hilst, Woltjer, Karssenberg, de Jong & André P.C. Faaij (2016)	Sensitivity analysis with the MAGNET CGE model and the PLUC land use model for Brazilian biofuel production. Highlights that LUC area has very high uncertainty.

3.3. Integrated Assessment Models (IAM)

Integrated assessment models (IAMs) have been developed as a **tool to investigate the interactions between human and natural systems in order to evaluate the impacts of different policy settings**. IAMs tend to have a long term (2050-2100) and global scope, simultaneously integrating many interrelated systems (land use, energy system, biophysical stock and flows, economics, demographics, etc.). Biofuel feedstocks usually fall under broad categories such as "agricultural crops", "non-food crops" or forestry and land changes are described in aggregate terms, usually on a regional and biome scale. The usefulness of IAMs lies therefore in the identification of potential tradeoffs between systems to be considered in future research and frame boundaries for lower scale assessments, both in time and space. Due to the need to aggregate technologies, biophysical conditions and market effects, they lack important details and may not capture all relevant aspects appropriately.

In a pre-2012 landmark study Melillo et al. (2009) coupled a CGE and a process based terrestrial biogeochemistry model into an IAM (EPPA-GTAP). This IAM was used to generate global land-use scenarios and explore direct and indirect GHG effects of possible land-use changes from an expanded global cellulosic bioenergy program over the 21st century, covering most of the transport fuels demand by biofuels by the end of the century. Kraxner et al. (2013) combined the GLOBIOM (land use economics), PRIMES (energy system), EPIC (crop growth) and G4M (forestry) models into one IAM. While ILUC is not computed explicitly, the study focuses on how to avoid large scale deforestation while ramping up 1st generation and advanced biofuel production to very high levels in 2050.

3.4. Causal Descriptive models (CD)

Since 2011, a number of studies attempt to **investigate ILUC from a non-economic perspective** (Baral & Malins, 2016; Bird, Zanchi, & Pena, 2013). Other studies place their focus on the p**otential of biofuels from feedstocks that would specifically avoid ILUC**, such as abandoned lands and residues (Davis et al., 2012; de Wit, Lesschen, Londo, & Faaij, 2014; Diogo et al., 2014; Zetterberg & Chen, 2015). The findings of the above studies largely reiterate the results of economic models, pointing out the presence of ILUC and potential mitigating measures.

3.5. Hybrid-Life Cycle Assessments (LCA)

In practice, most of the LCA studies include direct effects of the production and use of the biofuels, but typically ignore the indirect effects, or treat them inefficiently. Even though some methods were proposed (hybrid LCA), they have not yet been widely adopted in practical applications. These types of studies move away from classical LCA and tend to fall under the LCA sub-category of "**consequential-LCA**" since they aim to **account for marginal changes** (R J Plevin, Delucchi, & Creutzig, 2014). Reviews of LCA studies have shown that although LCA is standardized, its application to biofuels leads to inconclusive results often fraught by a high variability and uncertainty. This is due to differences in quantifying the environmental impacts of feedstock production, and the difficulties encountered when considering LUC effects. The main conclusion being that LCA needs to be adapted and combined to other tools such as economic modelling in order to provide a more reliable assessment of the biofuels chain. In fact, both tools may complement each other. On the one hand, the use of results from economic models in consequential LCA would enhance the quality of ILUC estimation. On the other hand, complementing economic models by a LCA would broaden the range of environmental indicators used to assess biofuels performance, including local impacts such as eutrophication, air quality or (eco)toxicity.

Table 6 . (Hybrid) Life Cycle Assessment studies(Landmark and post-2012)

Study	Aim and main findings
Cherubini & Stromman (2010)	Review of LCA studies, highlighting the lack of ILUC in these analyses. See also section 3.1.
Acquaye et al. (2011)	Computation of ILUC of rape methyl ester biodiesel based on theoretical global average ILUC factors, summing up to 16% of total LCA-emissions.
Acquaye et al. (2012)	GHG emissions calculation of different biofuels, including ILUC.
Malça & Freire (2012)	Evaluates LUC scenarios and uncertainty in the LCA of wheat-based bioethanol, finding that LUC dominates the GHG intensity.
Ben Aoun et al. (2013)	Review of methodologies to include LUC effects in LCAs. Concludes that LCA should be adapted and combined to other tools in order to provide a more reliable assessment of the biofuels chain.
Humpenoder et al. (2013)	Analysis of LUC of 1st generation biofuels in the EU. Concludes that if LUC is considered, GHG emission savings are between -2% and 13%.
Bento & Klotz (2014)	Quantifies emission impacts of 4 US biofuel policies with a range from -16 gCO_2-eq/MJ to +24 gCO_2-eq/MJ corn ethanol added by the policy.
Prapaspongsa & Gheewala (2016)	A CLCA of biofuels production in Thailand. ILUC emissions from cassava- and molasses-bioethanol are found equivalent to 39-76% of the emissions from gasoline.

3.6. Empirical approaches

In a pre-2012 landmark study Fritsche, Sims and Monti (2010) indicated that, in contrast to data-intense and complex economic models, **deterministic approaches** that use calculations which **simplify the simulations of trade and respective LUC effects through statistical data on trade and historic land use,** are needed. If used to project potential future ILUC, these methods need to be complemented with various assumptions on, for example, future trade patterns, and displacement ratios for incremental land use for biomass feedstock production.

In such approaches, the key simplifying assumption is that (changes in) current patterns of land use for producing traded agricultural commodities are an adequate proxy to derive global averages of potential GHG emissions from ILUC. A second assumption is that for the near future, the pattern of global trade in agricultural commodities can be derived from observed trade trends. The ILUC factor approach assumes that the potential release of CO_2 from LUC caused by displacement is a function of the land used to produce agricultural products for export, since trade flows will be affected by displacement.

Table 7 . Studies with empirical approaches (Landmark and post-2012). Source: Own elaboration

Study	Aim and main findings
Fritsche, Sims and Monti (2010)	Review of current state of GHG emission calculation of bioenergy. Proposes the use of non-economic models to simplify simulations.
Lywood (2013)	Estimates historic ILUC impacts of EU biodiesel, concluding that overall GHG benefits have been achieved.
Nassar & Moreira (2013)	Claims that sugarcane production in Brazil has very low ILUC effects since it leads to intensification.
Dunkelberg (2014)	A bottom-up empirical approach in the case study areas (Brazil, Malawi and Germany), highlighting that ILUC may vary significantly across locations and depends heavily on how it is allocated across products.
Overmars et al. (2015)	Uses FAO data to estimate historic ILUC factors, suggesting that ILUC factors are not constant.

4. ILUC research outside the EU and US

Table 8 lists studies that have at least one **co-author which is not located in the EU or US**, or specifically focuses on **ILUC effects outside of these regions**. These studies rarely provide quantitative results concerning the ILUC effect (exceptions include Melillo et al., 2009; Ferreira-Filho et al., 2014), instead focusing on: overall land use changes, the potential of producing biofuels under different constraints, and economic/energy/emission evaluation of specific supply chains without focusing on ILUC.

Among the studies there is almost complete agreement that **(I)LUC will be big in countries in the tropics**, something which is corroborated by observed land change patterns (Gibbs et al., 2008; Lapola et al., 2010; Miyake, Renouf, Peterson, McAlpine, & Smith, 2012; Okoro, Schickhoff, Bohner, & Schneider, 2016; Yeh, 2013). A number of studies have suggested that there is significant potential to **mitigate this by increasing yields or livestock stocking rates of pastures** (Gibbs et al., 2008; Lapola et al., 2010; Lossau et al., 2015). One detailed modelling study highlights the ranges of ILUC values noting that the "interval is so wide that it is likely to straddle any legislation threshold, our opinion is that threshold evaluation for iLUC indicators should not be implemented in legislation" (Verstegen et al., 2016a).

Publications originating from countries where literature indicates the largest risk for ILUC, primarily focus on discussions, assessments and reviews (with Moreria et al. (2014) being a notable example of the use of an economic model). Brazil produces most of the research and publications, with a (not peer reviewed) study by Nassar and Moreira (2013) highlighting that biofuel production in Brazil should be considered low ILUC-risk as it has taken place while increasing yields. Other Brazilian studies highlight the rational of farmers when choosing between shifting to biofuel production or investing in dairy farming (Novo, Jansen, & Slingerland, 2012), highlight the available potential for further expansion, especially if yields continue to increase (Alkimim, Sparovek, & Clarke, 2015; Ferreira Filho et al., 2014; Leal, Horta Nogueira, & Cortez, 2013; Souza, GM; Victoria, RL; Joly, CA; Verdade, 2015; Strassburg et al., 2014), or provide empirical results concerning land use change and its emissions (Mello et al., 2014). However critical studies have also been published, highlighting potential negative aspects, particularly for biodiesel (Castanheira et al., 2014).

Besides Brazil, relevant studies have also come from Malaysia and Thailand. In Malaysia the GHG impacts of palm oil expansion have been assessed, highlighting the potential negative role of ILUC, but also emphasizing the huge uncertainty involved (Hansen, Olsen, & Ujang, 2014) and that regulations using ILUC as a basis are not supported by solid scientific evidence and do not account for developments that ease the pressure for land expansion (Næss-Schmidt & Hansen, 2014). In Thailand, LCA assessments have been made for palm-based biodiesel, as well as the country's bioethanol policy (Prapaspongsa & Gheewala, 2016; Silalertruksa & Gheewala, 2012a). These studies generally reveal that ILUC worsens the GHG balance, however highlighting that there still is a significant potential for climate beneficial biofuels.

Table 8 . Summary of studies focusing (either supply or demand) in ILUC and other effects from biofuels produced outside the EU and US. Source: Own elaboration

	Country of research[18]	Focus Country[19]	Biofuel type	Purpose	Approach Method	Conclusion Finding	Research done for
Gibbs et al. (2008)	USA Canada	Tropics (supply)	1st Gen. and advanced	Assess carbon pay-back periods	Review	Biofuel expansion into natural tropical ecosystems will lead to net carbon emissions for decades to centuries. Carbon benefits are possible from expanding high-yielding crops, such as sugarcane and oil palm, into already degraded lands.	NA
Francesco Cherubini et al. (2009)	Austria Australia	NA	1st Gen. and advanced ethanol, biodiesel	Assess issues and recommendations for improving LCA of bioenergy systems	Review	Due to many site-specific issues, uncertainties and complexities, it is impossible to give exact values for the GHG effects of bioenergy use.	NA
Mathews & Tan (2009)	Australia	NA	1st Gen. and advanced ethanol	Probed assumptions of Searchinger et al. (2008)	Review	Though ILUC is a serious problem, the Searchinger et al. (2008) study is overly pessimistic and not reproducible.	NA
Melillo et al. (2009)	USA Brazil China	NA	1st Gen. ethanol, eucalyptus, poplar switchgrass	Examine direct and indirect effects of expanded bioenergy program	CGE model	Indirect carbon loss may be up to twice as much as direct. Increased fertilizer use may be even more important in terms of global warming potential.	NA
Fritsche, Sims, et al. (2010)	Germany New Zealand Italy	NA	NA	Review ILUC GHG emissions	Review	Biofuels should be produced from excess farm and forest residues. Approaches identified in order to translate ILUC factors into practical regulations.	NA
Lapola et al. (2010)	Germany Kenya	Brazil (supply & demand)	1st Gen. ethanol and biodiesel	Assess ILUC and DLUC of 2020 biofuel targets	Causal Descriptive (land use) model	Biofuels contribute to deforestation by 2020 creating a carbon debt of about 250 years. Using oil palm performs better. A small increase of livestock density could avoid the ILUC.	NA
Arima, Richards, Walker, & Caldas (2011)	USA	Brazil (supply)	1st Gen.	Confirm ILUC in Brazil statistically	Empirical	LUC is significant and considerable. A 10% reduction of soy in old pastures would have decreased deforestation by 12% - 40% in heavily forested counties of the Brazilian Amazon.	NA
Khatiwada, Seabra, Silveira, & Walter (2012)	Sweden Brazil	Brazil (supply)	1st Gen. ethanol (sugarcane)	Critically examine methodologies in existing regulatory schemes (EU, UK & US)	Discussion	Regulatory schemes vary greatly among themselves. Agricultural practices, co-product credits and uncertainties around ILUC are major areas of divergences.	NA
Lesschen et al. (2012)	Netherlands Ukraine	Ukraine (supply)	2nd Gen.	Determine financial and GHG cost of avoiding ILUC	Empirical	GHG emissions on low quality soil without ILUC (12.5 gCO_2-eq/MJ) are higher than for good quality soil grown switchgrass with ILUC (0.1 gCO_2-eq/MJ pellet). Cost for low quality soils are 22% higher.	Government of Ukraine

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[18] This is determined from the author affiliations or commissioning institute. Countries listed according to author order.

[19] Where it is possible to ascertain, whether the focus region acts as a biomass supplier or demand region is highlighted.

	Country of research[20]	Focus Country[21]	Biofuel type	Purpose	Approach Method	Conclusion Finding	Research done for
Miyake et al. (2012)	Australia	Brazil Indonesia Malaysia EU US (all supply)	NA	Review dynamics and patterns of (I)LUC	Review	Bioenergy-driven land-use change has affected and will impact most severely on the "land- and resource-abundant" developing regions, where economic development takes priority over sustainable land-use policies, and the enforcement capability is limited.	NA
Novo et al. (2012)	Brazil Netherlands	Brazil (supply)	1st Gen. ethanol (sugarcane)	Determine heuristic tool in order to identify strategies for shifting from dairy farming to biofuel production	Empirical	Farmers that shift to sugarcane are not spurred only from better prices, but mainly changes in perceptions of labour constraints, risks and opportunities offered by diversification.	NA
Silalertruksa & Gheewala (2012b)	Thailand	Thailand	Biodiesel	Evaluate sustainability of biodiesel for transport in Thailand, while satisfying demand for food.	Causal-Descriptive	Emissions depend heavily on what type of land is converted, and ILUC worsen overall balance.	NA
Alvarenga et al. (2013)	Belgium Germany	Brazil (supply)	1st Gen. ethanol	Determine ILUC for bioethanol-PVC	LCA	Environmental gains if iLUC is kept below 5.7% of the sugarcane cultivation area.	NA
Berndes, Ahlgren, Borjesson, & Cowie (2013)	Sweden Australia	NA	NA	Discuss bioenergy and land use change	Discussion	Though quantifications of LUC emissions do not support the use of bioenergy to mitigate GHG emissions, bioenergy's contribution must reflect a balance between near-term and long-term targets.	NA
Le, van Ierland, Zhu, & Wesseler, (2013)	Netherlands Germany	Vietnam (supply)	1st Gen. ethanol	Assess energy and emissions	Empirical/ Discussion	Variation in results due to yields, energy efficiency and by-product analysis.	NA
Leal et al. (2013)	Brazil	Global (supply & demand)	1st Gen. ethanol	Assess land use effects of meeting IEA, RED and RFS targets	Review, scenario analysis	Land use demands for ethanol production by 2030 do not give reasons for concern on a global scale, but may produce significant local impacts.	NA
Nassar & Moreira (2013)	Brazil	Brazil (supply)	1st Gen. ethanol	Present evidence that sugarcane is a low ILUC-risk resource	Discussion	Evidence presented demonstrates that sugarcane produced in Brazil is a low-ILUC raw material, and its production is more energy and land efficient than any other food feedstock.	ICONE
Nunez et al. (2013)	Mexico USA	Brazil USA (supply)	1st Gen. ethanol (sugarcane, maize Advanced ethanol (cellulosic)	Develop a price endogenous model to simulate the effects of biofuel mandates	PE	Mandates can be met with small increases in commodity prices and increases in livestock intensity. ILUC not included.	NA

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	Country of research[22]	**Focus Country**[23]	**Biofuel type**	**Purpose**	**Approach Method**	**Conclusion Finding**	**Research done for**
Poppens et al. (2013)	Netherlands	Ukraine (supply and demand) Netherlands (demand)	Pellets	Assess supply chain performance for pellets	Case Study	Potential for low ILUC-risk reed exists. Risks depend on displacing current uses such as animal feed, bedding and maintaining soil organic carbon.	WUR
Yeh (2013)	USA	Brazil (supply)	1st Gen. Biodiesel	Develop scenarios to measure land use impact	UPLAN land use model	dLUC: 14–84 gCO_2-eq/MJ	NA
Castanheira et al. (2014)	Portugal Brazil	Brazil (supply)	Biodiesel	Identify potential environmental impacts of biodiesel production in Brazil	Discussion	Impacts of land use change on GHG emissions were found to be critical. Certification and zoning can play an important role in the sustainability of emerging biodiesel.	
Diogo et al. (2014	Netherlands Argentina	Argentina (supply)	Soybean biodiesel and switchgrass ethanol	Determine low ILUC-risk biofuel potential	Land use model	Limited potential in BAU scenarios. In a "progressive scenario", switchgrass is particularly promising.	NA
Dunkelberg (2014)	Germany	Malawi Brazil Germany (supply)	1st Gen. ethanol	Determine ILUC	Empirical	Best estimates for ILUC are −11 gCO_2-eq/MJ for sugarcane ethanol produced in Malawi. Brazil and Germany are 24 gCO_2-eq/MJ of and 50 gCO_2-eq/MJ of respectively.	PhD. Thesis
Ferreira Filho et al. (2014)	Brazil Australia	Brazil (supply)	1st Gen. ethanol	Analyse ILUC in brazil	CGE	Each new hectare of sugarcane requires 0.14 ha of new land and another 0.47 ha converted from pasture use. Thus policies limiting deforestation are unlikely to prevent ethanol expansion.	NA
Hansen et al. (2014)	Denmark Malaysia	Malaysia (supply)	Palm biodiesel	Identify GHG emissions associated with oil palm expansion	LCA	LUC emissions are responsible for approx. half of total emissions. Results sensitive to ILUC assumptions.	NA
Langeveld et al. (2014b)	Netherlands Australia	Brazil USA Indonesia Malaysia China Mozambique South Africa EU27 (supply)	1st Gen. ethanol Biodiesel	Review observed land use change patterns	Empirical	Between 2000-2010, despite substantial expansion of biofuel production, more land has become available for non-fuel applications. Biofuel policies have had a small effect on observed land use changes.	NA
Laurance et al. (2014)	USA Australia	Tropical countries	NA	Effects of growing population and consumption on land use	Discussion	Study foresees major expansion and intensification of tropical agriculture, continued loss of tropical forests, pivotal road of roadways in determining spatial patterns, intensified conflicts between food production and nature conservation.	NA

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[23] Where it is possible to ascertain, whether the focus region acts as a biomass supplier or demand region is highlighted.

	Country of research[24]	Focus Country[25]	Biofuel type	Purpose	Approach Method	Conclusion Finding	Research done for
Liu et al. (2014)	China	NA	NA	Review of effects of biofuel production on biodiversity	Discussion	Intensive management of biofuel production raises the risk of fragmentation, native extinction and bio-invasion. At an ecosystem level diversity and the food web may be damaged.	NA
Mello et al. (2014)	Brazil USA France	Brazil (supply)	1st Gen. ethanol	Determine payback times	Empirical	Soil C stocks decrease following LUC from native vegetation and increase when cropland is converted to sugar cane. The payback time is 8 years for native vegetation and 2-3 years for pastures.	NA
Moreira et al. (2014)	Brazil	Brazil (supply)	1st Gen. Jet fuel	Determine life cycle emissions	CGE (GTAP)	Feedstock production and LUC were the main sources of emissions, respectively estimated as 14.6 and 12 gCO_2-eq/MJ.	NA
Næss-Schmidt & Hansen (2014)	Malaysia	Malaysia	1st Gen. Oilcrops	Review ILUC methods	Discussion	Models (and thus EU ILUC policy) do not sufficiently recognise local conservation efforts, and, since ILUC methods are not consistent, ILUC should not be a basis for regulation.	NA
Strassburg et al. (2014)	Brazil Poland UK USA	Brazil (supply)	NA	Assess potential for of intensification at mitigation land use change	Discussion	A slight increase in pastureland productivity (15-20%) would be enough to meet demands for meat, crops, wood products and biofuels until at least 2040.	NA
Alkimim et al. (2015)	Brazil USA	Brazil (supply)	NA	Identify land potential for biofuels, without compromising forested lands	Spatial databases	Converted pasturelands could provide up to 50MHa of highly suitable crop land, more than the area currently used for sugarcane production in Brazil.	NA
Creutzig et al. (2015)	Germany India Sweden Denmark, Norway USA Spain Netherlands Austria Brazil Switzerland Scotland Mexico	NA	NA	Assess bioenergy from multiple perspectives.	Discussion	High variability in pathways, uncertainties in technologies, and ambiguity in political decisions render forecasts very difficult. However, uncertainty about projections should not preclude pursuing beneficial bioenergy options.	NA
Lossau et al. (2015)	Germany Austria	Brazil (supply)	1st and 2nd Gen.	Identify biofuel potentials meeting sustainability criteria	Empirical	84 Mha residual land of which 37 Mha occurred outside the territory of the Amazon biome and was neither legally protected nor categorized as highly biodiverse land. Yield increases in agriculture could provide large swathes of land.	Daimler/IIASA/TU Berlin

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[25] Where it is possible to ascertain, whether the focus region acts as a biomass supplier or demand region is highlighted.

