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Progress and barriers in understanding and preventing indirect land-use change

Vassilis Daioglou[ORCID], Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands; PBL Netherlands Environmental Assessment Agency, Hague, The Netherlands

Geert Woltjer, Wageningen Economic Research, Wageningen University and Research, Hague, The Netherlands

Berien Elbersen, Wageningen Environmental Research, Wageningen University and Research, Wageningen, The Netherlands

Goizeder Barberena Ibañez, National Renewable Energy Centre of Spain (CENER), Ciudad de la Innovación, Sarriguren, Spain

Bart Strengers, PBL Netherlands Environmental Assessment Agency, Hague, The Netherlands

David Sánchez Gonzalez, Javier Gil Barno, National Renewable Energy Centre of Spain (CENER), Ciudad de la Innovación, Sarriguren, Spain

Detlef P. van Vuuren, Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands; PBL Netherlands Environmental Assessment Agency, Hague, The Netherlands

Abstract: Climate change mitigation pathways have highlighted both the critical role of land-use emissions, and the potential use of biofuels as a low-emission energy carrier. This has led to concerns about the emission mitigation potential of biofuels, particularly related to indirect land-use change (ILUC). This arises when the production of biofuels displaces the production of land-based products elsewhere, either directly or via changes in crop prices, leading to indirect greenhouse gas (GHG) emissions. We review a large body of literature that has emerged on ILUC assessment and quantification, highlighting the methodologies employed, the resultant emission factors, modeled dynamics driving ILUC, and the uncertainty therein. Our review reveals that improvements in ILUC assessment methods have failed to reduce uncertainty and increase confidence in ILUC factors, instead making marginal improvements to economic models. Thus, while assessments have highlighted measures that could reduce ILUC, it is impossible to control or determine the actual ILUC resulting from biofuel production. This makes ILUC a poor guiding principle for land-use and climate policy, and does not help with the determination of the GHG performance of biofuels. Instead climate and land-use policy should focus on more integrated protection of terrestrial resources, covering all land-use-

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Introduction

Recent assessments of climate change mitigation strategies have highlighted the potentially pivotal role of biomass and biofuels in meeting the Paris climate targets.[1–3] Biomass is expected to make significant contributions to future energy and material supply, particularly to replace fossil fuels in transport, as feedstock for biomaterials, and possibly for combustion combined with carbon capture and storage (CCS) to remove carbon dioxide from the atmosphere actively – so-called negative emissions.[1,2,4–11] In response, policies have been put in place in several countries to promote biomass use, mainly as biofuels.[12–15] At the same time, however, strong concerns have been raised regarding the potentially large land requirements for biomass production, as this demand will be additional to the already increasing demand for food and feed under the influence of a growing world population.[16–18]

The incremental use of land for agricultural production, whether as a result of demand for biofuels, food, feed or other non-food applications, can lead, directly or indirectly, to an increase in CO_2 emissions and to the loss of natural habitats, with adverse effects on biodiversity and ecosystem services. Land-use change (LUC) emissions arise from the changes in carbon stocks in biomass and soils when a certain land cover type is converted towards productive use (i.e. converting natural grasslands / forests into agricultural production).[19] Besides emissions from direct land-use change at the location of production, so-called indirect land-use change (ILUC) arises when biomass production displaces the production of land-based products (crops or animal products) to other locations, either directly or through changes in agricultural prices.[20,21] Changes of agricultural commodity prices due to this increased competition for land have potential consequences for food security and agricultural productivity.[22] Since these potential externalities first came to light, a lot of research has been conducted to quantify ILUC-related greenhouse-gas emissions (GHG). Earlier overviews of ILUC studies highlighted, above all, the large range in results.[20,23–27] These studies also indicated the need to further develop the methods to estimate ILUC to reduce the associated uncertainty ranges. It has been suggested that the further improvement of ILUC assessment methods would allow for a reduction of uncertainty as well as better insight and improved policy advice concerning how ILUC can be avoided.

We recently conducted an extensive review of ILUC literature and research over the last 9 years – this was done in support of the revised EU Renewable Energy Directive.[28,29] We reviewed 136 ILUC studies in detail, with 31 of these reporting quantitative ILUC emissions factors per mass unit allowing for quantitative comparison. As the ILUC literature mostly concentrates on biofuels, our discussion here focuses on this application of biomass. As part of this work, we have created a database of ILUC factors from key studies across a range of biofuels. In the supporting information, we have indicated the literature review criteria, and a summary of the quantitative literature. Here, however, we provide a synthesis of the insights gathered from the review. This includes an overview of ILUC, the role it has played in assessing climate change mitigation options and relevant policy, an outline of the different research methods and reported ILUC factors for different biofuels, the key factors contributing to uncertainty in our understanding of ILUC, and the usefulness of ILUC as a guiding principle for biofuel and environmental policy.

ILUC in science and policy

Biofuels are considered an option to reduce GHG emissions because, unlike fossil fuels, the carbon content in the fuel is renewable, i.e. the carbon emitted during combustion of the biofuel is absorbed during the growth of biomass, forming a closed cycle. However, unless crop residues that would otherwise go to waste are used, the production of biomass requires land. Converting land for biomass production, especially natural lands, leads to a disruption of land-based carbon stocks and, typically, to an overall net emission. These emissions can arise through the conversion of natural forests or grasslands releasing their previously stored carbon, or foregone carbon sequestration from the continued growth of the natural vegetation.[19] When estimating the overall climate contribution of biofuels, this emission has

to be accounted for. The sources of the 'direct' land-use change emissions mentioned above are straightforward to measure but the potential emissions arising from the diversion or displacement of existing (or future) non-energy crop production elsewhere due to the establishment and production of biofuels are more contentious. It has been demonstrated that this ILUC could easily lead to a situation in which biofuels lead to more GHG emissions than their fossil fuel counterpart if not properly controlled and accounted for in climate policy.[21,30–32]

To address these concerns, EU and US policy has decided to take ILUC into account. The European Union's 2018 directive on the promotion of renewable energy sources (the RED II) caps the volume of biofuels produced from food and feed crops (no more than 1% point higher than the 2020 national share, with a maximum of 7% of final energy consumption in transport), gradually decreasing to zero by 2030 at the latest. In order to account for the emissions from indirect land-use change, the directive assigns ILUC emission factors to different biofuel feedstocks, based on a weighted average of modeled feedstock values.[29] In the USA, the Energy Independence and Security Act of 2007[33] aims to (amongst other objectives) steer the USA towards the production of clean renewable fuels. The Act categorizes fuels (renewable; advanced; biomass based; cellulosic) based on their GHG emission reduction when accounting for their lifecycle emissions, including 'indirect emissions such as significant emissions from land use changes'. The mean (and 95% confidence interval) GHG emissions reductions achieved by different biofuels were presented in the Renewable Fuel Standard (RFS2).[34] On a state level, the California Air Resource Board Low Carbon Fuel Standard (CARB-LCFS) aims to reduce the carbon intensity of transport fuels consumed in the state. The California Air Resource Board (CARB) estimates the amount of ILUC emissions through the use of agro-economic models and emission-factor databases.[35,36]

Indirect land-use change, by definition, takes place at a different place from where biomass is produced, possibly even in different countries and with significant time lags due to global trades.[37] Often interacting actions by multiple actors, including producers and consumers, are involved. It is therefore very difficult to attribute causality empirically. This means research methods to estimate ILUC factors (including those used in the policies mentioned above) are overwhelmingly model based.

Modeling assessments have shown that risk of ILUC is exacerbated by producing biofuels on land formerly used for agricultural production, or using feedstocks that could also cater for food or feed production. Strategies that proposed to

control and reduce ILUC include (i) prioritizing low ILUC-risk feedstocks; (ii) use of abandoned and degraded lands; (iii) increase agricultural yields; and (iv) protect areas with high carbon stocks.[20,37–40] The common thread amongst these measures is the aim to reduce the land required for biofuels, or the displacement of agriculture. Low ILUC-risk feedstocks include the use of residues that do not demand extra land, and short-rotation crops or perennials, which tend to have higher biofuel yields and increase land-based carbon stocks. Yet, as highlighted in detailed assessments, it is important to practice caution due to feedstock-specific effects. For example, as highlighted in Valin, *et al.*,[40] even though palm oil has a high yield it has very high ILUC effects due to its strong impact on deforestation and peatland conversion.

While using models to investigate potential ILUC effects, previous reviews have highlighted a number of methodological issues that give rise to uncertainty, wide variation in ILUC factors, and affect the robustness of the results.[20,24,41] These issues can be summarized in three broad categories:

1. Quality of datasets and assumptions used by the models. This includes multiple uncertainties, which affect the displacement of crops, land-use dynamics, consumer behavior, and international trade. Key elements include historic trade patterns and the extent to which they reflect future projections of trade, maps of carbon stocks (and LUC emission factors), projected (marginal) crop yields, and the availability and projection of abandoned lands.

2. Representation of price effects and elasticities of substitution. This is essential to represent how the supply and demand of agricultural commodities is affected by changes in relative prices, and thus the consequent effects on LUC. Elasticities of substitution are typically determined through econometric analysis of observed historic substitution. However, these elasticities may vary across crops, world regions, and time. In the context of ILUC research, critical price effects are represented by demand elasticity (i.e. changes in demand of different products in response to price changes) and substitution elasticity (including the substitution between different agricultural commodities, but also between production factors, i.e. increasing yields as a response to an increase in prices).

3. Aggregation, coverage of commodities, and inclusion of by- and co-products. The aggregation and inclusion of crops (food, feed, and fuel) is crucial in representing potential substitutions and indirect effects. Furthermore, by-products and co-products of biofuel

feedstocks can themselves be used to meet regional food / feed demand (i.e. dried distiller grains in the production of ethanol), which in turn significantly affects ILUC by reducing the amount of displaced food / feed production.

The same reviews have proposed that these issues could be overcome with the improvement and development of novel methods to investigate ILUC. In the remainder of this perspective we give a critical overview of the methods used to determine ILUC effects, how these have evolved over the past 10 years, and their usefulness in guiding climate and renewable energy policy.

ILUC methods and results

In total, four broad groups of research methods can be identified. Below we provide a short description of the methods and the most recent assessments that have been based on them. These methods span a number of different paradigms and focus areas, but ILUC is inherently an economic phenomenon, driven by reactions to changes in relative prices. Thus, all methods share some form of representation of economic behavior. This is either at the core of the methodology, or occurs by calibrating economic effects to observed behavior.

Economic equilibrium models, including partial equilibrium (PE)[21,40,42,43] or computable general equilibrium (CGE)[25,44–50] models, calculate the extent and approximate location of direct and indirect LUC as a result of a change in biofuel demand by using market principles such as substitution, intensification, and international trade. Land-use change and ILUC emissions use emission factor databases. Partial equilibrium models focus on specific sectors of the economy, which, in the context of biofuels, are usually the agricultural sector, the biofuel sector, and sometimes the forestry sector. The CGE models represent the entire economy and thus contain an explicit representation of factor markets for land, labor, and capital. To keep CGE models manageable, the level of detail of the agricultural / biofuel sector tends to be much lower. Market equilibrium models have the advantage that they capture the economic links between economic sectors and factor markets, and thus represent land-use intensification and LUC endogenously.