	Country of research[26]	Focus Country[27]	Biofuel type	Purpose	Approach Method	Conclusion Finding	Research done for
T. D. Searchinger et al. (2015)	USA Kenya Germany Australia	Africa (Savannahs and shrublands)	1st Gen. ethanol (maize), biodiesel (soybeans)	Carbon and biodiversity effects of converting Afircan savannahs and scrublands	Vegetation model (LPJmL), crop model (DSSAT), carbon stock databases	Only 2-11.5% of these lands have a meaningful potential to be low-carbon sources.	NA
Souza, GM; Victoria, RL; Joly, CA; Verdade (2015)	Brazil	NA	NA	A collective effort to assess bioenergy and sustainability. Includes chapter on ILUC.	Review and discussion	From a policy perspective, ILUC can be mitigated via (i) zoning and monitoring to prevent deforestation, (ii) Increasing bioenergy production per hectare, (iii) close yield gaps, and, (iv) develop crops suitable for marginal and degraded lands.	FAPESP, Brazil
Grundy et al. (2016)	Australia	Australia	Biofuels and bioelectricity from wheat, stubble and woody perennials.	Generate scenarios for Australian agricultural production and land use to 2050	Integrated Systems Modelling	High levels of food/fibre production can co-exist with non-food land uses motivated by market responses to global change and domestic policy.	NA
Okoro et al. (2016)	Germany	Niger Delta (supply)	1st Gen. biodiesel	Map LUC	Empirical	In the 1999-2005 to 2009-2015 forested area decreases with most area converted to oil palm.	NA
Prapaspongsa & Gheewala (2016)	Thailand	Thailand (supply)	1st Gen. ethanol	Assess ILUC from Thailand's bioethanol policy	LCA	Cassava and molasses ILUC account for 39% (±8%) to 76% (±15%) of the GHG emissions from gasoline.	NA
Verstegen, van der Hilst, Woltjer, Karssenberg, de Jong & Andre P. C. Faaij (2016)	Netherlands	Brazil (supply)	1st Gen. ethanol	Calculate ILUC and DLUC	CGE (MAGNET) and land use model (PLUC)	Given the 95% confidence interval, the iLUC area in Brazil might be 2.4 times as high or as low as the projected mean. As the confidence interval is so wide that it is likely to straddle any legislation threshold.	NA
Furumo & Aide (2017)	Puerto Rico	Latin America	Palm Biodiesel	Characterize oil palm expansion	Empirical	79% of expansion replaced previously used lands (mostly cattle pastures), the rest coming from forests. 70% of exports stayed within Latin America.	NA

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[27] Where it is possible to ascertain, whether the focus region acts as a biomass supplier or demand region is highlighted.

5. GHG factors results and evidence in relation to all production pathways

Among the reviewed literature, **30 studies reported quantitative ILUC emission factors** based on a range of methods. Therefore, these studies were selected because they report (I)LUC per mass unit, and thus can be compared.

The methods adopted by the studies can be summarised as follows:

- **Seventeen studies applied PE-, CGE- or IAM-models** (Al-Riffai et al., 2010; CARB, 2009; Dumortier et al., 2011; Edwards et al., 2010; Flugge et al., 2017; T W Hertel et al., 2010; D Laborde, 2011; David Laborde et al., 2014; Melillo et al., 2009; Moreira et al., 2014; Mosnier et al., 2013a; Richard J Plevin et al., 2010, 2015; T. Searchinger et al., 2008; Farzad Taheripour & Tyner, 2013; W. Tyner et al., 2010; Valin et al., 2015).
- **Six studies were based on Hybrid Life Cycle Assessments** (A.A. Acquaye et al., 2011; Adolf A Acquaye et al., 2012; Bento & Klotz, 2014; Boldrin & Astrup, 2015; Mullins et al., 2011; Prapaspongsa & Gheewala, 2016).
- **Five studies were based on empirical approaches** (Dunkelberg, 2014; Fritsche, Hennenberg, et al., 2010; Lywood, 2013; Overmars et al., 2015, 2011).
- **One study used a causal descriptive model** (Baral & Malins, 2016).
- **One study was based on expert opinion** (CARB, 2014)**.**

Studies are included in the analysis only when results were presented in emissions per energy or mass unit. All emission factors have been harmonised to gCO_2-eq/$MJ_{Biofuel}$ and are grouped by feedstock and ordered by year of publication. In further detail:

Table 9 . Summary of studies including GHG ILUC factor results. Source: Own elaboration

Reference and institution	Feedstock	Biofuel type	Result, average in brackets[28] (gCO_2-eq/MJ)	Approach Model	Type of research	Sensitivity analysis method	Research done for	Notes[29]
Summary of pre-2012 landmark studies including GHG ILUC factor results								
Acquaye et al. (2011) - Multiple	Rapeseed	Biodiesel	14-42 (33)	Hybrid LCA	Primary research	Maximum-minimum cut-offs, based on own calculation	Peer reviewed publication	20 year amortization. Includes DLUC
Al.-Riffai et al. (2010) - IFPRI	Sugarbeet Sugarcane Maize Wheat Palm Rapeseed Soybean Sunflower	1st gen. ethanol 1st gen. ethanol 1st gen. ethanol 1st gen. ethanol Biodiesel Biodiesel Biodiesel Biodiesel	16-65 (41) 18-19 (18) 54-79 (67) 16-37 (27) 45-50 (47) 51-54 (52) 67-75 (71) 56-61 (58)	CGE (MIRAGE)	Primary research (based on GTAP database)	BAU and full trade scenarios	IFPRI	20 year amortization
CARB (2009)	Sugarcane Maize Soybean	1st gen. ethanol 1st gen. ethanol 1st gen. ethanol	32-57 (46) 18-44 (30) 27-51 (42)	CGE (GTAP)	Primary research	Scenario Analysis	CARB	30 year amortization
Edwards et al. (2010) – JRC-EC	Wheat Maize Palm Rapeseed Oilseeds	1st gen. ethanol 1st gen. ethanol Biodiesel Biodiesel Biodiesel	16-155 62 47 222 57	Multiple PE & CGE (GTAP, FAPRI-CARD, AGLINK-COSMO, LEITAP, IMPACT, CAPRI)	Model comparison	Model projections, quasi-harmonized scenarios	JRC-EC	20 year amortization. Includes DLUC
Fritsche, Hennenberg, and Hünecke (2010) – Öko-Institut	Sugarcane Wheat Palm Soybean Rapeseed SRC	1st gen. ethanol 1st gen. ethanol Biodiesel Biodiesel Biodiesel Advanced	21-42 34-67 18-36 41-67 33-67 38-75	Empirical	Primary research	Sensitivity on ILUC emission factor (high/low). Based on own line of reasoning and literature	Öko-Institut	20 year amortization

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[28] Mean displayed only if more than two scenarios were presented.
[29] Harmonize to 20 years. (Multiplied by “Amortization period / 20 years”)

Reference and institution	Feedstock	Biofuel type	Result, average in brackets[30] (gCO_2-eq/MJ)	Approach Model	Type of research	Sensitivity analysis method	Research done for	Notes[31]
Hertel et al. (2010) – Multiple	Maize	1st gen. ethanol	27	CGE (GTAP-BIO)	Primary research	Gaussian Quadrature	Peer reviewed publication	30 year amortization. Includes DLUC
Laborde (2011) – IFPRI	Wheat	1st gen. ethanol	8-18 (14)	CGE (MIRAGE)	Primary research (based on GTAP database)	Monte-Carlo	IFPRI	20 year amortization. Includes DLUC
	Maize	1st gen. ethanol	6-13 (10)					
	Sugarbeet	1st gen. ethanol	1-13 (7)					
	Sugarcane	1st gen. ethanol	7-27 (16)					
	Palm	Biodiesel	47-60 (54)					
	Soybean	Biodiesel	38-74 (56)					
	Sunflower	Biodiesel	31-72 (53)					
	Rapeseed	Biodiesel	28-81 (55)					
Melillo et al. (2009) – Multiple	Eucalyptus Poplar Switchgrass	Advanced	181-190	CGE (EPPA)	Primary research (based on GTAP database)	Scenario analysis, own elaboration	Peer reviewed publication	30 year amortization
Mullins, Griffin, and Matthews (2011) – Carnegie Mellon University	Maize	1st gen. ethanol	25-75 (49)	CLCA	Primary research	Monte-Carlo. Own line of reasoning based on results in literature	Peer reviewed publication	30 year amortization
	Switchgrass	Advanced	-15-103 (44)					
Overmars et al. (2011) – Netherlands Environmental Assessment Agency (PBL)	Wheat Sugarcane Sugarbeet Rapeseed Soy Palm	1st gen. ethanol Biodiesel	26-154 (79) 30-204 (97)	Empirical	Secondary research (based on results from IMAGE and other databases)	Uncertainty analysis. Own line of reasoning	Peer reviewed publication	20 year amortization
Plevin et al. (2010) – Multiple	Maize	1st gen. ethanol	21-142 (57)	PE (reduced form)	Secondary research	Monte-Carlo. Own line of reasoning.	Peer reviewed publication	30 year amortization
Searchinger et al. (2008) – Multiple	Maize	1st gen. ethanol	104	PE (GREET)	Primary research	Model projection. Own line of reasoning	Peer reviewed publication	30 year amortization
Tyner et al. (2010) – Purdue University	Maize	1st gen. ethanol	14-23 (18)	CGE (GTAP)	Primary research	Scenario analysis. Own line of reasoning	Purdue University	30 year amortization. Includes DLUC

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[30] Mean displayed only if more than two scenarios were presented.

[31] Harmonize to 20 years. (Multiplied by "Amortization period / 20 years")

Reference and institution	Feedstock	Biofuel type	Result, average in brackets[32] (gCO_2-eq/MJ)	Approach Model	Type of research	Sensitivity analysis method	Research done for	Notes[33]
Summary of post-2012 studies further developing pre-2012 approaches, including GHG ILUC factor results								
Acquaye et al. (2012) – Multiple	Sugarcane	1st gen. ethanol	18	Hybrid LCA	Primary research	None	Peer reviewed publication	20 year amortization
	Sugarbeet	1st gen. ethanol	4					
	Maize	1st gen. ethanol	22					
	Soybean	Biodiesel	21					
	Rapeseed	Biodiesel	31					
	Palm	Biodiesel	9					
	Cooking Oil	Biodiesel	0					
Dumortier et al. (2011) – Multiple	Maize	1st gen. ethanol	57-65 (61)	PE (CARD)	Primary research	Scenario analysis. Own line of reasoning	Peer reviewed publication	30 year amortization
Flugge et al. (2017) – ICF	Maize	1st gen. ethanol	1-17 (9)	CGE (GTAP)	Primary research	Soil carbon databases	USDA	30 year amortization
Laborde et al. (2014) – IFPRI & JRC-EC	Sugarbeet	1st gen. ethanol	5-12 (7)	CGE (MIRAGE)	Primary research (based on GTAP database)	Scenario analysis. Own line of reasoning	JRC-EC	20 year amortization
	Sugarcane	1st gen. ethanol	13-18 (14)					
	Maize	1st gen. ethanol	10-15 (12)					
	Palm	Biodiesel	54-64 (57)					
	Rapeseed	Biodiesel	53-68 (57)					
	Soybean	Biodiesel	55-72 (62)					
	Sunflower	Biodiesel	50-63 (55)					
Moreira et al. (2014) – Multiple	Sugarcane	1st gen. ethanol	12-17	CGE (GTAP-BIO-ADV) and Emissions model (CA-GREET)	Primary research	Scenario analysis (study also includes Monte-Carlo). Own line of reasoning	Peer reviewed publication	30 year amortization. Includes DLUC
Mosnier et al. (2013) – Multiple	Maize	1st gen ethanol	20-46 (31)	PE (GLOBIOM)	Primary research	Scenario analysis. Own line of reasoning	Peer reviewed publication	30 year amortization

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[32] Mean displayed only if more than two scenarios were presented.

[33] Harmonize to 20 years. (Multiplied by “Amortization period / 20 years”)

Reference and institution	Feedstock	Biofuel type	Result, average in brackets[34] (gCO_2-eq/MJ)	Approach Model	Type of research	Sensitivity analysis method	Research done for	Notes[35]
Overmars et al. (2015) – PBL & JRC-EC	Wheat	1st gen. ethanol	10-21 (16)	Empirical	Secondary research (based on results from the IMAGE and CSAM models)	Compare models and allocation. Evaluation of historical yield and land use change data	JRC-EC	20 year amortization
	Sugarbeet	1st gen. ethanol	7-19 (12)					
	Maize	1st gen. ethanol	6-13 (10)					
	Sugarcane	1st gen. ethanol	5-19 (12)					
	Rapeseed	Biodiesel	170-241 (204)					
	Soybean	Biodiesel	187-257 (224)					
	Palm	Biodiesel	171-249 (201)					
	Sunflower	Biodiesel	171-243 (206)					
	Jatropha	Biodiesel	58-130 (93)					
	Wheat straw	Advanced	0-3 (1)					
	Willow-poplar	Advanced	2-4 (3)					
	Switchgrass	Advanced	1-3 (2)					
Plevin et al. (2015) - Multiple	Maize	1st gen. ethanol	26-68 (41)	CGE (GTAP-BIO-ADV) and Emissions model (AEZ-EF)	Primary research	Monte-Carlo. Own line of reasoning	Peer reviewed publication	30 year amortization
	Sugarcane	1st gen. ethanol	4-56 (26)					
	Soybean	Biodiesel	21-71 (40)					
Taheripour & Tyner (2013) – Purdue University	Corn	1st gen. ethanol	13-23 (17)	CGE (GTAP-BIO)	Primary research	Different emission factor databases	Peer reviewed publication	Amortization period unclear. Includes DLUC
	Corn stover	Advanced	-0.9- -1.6 (-1.3)					
	Miscanthus	Advanced	6-32 (17)					
	Switchgrass	Advanced	20-74 (44)					
Valin et al. (2015) Ecofys, IIASA & E4tech	Wheat	1st gen. ethanol	-40-70 (34)	PE (GLOBIOM)	Primary research	Monte-Carlo. Own line of reasoning	DG-ENER	20 year amortization. Includes DLUC
	Maize	1st gen. ethanol	-75-60 (14)					
	Barley	1st gen. ethanol	-50-90 (38)					
	Sugarbeet	1st gen. ethanol	-15-35 (15)					
	Sugarcane	1st gen. ethanol	-20-175 (17)					
	Maize Sillage	1st gen. ethanol	21					
	Sunflower	Biodiesel	0-170 (63)					
	Palm	Biodiesel	20->400 (231)					
	Rapeseed	Biodiesel	-10-130 (65)					
	Soybean	Biodiesel	10->400 (150)					
	Cereal straw	Advanced	0-30 (16)					
	Perrenials	Advanced	-30-5 (-12)					
	SRC	Advanced	-50- -10(-29)					
	Forest Residues	Advanced	17					

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[34] Mean displayed only if more than two scenarios were presented.
[35] Harmonize to 20 years. (Multiplied by “Amortization period / 20 years”)

Reference and institution	Feedstock	Biofuel type	Result, average in brackets[36] (gCO_2-eq/MJ)	Approach Model	Type of research	Sensitivity analysis method	Research done for	Notes[37]
Summary of post-2012 studies with original approaches, including GHG ILUC factor results								
Baral & Malins (2016) – The International Council on Clean Transportation	Rapeseed	Biodiesel	18-101 (55)	Causal Descriptive model	Secondary research (biofuel demand and emission taken from multiple models/databases)	Scenario analysis. Own line of reasoning	Peer reviewed publication	20 year amortization
Bento & Klotz (2014) – Cornell University	Maize	1st gen. ethanol	30-35	CLCA	Primary research	Scenario analysis. Own line of reasoning	Peer reviewed publication	Amortization period unclear
Boldrin & Astrup (2015) – Technical University of Denmark	Rapeseed	Biodiesel	29-75	CLCA	Secondary research	Allocation criteria based on existing national and supra-national guidelines	Peer reviewed publication	Amortization period unclear
CARB (2014)	Maize Sugarcane Sorghum Soybean Palm Rapeseed/Canola	1st gen. ethanol 1st gen. ethanol 1st gen. ethanol Biodiesel Biodiesel Biodiesel	20 12 19 29 71 15	Expert group	Primary research	Expert opinion	CARB	Amortization period unclear
Dunkelberg (2014) – Technical University of Berlin	Sugarcane	Ethanol	1-144	Empirical	Primary research	Calculation. Own line of reasoning	Dr.Ing Thesis	100 year amortization
Lywood (2013)	Rapeseed	Biodiesel	-115-21	Empirical	Secondary research	Assumptions on co-product benefits and trade. Own line of reasoning	Sofiprotéol	100 year amortization
Prapaspongsa & Gheewala (2016) – Multiple	Cassava-Molasses	1st gen. ethanol	30-68 (45)	CLCA	Primary research	Scenario analysis. Own line of reasoning	Peer reviewed publication	20 year amortization

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[36] Mean displayed only if more than two scenarios were presented.
[37] Harmonize to 20 years. (Multiplied by "Amortization period / 20 years")

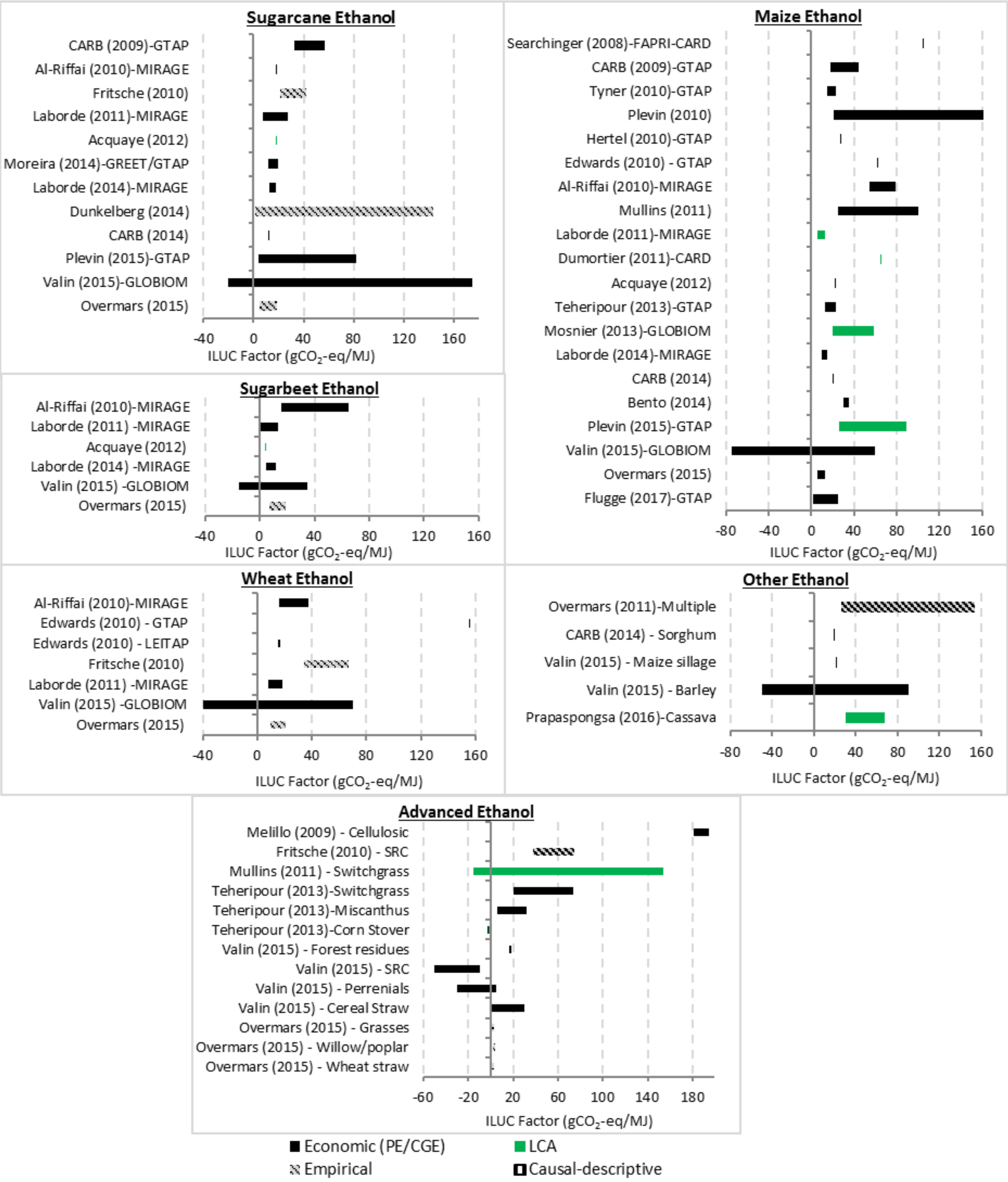

Figure 3 Summary of ILUC factors for ethanol production. Colours highlight the method each study employs. Note, these values have **not** been harmonized for amortization period. **Source:** Own work.