Hybrid life-cycle assessments

Hybrid life-cycle assessments as an extension to classical life-cycle assessments (LCAs). Hybrid life-cycle assessments (also known as consequential LCAs) add indirect effects to the detailed LCA representations of specific sectors or

processes.[51–57] Life-cycle assessments have the advantage that the methods are standardized and have a high level of detail concerning processes. However, the application of these methods is hampered by uncertainty, arising from difficulties in quantifying indirect and market-mediated environmental impacts of feedstock production.[58] To overcome this, efforts have been made to couple classical LCA with economic techniques such as input–output analysis or equilibrium models, giving rise to HLCA.

Causal descriptive (CD) models

Since 2011 there have been attempts to investigate ILUC from a non-economic perspective. Causal descriptive models 'map out a chain of significant causes and effects in response to additional biofuel demand'.[59,60] As such, causality is central to these models, making the results more accessible and understandable than those of standard economic models. However, given that ILUC is an economic process, (I)LUC causality in CD models has to be calibrated to existing economic models or observed trade patterns.

Empirical approaches

Empirical approaches aim to estimate past ILUCs and are largely based on the observations of historic trends regarding land use, intensification, and agricultural trade. As in CD models, a key assumption is that current agricultural trade and land-use patterns are an adequate proxy to derive global averages of potential GHG emissions from ILUC. When estimating potential future ILUC effects this assumption is extrapolated into the near future, expecting global trade and land-use patterns to follow observed trends. This method has been used to determine historic ILUC impacts of EU biofuel demand[37,61–63] but also to estimate region-specific ILUC effects of historic biofuel production.[64,65]

The studies providing quantitative estimates on ILUC identified in our assessment provide a total of 271 data points covering different biofuel production chains and ILUC assessment methods, as shown in Fig. 1. Overall, the results show a very high variation, ranging from −94 to over 400 $kgCO_2/GJ_{Biofuel}$, or, in qualitative terms, from a 'carbon sink' to 'multiple times worse than gasoline' (for reference, the emission factor of gasoline is approximately 90 $kgCO_2/GJ_{Gasoline}$[66]).

It is important to consider specific biofuel production methods. The best performers, based on their median values, are advanced ethanol (median = 4.5 $kgCO_2/GJ_{Gasoline}$), sugarbeet ethanol (12 $kgCO_2/GJ_{Gasoline}$), sugarcane ethanol (19 $kgCO_2/GJ_{Gasoline}$), and wheat ethanol (21 $kgCO_2/GJ_{Gasoline}$) while all biodiesel technologies have median emission factors greater than 50 $kgCO_2/GJ_{Gasoline}$. However, even within a
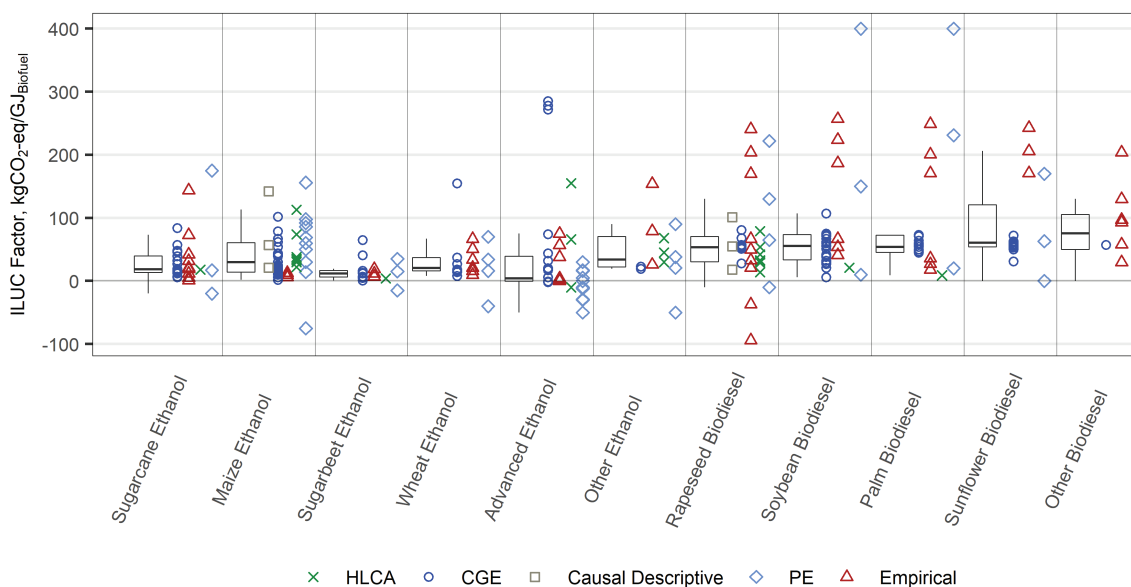
Figure 1. The ILUC factors for biodiesel and ethanol as reported in 31 quantitative studies. Factors shown for different feedstocks and assessment methods. Boxplots indicate the mean and inter-quartile range. Whiskers extend no further than 1.5 times the inter-quartile range or the minimum (lower) or maximum (upper) values. All factors assume a harmonized amortization period of 20 years.

single biofuel, the variability in results is very high, with the fuel-specific coefficient of variation being 75–200% (although the coefficient of variation within single studies may be smaller). This high variation arises from the underlying uncertainty and sensitivity of ILUC assessment methods.

Decomposition of ILUC results

To better understand the source of uncertainty in the modeled GHG emissions of ILUC, it is important to understand the main steps (components) in the analysis and how these are addressed in the different studies. In our review the studies were integrated into one framework where the studies were decomposed into seperate analysis steps covering the following aspects:

1. Assumed trends in yields and productivity.
2. Accounting of co-products.
3. Effects on overall consumption and agricultural yields.
4. Relocation of agricultural production.
5. Location of area expansion.
6. Emission factors per type of land-use change.
7. Greenhouse gas effect of biofuel and other policies.

The starting point of the calculation of ILUC is gross land use of the biofuel feedstock, which depends on trends in yields. However, if biofuel production also results in the production of by-products such as animal feed, less non-biofuel land is needed for animal feed production. While this may seem straightforward, the substitution processes may be complicated and result in diverse effects on emissions across studies; in some studies the effect is even an increase in land use and GHGs.[61]

In economic models the extra demand for agricultural land as a consequence of biofuel production induces increases in prices of land and agricultural commodities. The price increase of agricultural commodities in economic models reduces consumption for non-biofuel crops, which is to a large extent demand for food or feed. This effect depends on the price elasticities of supply and demand, which are highly uncertain. Besides the consumption effect, the increased land prices induced from biofuel demand may also lead to increases in agricultural land productivity in economic models. This results in reduced net land use. The increased land productivity can be caused by using more fertilizer, labor and capital, or by technological developments. The last is mainly a long-term effect, and is not included in most models. For both the consumption and yield effects, one may doubt to what extent the benefits of the increased land productivity should be attributed to biofuel production, or at least whether the effect of this on the calculated ILUC factor should be made explicit.

Furthermore, as a consequence of biofuel production non-energy crops may be displaced to other locations with

different land productivity. This may reduce or increase ILUC. A lot of uncertainty exists related to the type of land converted by agricultural expansion and its GHG emissions, including how much carbon is emitted with land clearance, or the amount of carbon emissions because of peatland development. In the studies reviewed, the effects on GHG emissions of these conversions, which may be different across locations, are generally not made explicit and the approaches and factors used differ among the studies.

Interestingly, the above effects differ between studies resulting in varying intermediate results. The effect of the ILUC components on the total ILUC GHG emission calculation may thus either strengthen each other or cancel each other out. This implies that any agreement across models does not necessary imply a robust result. A telling example concerns the projections of the ILUC factor of maize ethanol as determined by Laborde[45] and Valin, *et al.*,[40] at 14 and 10.8 kgCO2/GJ respectively. The difference in ILUC factors between them is relatively small, but the underlying causes

are fundamentally different, with Valin *et al.* projecting changes in agricultural area more than 10 times greater than Laborde *et al.* and locating these land-use changes mainly in Europe, whereas Laborde *et al.* assumes them to be mostly located in South America. For further details on this decomposition please refer to the supporting information.

Uncertainty and sensitivity

Multiple studies have tested the uncertainty and sensitivity of their results either through scenario analyses, by varying a given parameter, or through Monte Carlo and systematic sensitivity analyses (see Table S1 in the supporting information). These studies show large parametric uncertainty that does not seem to have become smaller over time, as shown in Fig. 2. Parameters tested include various elasticities (demand, production factors, land transformation, international trade, and yield),[40,45,47,48] yield projections,[32,40,45,47,48,67] the degree to which a certain
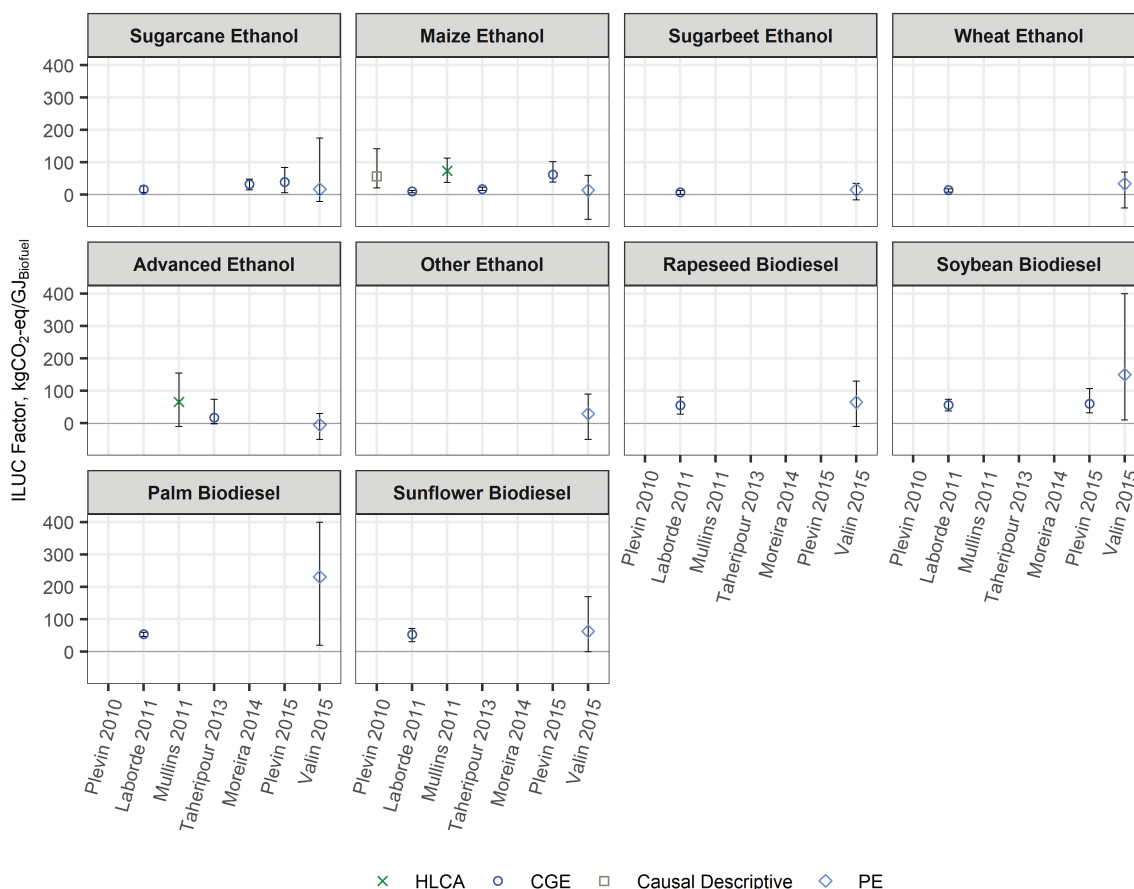