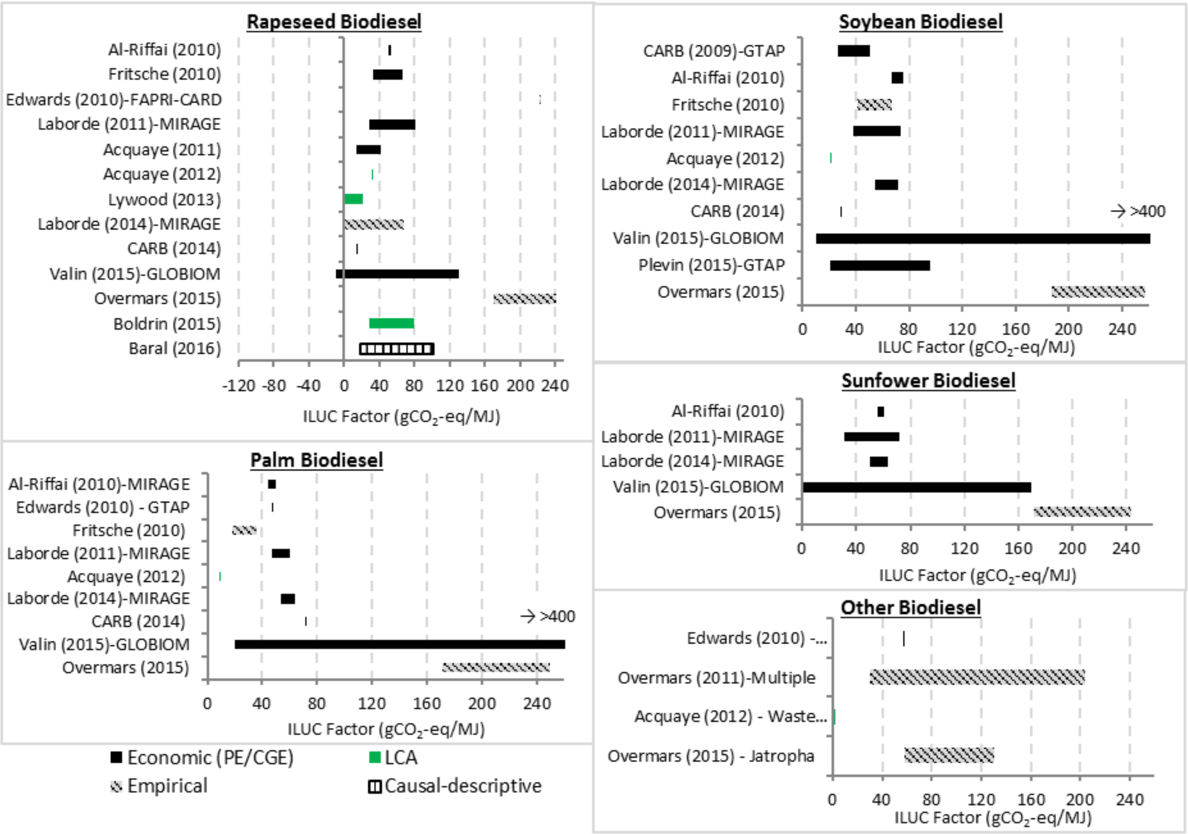

Figure 4 Summary of ILUC factors for biodiesel production. Colours highlight the method each study employs. Note, these values have **not** been harmonized for amortization period. **Source:** Own work.

Overall, the results show a **high variation**, with the ranges presented reflecting the **variety of approaches**[38]. Concerning the modelling studies, results further vary because of **differences in data sets, parameter choices, scenarios**, etc. On average[39] the highest ILUC factors in the assessed quantitative studies carried out in the time period 2009 - 2015, are related to the production of **biodiesel** (median 52 $gCO_{2\text{-}}$eq/MJ), palm showing the highest variation in results in available research. Estimates of ILUC factors for palm oil biodiesel tend to be higher (median 216 $gCO_{2\text{-}}$eq/MJ) than other vegetable oils in studies (such as Overmars 2015 and Valin 2015) that take into account the increased emission from, and uncertainty of, peatland conversion. First generation **ethanol** presents a median ILUC factor of 21 $gCO_{2\text{-}eq}$/MJ, with sugar crops (sugarcane and sugarbeet) showing the lowest ILUC factors, while maize has the highest numbers.

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[38] It is important to note that seven of the studies quoted in the above results, covering all feedstocks, explicitly calculate total LUC emissions, i.e. a combination of indirect and direct LUC (see Table 9 for details). Ommiting these studes does not affect the median (or mean) values.

[39] All number quoted below assume a harmonized amortization period (20 years).

Advanced biofuels, present a median ILUC factor of 5 gCO_2-eq/MJ. It is important to stress though that unlike other feedstocks where there are multiple studies (18 for biodiesel and 24 for 1st generation), there are only six studies presenting results on advanced biofuels (Fritsche, Hennenberg, et al., 2010; Melillo et al., 2009; Mullins et al., 2011; Overmars et al., 2015; Farzad Taheripour & Tyner, 2013; Valin et al., 2015). Among these studies, there is significant disagreement and differences in methodological approaches as the types of lands assumed to be used for dedicated cropping with woody and perennial crops are defined differently in terms of current use status.

The **negative ILUC factors** of Valin et al. (2015), which present an overall improvement in land based carbon stocks with the production of biofuels, are mainly due to direct land use change, that is, the improvement in carbon stocks on the land on which biomass is produced, outweighing the emission from ILUC. Thus these negative factors are not due to ILUC, but rather due to LUC which outweigh the otherwise positive ILUC factors. Furthermore, ILUC emissions are also low in the case of the Valin et al. (2015) study, because the land used for dedicated cropping is assumed to be unused before it is converted into dedicated crops. In the study of Melillo et al. (2009) for example this unused status of land is not assumed, leading to much higher ILUC factors.

A number of points have to be raised in order to help with the interpretation of the above results. These (I)LUC factors are based on studies whose **scenarios are not consistent**, and thus the **level of biofuel demand is not harmonised**. These factors are **not linear** and would thus **vary with changing levels of biofuel demand**. Additional to this, increasing demands, may lead to different marginal feedstocks being used, further complicating the predictability of these ILUC factors.

Furthermore, results are very sensitive to **methodological assumptions**, i.e. Baral & Malins (2016) used a **non-economic causal-descriptive model** to determine ILUC effects of rapeseed biodiesel across a number of scenarios. They find that in a "central scenario" the ILUC factor is 57 gCO_2-eq/MJ. When considering impacts of reduced food consumption, this falls to 18 gCO_2-eq/MJ, a considerably stronger effect than computed by equilibrium models. The highest value (101 gCO_2-eq/MJ) illustrates a case where oilseed rape for the EU vegetable oil market is displaced by palm grown on peat soils. The large biodiesel ranges presented by Valin et al. (2015), using a **partial equilibrium model**, are due to uncertainty in the natural vegetation displacement, particularly peat lands.

For empirical and LCA studies, advanced biofuels have a range of -23–155 gCO_2-eq/MJ, 1st generation ethanol of 1-154 gCO_2-eq/MJ and biodiesel of -94-257 gCO_2-eq/MJ. The large ranges presented are due to the methods adopted, highlighting the effect of different ILUC compensation measures, such as increased cattle stocking rates or reduced meat consumption, the way by-products are accounted for, and the choice of emissions factors for different land conversion.

6. General principles of ILUC[40] research

6.1. Decomposition approach

When going through ILUC studies, a large number of parameters are used to generate the results, where parameters are different for different models. Consequently, it is not straight forward to trace the causal relations between parameters in complex models to the final ILUC results (C. Malins et al., 2014; T. Searchinger et al., 2015a). Therefore, in the context of this report a **decomposition methodology** has been developed to understand the results of different studies.

The methodology developed in the context of this report is based on **decompositions** accomplished in some of the key ILUC studies like Valin et al. (2015), Laborde (2011), Searchinger et al. (2015), Allen et al. (2013) and Malins et al. (2014). An attempt has been made to integrate these decomposition methods into one framework. The main purpose is to compare the most significant ILUC studies and to make clear where the most important causes of uncertainty come from.

The basic idea of this approach is a **stepwise decomposition** of the biofuel feedstock land use by starting with a gross feedstock area per GJ and resulting in the net land use change after taking into account the following impacts:

- Gross land use of the biofuel feedstock
- Reduced area because of co-production of by-products
- Reduced area because of reduced demand for non-biofuel crops
- Reduced area because of increase in yields of both biofuel feedstocks and other agricultural commodities
- Relocation of production to areas or crops with different yields

Some studies only focus on the change in crop area, while other studies also include permanent grassland or managed forest area[41] explicitly in their analysis.

The starting point to understand the fundamental components of ILUC as a consequence of biofuels, is executing an analysis **per biofuel pathway.** When ILUC factors per pathway are known, one can aggregate them to the effects of a biofuels policy, taking into account that there may be non-linearity in the system.

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[40] Land use change (LUC), the sum of direct and indirect land use change, is likely to be a more appropriate term because models can not differentiate between direct and indirect land use change and normally report just land use change. However, because ILUC is the term standardly used, the report follows this convention.

[41] This is a land use category defined in the GTAP-AEZ database (CARB, 2009) that is for example used in the general equilibrium model MIRAGE (Laborde et al., 2014).

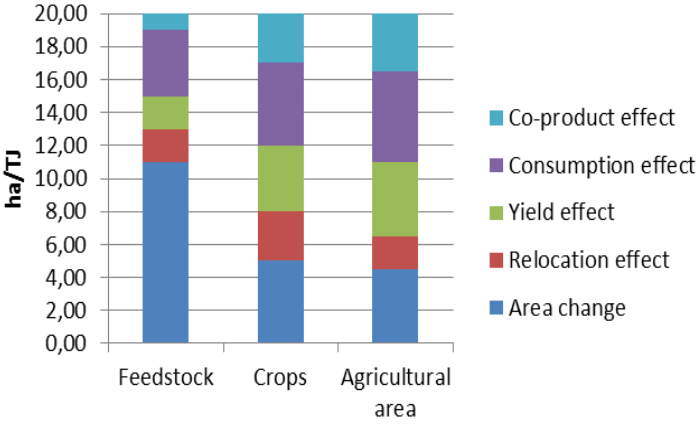

Figure 5 Overview of the ILUC decomposition.
Source: Own work.

Figure 5 provides an **example of an ILUC decomposition for a specific pathway** in hectares per TJ. The numbers in this graph have no empirical meaning; they just illustrate the principle. In this case the area feedstock per TJ (for example maize, wheat, soybean, or palm oil) of biofuel is 20 ha. If nothing would happen with production of the feedstock crop for non-biofuel purposes nor the yields of the feedstock, the **total increase in area** needed to produce the extra 1 TJ of biofuels would also be 20 hectares. This is represented by the size of the first column. If also nothing happens with other crop production, this would imply that total crop area also increases with 20 hectares. This is represented by the second column. Finally, the expansion of total cropland could be into grassland area. If also production and yields of grassland remain the same, then total cropland and grassland area have to expand by 20 hectares, and this is at the cost of natural area. This is represented in the third column.

In practice expansion of feedstock area will be less than 20 hectares because of **different mechanisms** included in the elements of the feedstock column, resulting finally in the total feedstock area expansion. In addition, mechanisms for other crops may reduce or increase land use, which combined with the changes in the feedstock crop, generate the expansion of cropland area in the second column. The same holds if mechanisms that change grassland area are included, represented in the third column.

Besides, the **components that explain the difference** between gross land use change and the final expansion of feedstock area, cropland area and cropland plus grassland area shall be considered.

First, because the land used for the biofuel may produce the biofuel together with other products such as animal feed (**co-products**), and these other products may reduce the need of substituting them. In this example the co-product reduces the area needed for the feedstock crop in 1 ha (first column), and the area needed for other crops in 2 ha, implying 3 ha for all crops together (second column). Besides it also reduces the need for grassland in 0.5 ha. This implyies that utilised agricultural area growth is 3.5 ha less than the original 20 ha needed to produce the feedstock (third column). Be aware that the numbers are only for illustrative purpose and have no empirical meaning.

The increase in land requirements is further reduced because the area needed for the biofuel feedstock gives pressure on the land market and maybe other input markets and therefore land prices and commodity prices rise. The increase in prices induces a reduction of feed, food, consumption or waste of other non-biofuel uses. **Reduced demand** reduces the area expansion. Again, the reduction of demand (consumption and waste) not only reduces the area expansion of the crop that is used as biofuel feedstock, but may also reduce the area for other crops or livestock.

Third, because of the higher commodity and land prices, it may be beneficial to **increase supply side efficiency**, in particular yields. The feedstock yields increase, but also the yields of other crops, and maybe also the yields of grassland.

Finally, all substitution processes because of price changes imply that different commodities are produced having different area requirements per unit of output, and maybe also that land conversion and crop production takes place in different regions with different yields. This is included here as the **relocation effect**, that can be both negative and positive.

What is left over is the **total area change**. In most cases the increase in feedstock area will be more than the increase in crop area, and this will be more than the increase in utilised agricultural area. When needed, one may add a fourth column that includes utilised agricultural area plus managed forest.

The decomposition approach above provides the decomposition in hectares. In order to understand the decomposition further, the changes in hectares need to be related to GHG emissions. In order to do this, it shall be determined which land is converted (i.e. location of area expansion), and the GHG emissions changes related with these conversions (i.e. the emission factors).

6.2. Stepwise decomposition approach

Once the idea behind the decomposition is discussed in the previous section, it is certain that each column of Figure 5 takes a number of steps to go from the total land use for the biofuel towards the net increase in feedstock area, cropland area or cropland plus grassland area. These steps are described in this section in further detail. Initially first column in Figure 5 is discussed, and then the steps in the other two columns are shortly described, followed by the steps needed to come from land use change towards GHG emissions.

Step 1: Gross land use for the production of the feedstock for biofuels production (per pathway)

Growing the feedstock of biofuels, the biofuels area, requires an area that is determined by the energy per kg of feedstock biofuel and the yield of land. This is a straightforward calculation. The result is quantification of direct land need for production of biofuel feedstock.

Step 2: Reduced area because of production of by-products (co-product effect)

The production of biofuels generates by-products, mainly animal feed (i.e. rapeseed cakes, soybean cakes, DDGS from wheat and maize) that may reduce land use for the production of animal feed elsewhere. This explains why the gross land use need for biofuels production (biofuel area), is more than the net area needed.

This is also a technical relationship, but the calculation about which animal feed is substituted away can be relatively complicated (i.e. to what extent can soybean cake be substituted by rapeseed cake or wheat). Furthermore, normally land for production of other crops than the biofuel feedstock is converted, so it is more relevant for the analysis of the increase of total crop expansion than for the analysis of feedstock area expansion. A careful analysis of the effect of all substitutions in the chain is required for this, where the reduction in feedstock area is only a part.

Other by-products like electricity have no land use change consequences, but have GHG emissions consequences, that normally are tackled in a standard LCA analysis of direct emissions.

Step 3: Reduced area because of reduced demand for non-biofuel crops (consumption effect)

The increase in demand for the biofuel feedstock may generate a price increase of the biofuel feedstock that is also used for other purposes. The increase in price may also generate a reduction in demand for the feedstock for other purposes. This may be because the feedstock is used more efficiently for these purposes (i.e. reduction of food waste), or because consumption is reduced. In case of use for food, this implies that less is available for nutrition or that waste is reduced. If the lower demand is for animal feed, this will have consequences for other types of feed or consumption of meat.

Step 4: Reduced area because of increase in yields of both biofuel feedstock and other agricultural commodities (yield effect)

The increase in price may generate a yield increase, reducing the amount of land needed for the biofuel, but at the same time changing land use GHG emissions because of increased fertilizer use, and perhaps also emissions related with mechanization. As far as the yield increase is on the area of biofuels, this is included in LCA analysis, but if it is on crops for other purposes, it is not included in standard GHG analysis, even though it is relevant for the calculation of net GHG emissions.

Next to the yield effect, as a consequence of price changes, average yields may also change because average and marginal yields differ. In most econometric analysis on the yield elasticity, the effects are combined. But in most models, the difference between marginal and average yields, and the increase of average yields on current land, are analytically separated. However, the difference is not visible in most model outputs, where normally average yields or production and area are reported.

While statistics are normally on harvested area, for land cover the physical area is the relevant criterion. This implies that increase in double cropping (i.e. when land has more than one harvest per year), or reduction of unused cropland are included in the yield increase component.

Step 5: Relocation of production to areas or crops with different yields (relocation effect)

Normally, the exercise above will be accomplished with standard yields (i.e EU yields). However, because some production is taking place in other regions with different yields, LUC changes will be different. Second, there may also be substitution processes going on in animal feeding, where production area needs per unit of feed differ depending on the feedstock substituted, and the regional yields for its production. These relocation effects, which can be both positive and negative, also need to be considered.

Step 6: Net increase in feedstock area for biofuels (area change)

Both yield and demand effects reduce the additional land needs for the feedstock of the biofuel. This generates the net expansion of land due to the production of the feedstock for biofuels. However, the difference between gross and net land use effect may be at the cost of GHG emissions increase related to agriculture practices (i.e yield increases require more fertilizer inputs that generates GHG emissions), or at the cost of food, feed and other non-biofuel consumption in the case of demand reductions.

6.3. Additional details on the decomposition approach

Analysis at cropland level

The analysis of the area of the feedstock crop is only part of the total analysis. This expansion of feedstock area is at the cost of other types of land. For analytical simplification, it can be assumed that feedstock production is at the cost of other cropland, as direct land use change is either forbidden under the RED, or accounted under the direct emission methodology. This implies that these other crops have to be produced elsewhere, have to be produced with a higher yield, or demand for these crops must be reduced. This is the same line of reasoning as with the feedstock area, except for that instead of an increase in demand, the driving force is a reduction in area.

However, the required crop area of other crops may be changed also because of the co-production of by-products of the biofuel production, especially animal feed. So, the demand for crops may be reduced as a consequence of substitution of the biofuel by-product. Furthermore, the demand for other crops may be changed because of changes in livestock production caused by price changes of livestock products. All these effects are included in the share of original crop land use needs, that is absorbed by demand reduction, and these elements may be split out. The end result is the increase in crop area as a consequence of the increase in biofuel demand.

Analysis of pasture land

For analytical simplification purposes, it can be assumed that i.e. the cropland expansion is at the cost of permanent grassland. Again the same line of reasoning can be followed, i.e. the tension between currently used permanent grassland and demanded area can be solved by yield increases, consumption reduction and area expansion. If it is accomplished through intensification of livestock, this will probably generate extra demand for crops for animal feed (instead of less energy intensive feed), as discussed above, although part of intensification can be accomplished through higher grassland productivity as a consequence of fertilisation, mechanisation or other methods. As far as the reduction in land use is caused by reduced livestock production, this may have consequences for meat and milk consumption and food waste reduction. The end result is a net reduction in permanent grassland.

Analysis of managed forest land

In some studies, also consequences for managed forest land are taken explicitly into account. The expansion of agricultural land into other types of land, gives a pressure on managed forest land, and again this may be accomplished through consumption reduction, yield increases and area expansion into other types of area (pastures, abandoned land, etc.).

Location of area expansion

What is defined as total land expansion depends on the model. In most cases (Laborde, 2011; Valin et al., 2015) it is cropland expansion by converting non-cropland into cropland, in some cases it is agricultural land expansion by converting other types of land (abandoned land) into cropland or grassland, and in some cases it is agricultural land expansion by conversion of managed forests, or conversion of non-managed forests into managed forests. When total land use conversion is known, it is important to know which type of land is converted. Depending on the study, the end result of the exercise is an expansion that will be at the cost of the remaining land use types, with highest impacts in case of conversion of natural forest land, peat land and other natural land (direct conversion of natural forests and other highly biodiverse areas as well as peatland and other high carbon areas is forbidden under the RED sustainability criteria). The distribution of area expansion over different types of pristine areas is the next step in the analysis. This may depend on the region where expansion happens, but depends also on the assumptions on which types of land are most likely to be converted in practice.

Emission factors

The end result of the whole exercise is a table of changes of each land use type per region. These land use changes need to be translated into GHG emission changes. Each type of land use has a different carbon stock. So, when land use changes, the carbon stock of land changes, and this carbon change may be emitted in or captured from the air, or otherwise may be associated to products produced from the feedstock cultivated on the converted land. Direct and indirect land use change emissions may arise from two mechanisms; (i) loss of carbon stock in above and below ground biomass, (ii) foregone sequestration (or carbon loss) which would have occurred if the initial land cover remained.

Concerning the first, the way in which the land transition is accomplished determines also how much GHG is released. For example, by burning forests all carbon stock will be released in the air, while if wood is harvested the carbon stock will be captured in the products made from it, or burned as biofuel. So, the share of carbon stock that is released in the air is also an important factor explaining the emission factors. For the latter (foregone sequestration), assumptions on "counterfactual" land use and climate are important. For instance, if biomass production moves onto agricultural land which would otherwise be abandoned, this land may have reverted to natural vegetation, potentially becoming a carbon sink. For both emission types, emission factors are usually quantified over a fixed period (20 years – as in the EU, or 30 years – as in the US) and averaged over the years.

Aggregation towards biofuel policies

The outcomes per biofuels pathway may be aggregated towards the totals as a consequence of biofuels policies. Normally, the outcome of a biofuels policy is just the sum of all the effects of the biofuels pathways used in the production. Analysing how the choice of biofuel pathways is made is sometimes endogenously determined and often based on current feedstock mix.

7. Research results available on the ranges of uncertainty identified in ILUC estimations

Analysis of the uncertainty of ILUC factors that are found in different studies is complex because it arises from the large number of uncertainties of different models. A good overview of ILUC GHG emissions ranges is presented in Table 9, and besides, in the following table more detailed information of studies focusing on ILUC uncertainty is presented.

Table 10 . Summary of studies including ILUC uncertainty results. Source: Own elaboration

Ref.	Result on uncertainty	Feeds tock	Biofuel type	Approach Model	Type of sensitivity analysis	Research done for
Malins et al. (2014)	Uncertainty of specific components. The most important of which are "elasticity of yield to price", "crop switching" and "carbon stock of new land". Each of these may vary results by 10-150 gCO_2-eq/MJ	Corn	1st gen. ethanol	Sensitivity analysis by best and worst case per ILUC component for GTAP and simple model. Large ranges	Own researching using modelling results from other studies	International Council on Clean Transportation
Gohin (2014)	Ranging yield elasticity (0-2): 10.8-68.6 gCO_2-eq/MJ; Ranging substitution elasticity (0-0.37): 11.2-61.5 gCO_2-eq/MJ	Corn	1st gen. ethanol	Analysis of results from FAPRI and GTAP-BIO	Own researching using modelling results from other studies	NA
Tyner & Taheripour (2016)	Corn 10-35 gCO_2-eq/MJ; Soy 18-47 gCO_2-eq/MJ	Corn, soy	1st gen. ethanol	Scenarios varying systematically one parameter at a time	Additional sensitivity analysis	CARB

Most studies on uncertainty of ILUC use **Monte Carlo analyses** by varying systematically a number of parameters in the model, and the outcome is in most cases that the spread is very large, while there is no a priori reason why one set of parameters is better than the other, nor that the average values are the most plausible ones (D Laborde, 2011; W. E. Tyner & Taheripour, 2016; Valin et al., 2015).

Since uncertainty is distributed over the different components of ILUC, first an overview is provided on the available information of the different components of ILUC. Then a number of studies analysing uncertainty are discussed.

7.1. Key assumptions

Because the outcome of models is determined by the assumptions of the different components of ILUC, in order to understand the uncertainties, it is necessary to explore the evidences available behind the mechanisms that are implicitly used in the models. Malins et al. (2014) and Searching et al. (2015) provide a comprehensive overview of current empirical evidence, and therefore the description below uses the information in these studies as a starting point.

7.1.1. Trends in yields

Area of feedstock that is necessary per TJ of biofuel depends on the **average crop yields, energy content per crop** and **energy conversion efficiency in the processing plant** per ton of crop. Especially crop and processing yields develop over time, and therefore are important for area use per TJ. The area of ILUC per TJ of biofuel is expected to be roughly proportional to the increase in feedstock area per TJ of biofuel, because almost all components of ILUC increase with the area increase needed for the biofuel. Therefore, also GHG emissions are set to be proportional to area per TJ of biofuel.

Global yields for crops increased on average 2% per year between 1961 and 2006 because of new crop varieties, increased use of pesticides and fertilizers, and improved access to irrigation (Baldos & Hertel, 2016; Burney, Davis, & Lobell, 2010). The **increase in potential yields**, i.e. the yield that can be reached with current technology at optimal conditions, ranges between 0.6% and 1.1% annually. Regarding closing the gap between potential and actual yields, according to some estimates, total factor productivity in farms[42] increased only a little bit less than yields (Baldos & Hertel, 2016).

Future yield growth is difficult to predict. R&D expenditures have been reduced in the 1990s, but increased in the 2000s. Because a larger fraction of current R&D expenditures is private compared with the past, it may be that promotion of the innovations is more difficult. Climate change may influence productivity growth, where for example increasing temperatures may reduce crop yields while increased CO_2 concentrations in the air may increase yields (Baldos & Hertel, 2016).

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[42] Total factor productivity is the productivity of all production factors together, normally aggregated by value share of these production factors in total value added.

Another key poiny is to what extent further potential yield improvements are possible. Statistically, the expectation is that the growth rate of yields will be lower in the future, especially because yields were growing at an arithmetic rate instead of a geometric rate, implying that the percentage rate of yield growth is going down (T. Searchinger, Edwards, Mulligan, Heimlich, & Plevin, 2015b). It may be that through extra R&D expenditures, such as faster improvements in farming practices, or the acceptance of new techniques like genetic modification, yields can grow more in the future than may be expected based on past growth rates, but this is something that must be proven. There are also arguments that climate change and other factors will reduce the growth rate of yields further.

Future yield growth is relevant to predict the area need of biofuels production. But besides, in combination with demand factors such as population, GDP growth and income distribution, it has consequences in the area needed for non-biofuel purposes, and therefore potential land available for biofuel production.

Looking at recent history, Langeveld et al. (2014) show that between 2000 and 2010 global utilised agricultural area was reduced by 47 million ha. This is partly caused by increased multi-cropping, which increased harvested area on the same crop area in 92 million ha (7% of a total of 1.4 billion ha). The background of utilised agricultural area reduction may be urbanisation, tourism and increase of nature area, but also land abandonment because land use is not profitable anymore or because of land degradation. With respect to Brazil, utilised agricultural area increased in 12 million ha, where 4.9 million ha of harvested area were added by increased double cropping. On that topic, increase in yields because of double cropping is only 10% of the total yield increases, and therefore makes not a significant difference in the calculation of ILUC (JRC, 2015).

7.1.2. Consumption reduction

Part of the increase in demand for agricultural crops as a consequence of the increase of biofuel demand, is accommodated through a **reduction in demand for crops for food, feed and other non-biofuel purposes**. This makes it relevant in the food versus fuel debate, although also some non-food agricultural demand like palm oil for cosmetics will be replaced, for which the substitutes may also have GHG emissions. The share of biofuel land expansion accommodated through consumption reduction **depends on the response of demand compared with the response of supply with respect to price**, i.e. the price elasticity of demand versus the price elasticity of supply. A difficulty in the estimation of **relevant elasticities** is that it is not only about the effect on specific commodities, but also on all crops together, and even the effect on livestock production.

So, the essential question is to what extent the amount of food, both crop-based and livestock, is reduced as a consequence of biofuel policies.

The share of biofuel land expansion accommodated through consumption reduction is determined by the difference between the price elasticity of supply and demand. Most economic models have implicit or explicit **price elasticities** of supply that are equal to or a little bit higher than the price elasticity of demand, implying that between 30% and 50% of ILUC is reduced through consumption changes, although it is a little bit less in the GLOBIOM results (Valin et al., 2015).

Although **demand elasticities** from different sources of literature, especially of the US and China, are available on the ERS-USDA website (ERS-USDA, n.d.), the foundation is relatively weak, and the database is no longer updated. Recent econometric studies trying to estimate both supply and demand elasticities for agricultural commodities are Haile et al. (2016), Berry & Schlenker (2011) and Roberts & Schlenker (2013), using advanced instrumental variable techniques. They come at supply elasticities around 0.1 and demand elasticities around -0.05, implying that an increase in demand for biofuels of 5%, increases the price of the four main staple food commodities in 35% (Roberts & Schlenker, 2013, p. 2279). They suggest that these elasticities are also relevant for the long term, but Baldos and Hertel (2016) suggest that long term elasticities are much higher, because there are more adjustment possibilities in the long term than in the short term. Based on Muhammad et al. (2011) they conclude that the price elasticity of demand ranges between 0.30 and 0.86, the crop yield elasticity to land rents about 0.11 (Lubowski, Plantinga, & Stavins, 2006), the yield elasticity to price about 0.25 (Keeney & Hertel, 2009), and the area elasticity to price about 0.05, implying a supply elasticity of about 0.3. This is the same as estimated by Scott (2013). Hertel & Baldos (2016, p. 42) suggest that the area elasticity of supply is about 0.05 after 5 years, and 0.15 after 20 years.

Persson (2016) shows in a literature overview that price elasticities of demand of CGE and PE models are around -0.7, but that they range between 0 and -3.4. However, average supply elasticities of the PE models studied are significantly lower at about 0.45, and CGE models have on average a supply elasticity of about 2.48. This is much larger than estimated, but the estimations are normally short term elasticities for specific commodities, instead of long term elasticities for crops as a whole.

Long term price elasticities of supply and demand will be different from **short term** elasticities.

In perfect competition price elasticities of supply tend towards infinity, and Schmidt et al. (2015) suggests that consumption effects should not be taken into account at all. However, for agriculture, there is always a restriction on the availability and quality of land, so costs and therefore price, may increase when less suitable land has to be taken into cultivation.

Searchinger et al. (2015) and Malins et al. (2014) suggest to exclude the part of GHG emissions reduction related to reduced food consumption from their GHG emission calculations, or to make the trade-offs transparent. For this reason, Searchinger et al. (2015) presents results of three different studies with and without the effect of reduced food consumption. However, most researchers do not make explicit what the effect of non-biofuel demand reduction is on the ILUC factors calculated.

7.1.3. Yield increase

The **share of production increase accommodated through yields** depends on the **price elasticity of yields compared with the price elasticity of area expansion**. Gohin (2014) shows that analysis of yield elasticity without consideration of land elasticity is not very meaningful, so the fundamental issue is the relative size of both elasticities.

When interpreting results of **price elasticities of yield**, it has to be taken into account that they are a combination of differences between yields on new area compared with average area (the marginal yields) that are in some models explicitly included, and changes in yield on current land (that includes increases in double cropping). Searchinger et al. (2008) assumes these two effects cancel out, but all more recent studies assume that the net effect is positive, i.e. an increase in biofuel production increases yields.

The price elasticities of area and yield do conceptually not include the effect of **marginal yields**[43]. However, the estimation these two cannot be disentangled, and therefore in practice the ratio between yield and area elasticities, both with respect to price and production, should be the same. This ratio is the essence of explaining the share of production increase accommodated through area expansion.

Al.-Riffai et al. (2010, p. 92) suggest that "there are **no robust estimates from the econometric literature** because of the complexity of the linkage and the highly fragmented data available for land use in deforested regions, the lack of a continuous time series on local prices, and more importantly, land rent, when they exist" (Malins et al. 2014, p. 91).

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[43] Marginal yields are the yields on extra land taken into use.

The analysis for the California Air Resource Board (Carb, 2011) is originally based on a paper by (Keeney & Hertel, 2009), reviewing literature on yield elasticities for the US and suggesting a yield elasticity of about 0.25. Berry (2011) and later Searchinger et al. (2015), dispute the size of this elasticity based on a different interpretation of the literature and the fundamental issue of **endogeneity** of both price, yield and area change.

Another criticism on econometric estimates is that most estimations are on **short term** effects, where it is plausible that supply responds much less in the short term than in the long term because area expansion and yield increases require investments (Berry, 2011, p. 7). Besides, the elasticities of the econometric studies are **crop specific**, or in Berry & Schlenker (2011) specific for the combination of four crops. The total supply elasticity implicit in these estimates is so small that it is inconsistent with long term dynamics of agricultural markets where supply elasticities probably tend to much higher values.

Roberts and Schlenker (2013) use **instrumental variable techniques** (using weather as the main tool) to analyse yield and area elasticities for wheat, corn, rice and soy, where production is defined by total digestible energy content. They find that yield elasticities are small compared with area elasticities. This is developed further by Berry & Schlenker (2011) with estimations not only for the US but also for the whole world, and a more advanced use of instrumental variable techniques. They find a global short-run price elasticity of area of around 0.1, and a price elasticity of yield around zero. Area elasticities are significantly higher, but also far below 1 (around 0.2) for all estimations. Although some yield elasticities are significantly positive, others are significantly negative, showing how unreliable current estimation techniques and data still are (Roberts and Schlenker, 2013).

Miao et al. (2016) estimate the responsiveness of crop yield and area of US corn and soybean to prices and climate by a **panel data instrumental variable analysis** with county fixed effects on US yearly data for 1977-2007. They find a significant own price elasticity of corn yield of 0.23, but not for soybean yield (p. 194), while the price elasticities for area are respectively 0.45 and 0.63, implying that in the short run area expands more than yields, even for corn. The lagged fertilizer price index has a significantly negative effect on corn yield and a significantly positive effect on both corn and soybean area.

Haile et al. (2016) use **dynamic panel data estimation techniques** on a multi-country multi-crop panel data set, and find own price elasticities of yields for wheat, corn, soybeans and rice of 0.166, 0.094, 0.146 and 0.043 and area elasticities of 0.075, 0.069, 0.146 and 0.024, respectively. They find also significant negative yield effects of increases in crop price volatility, which may be relevant if an inflexible biofuels policy increases volatility in agricultural prices.

The final recommendation from the CARB Elasticities Values Subgroup (Carb, 2011) is to use a yield elasticity of 0.25, taking into account that long term elasticities are larger than short term elasticities because of double cropping and the time lag in introducing new seed varieties or management practices. This argument is still defended by them as valid, independent of newer econometric studies with lower short term elasticities. However, the share of ILUC reduced by yield increases is determined by a combination of yield and area elasticities.

Some authors (B. A. Babcock, 2015; B. A Babcock & Iqbal, 2014; Overmars et al., 2015, 2011) suggest to use **historical data** to estimate the fraction of production increase accommodated through yield increases. However, none of these studies differentiates between changes in yields caused by price increases, and yield increases caused by exogenous processes like technological change or economic development.

In summary, some information is available on short term yield and area elasticities for specific crops. However, it is **extremely difficult to get reliable information on long term effects of production increases on yields**, because it is almost impossible to disentangle exogenous trends in yields from price-induced yields. Furthermore, yield increases of crops as a whole is even more difficult to estimate. The evidence on yield effects is insufficient and mainly short term.

7.1.4. Relocation of production

Yields in different regions differ. Yields of different crops differ. For example, when instead of maize, soybean is used for animal feeding, the required area for feed production increases.

However, the topic is broader. For example, Laborde (2011) proposes a free trade scenario for EU-biofuels, where more sugarcane ethanol is produced in Brazil. This has consequences for land use. It may also be that livestock production in Brazil is reduced because of competition of biofuels, and that this results in more livestock production in the EU, that requires less land and has less GHG emissions per kg meat. All these matters are implicit in CGE and PE models, and complicated to trace. Therefore, **no study is very explicit on this relocation effect**.

The **method by which international trade is modelled is an important aspect of international relocation of production**. The most common assumptions are the Armington assumptions. In these, current trade flows are the main determinant of future trade, and the minimum cost approach is stablished, where the region with the lowest cost (including transportation cost and sometimes some quadratic adjustment cost function) determines the location of additional production.

7.1.5. Location of area expansion[44]

Once it has been determined how large the expansion of cropland or total agricultural land is, the basic question is what **type of ecosystem** is destroyed. The first step is to determine the **fraction of cropland expansion into each type of land**, the so-called land extension coefficients (LEC) (Malins et al., 2014).

These LEC's may be determined by comparing **satellite data on land cover**, as is done by Winrock-MODIS (Malins et al., 2014). However, their approach is criticized because there is much uncertainty in satellite data. When 5% of area is incorrectly allocated and when this is random, almost 10% of land use changes that are measured may be wrong; this is a multiple of actual real land use changes (Malins et al., 2014, p. 97). Miettinen et al. (2012) provide more robust results with much more precise satellite data. However, MIRAGE uses Winrock-Modis LECs to allocate land expansion over land categories (Malins et al., 2014, p. 98). Besides, Lark, Meghan Salmon, and Gibbs (2015) show that for the US, the expansion of soybean area and maize area that is triggered by biofuels expansion is to a large extent into land that has not been used for agriculture before, and that is less suitable for conversion "raising concerns about adverse environmental and economic costs of conversion".

A second approach to allocate land expansion is accomplished in **models like MIRAGE** (Laborde et al., 2014) and **GTAP** (CARB, 2009), where a CET function based on *relative prices,* determines to what extent cropland expands into managed forest land and commercial grassland (Malins et al., 2014, p. 97). This approach cannot be used to analyse expansion into pristine land, because for this land no prices are available.

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[44] For this section, the analysis is based on Malins et al. (2014) and page numbers refer to this study.

Most models tend to allocate **more land expansion into grassland than into forest** (Malins et al., 2014, p. 98-9, figure 3.11). Forests store more carbon than shrub land and shrub land more than grassland. GTAP (CARB, 2009) includes only grassland and managed forest to expand in, MIRAGE (Laborde et al., 2014) also does not include shrub land, while FASOM uses 25 different forest species types and 18 forest management intensities. So this fact, may influence carbon consequences.