Figure 2. Ranges of ILUC factors presented by specific studies, which have conducted parametric uncertainty analysis with their models. Points indicate the mean ILUC factor per study and whiskers indicate the minimum and maximum. For Moreira (2014) the range indicates the mean ± the standard deviation.

commodity can expand into a given land type,[32,40,45] LUC and non-LUC emission factors (fertilizer runoff, non-renewable energy use, etc.),[32,40,46–48,67] production periods,[32] co-product value,[40,47] and water availability.[40] Inherent spatial heterogeneity (yields and carbon pools at specific locations), even in one region, can lead to a very large variation in outcomes, even when using a single method.[19] Uncertainties concerning elasticities also apply to other HLCA and CD methods because, as mentioned above, they tend to be coupled or calibrated to economic equilibrium models. The analyses reviewed indicate that the most important uncertainties are projected crop yields, benefits of co-products, terrestrial carbon fluxes, and consumer and producer responses to changes in prices. Studies that investigate the uncertainty of both economic and biophysical uncertainties agree that most of the sensitivity arises from the economic aspects.[32,40,45,46,48]

This review has shown that further ILUC assessments are not necessarily improving the quantification of ILUC, nor narrowing down the uncertainty ranges. Very high coefficients of variation in ILUC factors means that the ambition to reduce ILUC uncertainty by improving and diversifying ILUC methods has not materialized (See Fig. S1 in the supporting information). As stated in uncertainty analyses, the variability around biophysical factors, as well as the complexities and causalities of the global system models aim to represent, lead to uncertainties that are unlikely to reduce over time or improve the judgment on a central value.[32,40] Additionally, it has been argued that the distributions that uncertainty analyses show a large number of observations around the median value. However, because of fundamental uncertainties, all the points of the distributions should be considered seriously.[45] The ILUC assessments persistently suffer from multiple forms of uncertainty, including 'model structure' (i.e. lack of sufficient understanding of the system), scenario uncertainty, and 'parameter uncertainty',[68] where a large part of the uncertainty arises due to inherent variability – and not from imperfect knowledge. While improved empirical efforts can reduce the uncertainty of LUC and ILUC emission factors for a specific location, the uncertainty with respect to policy, demand volume, substitution elasticities, or allocation are a function of uncertain policies and actor behavior.

Conclusion

The high level of uncertainty and lack of convergence in ILUC assessments does not mean that the studies have no scientific or policy value, as they have highlighted measures that may mitigate its incidence. These include the use of

available residues and second-generation biofuels, avoiding high-risk oil-crops, utilizing lands that do not compete with non-energy crop production (i.e. strategic use of abandoned lands), investing in improving yields (particularly in areas with high yield gaps), overall efficiency of agriculture, and protecting areas with high carbon and biodiversity value, or areas that are shown to potentially have high ILUC risk. Thus, while these studies are helpful at pointing out key policy instruments, we find it unlikely that such assessments can lead us to more 'definitive' or 'most likely' ILUC factors. Furthermore, it is important to note that most ILUC studies assume a given biofuel demand, while future demand for biofuels may lead to changing ILUC factors over time. The relationship between LUC emissions and biofuel production levels is typically ignored in ILUC studies.[19] Recent ILUC studies have either introduced new assessment methods or made marginal improvements to CGE/PE models. However, their main conclusions focus on highlighting options for policies and technologies to minimize and manage ILUC. In fact, the knowledge gaps and recommendations highlighted by previous ILUC reviews remain largely unchanged,[20,23,24,41,69–71] and are likely to remain into the future.

Thus, while ILUC is a real problem, single ILUC-factors are a poor guiding principle for biofuel, land-use, and environmental policy making. In fact, the inherent and persistent uncertainties around potential market effects on agriculture and land use limit the usefulness of specific ILUC factors. Still, policies such as the European Union's Renewable Energy Directive (EU-RED) prescribe allowable emission factors for biofuels.[29] As a 'mean' value it has little scientific underpinning and will vary strongly depending on circumstances; it may put into question the emission mitigation achieved from biofuel use in the EU.

The view that land-use emissions are critical towards understanding the role of biofuels in climate change mitigation scenarios has been voiced multiple times by integrated assessment models.[4,10,31] It is important to note that ILUC is an artifact of restricted system boundaries and not a phenomenon different from direct-LUC. Indirect effects are direct effects somewhere else. The complexity concerning understanding and controlling ILUC effects assessed above brings up the question how useful it is to focus certification specifically on ILUC from biofuels while many other agricultural products have a much larger impact on land-use. Instead, a more progressive approach may depend on a more comprehensive 'land-use' policy that aims to avoid the CO_2 and other impacts for all land-use related products. This would make ILUC 'disappear' as all land-use changes would be accounted for. This has led to calls to make carbon accounting under the UN Framework Convention on Climate Change completely

global, and push climate policy to set a cap on all LUC-related emissions (not just biofuels) for all countries, and encourage policies that protect forests (or even encourage afforestation) and best practices in agricultural production.[30,37,72] Clearly, in the context of international trade in agricultural and energy commodities, verifiable implementation of such policies is very challenging. However, national and regional policies aiming at promoting low LUC footprint of imported agricultural products (including energy and non-energy crops) can assess their trade partners based on their environmental legislation, aided and verified by satellite monitoring. From a scientific research perspective, analysis of land-based services should have an integrated 'bioeconomy' approach (including food, feed, fuel, fiber, etc.), which would ensure that shifting LUC from one sector to another is avoided.