A third approach to address the allocation of cropland expansion, may be the use of a **land allocation models**. In such models, land characteristics per grid cell (i.e rainfall, slope, soil quality, proximity to roads and distance to existing production areas), determine the probability of land conversion (Malins et al., 2014, p. 98). Malins et al. (2014) refer in this context to the work carried out by the Joint Research Center of the European Commission (Hiederer & Ramos, 2010). The land allocation models CLUE and IMAGE have been used for the same purpose in other studies, and besides more land allocation models are available.

Different types of models have **different land categories**, and many of them are based on FAO statistics. The way land is categorized is essential for the availability of land that is currently not used. JRC (2015) argues that the availability of fallow land is overestimated as a source of crop area, because in many studies unharvested cropland is used as a proxy for available land. However, some harvested crops are not in the statistics, and thus, part of land that is not harvested in the FAO statistics is harvested in reality, and therefore should not be included as unharvested area.

Furthermore, a lot of **unharvested land** is unharvested for a reason. There are many reasons for land not generating a harvest such as; failed harvests through weather events, land is left fallow with or without a cover or nitrogen fixing crop to improve soil fertility, there is no harvest yet as it concerns establishment of a perennial crop, or the land is not harvested in order to have a buffer for fluctuations in demand over the years. There may also be nature reserve areas that are considered as fallow, while regulations do not allow their use. Furthermore, there is no indication that cropland expansion occurs preferentially in regions where crop area has been recently reduced, implying that there were reasons to abandon the land. In summary, if land is not harvested there might be a number of (economic) reasons for this.

Own analysis. Laborde (2011) versus Valin et al. (2015)

Different models have different results.

Different models may have different mechanisms, which are mainly related to the implicit assumptions on the different components of ILUC, rather than with the model itself. These differences are illustrated by decomposing the results of the two main studies for the **EU** for **maize ethanol** (Laborde, 2011 and Valin et al., 2015). The difference in emissions is relatively small, i.e. 14 and 10.8 g CO_2-eq/MJ respectively. However, the emissions have different causes, as illustrated by the change in agricultural land area, which is more than 10 times higher in Valin et al. (2015) than in Laborde (2011).

Although land area and GHG emissions are stated explicitly in both studies, the decomposition below is a very rough attempt to interpret figures in the models, implying that the approximate tendency is correct, but that the exact figures are an interpretation of the authors of this report.

Table 11 Model outcome comparison for maize ethanol. Source: own calculations, partly based on Searchinger et al. 2015

	Valin et al. (2015)		Laborde (2011)	
	ha/TJ	%	ha/TJ	%
Gross feedstock area	15.6		13.5	
By-product	4.1	26%	6	44%
Net feedstock	11.5		7.6	
Feed demand	3.4	29%	3.9	52%
Production increase	8.2		3.6	
Yield increase	2.3	28%	2.7	75%
Cropland change (calculated)	5.9		0.9	
Reallocation effect	-1.8	-30%		
Cropland change	7.7		0.9	
Grassland area change	1.3	17%	0.4	43%
Agricultural land	6.4		0.5	

Both studies start with more or less the same gross feedstock area per TJ, but Laborde (2011) reduces the area needed already with a percentage that is 70% higher than Valin et al. (2015), and the same holds for the reduction in demand for animal feed as a consequence of higher maize prices.

Land demand reduction because of price-induced yield increases as a percentage of land use, is 150% higher in Laborde (2011), and the difference is even more because in Valin et al. (2015), an unexplained part that we call reallocation effect is left. Finally the percentage of cropland expansion that is accommodated through a reduction in grassland area, is also 150% higher in Laborde (2011).

If land use changes are so much different in the two models, why are the GHG emissions more or less the same? The answer is that except for grassland and peatland, different types of lands are converted and different types of GHGs are taken into account (see Table 12). While in Valin et al. (2015), mainly natural land and abandoned land in the EU are converted (where carbon sequestration on cropland is explicitly taken into account), Laborde (2011) converts mainly managed forests, and also grassland, both with a much higher amount of carbon stock per hectare.

Table 12 Model outcome comparison for maize ethanol with respect to carbon accounting. **Source:** own calculations

Valin et al. (2015)			Laborde (2011)		
	ha	tCO_2/yr		ha	tCO_2/yr
Natural land	5.70	9			
Abandoned	2.00	6	Managed forest	0.48	6.0
Cropland	7.70	-4	Natural forest	0	0.0
Grassland	1.30	1	Grassland	0.4	2.0
Peatland	0.03	2	Peatland	0.05	2.8
Total		14	Total	0.88	10.8

In summary, it is not easy to get a precise insight into the land use dynamics based on the information provided in the studies. However, the rough dynamics is clear, and it is also clear that the GHG emissions in the two reports have completely different backgrounds.

7.2. Uncertainty Analysis[45]

Valin et al. (2015) analysis in some studies

Valin et al. (2015) (IIASA/Ecofys – GLOBIOM model) perform a Monte Carlo sensitivity analysis to analyse uncertainties. They vary a large number of parameters, and sometimes assume that some parameters vary independently of each other, and other parameters vary in the same direction. In annex V of Valin et al. (2015), the sensitivity analysis is presented in detail. A representative idea of what type of information comes out of it, is presented below for maize ethanol.

Valin et al. (2015) show per feedstock the average, 25-75% and 5-95% uncertainty ranges for different GHG emissions components, i.e. natural vegetation conversion, natural vegetation reversion, agricultural biomass, soil organic carbon and peatland conversion (see Figure 6). These variations are the consequence of systematic variation of the parameters, but it is not possible to decompose the uncertainties in the components of LUC. The result is a total distribution of ILUC factors that is extremely broad, with the 90% interval for maize between -70 and +60 gCO$_2$-eq/MJ, which is extremely wide compared with the average.

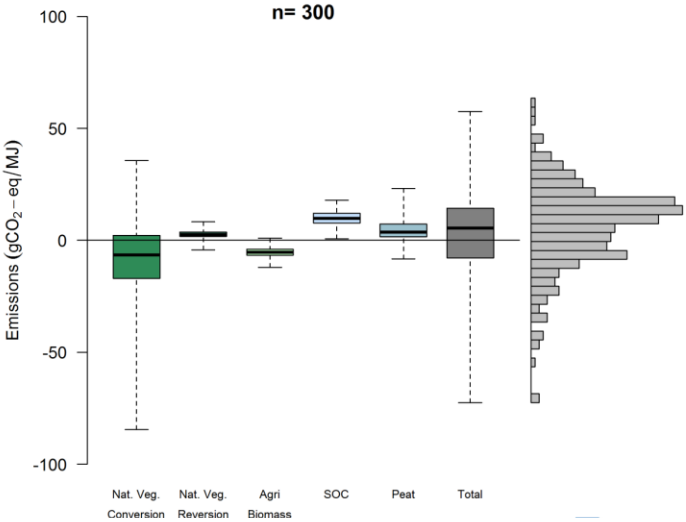

Figure 6 Detail of Sensitivity Analysis. **Source:** Valin et al. (2015).

Valin et al. (2015) conclude that important uncertainties remain, because of variability around biophysical values and around causalities assumed by the modelling approach (p. xiii).

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[45] For this section, the analysis is based on the highlighted studies, and page numbers refer to these studies.

Plevin et al. (2010, 2015) studies

Plevin et al. (2010) conclude that "lack of data and understanding (epistemic uncertainty) prevents convergence of judgment on a central value for ILUC emissions. The complexity of the global system being modelled suggests that this range is unlikely to narrow down." (p. 8015). There is a lack of consistency in expert judgment on correct parameter values, functional relationships and the efficacy of models to represent the relevant processes.

This makes it difficult to model uncertainty probabilistically, and so it may be better to evaluate different scenarios (p. 8016). Despite this, they develop a simple ILUC model that distinguishes the fuel yield, the net displacement factor, the relevant production period to which emissions have to be allocated, emissions factors for forest, grassland and wetland, and the fraction of cropland expansion going into these land cover types.

In their analysis they conclude that the net displacement factor (i.e. the economic part of the analysis), accounts for about 70% of the variance in the emission factors. According to them, it is unlikely that modellers will be able to reduce the uncertainty in this parameter significantly (p. 8019).

In Plevin et al. (2015) a Monte Carlo simulation is accomplished in a combination of the general equilibrium model GTAP-BIO-ADV, and the carbon accounting model AEZ-EF. They analyse US maize ethanol, Brazilian sugar cane ethanol and US soy biodiesel. They analyse parametric uncertainty in the combined models, and identify the main parameters that generate the variance of ILUC emissions in the Monte Carlo simulations. Choices on distribution of parameters are based on expert judgment, literature, other model's outputs and sometimes measurement (p. 2659).

In their simulations Plevin et al. (2015) find that 70% of variance in emission factors is caused by the economic model, and 30% by carbon accounting. With respect to uncertainty in carbon accounting, available data on biomass are uncertain, and estimates of soil carbon fluxes from land-cover change, where the remote sensing is used to allocate land cover, are highly uncertain (p. 2657).

In their interpretation Plevin et al. (2015) conclude that handling of uncertainty depends on the cost of error, and suggest the application of a safety-factor to prevent wrong decisions (p. 2663).

ICCT's simple model uncertainty analysis

Just as Plevin et al. (2010), Malins et al. (2014) developed a simple macro-ILUC model in order to get a better understanding on the fundamental causes of ILUC. In contrast with the standard policy assumption of zero net ILUC, it starts with the situation where all biofuel land is at the cost of pristine area.

The components that reduce ILUC are the reduction in food consumption, the increase in yields, the use of by-products, the location and type of crops compared with average global yields, the elasticity of area to price, and the carbon stock of new land. Figure 7 shows the resulting distribution for corn ethanol using assumptions that are relatively consistent with the CARB's ILUC estimate, and varying for each parameter a best and worst case, with parameter choices based on judgment and parameter values in the literature (p. 110). The analysis shows that varying one of these parameters, while keeping the others on the default values, provides already very large ranges of ILUC.

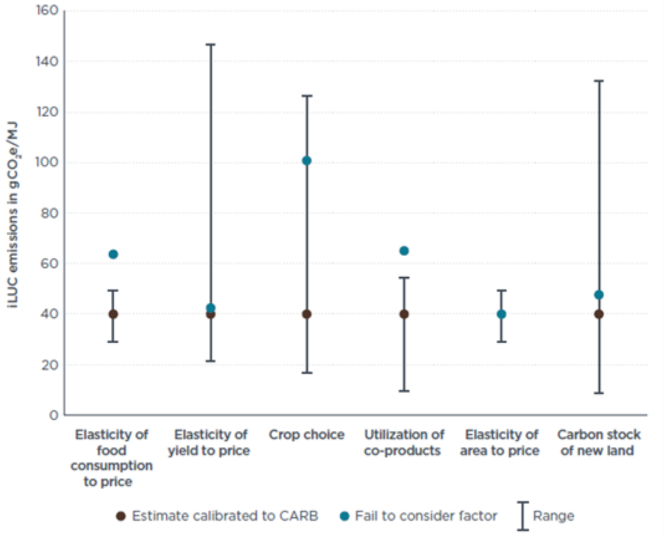

Figure 7 Illustrative model of how assumptions for each parameter affect ILUC results for U.S. corn ethanol. **Source:** Malins et al. (2014)

CARB sensitivity analysis

Tyner & Taheripour (2016) perform a sensitivity analysis in the ILUC analyses performed for the CARB and determining its 2015 ILUC factors for biofuels regulation. Instead of a Monte Carlo analysis, Tyner & Taheripour (2016) perform a number of simulations to indicate the effect of systematically varying some parameters. One is the crop yield price elasticity, and another the emission factor for conversion of a specific, low-carbon type of grassland, that in the past had been used as cropland or cropland-pasture, that is used in the GTAP model[46] (CARB, 2015). Also a correction factor for marginal productivity compared with average productivity based on a net

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[46] Cropland pasture includes "buffer land", upon which crops expand in profitable years and are not cultivated in unprofitable years. As economic models do not have any annual price fluctuations caused by the effect of weather on yields, they allow this land to be permanently occupied without encroaching on pasture land itself. But if this happened in real life, a farmer would convert more pasture land the next time he foresees a profitable year."

primary productivity indicator is investigated, as is the Armington elasticity, i.e. the reaction of trade on international price differences.

One finding of this study is that the size of ILUC depends on the size of the shock. This is caused by the CET elasticities for land. The increase in cropland with an increase in maize ethanol demand from 9.59 to 11.59 billion gallons is 30 % higher than an increase from 1.59 to 3.59 billion gallons. Resulting also in about 30% more GHG emissions, i.e. 16.5 instead of 12.5 gCO_2e/MJ.[47]

7.3. Possibilities to narrow down uncertainty

Many authors (Laborde, 2011; Plevin et al., 2010,2015; Valin et al., 2015) suggest that it will **not be easy to narrow down uncertainties** in the near future.

For example, Valin et al. (2015) conclude that important uncertainties remain, because of variability around biophysical values and around causalities assumed by the modelling approach (p. xiii). Plevin et al. (2010) conclude that “the lack of data and understanding (epistemic uncertainty) prevents convergence of judgment on a central value for ILUC emissions. The complexity of the global system being modelled suggests that this range is unlikely to narrow substantially in the near future. Fuel policies that require narrow bounds around point estimates of life cycle GHG emissions, are thus incompatible with current and anticipated modelling capabilities.” (p. 8015). Laborde (2011) mentions with respect to uncertainty that “ILUC can only be modelled, not measured, because it is generated by global mechanisms in a large interdependent system (p. V). The outcomes are the results of assumed causalities in the model (p. xiii), i.e. the understanding of the agricultural market system (p. xv) and on biophysical values. For both it is very difficult to reduce uncertainty. As a consequence of this inherent uncertainty that cannot be avoided, it is not suitable to include ILUC factors directly in the calculations" (p. xv).

Malins et al. (2014) are more optimistic. They state: “For each of the six factors identified here, **further research would help to narrow the range of ILUC results** and progressively increase confidence about the magnitude of ILUC for each feedstock” (p. 23).

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[47] Calculation based on table 3-33 of Tyner and Taheripour (2016), p. 40.

8. Different approaches used and results on taking by-products into account

The basic idea of **by-products** is that part of the harvest cannot be used for biofuels and is available for other purposes, especially **animal feeding**. For rapeseed and soybean based biodiesel, the by-product is protein-rich rapeseed and soybean meal (cake), respectively. While for wheat and maize, it is dried distillers grains with solubles (DDGS). All these by-products are substitute protein-rich meals.

In simple models, this is just distributed according to the **weight**, the **energy content** or the **market value**, but in practice **substitution processes** are much more complicated.

Table 13 . Summary of most important studies including by-products in ILUC results. Source: Own elaboration

Reference	Model	Approach	By-products	Type of research	Research done for
Laborde (2011)	MIRAGE	Substitution through nested CES function	Protein rich feeds	Own modelling	EC
Valin et al. (2015)	GLOBIOM	Substitution through linear programming model	Protein rich feeds	Own modelling	EC
Overmars et al. (2015)	Historical	Value or energy shares	Protein rich feeds	Own modelling	EC
Lywood (2013)	Historical	Substitution approach	Protein rich feeds	Own modelling	SOFIPROTÉOL
Hertel and Baldos (2016)	GTAP	Substitution through nested CES function	Protein-rich feeds	Own modelling	NA

Most studies consider by-products, so in the table above only a small but representative selection is presented. In a lot of **causal models** like Overmars et al. (2015), by-products are simply handled according to the energy or value share in the final product. In more **advanced models** like **MIRAGE** (Laborde et al., 2014) and **GLOBIOM** (Valin et al., 2015), there is first a substitution between different **protein rich feeds,** and then a substitution between **energy and protein feeds**. In many models the increase in protein-rich feed by-products leads only partially to a reduction of other protein-rich by-products, while the main effect is that the energy-rich feed is reduced and sometimes also feed from grassland.

Although the substitution process in feed is relatively well described, the dynamics generated are not. The increase in by-products generates a price reduction of protein-rich feed, and depending on the price changes of other feed components, total crop-based feed price may either increase or decrease.

In MIRAGE (Laborde et al., 2014) and GLOBIOM (Valin et al., 2015), but not in GTAP (CARB, 2009), the substitution mechanism starts as the consequence of increased protein-rich animal feed. As far as the increase in biofuel by-products, i.e. rapeseed meal is accommodated through a reduction in production of other protein-rich feed, i.e. soy meal, this may generate a reduction of soy production reducing supply of soy oil, which is replaced with the cheapest oil on the market, palm oil, that produces less by-products. This way, the positive land use effect of a decrease in land use of feed by-products of biofuels, may be compensated by the relocation of oil production for non-biofuel demand. Thus, leading to conversion of peatland and carbon rich forests into palm oil plantations (Malins, Searle and Baral, 2014b).

What is the evidence for this mechanism? First, recent history increases in global vegetable oil demand are mainly accommodated through increases in palm oil production. Therefore, an increase in biodiesel demand, also generates an increase in palm oil production (Valin et al., 2015). Second, the results of the economic models are based on two important assumptions on substitution possibilities: that substitution between oil cake from rapeseed and oil cake from soy is relatively easy, that the ratio between vegetable oil production and oilcake production is more or less fixed, and that substitution between palm oil and soybean oil is relatively easy. The most adequate approach is not clear, but it is clear that models widely differ on assumptions about this mechanism, generating large differences in LUC GHG emissions from soy and rapeseed oil.

An alternative **historic approach** is found in Lywood (2013), who comes at a very high carbon benefit of rapeseed biodiesel because of substitution of by-products. Although data on the substitution process between rapeseed by-product and soybean is not fundamentally different from Valin et al. (2015), the outcome is. One reason is that in Lywood (2013), the reduction of soy oil production is compensated by reduced biodiesel production in Argentina, while it is compensated by increased palm oil production in Valin et al. (2015). Another reason is that in Valin et al. (2015) prices of oil meals are reduced, and therefore livestock production increases, and the share of protein meal in livestock increases. The result is a net expansion in cropland area, which is partly at the cost of high carbon peatland forests. On the contrary, Lywood (2013) presents a net reduction in land area; where the reduction in land area is mainly in South America, generating large reductions, and the increase in land area is mainly in the EU, with relatively low foregone sequestration GHG emissions.

In summary, it is very difficult to trace the consequences of by-product substitution in different studies due incomplete reporting, and results can be fundamentally different.

9. Research results on the possibility of factoring in the impact of EU policies in ILUC estimations.

In general, in ILUC studies **little is mentioned about the consequences of other EU-policies on ILUC GHG emissions**. Therefore only some possible effects of other policies are discussed, with only limited evidence derived from ILUC studies, and a large part based on logic.

Table 14 . Summary of studies including other policies on ILUC results. Source: Own elaboration

Ref.	Result	Policy	Biofuel type	Approach Model	Type of research	Research done for
Valin et al. (2015)	Reduction of GHG emissions as consequence of EU biofuels policy from 97 to 48 gCO_2-eq/MJ, and if no peatland conversion is effectively forbidden to 4 gCO_2-eq/MJ	Global CO_2 price of 50$ per ton	EU-biofuels mix	GLOBIOM	Own modelling	EC
Valin et al. (2015)	Foregone sequestration emissions may not happen because of annual mowing in order to receive CAP money, occasional mowing by smallholders, or extensive grazing.	CAP policy	All biofuels investigated.	Only mentioned as a warning	Comment to own modelling	EC
Laborde (2011)	More ethanol from sugar cane in Brazil	Trade policy for biofuels	EU-biofuels mix	MIRAGE	Own modelling	EC

Agricultural policies

Some agricultural policies may have consequences for LUC of biofuels. First, Valin et al. (2015, p. xiii) mention that foregone sequestration emissions may not happen because of annual mowing in order to receive CAP money, occasional mowing by smallholders, or extensive grazing.

Second, if agricultural policies promote less intensive schemes with lower yields, then this may increase the amount of land used for feed and food production, and therefore reduce the amount of low-carbon land that is available for biofuels. Also for example animal welfare regulation may influence the amount of land needed for food production.

Third, subsidy policy is an important aspect of agricultural dynamics. Decoupling of subsidies, reduced prices and made European feed more competitive compared to imported feed. Taheripour et al. (2011, p. 11) conclude that in the past, crop area in the US was mainly determined by government programs, while currently market forces become more important. The same holds more or less for the EU (C Malins et al., 2014).

Fourth, also rural development policy is sometimes focused on improving yields and efficiency of agriculture practises, as well as on improving infrastructures. This fact may provide the same type of effects as R&D and technology diffusion policies.

Environmental and climate policies

Environmental policies may reduce the opportunities to convert high biodiversity land. In most cases high biodiversity areas are also high carbon areas, so if high biodiversity areas are protected this may reduce the possibilities for land conversion. Legislation and enforcement of legislation in the regions where land use change happens is crucial, and country specific governance is therefore essential.

Environmental legislation in the EU may change options for land conversion. This can potentially force land conversion in areas with low carbon conversion costs. However, stricter environmental policies may also drive agricultural production out of the EU, with potentially larger GHG effects than it would have had in the EU. GHG emissions may be larger outside the EU because legislation and law enforcement is less or because land management practices are less efficient.

A consistent climate policy including prices, land conversion and GHG sequestration of forests, may reduce ILUC substantially. For example, Valin et al. (2015, p. 39) calculate that a price of 50$ per ton CO_2 would reduce LUC emissions from the EU biofuels policy from 97 gCO_2-eq/MJ to 48 gCO_2-eq/MJ, and if peatland would not be allowed to be converted to 4 gCO_2-eq/MJ . Dixon et al. (2016) model UN REDD policies by reducing available land in the model, but do not calculate emission factors based on this. Policies like REDD+ to prevent forest conversion are meant to accomplish some pricing of carbon in forests.

One of the broader issues debated in the context of biofuels climate policies is to what extent biofuels policy is the most cost-effective method to reduce GHG emissions in the transport sector.

Trade policies

More flexibility to import biofuels, potentially provides an opportunity to reduce GHG emissions. For example, direct GHG emissions from sugar cane ethanol are much lower than for maize or wheat ethanol, although indirect emissions depend substantially on the land use policy in the producing countries. Laborde (2011) models a free biofuel trade scenario where exactly this effect is found.

More flexibility in the trade of crops and livestock in general, may change the international relocation of land. If increased biofuels production in the EU is at the cost of other cropland in the EU because other regions are more cost competitive, while these other regions have lower yields or other reasons for larger GHG emissions, the indirect land use effects of EU biofuels may increase with more free trade.

On the other hand, trade policy can also be used as an instrument to force third countries for stricter compliance to environmental regulation. If tariff reduction in free trade agreements are made conditional on environmental policies, then LUC of biofuels may be reduced.

R&D and technology diffusion policies

First, research on advanced biofuel technologies and technologies to improve yield on marginal land, may result in the development of low ILUC-risk biofuel pathways. This may happen to the extent that it provides profitable opportunities for biofuels production, while it is not possible to produce other commodities on that land in a cost-effective manner.

Second, research devoted to increasing yields for biofuel feedstock will reduce direct land use change, and therefore also indirect land use change (being normally a fixed fraction of direct land use change).

Third, research leading to a general increase in yields will reduce the amount of land that is needed for non-biofuel purposes. This land may be low carbon land without competitive uses, that may be used for biofuel production. However, in quantifying GHG effects the capacity of abandoned land to sequester carbon must be taken into account.

What has been said about R&D, holds also for technology diffusion that is meant to spread the knowledge that has been generated by R&D. R&D without diffusion of the knowledge generated, is not effective.

10. Availability of research on other indirect effects of the EU biofuel policy.

The literature review described in this report focuses primarily of GHG emission due to ILUC. Nonetheless, during the review, a number of studies pointed out other important direct and indirect effects of biofuel production.

Table 15 . Summary of studies including other indirect effects results. Source: Own elaboration

Ref.	Other Indirect Effect	Biofuel type	Impact	Approach Method	Type of research	Research done for
Melillo et al. (2009)	Nitrous Oxide Emissions	Cellulosic feedstocks	Nitrous oxide emissions may be greater than carbon loss in terms of warming potential, due to additional fertiliser use.	IAM	Own modelling	NA
Banse et al. (2011)	Agricultural Commodity prices	1st Generation	Import of biofuels will be strong, even under scenario settings which prohibit international trade. Global land expansion by 1-5%. The long term trend of declining agricultural prices may be reversed.	CGE	Own modelling	NA
Persson (2016b)	Agricultural Commodity Prices	Multiple	Significant uncertainty concerning the effect of increased biofuel production on food prices.	Review	External sensitivity analysis	NA
Immerzeel et al. (2014)	Biodiversity	Multiple	Impacts depend on initial land use and generally negative, especially in tropical regions. Advanced biofuel mitigate this.	Review	NA	NA

Melillo et al. (2009) compared different long-term biofuel production pathways using an IAM linking economic and terrestrial biogeochemistry model. Their results show that indirect land use will be responsible for substantially more carbon loss (up to twice as much) than direct land use. However, because of predicted increases in fertilizer use, nitrous oxide emissions will be more important than carbon losses themselves in terms of warming potential. A global GHG emissions policy that protects forests and encourages best practices for nitrogen fertilizer use can dramatically reduce emissions associated with biofuels production.

Persson (2016) reviewed t the impact of increased bioenergy demand on **agricultural commodity prices**. This study suggests that there is still considerable uncertainty around how prices are affected by biofuel demand. Three areas were identified where effort needs to be directed to improve models and data, in order to better predict both current and future impacts of biofuel demand: (1) increase the understanding and empirical evidence on price elasticities, (2) price transmission in international agricultural markets, and (3) better capture the forces (including policies) that shape the future expansion of cropland.[48]

Regarding the impact of bioenergy in **biodiversity**, many studies have been produced in this direction. A review of different studies addressing bioenergy impact on biodiversity was done by Immerzeel et al. (2014). In their study, they analysed 53 studies and also summarized them, by the area of focus, crop, studied taxonomic groups, etc. The conclusion of the study was that "reported impacts depend on initial land use and are mostly negative, especially in tropical regions. The impacts of second generation bioenergy crops tend to be less negative than first generation ones, and are in some cases positive (at the field level), in particular in temperate regions. Land-use change appears as the key driver of biodiversity change, whereas the associated habitat loss, alterations in species richness and abundance are the main impacts addressed".

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[48] There is also an extensive literature on food security consequences of biofuels, but not in the context of ILUC analysis.

11. Availability of ILUC research data on impacts of advanced biofuels produced from dedicated energy crops[49]

Advanced biofuels, present a median ILUC factor of 5 gCO_2-eq/MJ. It is important to stress though that unlike other feedstocks where there are multiple studies (18 for biodiesel and 24 for 1st generation), there are only six studies presenting results on advanced biofuels (Fritsche, Hennenberg, et al., 2010; Melillo et al., 2009; Mullins et al., 2011; Overmars et al., 2015; Farzad Taheripour & Tyner, 2013; Valin et al., 2015). Among these studies, there is significant disagreement and differences in methodological approaches as the types of lands assumed to be used for dedicated cropping with woody and perennial crops are defined differently in terms of current use status.

A comprehensive overview of ILUC GHG emissions ranges of advanced biofuels produced from dedicated energy crops is presented in Table 9. Besides, in the next section related to low ILUC-risk biofuels certification and main mitigation options, more detailed information of studies focusing on ILUC of dedicated energy crops is presented (Table 16).

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[49] Crops dedicated to production of energy. This category comprehends non-food, lignocellulosic crops, belonging to the 2nd generation feedstock. Species included are both herbaceous and woody such as miscanthus, switchgrass, reed canary, giant reed, cardoon, willow, poplar and eucalyptus among others (Perpina-Castillo et al. JRC 2015).

12. Overview on availability of research on low ILUC-risk biofuels certification and main mitigation options

In order to prevent ILUC effects, different **mitigation** options including **low-ILUC biofuels,** are suggested in a wide number of studies discussed in this chapter.

The starting point for the inventory of low-ILUC biofuels is the definition in the ILUC Directive (EU) 2015/1513, that defines the concept as: "biofuels, the feedstock of which were produced within schemes which reduce the displacement of production for purposes other than for making biofuels". In other words, it concerns measures that reduce displacement, but not necessarily mitigate it completely.

In the LLIB[50] methodology study (Ecofys, 2012), produced by Ecofys in collaboration with the RSB Secretariat at EPFL and WWF International, three levels of approaches are mentioned:

1. Prevent unwanted direct land use change globally and for all sectors.
2. Reduce pressures on land from the agricultural sector as a whole.
3. Reduce/prevent indirect impacts at the (biofuel) project level.

Many studies indicate, that mitigation of land use changes for agriculture or forestry as a whole, are most effective in bringing down risks for ILUC related emissions. However, the literature focuses at project level, and therefore, **ILUC mitigation strategies** discussed in the following chapter, mostly focus at the project level.

Four categories of options are commonly found in the literature (Wicke et al., 2012; Plevin et al., 2013; Fritsche, Sims, et al., 2010 and see Table 16):

1. Prioritize **low ILUC- risk feedstock.**
2. Prioritize **abandoned and unused degraded lands**.
3. To **increase agricultural yields.**
4. To **protect areas** with high carbon stock and/or high biodiversity values.

In a fifth sub-section of this chapter, certification systems, which often include strategies to avoid or bring down ILUC effects of biofuel production, are discussed with a complete focus on biofuel project level

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[50] Low Indirect Impact Biofuel (LIIB) Methodology

Table 16 . Summary of studies including low ILUC-risk biofuels and mitigation strategies. Source: Own elaboration

Reference	Approach Method	Feedstock	ILUC mitigation strategy	Type of research	Research done for
Plevin *et al.* (2013)	Review study	Perennial grasses	Grow perennial grasses on land that does not compete with food production (i.e. marginal lands)	Review of modelling studies	University, Berkeley
		Wheat straw	Use residues	Review of modelling studies	University, Berkeley
Overmars et al. (2015)	Historic trade data analysis	Wheat straw	Use residues	Own analysis	JRC
Valin et al. (2015)	PE model application	Forestry residues	Use residues	Own modelling	IIASA
Valin et al. (2015)	PE model application	Switchgrass and miscanthus	Grow perennial grasses on land that does not compete with food production (i.e. abandoned arable lands)	Own modelling	IIASA
Van der Laan et al. (2016)	Integrated spatial analysis	Oil Palm	Grow oil palm on land that does not compete with food production (under-utilised lands)	Own MIRAGE model application & quantitative & spatial assessment	University Utrecht-Copernicus
Nsanganwimana et al. (2014)	Review	Woody and perennial crops	Grow perennial crops on contaminated soils	Review	University Lille
Wicke et al., (2015); Gerssen-Gondelach et al. (2015); Brinkman et al. (2015); Tešić et al. (2010)	Spatial analysis and analytical approach	Rapeseed, corn, miscanthus	Increase yield in conventional food crops to use unused land for energy crops	Own MIRAGE model application & quantitative & spatial assessment	University Utrecht-Copernicus
Lapola et al. (2010)	PE model application	Sugarcane, Eucalyptus, Soya	Increase livestock productivity per area of grazing land	Own model application	Center for Environmental Systems Research-Kassel and Max Planck institute
Schueler et al. (2013)	Review	Not specified	RED sustainability criteria to avoid use of high carbon stock and high biodiverse areas	Review of other modelling studies	Potsdam Institute for Climate Impact Research, Potsdam
Frank et al. (2013)	PE model application	Sugar cane, corn, wheat, rapeseed, palm oil, soybeans, forest biomass, wood processing residues, short rotation tree plantations	RED sustainability criteria to avoid use of high carbon stock and high biodiverse areas, use of unused lands	Own modelling	IIASA

Elbersen et al.	Post model and spatial analysis approach	Agricultural residues, dedicated woody and grassy crops, waste, forest biomass	RED sustainability criteria to avoid use of high carbon stock and high biodiverse areas and higher minimal GHG reduction criteria for bioenergy (incl. biofuels) (above RED) in different scenarios, use of unused lands	Post-model analysis CAPRI output	Alterra-Wageningen
Böttcher et al. (2013)	PE model application	Sugar cane, corn, wheat, rapeseed, palm oil, soybeans, forest biomass,	Sustainability constraints on land use and GHG mitigation targets for biofuels, use of unused lands	Own modelling	IIASA
Junker et al. (2015)	Review	Rapeseed and other conventional food crops	RED GHG reduction target and impact on rapeseed	Review of other modelling studies	Thünen Institute of Market Analysis, Braunschweig

12.1. Low ILUC-risk biofuels

An important strategy suggested in many studies for the production of low ILUC-risk biofuels, is the **use of residues and by-products**. These can include **agricultural residues** (i.e. straw, stover, manure), **forestry residues** (i.e. branches, stumps), by-products of the food processing industry (i.e. animal fats) and of the **wood processing industry** (i.e. bark, sawdust), or **other types of waste and residues**[51] (i.e. demolition wood, organic fraction of municipal solid waste) (Fritsche, Sims and Monti, 2010 and also Table 16).

Several studies evaluate the **sustainable potential of residues and by-products** in the EU and other regions, taking into account various theoretical, technical, socio-economic and environmental limitations.

These studies indicate that the sustainable potential of residues from agricultural and forestry, that is or will become available in the EU, at attractive prices, can be **substantial**, although estimates **vary considerably** (Dees et al., 2017; Khawaja and Janssen, 2014; Mantau et al., 2010; Pudelko, Borzecka-Walker, and Faber, 2013; Spöttle et al., 2013). A key aspect thereby is **how much** agricultural harvest residues can be removed from the field, without decreasing the soil organic carbon content and productivity of the soil. A number of studies investigate how much agricultural harvest residues can be used without reducing soil fertility, for example using the CESAR model (Vleeshouwers and Verhagen, 2002) and the CENTURY Soil Organic Matter

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[51] Distinction between waste and residues cannot be made based on the definition of pathways, as the EU legislation (Waste Framework Directive) defines waste as "substance or object which the holder discards or intends or is required to discard". Therefore, only the term residue is used.

Model (Campbell and Paustian, 2015; Melorose, Perroy, and Careas, 2015; Monforti-Ferrario et al., 2015). Dees et al. (2017) suggest that about 50% of straw can be removed without reducing soil carbon, although this removal level varies strongly per region. These studies take as a starting point the stabilisation of organic carbon levels. If the aim should be increase of the soil organic carbon levels, residue removal rates would be lower however.

At this moment, the most important production and use of residues for the production of biofuels in the EU, concerns **hydrogenated vegetable oils (HVO)** produced from used cooking oils, animal fats and other waste oils and fats. Also important is the use of **methanol** produced from glycerine from first generation biodiesel production. On the contrary, the production of **ethanol** from wheat straw and sawdust is currently very limited.

No studies were available evaluating ILUC effects of the use of used cooking oils, animal fats, other waste oils and fats or glycerine for biofuel production. The use of second generation biofuels produced from lignocellulose residues is, and will likely remain, very limited during the coming years. However, a few studies have been carried out to evaluate the ILUC effects of using residues for biofuels production.

Overmars et al. (2015) quantified the **ILUC effects of ethanol produced from wheat straw in the EU**. The ILUC effects are quantified by assigning part of the ILUC effects of wheat production in the EU to straw. Based on the value ratio, the value of wheat straw is 5% of the value of wheat grains. The calculation of the ILUC effects of wheat straw are based on historical data for 2004-2012 about the contribution of yield and area growth to higher wheat production in the EU.

The best approach of Overmars et al. (2015), results in negligible ILUC emissions of 2-3 gCO_2-eq/MJ ethanol produced from wheat straw, compared to 10-21 gCO_2-eq/MJ wheat ethanol. However, the additional use of straw may result in soil degradation. Aspect that has not been addressed by Overmars et al. (2015). Taheripour et al. (2013) suggest that soil degradation can be compensated by adapting fertilisation inputs. They estimate that 23% of corn stover supply cost goes to fertilizer inputs, that are used to compensate for fertility loss.

Besides, Valin et al. (2015) quantify with the GLOBIOM model the ILUC effects of cereal straw-based biofuels in the EU. The resulting ILUC effects are 16 gCO_2-eq/MJ. These ILUC emissions result from straw overharvesting in specific regions of EU, and consequently a loss of soil carbon, and a yield reduction as a result of nutrient depletion, is produced. In case wheat straw harvesting is limited to a sustainable removal rate of 33-50%, then no yield decreasing effects occur according to Valin et al. (2015), and the ILUC effects are consequently zero.

Valin et al. (2015) also quantified the **ILUC emissions of second generation biofuel production from forestry residues** with GLOBIOM. The total net emissions are modelled at 17 gCO_2-eq/MJ biofuel. These emissions are the result of a lower build-up of soil organic carbon. In the strict sense however, these can be categorized in the LUC emissions, rather than in the indirect emissions.

An interesting mechanism in some economic studies is that harvesting of by-products of agricultural products, may generate an extra income for these agricultural products, and therefore creates an incentive to expand the production of these crops (Dunn et al., 2013; Pratt and et al., 2014; Taheripour and Tyner, 2015; Thompson and Tyner, 2014). Yet, results indicate that the ILUC effects are limited compared to first generation biofuels.

12.2. Feedstock grown on areas that do not compete with food production and that are not used for other purposes

Another ILUC reduction option is the production of woody or grassy energy crops on **areas that are not suitable for rotational crops** (mainly used for food and first generation biofuels), **and do not compete with other land uses** (marginal land). According to Plevin et al. (2013) the most beneficial situation from a climate change perspective is to grow **perennial grasses, such as switchgrass, miscanthus, or mixed prairie grasses on marginal land**, which deep root systems can increase the soil carbon content and improve soil structural properties.

There are several studies that assess the **potential of abandoned farmland, under-utilised, contaminated, fallow land, unused and degraded areas for the production of biomass crops**. In most studies these lands are not clearly defined and this explains why these 5 terms are used in the context of this report (see also Table 16). The key assumption in all studies evaluated (Valin et al., 2015; Plevin et al., 2013; Overmars et al., 2015; van der Laan, Wicke and Faaij, 2015; Elbersen et al., 2013; Nsanganwimana et al., 2014; Frank et al., 2013), is that these lands used for the production of biomass for biofuels, would otherwise remain unused.

Unused land availability assumptions are however very challenging to make, and in none of the studies, the estimates of these land resources are underpinned with empirical evidence. The challenge of making reliable estimates of cropland expansion options is also confirmed in the study of Eitelberg, van Vliet, and Verburg (2015), who show a range in cropland availability at global level from 1,552 to 5,131 Mha, including the 1.550 Mha that is already cropland. Part of the additional cropland availability above the current cropland area will need to come from lands regarded "unused, marginal, abandoned, underutilised". Differences in estimates of cropland size by Eitelberg, van Vliet, and Verburg (2015) are attributed to institutional assumptions, i.e. which land covers/uses (i.e. forests or grasslands) are societally or governmentally allowed to convert to cropland, while there was little variation in biophysical assumptions. The analysis by Eitelberg, van Vliet, and Verburg (2015) confirms that land availability is linked to strong uncertainty, while it can have a large influence on the outcomes of model based assessment.

Valin et al. (2015) quantified with the GLOBIOM model the **ILUC effects of biofuels made from switchgrass and miscanthus grown on abandoned lands**. The results show that these have no ILUC emissions, and that they even have a positive mitigation effect on GHG emissions (-12 gCO_2-eq/MJ for FT biodiesel). The mitigation of GHG emissions, is the result of the sum of: (a) foregone sequestration on abandoned cropland, (b) conversion of natural vegetation to agricultural land, and (c) an increase of the above and below ground carbon content from the establishment of switchgrass and miscanthus. The use of abandoned lands for cropping of miscanthus and switchgrass is especially expected to take place in Europe, according to the Valin et al. (2015) GLOBIOM assessment. This new production requires 1.4 Million ha in the EU, from which 300,000 ha. is expected to be sourced from abandoned land and 580,000 ha from other natural vegetation.