The climate change mitigation targets outlined in the Paris Agreement as well as the UN Agenda on Sustainable Development require a maintenance (and possible increase) of land-based carbon stocks, while also increasing agricultural production.[73–76] As the Paris agreement applies to all land uses irrespective of their product, the response to the challenge of climate change should not be driven by different policies focusing on different facets of land-based emissions. Only an integrated approach to LUC and the management of natural assets will ensure the achievement of effective climate change mitigation, and other land-based sustainability goals.

Acknowledgements

References

1. Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V *et al*., *Global Warming of 1.5°C Ch. 2*. Cambridge, United Kingdom: Intergovernmental Panel on Climate Change, (2018).

2. Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K *et al*., in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth assessment Report of the Intergovernmental Panel on Climate Change*, Vol. **98**, ed. by Edenhofer O, United Kingdom: Cambridge University Press, (2014).Ch. 6

3. Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Portner HO, Roberts DC *et al*., *IPCC SSpecial Report on Climate Change, Desertification, Land, Degradation, Sustainable Land Management, Food Security, and*

4. Bauer N, Rose SK, Fujimori S, van Vuuren DP, Weyant J, Wise M *et al*., Global energy sector emission reductions and bio-energy use: Overview of the EMF-33 model comparison. *Clim Change* (2018).

5. Bauer N, Calvin K, Emmerling J, Fricko O, Fujimori S, Hilaire J *et al*., Shared socio-economic pathways of the energy sector – quantifying the narratives. *Glob Environ Chang* **42**:316–330 (2017). https://doi.org/10.1016/j.gloenvcha.2016.07.006.

6. Minx JC, Lamb WF, Callaghan MW, Bornmann L and Fuss SJERL, Fast growing research on negative emissions. *Environ Res Lett* **12**:035007 (2017).

7. IEA, *Technology Roadmap: Delivering Sustainable Bioenergy*. International energy Agency, Paris, p. 94 (2017).

8. Muri H, The role of large—scale BECCS in the pursuit of the 1.5 C target: An earth system model perspective. *Environ Res Lett* **13**:044010 (2018).

9. EASAC, Negative emissions technologies: What role in meeting Paris agreement targets? *EASAC Policy Report* **35**:45 (2018).

10. Daioglou V, Doelman JC, Wicke B, Faaij A and van Vuuren DP, Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Glob Environ Chang* **54**:88–101 (2019).

11. Schmidt HP, Anca-Couce A, Hagemann N, Werner C, Gerten D, Lucht W *et al*., Pyrogenic carbon capture and storage. *GCB Bioenergy* **11**:573–591 (2019).

12. EU. Directive (EU) 2015/1513 of the European Parliament and of the Council. 29 (2015).

13. EU, Directive 2009/28/EC of the European Parliament and of the council of 23 April 2009. *J Eur Union* **140**:47 (2009).

14. EPA, *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program*, Vol. **75**. Washington DC, USA: Environmental Protection Agency, pp. 14669–15320 (2010).

15. Sorda G, Banse M and Kemfert C, An overview of biofuel policies across the world. *Energy Policy* **38**:6977–6988 (2010). https://doi.org/10.1016/j.enpol.2010.06.066.

16. Popp A, Rose SK, Calvin K, van Vuuren DP, Dietrich JP, Wise M *et al*., Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Clim Change* **123**:495–509 (2014). https://doi.org/10.1007/s10584-013-0926-x.

17. Gough C, Garcia-Freites S, Jones C, Mander S, Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability* **1**:1–9 (2018).

18. Heck V, Gerten D, Lucht W and Popp A, Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat Clim Change* **8**:151–155 (2018).

19. Daioglou V, Doelman JC, Stehfest E, Müller C, Wicke B, Faaij A *et al*., Greenhouse gas emission curves for advanced biofuel supply chains. *Nat Clim Change* **7**:920–924 (2017).

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

21. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J *et al*., Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **319**:1238–1240 (2008).

22. Hasegawa T, Fujimori S, Havlík P, Valin H, Bodirsky BL, Doelman JC *et al*., Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat Clim Change* **8**:699–703 (2018).

23. Fargione JE, Plevin RJ and Hill JD, The ecological impact of biofuels. *Annu Rev Ecol Evol Syst* **41**:351–377 (2010).

Greenhouse gas fluxes in Terrestrial Ecosystems 43. United Kingdom: WMO/UNEP, (2019).

24. Njakou Djomo S and Ceulemans R, A comparative analysis of the carbon intensity of biofuels caused by land use changes. *GCB Bioenergy* **4**:392–407 (2012).

25. Verstegen JA, van der Hilst F, Woltjer G, Karssenberg D, de Jong SM and Faaij APC, What can and can't we say about indirect land-use change in Brazil using an integrated economic–land-use change model? *GCB Bioenergy* **8**:561–578 (2016).

26. Kim S and Dale BE, Indirect land use change for biofuels: Testing predictions and improving analytical methodologies. *Biomass Bioenergy* **35**:3235–3240 (2011).

27. Zilberman D, Indirect land use change: Much ado about (almost) nothing. *GCB Bioenergy* **9**:485–488 (2017).

28. Woltjer G, Daioglou V, Elbersen B, Barberena Ibañez G, Smeets E, Sánchez González David *et al.*, *Study Report on Reporting Requirements on Biofuels and Bioliquids Stemming from the Directive (EU) 2015/1513*. European Commission, Brussels, p. 124 (2017).

29. EU, Directive 2018/2001 of the European Parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *J Eur Union* **128**:82–209 (2018).

30. Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S *et al.*, Indirect emissions from biofuels: How important? *Science* **326**:1397–1399 (2009).

31. Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R *et al.*, Implications of limiting CO2 concentrations for land use and energy. *Science* **324**:1183–1186 (2009). https://doi.org/10.1126/science.1168475.

32. Plevin RJ, Jones AD, Torn MS and Gibbs HK, Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environ Sci Technol* **44**:8015–8021 (2010).

33. 2007, E. I. a. S. A. o. in 110–140 (ed United States Congress) 310 (Washington DC, 2007).

34. EPA. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. 1109 (United States Environmental Protection Agency, 2010).

35. Leland A, Hoekman SK and Liu XV, Review of modifications to indirect land use change modeling and resulting carbon intensity values within the California low carbon fuel standard regulations. *J Clean Prod* **180**:698–707 (2018).

36. CARB. (ed California Air Resource Board) 148 (California, USA, 2015).

37. Fritsche UR, Sims RE and Monti A, Direct and indirect land-use competition issues for energy crops and their sustainable production–an overview. *Biofuels Bioprod Biorefin* **4**:692–704 (2010).

38. Van de Staaij J, Peters D, Dehue B, Meyer S, Schueler V, Toop G *et al.*, Low Indirect Impact Biofuel (LIIB) methodology–version zero, Ecofys, EPFL and WWF International (2012).

39. Gerssen-Gondelach SJ, Wicke B and Faaij AP, GHG emissions and other environmental impacts of indirect land use change mitigation. *Bioenergy* **9**:725–742 (2017).

40. Valin H, Peters D, van den Berg M, Frank S, Havlik P, Forsell N *et al.*, *The Land Use Change Impact of Biofuels Consumed in the EU: Quantification of Area and Greenhouse Gas Impacts*. ECOFYS, Utrecht, p. 261 (2015).

41. Liska AJ and Perrin RK, Indirect land use emissions in the life cycle of biofuels: Regulations vs science. *Biofuels Bioprod Biorefin* **3**:318–328 (2009).

42. Dumortier J, Hayes DJ, Carriquiry M, Dong F, du X, Elobeid A *et al.*, Sensitivity of carbon emission estimates from indirect land-use change. *Appl Econ Perspect Policy* **33**:428–448 (2011).

43. Mosnier A, Havlík P, Valin H, Baker J, Murray B, Feng S *et al.*, Alternative US biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth. *Energy Policy* **57**:602–614 (2013).

44. Al-Riffai P, Dimaranan B and Laborde D, *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*, Vol. **125**. IFPRI, Washington, DC (2010).

45. Laborde D, *Assessing the Land Use Change Consequences of European Biofuel Policies*. Washington, DC, USA: IFPRI, (2011).

46. Taheripour F and Tyner WE, Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors. *Econ Res Int* **2013**(12):1–12 (2013).

47. Moreira M, Gurgel AC and Seabra JE, Life cycle greenhouse gas emissions of sugar cane renewable jet fuel. *Environ Sci Technol* **48**:14756–14763 (2014).

48. Plevin RJ, Beckman J, Golub AA, Witcover J and O'Hare M, Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change. *Environ Sci Technol* **49**:2656–2664 (2015).

49. Searchinger T, Edwards R, Mulligan D, Heimlich R and Plevin R, Do biofuel policies seek to cut emissions by cutting food? *Science* **347**:1420–1422 (2015).

50. Chen R, Qin Z, Han J, Wang M, Taheripour F, Tyner W *et al.*, Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. *Bioresour Technol* **251**:249–258 (2018).

51. Cherubini F and Strømman AH, Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour Technol* **102**:437–451 (2011).

52. Acquaye AA, Sherwen T, Genovese A, Kuylenstierna J, Lenny Koh SC and McQueen-Mason S, Biofuels and their potential to aid the UK towards achieving emissions reduction policy targets. *Renew Sustain Energy Rev* **16**:5414–5422 (2012).

53. Acquaye AA, Wiedmann T, Feng K, Crawford RH, Barrett J, Kuylenstierna J *et al.*, Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis. *Environ Sci Technol* **45**:2471–2478 (2011).

54. Humpenöder F, Schaldach R, Cikovani Y and Schebek L, Effects of land-use change on the carbon balance of 1st generation biofuels: An analysis for the European Union combining spatial modeling and LCA. *Biomass Bioenergy* **56**:166–178 (2013).

55. Bento AM and Klotz R, Climate policy decisions require policy-based lifecycle analysis. *Environ Sci Technol* **48**:5379–5387 (2014).

56. Prapaspongsa T and Gheewala SH, Risks of indirect land use impacts and greenhouse gas consequences: An assessment of Thailand's bioethanol policy. *J Clean Prod* **134**:563–573 (2016).

57. Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B and Woess-Gallasch S, Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resour Conserv Recycl* **53**:434–447 (2009).

58. Plevin RJ, Delucchi MA and Creutzig FJ, Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *J Ind Ecol* **18**:73–83 (2014).

59. Baral A and Malins C, Additional supporting evidence for significant iLUC emissions of oilseed rape biodiesel production in the EU based on causal descriptive modeling approach. *GCB Bioenergy* **8**:382–391 (2016).

60. Bird DN, Zanchi G and Pena N, A method for estimating the indirect land use change from bioenergy activities based on the supply and demand of agricultural-based energy. *Biomass Bioenergy* **59**:3–15 (2013).

61. Lywood W, *Estimate of ILUC Impact of EU Rapeseed Biodiesel Based on Historic Data*. Surrey, United Kingdom: Lywood Consulting, p. 33 (2013).

62. Overmars K, Edwards R, Padella M, Prins AG and Marelli L, *Estimates of Indirect Land Use Change from Biofuels Based on Historical Data*. Joint Research Centre - Institute for Energy and Transport, Luxembourg, p. 52 (2015).