So, it is basically assumed that the carbon value of the biofuel feedstock is higher than the carbon stock or carbon sequestration potential of the original vegetation. To underpin this type of analysis, several studies highlight the potential of woody and grassy energy crops to restore contaminated soils, although the potential is determined by local and regional conditions (Nsanganwimana et al., 2014). Valin et al. (2015) analyse also biodiesel from **short rotation coppice plantations,** with even larger mitigation effects of -29 gCO_2-eq/MJ biodiesel, because of larger carbon sequestration by the crop than with switchgrass and miscanthus.

The use of **abandoned agricultural land** by Valin et al. (2015) is explored in the abandoned agricultural land scenario, and is implemented in combination with a reduction of biofuels made from palm oil, soybean oil and sugar cane, so the effect cannot be split off easily. Furthermore, it is logical that GHG emissions because of biofuel production combined with incentives to use abandoned land, will not have fundamentally different results for GHG emissions than a baseline with incentives to use abandoned land in general.[52]

12.3. Increasing the efficiency of agriculture, forestry and bioenergy production chains

Several studies emphasize the importance of **improving the efficiency of agriculture**, in order to avoid the conversion of natural vegetation and associated undesirable effects on biodiversity, and GHG emissions from ILUC (Brinkman et al., 2015; Gerssen-Gondelach et al., 2015; Langeveld et al., 2014; Peters et al., 2016; Souza, GM; Victoria, RL; Joly, CA; Verdade, 2015; Tešić et al., 2010; Wicke et al., 2015). However, as discussed previously, the endogenous yield increase from higher demand for crops for biofuels production is **insufficiently large to avoid an expansion of agricultural land and ILUC effects**. Policies aimed at increasing the productivity of crop and livestock production, including those of intercropping and integrated systems such as agro-forestry systems (Jose and Bardhan, 2012; Nair, Kumar and Nair, 2009), are therefore needed. These can have a large effect on land use, and thus on GHG emissions of food and biofuel production.

Already in the last decades, changes towards **double cropping** have contributed to increase the amount of available food and biomass (Langeveld et al., 2014a; Bonner et al., 2016). In the ITAKA project (Junquera, 2015), **Camelina** was identified as a very suitable crop to be grown on fallow land to become part of the **rotation**, particularly in arid regions. It can provide extra income to farms, and helps to increase the productivity of the land in a sustainable manner.

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[52] Acknowledgments to Robert Edwards for providing this argument.

Projections by FAO indicate that, most production increases (90%) are expected to be supported by a combination of **yield improvement and increasing cropping intensity** (Nachtergaele, Bruinsma, Valbo-Jorgensen, & Bartley, 2009). The room for yield improvements is still very large, as is also robustly underpinned by the "Global Yield Gap Atlas"[53] (van Ittersum et al., 2016), and specifically for the production of biomass for bioenergy (Achterbosch, Meijerink, Slingerland, & Smeets, 2013).

However, a higher productivity cannot be allocated to the production of biofuels only, unless the increased productivity is implemented to offset the ILUC effects of biofuels. The latter can happen at project level, as illustrated in low-ILUC certification approaches discussed in next chapter.

Estimates with the MAGNET CGE model suggest that, compensating ILUC effects through higher investments in R&D in agriculture can be realised at **limited additional costs,** both in the EU but especially in developing regions (Kristkova et al., 2016). They estimate the costs of R&D investments to avoid negative LUC effects at 0.4 to 0.6 $/GJ, which is limited compared to biomass price.

An example of cheap compensation of the ILUC effects of biofuels production in Brazil is the study of Lapola (2009), which showed that a small increase in livestock productivity in Brazil is sufficient to accommodate land use increase for biofuels, and mitigate related GHG ILUC emissions.

A comment to all approaches related to R&D investment or intensification for higher yields, is that these policies are **as useful for food production as they are for biofuel production**. If investments are profitable to compensate for biofuels production, they are also for other production purposes.

12.4. Protecting areas with high carbon stock and/or high biodiversity values

The **benefits of protection of natural vegetation and lower ILUC GHG emissions from food and biofuels production, cannot be allocated to the production of biofuels only**, unless these policies are implemented as part of the policies that stimulate the sustainable production and use of biofuels. Moreover, the **protection of natural vegetation may limit ILUC GHG emissions of biofuels**, but this may also lead to a **trade-off, with higher food prices and higher impact on food consumption**.

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[53] The Global Yield Gap Atlas (GYGA) providing a web based tool to identify yield gaps in main crops all over the world is the result of an international collaboration among agronomists with knowledge of production systems, soils, and climate governing crop performance in their countries. Detailed maps and associated databases are displayed and available to download at the website of the Global Yield Gap Atlas

Winchester & Reilly (2015) conclude that **global bioenergy use increases deforestation, if no costs are associated with GHG emissions from land use change**. As regions are linked via international agricultural markets, irrespective of the location of bioenergy production, natural forests decrease is larger in regions with the lowest barriers to deforestation.

Valin et al. (2015) evaluate **the impact of global policies to limit deforestation and peatland drainage, on ILUC GHG emissions of biofuels**. A price of 50 $/t CO_2 emissions from deforestation, reduces LUC emissions of the EU 2020 biofuel mix from 97 gCO_2-eq/MJ biofuel to 48 gCO_2-eq/MJ. If also emissions from peatland are avoided, then the overall LUC emissions from biofuels used in the EU would further decrease to 4 gCO_2-eq/MJ. The share of crops used for biofuels production that is diverted from the food and feed sector, is however higher in these low deforestation scenario compared to the default scenario of biofuel use in the EU.

In summary, measures to reduce deforestation and peatland drainage are especially effective if they are **accommodated to all land using sectors**, and not only to biofuels sector. The protection of high carbon areas reduces ILUC, but at the same time increases agricultural prices.

12.5. Low ILUC-risk biofuels certification systems

Most existing certification schemes **do not explicitly deal with ILUC**, but several, include **measures that avoid undesirable DLUC effects,** and **indirectly avoid or compensate ILUC effects**.

Following, the specification in the Directive (EU) 2015/1513 to identify options of low ILUC-risk biofuels through the use of certification schemes. In the Directive, low ILUC-risk biofuels are defined as "biofuels, the feedstock of which were produced within schemes which reduce the displacement of production for purposes other than for making biofuels".

In response to this, Ecofys published a study "Methodologies identification and certification of `low ILUC-risk biofuels" (Peters et al., 2016), in which two methodologies are presented to certify low ILUC-risk biofuels. The focus of the approach is therefore at biofuel project level, and 2 options of low-ILUC certification approaches are presented:

1. **Higher crop yields** through improved inputs and management practices, including; better fertilisation, sowing practices, crop rotation, crop protection, pollination, harvest, and precision farming or,

2. **Expanding agriculture on previously non-agricultural land with low carbon stocks and low biodiversity value**.

Both options were already discussed above, but the proposed methodology is studied a little bit more in-depth.

The key starting point of the approach is that of **"additionality"**. The economic operator (which can be one farmer or a group of farmers or a whole region), needs to prove that additional biomass that can be certified as "low ILUC-risk", is produced in a baseline situation, and that the incentive to increase yields or take unused lands in production, comes from additional non-food biomass demand.

The identification of biomass supply from **higher crop yields** is based on a comparison of the development of the actual productivity, compared to the trend line development of crop yields. If feedstock producers can demonstrate that yield increases are above the trend line, then the additional production is qualified as low ILUC-risk feedstock. Crucial thereby is that, the higher productivity does not occur in absence of biofuel production, and can be attributed to improved management. However, it is extremely difficult to prove that a farmer would not have **implemented the measures** to increase yield without biofuels. Whether the biomass yielded above trend line can be certified completely as low ILUC-risk, cannot be ensured completely. No studies are known that have further investigated this situation at higher national and global scale, in terms of different levels of take up of this strategy and indirect impacts (Sammy, Takriti, Malins, & Searle, 2016).

It will also be very challenging to determine which part of the yield increase is related to the listed management adaptations allowed in the certification scheme, and which come from more unsustainable practices (i.e. increased irrigation in zones coping with aridity). After all, yield increases can only be reached if limitations for the inputs required, are declined (i.e. more nitrogen use can only result in a yield increase if there is also enough water).

The second strategy of **growing biomass crops on unused lands,** requires economic operators to prove the absence of other provisioning services on this land in the last 5 years, in order to ensure "additionality". Furthermore, it is required to comply with EU RED sustainability criteria for biofuel production, when land is taken into production. Therefore, (Peters et al., 2016) pay much attention to techniques and data for verifying the unused land status. This is carried out by using the Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) based on satellite data, that are however not very well validated.

Elbersen et al. (2014) suggest that a **5 year unused land status** is too short to prove that there are not extensive grazing practices, while it is also difficult to define which land is exactly high carbon stock, and which feedstock may be expected to increase carbon sequestration compared to the native vegetation (Lewandowski et al., 2015; Lord, 2015; Masters et al., 2016; Monti & Zegada-Lizarazu, 2016; Mbonimpa et al., 2016).

Peters et al. (2016b) study proposes a **10 year certification period**, that may be too long**,** because within such a period it may also become needed for feed and food production (Monti and Zegada-Lizarazu, 2016; Lewandowski et al., 2015; Larsen et al., 2014; Fagnano et al., 2015). However, it may also be too short because perennial plantations require a longer period to build carbon stock and to make a profit.

One should consider at the same time, that limiting agricultural expansion to previously non-agricultural land with low carbon stocks and low biodiversity value, are most effective in avoiding ILUC effects if **extended to all land uses including food and feed** (Ecofys, 2013; Bottcher et al., 2013; Frank et al., 2013).

The low ILUC-risk approach is one type of approach that is aimed at project level. This is presented by Ecofys as a one level project approach, which is **not seen as the only solution to bringing down ILUC emissions** (Ecofys, 2013). Therefore, it does not imply that other higher level approaches in all land using sectors, such as taking policy measures that prevent unwanted direct LUC and reduce pressures on land, may be efficiently applied. Overall, low ILUC-risk biofuels certification approaches developed and also tested in case studies, by Ecofys in collaboration with World Wildlife Fund (WWF) and Roundtable for Sustainable Biomass (RSB) since 2009, are promising, but still need further adaptations to improve their effectiveness. This is in line with the conclusion made by Sammy et al. (2016), who also reviewed the low-ILUC certification approaches developed by Ecofys (2013). They conclude "that low ILUC impact biofuels, even though described through several measures and methodologies, are still in their **infancy state,** and would **require supplementary requirements** and risk analysis if were to be included in new European legislation".

13. Research recommendations

The review of the ILUC literature that is published since 2012 shows that the progress in the calculation of ILUC effects from biofuel production, and reduction of uncertainties, has been limited. This uncertainty is largely irreducible due to the complexity of market mediate effects. Further progress can be achieved through **better understanding of the different ILUC components**, **their sensitivities, and closure of data uncertainty gaps**. However, the "forecasting" of the full impact of LUC of biofuels will be limited and the validity of existing models will continue to be questioned.

Enhanced cooperation on improving the **availability of ILUC relevant data** at global level, and increased convergence in terms of **standardisation of data formats,** might help to increase transparency, and to narrow down uncertainties leading to large differences in research and sensitivity analysis results.

Making the background of modelling results explicit is something else than improving the knowledge that is incorporated in these results. The analysis of the evidence on the different components of ILUC shows that for most ILUC components the **scientific evidence is extremely poor**. Furthermore, when investigating and comparing the results of different ILUC analyses, it is difficult to track their precise **background**. This is consistent with the conclusion of Persson (2016, p. 479) that "far too many studies, simply focus on the quantitative outputs (i.e., price changes) of single model runs, without attempting to understand or explain the model dynamics that give rise to those results, compare outputs with empirical data, or conduct parametric and structural sensitivity analyses."

Thus, **datasets** on biofuel crop production must be **collected, synthesized and standardized** to **common data formats.** Analysis **of historical information** on agricultural production, trade, prices and yield, as well as land use changes may require further attendance in order to get a better understanding of the fundamental parameters that generate ILUC. Increased data availability and convergence of data formats and transparency, could also potentially help for validation of models and increase the use of empirical models. **Satellite monitoring** (GIS – systems) can support this development for different purposes, including ILUC research.[54]

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[54] i.e. Miettinen 2012, GRAS tool of the ISCC

Besides, a potential target for future research is to make **model outputs comparable**. A possible useful approach for comparing the results of different models, is the **decomposition of ILUC effects** developed in this study, which builds on various existing studies (i.e., Searchinger et al., 2015; Malins et al., 2014, Laborde, 2011; Valin et al., 2015).

With respect to **by-products,** an interesting approach could be to model biofuels increase with and without considering by-products, as for example is done by Taheripour et al. (2010). It would be useful if each biofuel scenario is run with and without biofuels, in order to make explicit what the consequences of by-products are, while in reporting the results it should be made explicit what land use is exactly changed. Further research, mainly empirical in nature, is required to get better insights into the complex dynamics of by-product substitution.

Further, literature suggests that there is still considerable uncertainty around how **agricultural commodity prices** are affected by biofuel demand (Persson, 2016). In order to better predict both current and future impacts of biofuel demand, effort needs to be directed to: (1) increase the understanding and empirical evidence on price elasticities, (2) price transmission in international agricultural markets, and (3) better capture the forces (including policies) that shape the future expansion of cropland.

In relation to yield elasticities, disagreements are found in literature based on different interpretations, and the fundamental issue of **endogeneity** of both price, yield and area change. Therefore, methods that correct the endogeneity problem, such as instrumental variable methods, should be further investigated in order to be applied.

In many studies considering **sustainable removal rates of residues**, the "maintenance" of soil organic carbon (SOC) is presented as a relevant benchmark to ensure carbon neutrality of residue use. However, SOC in many managed soils of the EU is not at a steady-state (Stolte et al., 2016). Therefore, in carbon-poor soils, it would be desirable to increase soil organic matter (SOM), which would allow productivity to be increased. The effect of increasing SOM in these situations leading to increased productivity, should be taken into account in new modelling studies addressing LUC and ILUC of biofuels.

There is still much uncertainty and little empirical evidence on the extend of land defined as "**unused, marginal, and/or underutilised and converted to crop land**". Further work on its identification and characterisation is recommended to bring down the uncertainty in model results (Eitelberg, van Vliet, and Verburg, 2015).

Finally, in relation to the methodologies presented to **certify low ILUC-risk biofuels** (Peters et al., 2016), these need further refinement, particularly regarding: (1) the prove of additionality through calculation of trend line baseline yields, (2) availability of reliable data in all potential sourcing regions in the world, and (3) risk for unsustainable increases in irrigation water consumption needed to increase yields in arid regions. Also, the evaluation of unused land status and the duration of certification of 10 years, still has many open ends which need to be evaluated further.

If applied alone, certification of low ILUC-risk biofuels might not be able to avoid all indirect effects (Sammy et al., 2016; Ecofys, 2013). Therefore, additional measures, beyond the scope of certification, need further research.

14. Conclusions

ILUC GHG emission factors identified in the literature vary significantly across biofuel pathways, studies and also within studies. Studies which have investigated **parametric uncertainty** conclude that parameter variation has a significant effect on the outcome, but that the empirical basis and scientific evidence is weak.

As a consequence of all **uncertainties** related to the modelling of the different components that determine ILUC effects, it is very **difficult to narrow them down**. The analysis by ICCT (Malins et al., 2014) shows that if the variation of each component is considered, then the plausible range of ILUC emissions can be very broad. If all uncertainties are combined, as is done in several sensitivity analyses, for a lot of biofuels, the variation in ILUC effects is even broader. However it is difficult to trace down the components that generate the probability distribution of ILUC GHG emissions. For this reason, doing a sensitivity analysis by just varying one parameter at a time, as is done in Malins et al. (2014), is potentially more informative when evaluating the impact of various assumptions.

Several mitigation options have been proposed that might avoid or reduce the ILUC effects of biofuel use. **Low ILUC-risk feedstocks**, especially **residues from forestry or agriculture** are **relatively promising**. Most studies have shown that ILUC GHG emissions of these, are from null to very low and considerably lower than those of crop based biofuels (Valin et al., 2015; Overmars et al., 2015; Taheripour et al., 2013). However, for these residues the **sustainable supply** may be limited, or harvesting of the residues may be at the cost of other uses of the residues or carbon loss in agricultural or forest land (Taheripour et al., 2013; Valin et al., 2015). Furthermore, harvesting by-products of agricultural products may generate an extra income, and may create an incentive to expand the production of these crops (Dunn et al., 2013; Pratt and et al., 2014; Thompson & Tyner, 2014; Taheripour & Tyner, 2015). Yet, results indicate that the ILUC effects are limited compared to first generation biofuels.

The use of degraded and low carbon land to grow perennials seems effective. The carbon value of the biofuel feedstock may be higher than the carbon value or carbon sequestration potential in the original vegetation, thus generating negative emissions from land use change (Valin et al., 2015; Nsanganwimana et al., 2014).

However, it is also important to consider why should “**unused, marginal, and/or underutilised and converted to crop lands”** lands be **prioritised** to biomass cropping for bioenergy. These marginal lands could also be used for the production of other commodities (like paper pulp and sometimes food), which would also be reducing the pressure on pristine areas or releasing agricultural land (Valin et al., 2015; Bottcher et al., 2013; Frank et al., 2013).

Measures to **increase yields** may be an adequate strategy to reduce GHG emissions of land use changes. However, it is clear that the increased yield stimulation coming only from biofuels will not be enough for bringing agricultural land use emissions down sufficiently. The same holds for a strategy to protect **areas with high carbon stocks**. Measures to reduce deforestation and peatland drainage are only **effective if they are implemented in all land using sectors, and not only in biofuels sector** (Valin et al., 2015; Bottcher et al., 2013; Frank et al., 2013). The protection of high carbon areas reduces ILUC, but may at the same time increase agricultural prices and this may lead to additional land use conversions for agricultural production, increasing GHG emissions. Policies stimulating higher land productivity should therefore, ideally, be focussed on all land using sectors. Also, measures preventing unwanted land use changes should apply to all sectors and globally, particularly protecting high biodiversity and carbon rich areas of importance for the provision of ecosystem services.

In general it can be concluded that the **certification of low ILUC-risk** biofuels alone might not be able to avoid all indirect effects (Sammy et al., 2016). When low ILUC-risk biofuels certification approaches were presented in 2012 (Ecofys, 2013), it was made clear that three levels of potential approaches are needed, of which low-ILUC certification addressing biofuels at project level was one. **Additional measures**, beyond the scope of certification, are therefore needed, such as integrated land use planning at regional and national levels, including effective territorial policies aimed at preventing unsustainable land use conversions in all sectors. The latter is also in line with conclusions made by Valin et al. (2015) and Bottcher et al. (2013), who show higher GHG mitigation effects in scenarios where RED criteria are widened to the whole agricultural and forest sectors.

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Appendix 1: Matrix details

The following matrix is a summary of all the bibliography selected for revision in this report, providing a summary of the insights of these papers and most important information of them.

1) Bibliographic details
    a. Authors
    b. Year of publication
    c. Title
    d. Journal
2) Aim, Method and Boundary Conditions
    a. Theoretical framework of study (i.e. empirical, review, model projections, scenarios analysis)
    b. Main objectives of the study
    c. Main methods used (i.e. case study, real life study, historical approach, partial/general equilibrium, life cycle analysis, consequential, discussion, name of model, etc.)
    d. Scenarios used and time-frame covered
    e. Allocation period for GHG calculation assumed
    f. Method concerning inclusion of by product allocation
    g. Economic and environmental impact fields covered (including GHG-ILUC emissions, biodiversity, etc.)
3) Assumptions on biofuel demand
    a. Demand region
    b. Biofuel types covered (1st gen, 2nd gen, biomaterials, bio-power, etc.)
    c. Conversion technologies covered and related technological advances taken into account
    d. Volumes of biofuel/bioenergy demand specified per period
    e. Demand policy targets or Stimulation policies assumed
4) Assumptions on biomass/biofuel supply
    a. Supply regions covered
    b. Types of Feedstock assumed to satisfy the demand
    c. Potential land changes included in analysis
    d. Feedstock covered for ILUC effect calculation
    e. Yield increase assumptions/source of yield increase data
    f. GHG emission data for conversions used/sources, emission factors
    g. Key stimulation policies for mobilization of supply assumed

    h. Other key data sets used (i.e. market elasticities)

5) Results
    a. Main locations where ILUC takes place and types of land use changes involved
    b. Calculation of the ILUC effect (GHG emissions gCO_2-eq/MJ)
    c. Net land-use effect
    d. Decomposition of the ILUC effect (i.e. land effect, price effect, yield effect, marginal yield, consumption effect, intensification effect)
    e. Other reported effects (i.e. effects on biodiversity, food security, ecosystem services, water, air, soil, rebound effect, carbon debt effect)
6) Evaluation
    a. Uncertainty addressed in the study? (sensitivity analysis, Monte Carlo analysis)
    b. Main conclusions and policy recommendations of the study
    c. Strengths and novel aspects of the study
    d. Weakness of the study

Appendix 2: Summary Matrix

	Authors	Title	Journal	Year
1	Achten, W. M. J.; Trabucco, A.; Maes, W. H.; Verchot, L. V.; Aerts, R.; Mathijs, E.; Vantomme, P.; Singh, V. P. & Muys, B.	Global greenhouse gas implications of land conversion to biofuel crop cultivation in arid and semi-arid lands â€“ Lessons learned from Jatropha	Journal of Arid Environments	2013
2	Acquaye, A. A.; Wiedmann, T.; Feng, K. S.; Crawford, R. H.; Barrett, J.; Kuylenstierna, J.; Duffy, A. P.; Koh, S. C. L. & McQueen-Mason, S.	Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis	Environmental Science {\&} Technology	2011
3	Acquaye, Adolf A.; Sherwen, Tom{\'{a}}s; Genovese, Andrea; Kuylenstierna, Johan; Lenny Koh, S. C. & McQueen-Mason, Simon	Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets	Renewable and Sustainable Energy Reviews	2012
4	Ahlgren, Serina & Di Lucia, Lorenzo	Indirect land use changes of biofuel production - a review of modelling efforts and policy developments in the European Union	Biotechnology for Biofuels	2016
5	Albanito, Fabrizio; Beringer, Tim; Corstanje, Ronald; Poulter, Benjamin; Stephenson, Anna; Zawadzka, Joanna & Smith, Pete	Carbon implications of converting cropland to bioenergy crops or forest for climate mitigation: a global assessment	GCB Bioenergy	2016
6	Alkimim, Akenya; Sparovek, Gerd & Clarke, Keith C.	Converting Brazil's pastures to cropland: An alternative way to meet sugarcane demand and to spare forestlands	Applied Geography	2015
7	Allen, B, Kretschmer, B, Kieve, D, Smith, C and Baldock, D (2013)	Biofuels and ILUC – Q&A: Answers to common questions surrounding the ILUC debate.	IEEP Report	2013
8	Allen, Ben; Baldock, David; Nanni, Silvia & Bowyer, Catherine	Sustainability criteria for biofuels made from land and non-land based feedstocks	IEEP Report	2016
9	Al-Riffai, P.; Dimaranan, B.; Laborde, D.	European Union and United States Biofuel Mandates	NA	2010
10	Alvarenga, Rodrigo A. F.; Dewulf, Jo; De Meester, Steven; Wathelet, Alain; Villers, Joseph; Thommeret, Richard & Hruska, Zdenek	Life cycle assessment of bioethanol-based PVC	Biofuels, Bioproducts and Biorefining	2013
11	Anderson-Teixeira, Kristina J.; Duval, Benjamin D.; Long, Stephen P. & DeLucia, Evan H.	Biofuels on the landscape: Is land sharing⍰ preferable to and sparing?	Ecological Applications	2012
12	Andrade de Sá, Saraly; Palmer, Charles; di Falco, Salvatore; de Sa, Saraly Andrade; Palmer, Charles & di Falco, Salvatore	Dynamics of indirect land-use change: Empirical evidence from Brazil	Journal of Environmental Economics and Management	2013
13	Arima, E. Y.; Richards, P.; Walker, R. & Caldas, M. M.	Statistical confirmation of indirect land use change in the Brazilian Amazon	Environ Research Letters	2011
14	Babcock, Bruce a & Iqbal, Zabid	Using Recent Land Use Changes to Validate Land Use Change Models	Report	2014
15	Babcock, Bruce A.	"Extensive and Intensive Agricultural Supply Response	Annu. Rev. Resour. Econ. 7.1 (2015): 333-348.	2015
16	Banse, Martin; van Meijl, Hans; Tabeau, Andrzej; Woltjer, Geert; Hellmann, Fritz & Verburg, Peter H.	Impact of EU biofuel policies on world agricultural production and land use	Biomass and Bioenergy	2011
17	Baral, Anil & Malins, Chris	Additional supporting evidence for significant iLUC emissions of oilseed rape biodiesel production in the EU based on causal descriptive modelling approach	GCB Bioenergy	2016
18	Belboom, S. & Léonard, A.	Importance of LUC and ILUC on the carbon footprint of bioproduct: case of bio-HDPEâ‹†	Mat{\'{e}}riaux {\&} Techniques	2014
19	Ben Aoun, Wassim; Gabrielle, Beno{\^{i}}t & Gagnepain, Bruno	The importance of land use change in the environmental balance of biofuels	OCL	2013
20	Bento, A. M. & Klotz, R.	Climate Policy Decisions Require Policy-Based Lifecycle Analysis	Environmental Science {\&} Technology	2014
21	Bentsen, Niclas Scott; Larsen, S{\o}ren & Felby, Claus	CO2 emissions from crop residue-derived biofuels	Nature Climate Change	2014
22	Berndes, Goran; Ahlgren, Serina; Borjesson, Pal & Cowie, Annette L.	Bioenergy and land use change-state of the art	Wiley Interdisciplinary Reviews-Energy and Environment	2013
23	Bicalho, Tereza; Bessou, Cecile & Pacca, Sergio A.	Land use change within EU sustainability criteria for biofuels: The case of oil palm expansion in the Brazilian Amazon	Renewable Energy	2016

24	Bird, David Neil; Zanchi, Giuliana & Pena, Naomi	A method for estimating the indirect land use change from bioenergy activities based on the supply and demand of agricultural-based energy	Biomass {\&} Bioenergy	2013
25	Boies, Xiaoyu Yan & Adam, M.	Quantifying the uncertainties in life cycle greenhouse gas emissions for UK wheat ethanol	Environmental Research Letters	2013
26	Boldrin, Alessio & Astrup, Thomas	GHG sustainability compliance of rapeseed-based biofuels produced in a Danish multi-output bio refinery system	Biomass and Bioenergy	2015
27	Bonner, McNunn, Muth, Tyner,	Development of Integrated bioenergy production systems using precision conservation and multicriteria decision analysis	Soil and Water Conservation	2016
28	Bonsch, M.; Humpenoder, F.; Popp, A.; Bodirsky, B.; Dietrich, J. P.; Rolinski, S.; Biewald, A.; Lotze-Campen, H.; Weindl, I.; Gerten, D. & Stevanovic, M.	Trade-offs between land and water requirements for large-scale bioenergy production	Global Change Biology Bioenergy	2016
29	Bottcher, H.; Frank, Stefan; Havlik, Petr & Elbersen, Berien	Future GHG emissions more efficiently controlled by land-use policies than by bioenergy sustainability criteria	Biofuels Bioproducts {\&} Biorefining-Biofpr	2013
30	Bowyer, Catherine	Anticipated Indirect Land Use Change Associated with Expanded Use of Biofuels and Bioliquids in the EU â€“ An Analysis of the National Renewable Energy Action Plans	NA	2010
31	Bringezu, Stefan; O'Brien, Meghan & Schutz, Helmut	Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources	Land Use Policy	2012
32	Brinkman M.L.J, Wicke B, Faaij A. P.C.	Low-ILUC-risk ethanol from Hungarian maize	Biomass and Bioenergy	2017
33	Brinkman, Marnix; Pisca, Iulia; Wicke, Birka & Faaij, Andre	ILUC prevention strategies for sustainable biofuels: Case study on the biodiesel production potential from rapeseed with low ILUC risk in Eastern Romania	Report	2015
34	Brinkman, Marnix; Wicke, Birka & Faaij, Andre	ILUC prevention strategies for sustainable biofuels. Case study on the production potential of low-ILUC-risk bioethanol from Hungarian corn	Report	2015
35	Broch, Amber; Hoekman, S. Kent; Unnasch, Stefan	A review of variability in indirect land use change assessment and modelling in biofuel policy	Environmental Science {\&} Policy	2013
36	Brunelle, Thierry & Dumas, Patrice	Can Numerical Models Estimate Indirect Land-use Change?	Report	2012
37	Calvin, Katherine; Wise, Marshall; Kyle, Page; Patel, Pralit; Clarke, Leon & Edmonds, Jae	Trade-offs of different land and bioenergy policies on the path to achieving climate targets	Climatic Change	2014
38	Carvalho Macedo, I., Nassar, A., Cowie, A., Seabra, J., Marelli, L., Otto, M., Wang, M.Q., Tyner, W. E. (2015)	Chapter 17 Greenhouse gas emissions from bioenergy	In: Mendez Sousa, G., Victoria, R.L., Joly, C., Verdade, L.M. (2015) (Eds.). Bioenergy and sustainability: bridging the gaps. Sao Paulo 2015	2015
39	Castanheira, E. G.; Grisoli, Renata; Freire, Fausto; Pecora, Vanessa; Coelho, Suani Teixeira; Geraldes Castanheira, {\'{E}}rica; Grisoli, Renata; Freire, Fausto; Pecora, Vanessa & Coelho, Suani Teixeira	Environmental sustainability of biodiesel in Brazil	Energy Policy	2014
40	Cherubini, F. & Stromman, A. H.	Life cycle assessment of bioenergy systems: State of the art and future challenges	Bioresource Technology	2011
41	Cherubini, Francesco; Bird, Neil D.; Cowie, Annette; Jungmeier, Gerfried; Schlamadinger, Bernhard & Woess-Gallasch, Susanne	Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations	Resources, Conservation and Recycling	2009
42	Creutzig, F.; Ravindranath, N. H.; Berndes, G.; Bolwig, S.; Bright, R.; Cherubini, F.; Chum, H.; Corbera, E.; Delucchi, M.; Faaij, A.; Fargione, J.; Haberl, H.; Heath, G.; Lucon, O.; Plevin, R.; Popp, A.; Robledo-Abad, C.; Rose, S.; Smith, P.; Stromman, A.; Suh, S. & Masera, O.	Bioenergy and climate change mitigation: an assessment	Global Change Biology Bioenergy	2015
43	Czyrnek-Del{\^{e}}tre, Magdalena M.; Chiodi, Alessandro; Murphy, Jerry D. & {\'{O}} Gallach{\'{o}}ir, Brian P.	Impact of including land-use change emissions from biofuels on meeting GHG emissions reduction targets: the example of Ireland	Clean Technologies and Environmental Policy	2016
44	Dandres, Thomas; Gaudreault, Caroline; Tirado-Seco, Pablo & Samson, R{\'{e}}jean	Macroanalysis of the economic and environmental impacts of a 2005-2025 European Union bioenergy policy using the GTAP model and life cycle assessment	Renewable and Sustainable Energy Reviews	2012
45	Davis, Sarah C.; Parton, William J.; Grosso, Stephen J. Del; Keough, Cindy; Marx, Ernest; Adler, Paul R. & DeLucia, Evan H.	Impact of second-generation biofuel agriculture on greenhouse-gas emissions in the corn-growing regions of the US	Frontiers in Ecology and the Environment	2012

46	De Vries, J. W.; Vinken, T. M. W. J.; Hamelin, L. & De Boer, I. J. M.	Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy â€“ A life cycle perspective	Bioresource Technology	2012
47	de Wit, Marc P.; Lesschen, Jan Peter; Londo, Marc H. M. & Faaij, Andre P. C.	Greenhouse gas mitigation effects of integrating biomass production into European agriculture	Biofuels, Bioproducts and Biorefining	2014
48	Decicco, John M.; Liu, Danielle Yuqiao; Heo, Joonghyeok; Krishnan, Rashmi; Kurthen, Angelika & Wang, Louise	Carbon balance effects of U.S. biofuel production and use	Climatic Change	2016
49	Delzeit, Ruth; Klepper, Gernot; Soder, Mareike	An evaluation of approaches for quantifying emissions from indirect land use change	Report	2016
50	Diogo, V.; van der Hilst, F.; van Eijck, J.; Verstegen, J. A. A.; Hilbert, J.; Carballo, S.; Volante, J. & Faaij, A.	Combining empirical and theory-based land-use modelling approaches to assess economic potential of biofuel production avoiding iLUC: Argentina as a case study	Renewable & Sustainable Energy Reviews	2014
51	Djomo, Sylvestre Njakou & Ceulemans, Reinhart	A comparative analysis of the carbon intensity of biofuels caused by land use changes	Global Change Biology Bioenergy	2012
52	Drabik, Dusan & de Gorter, Harry	EMISSIONS FROM INDIRECT LAND USE CHANGE : DO THEY MATTER WITH FUEL MARKET LEAKAGES?	review of agricultural and Applied Economics	2013
53	Dumortier, J.; Hayes, D. J.; Carriquiry, M.; Dong, F.; Du, X.; Elobeid, A.; Fabiosa, J. F. & Tokgoz, S.	Sensitivity of carbon emission estimates from indirect land-use change	Applied Economic Perspectives and Policy	2011
54	Dunkelberg, Elisa	A case-study approach to quantifying indirect land-use change due to expanding biofuels feedstock cultivation	Thesis	2014
55	Dunkelberg, Elisa; Finkbeiner, Matthias & Hirschl, Bernd	Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions	Biomass & Bioenergy	2014
56	Ecofys	The Low Indirect Impact Biofuels (LIIB) Methodology	Report	2013
57	Edwards, Robert; Mulligan, Declan & Marelli, Luisa	Indirect Land Use Change from increased biofuels demand	Report	2010
58	Edwards, Robert; Mulligan, Declan & Marelli, Luisa	Indirect Land Use Change from increased biofuels demand	Report	2010
59	Edwards, Robert; Padella, Monica; Vorkapic, Veljko & Marelli, Luisa	Historical deforestation due to expansion of crop demand : implications for biofuels	Report	2014
60	Elbersen, Berien; Fritsche, Uwe; Petersen, Jan-Erik; Lesschen, Jan Peter; Boettcher, Hannes & Overmars, Koen	Assessing the effect of stricter sustainability criteria on EU biomass crop potential	Biofuels Bioproducts {\&} Biorefining-Biofpr	2013
61	Elliott, Joshua; Sharma, Bhavna; Best, Neil; Glotter, Michael; Dunn, Jennifer B.; Foster, Ian; Miguez, Fernando; Mueller, Steffen & Wang, Michael	A Spatial Modelling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions	Environmental Science {\&} Technology	2014
62	Elobeid, Amani E.; Carriquiry, Miguel A. & Fabiosa, Jacinto F.	Land-Use Change and Greenhouse Gas Emissions in the Fapri-Card Model System: Addressing Bias and Uncertainty	Climate Change Economics	2012
63	Escobar, N.; Ribal, J.; Clemente, G. & Sanjuan, N.	Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty	Journal of Cleaner Production	2014
64	European Commission, Joint Research Centre, Institute for Energy and Transport, Sustainable Transport Unit – Luisa Marelli, Monica Padella, Robert Edwards, Alberto Moro, Marina Kousoulidou, Jacopo Giuntoli, David Baxter, Veljko Vorkapic, Alessandro Agostini, Adrian O'Connell, Laura Lonza, Lilian Garcia-Lledo.	THE IMPACT OF BIOFUELS ON TRANSPORT AND THE ENVIRONMENT, AND THEIR CONNECTION WITH AGRICULTURAL DEVELOPMENT IN EUROPE	for European Parliament's Committee on Transport and Tourism.	2015
65	Faber, A.; Borzecka-Walker, M.; Krasuska, E.; Jarosz, Z.; Pude{\l}ko, R.; Kozyra, J.; Syp, A.; Nier{\'{o}}bca, A. & Smagacz, J.	Indirect land-use change effects of biodiesel production: A case study for Poland	Journal of Food, Agriculture and Environment	2014
66	Fan, Jiqing Q.; Shonnard, David R.; Kalnes, Tom N.; Johnsen, Peter B. & Rao, Serin	A life cycle assessment of pennycress (Thlaspi aruense L.) -derived jet fuel and diesel	Biomass {\&} Bioenergy	2013
67	Fargione, Joseph E.; Plevin, Richard J. & Hill, Jason D.	The Ecological Impact of Biofuels	Annual Review of Ecology, Evolution, and Systematics	2010
68	Ferreira Filho, Joaquim Bento de Souza; Horridge, Mark; Ferreira, J. B. D. & Horridge, Mark	Ethanol expansion and indirect land use change in Brazil	Land Use Policy	2014
69	Finkbeiner, Matthias	Indirect land use change within LCA	Report	2013
70	Flugge, M., J. Lewandrowski, J. Rosenfeld, C. Boland, T. Hendrickson, K. Jaglo, S. Kolansky, K. Moffroid, M. Riley-Gilbert, and D. Pape, 2017	A Life-Cycle Analysis of the Greenhouse Gas Emissions of CornBased Ethanol	NA ICF for USDA	2017

71	Frank, Stefan; Bottcher, Hannes; Havlìk, Petr; Valin, Hugo; Mosnier, Aline; Obersteiner, Michael; Schmid, Erwin & Elbersen, Berien	How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets?	GCB Bioenergy	2013
72	Fritsche, U. R.; Sims, R. E. H. & Monti, A.	Direct and indirect land-use competition issues for energy crops and their sustainable production - an overview	Biofuels, Bioprod Biorefin	2010
73	Furumo, P.R., and Mitchell Aide, T	Characterizing commercial oil palm expansion in Latin America: land use change and trade	Environmental Research Letters	2017
74	Gabrielle, Benoit; Gagnaire, Nathalie; Massad, Raia Silvia; Dufoss, Karine & Bessou, Cecile	Environmental assessment of biofuel pathways in Ile de France based on ecosystem modelling	Bioresource Technology	2014
75	Galik, C. S. & Abt, R. C.	Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the south-eastern United States	Global Change Biology Bioenergy	2016
76	Garrain, Daniel; de la Rua, Cristina; Lechon, Yolanda; Garrain, Daniel; de la Rua, Cristina & Lechon, Yolanda	Consequential effects of increased biofuel demand in Spain: Global crop area and CO2 emissions from indirect land use change	Biomass {\&} Bioenergy	2016
77	Gawel, Erik & Ludwig, Grit	The iLUC dilemma: How to deal with indirect land use changes when governing energy crops?	Land Use Policy	2011
78	Gerbrandt, K.; Chu, P. L.; Simmonds, A.; Mullins, K. A.; MacLean, H. L.; Griffins, W. M. & Saville, B. A.	Life cycle assessment of lignocellulosic ethanol: a review of key factors and methods affecting calculated GHG emissions and energy use	Current Opinion in Biotechnology	2016
79	Gerssen-Gondelach, Sarah J.; Wicke, Birka & Faaij, Andre P. C.	GHG emissions and other environmental impacts of indirect land use change mitigation	GCB Bioenergy	2016
80	Gibbs, Holly K.; Johnston, Matt; Foley, Jonathan a; Holloway, Tracey; Monfreda, Chad; Ramankutty, Navin & Zaks, David	Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology	Environmental Research Letters	2008
81	Gohin, A.	Le changement d'affectation des sols induit par la consommation europ\'eenne de biodiesel : une analyse de sensibilit\'e aux \'evolutions des rendements agricoles. Working Paper SMART â€“ LERECO NÂ°13-07	Report	2013
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