63. Overmars KP, Stehfest E, Ros JP and Prins AG, Indirect land use change emissions related to EU biofuel consumption: An analysis based on historical data. *Environ Sci Policy* **14**:248–257 (2011).

64. Nassar AM and Moreira M, *Evidences on Sugarcane Expansion and Agricultural Land Use Changes in Brazil*. Sao Paulo, Brazil: Institute for the International Trade Negotiation (ICONE), p. 28 (2013).

65. Dunkelberg, E. *A case-study approach to quantifying indirect land-use change due to expanding biofuels feedstock cultivation* Dr.Ing thesis, Universität Berlin, (2014).

66. Garg, A., Kazunari, J. & Pulles, T. in *IPCC Guidelines for National Greenhouse Gas Inventories*. Kamiyamaguchi, Hayama, Kanagawa, Japan: Institute for Global Environmental Strtegies, (2006).

67. Mullins KA, Griffin WM and Matthews HS, Policy implications of uncertainty in modeled life-cycle greenhouse gas emissions of biofuels. *Environ Sci Technol* **45**:132–138 (2011).

68. Walker WE, Harremoës P, Rotmans J, van der Sluijs JP, van Asselt MBA, Janssen P *et al.*, Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integr Assess* **4**:5–17 (2003).

69. Harvey M and Pilgrim S, The new competition for land: Food, energy, and climate change. *Food Policy* **36**:S40–S51 (2011).

70. Malins C, Searle S and Baral A, *A guide for the perplexed to the indirect effects of biofuels production*. San Francisco, USA: The International Council on Clean transportation, (2014).

71. Panichelli L and Gnansounou E, Impact of agricultural-based biofuel production on greenhouse gas emissions from land-use change: Key modelling choices. *Renew Sustain Energy Rev* **42**:344–360 (2015).

72. Popp A, Humpenöder F, Weindl I, Bodirsky BL, Bonsch M, Lotze-Campen H *et al.*, Land-use protection for climate change mitigation. *Nat Clim Change* **4**:1095–1098 (2014). https://doi.org/10.1038/nclimate2444.

73. Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E *et al.*, Land-use futures in the shared socio-economic pathways. *Glob Environ Chang* **42**:331–345 (2017). https://doi.org/10.1016/j.gloenvcha.2016.10.002.

74. van Vuuren DP, Stehfest E, Gernaat DEHJ, van den Berg M, Bijl DL, de Boer HS *et al.*, Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat Clim Change* **8**:391–397 (2018). https://doi.org/10.1038/s41558-018-0119-8.

75. Doelman JC, Stehfest E, Tabeau A, van Meijl H, Lassaletta L, Gernaat DEHJ *et al.*, Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Glob Environ Chang* **48**:119–135 (2018).

76. Kriegler E, Bertram C, Kuramochi T, Jakob M, Pehl M, Stevanović M *et al.*, Short term policies to keep the door open for Paris climate goals. *Environ Res Lett* **13**:1–12 (2018).

Vassilis Daioglou

Dr Vassilis Daioglou is a researcher at the Copernicus Institute of Sustainable Development at Utrecht University, and a guest researcher at PBL Netherlands Environmental Assessment Agency. His research focuses on developing and using integrated assessment models to assess the climate-land-energy-water nexus.

Geert Woltjer

Dr Geert Woltjer is a senior researcher on nature and economics at Wageningen Economic Research. His current focus is on sustainability and the green economy, including projects on the macroeconomic impacts of the circular economy, natural capital, true pricing, biodiversity, and indirect land-use effects of biofuels.
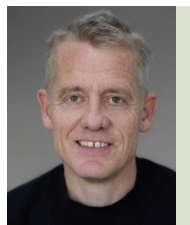
Bart Strengers

Bart Strengers is a senior researcher on climate change and biomass at PBL Netherlands Environmental Assessment Agency. His focus is on the energy transition (in particular the bio-economy) and on costs of climate policy, and he is a member of the Dutch delegation of the IPCC. He is also an advisor for the energy subsidy-program of the Netherlands (SDE++).

Berien Elbersen

Dr Berien Elbersen is a project coordinator and researcher at Wageningen University. She has more than 20 years of experience in national, European Commission, and European Environment Agency projects on environmental impact assessment of EU policies on land use, agri-environment, and the bioeconomy.

Goizeder Barberena Ibañez

Goizeder B. Ibañez has 10 years of experience as a researcher with specific focus on bioeconomy strategies and clustering, comprehensive sustainability assessments, and sustainable use of biological resources and production of biofuels / bioproducts. She is currently implementing and developing growth opportunities within the biomass area of the National Renewable Energy Center of Spain (CENER).

David Sánchez Gonzalez

David S. Gonzalez, is the head of the resource evaluation and biofuels service in CENER. He leads project activities related to biomass energy and bio-based products production, focusing mainly on biomass resource assessment and logistics supply, and solid biofuels and bio-based products sustainability criteria, including economic and GHG emissions assessments.

Detlef P. van Vuuren

Detlef van Vuuren is professor in integrated assessment of global environmental change at Utrecht University, and senior researcher at PBL Netherlands Environmental Assessment Agency. He is a member of the board of the Integrated Assessment Modelling Consortium, the Global Carbon Project, the Earth Commission, and the Royal Academy of Sciences and the Arts in the Netherlands.

Javier G. Barno

Javier G. Barno is the director of the Biomass Department of CENER, coordinating activities in several bioeconomy fields: bioresources evaluation, sustainability studies, techno-economic assessment studies, liquid biofuels, bioproducts, and solid biofuels. He has previously held various positions at the Fraunhofer UMSICHT Institute and the University of Zaragoza.