GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012), doi: 10.1111/j.1757-1707.2012.01207.x

# A model-based quantitative assessment of the carbon benefits of introducing iLUC factors in the European Renewable Energy Directive

CHRIS MALINS

*The International Council on Clean Transportation, 1225 I Street NW, Suite 900, Washington, DC, USA*

**Abstract**

The European Commission has a mandate from the EU's Renewable Energy and Fuel Quality Directives to propose a methodology, consistent with the best available science, to address indirect land use change (iLUC). One proposed solution to the iLUC problem is the application of iLUC factors in European fuels policy – it is widely expected that should the EU adopt such iLUC factors, they would be based on iLUC modelling using the International Food Policy Research Institute's (IFPRI) MIRAGE model. Taking the iLUC factors from IFPRI MIRAGE as our central estimate, we use Monte Carlo analysis on a simple model of potential biofuel pathways for Europe to assess the likely average carbon saving from three possible European biofuel policy scenarios: no action on iLUC; raised GHG thresholds for direct emissions savings; and the introduction of iLUC factors. We find that without iLUC factors (or some other effective iLUC minimization approach) European biofuel mandates are unlikely to deliver significant GHG emissions benefits in 2020, and have a substantial probability of increasing net GHG emissions. In contrast, the implementation of iLUC factors is likely to significantly increase the carbon savings from EU biofuel policy. With iLUC factors, it is likely that most permitted pathways would conform to the Renewable Energy Directive requirement for a minimum 50% GHG reduction compared to fossil fuels.

*Keywords:* biodiesel, biofuel, IFPRI MIRAGE, indirect land use change, RED, sustainability.

*Received 28 June 2012 and accepted 21 July 2012*

## Introduction

When mandates force the expansion of biofuel production, the feedstock must come from some combination of the following:

- Reduced stocks of agricultural commodities;
- Reduced consumption in food and other sectors;
- Increased productivity on currently cultivated land;
- Cultivation of biofuel feedstock on currently uncultivated land.

Reducing stock is not sustainable in the long term, and hence can be seen as delaying the occurrence of the last three possibilities. Hence, whatever amount of the feedstock needed for biofuel production is not taken from other end users or generated through yield increase must be produced by expanding the area of agricultural cultivation – this requires land use change.

Correspondence: Chris Malins, tel. + 1 202 407 8341, fax + 1 202 5341601, e-mail chris@theicct.org



In the language of the biofuels literature, there are two types of land use change – direct land use change (dLUC) and indirect land use change (iLUC). A dLUC is said to have occurred whenever a specific and identifiable parcel of land that was not previously used to grow a given biofuel feedstock crop is reassigned for the cultivation of that crop, with feedstock grown on this land supplied to a specific biofuel processing facility. This would include, for instance, an area of forest being cleared to make way for a sugarcane crop specifically intended to supply an ethanol plant. Categorizing a land use change as direct tells us nothing about whether the use of that plot of land would have changed in a given period if there had been no increase in feedstock demand for biofuels.

Indirect land use change, in contrast, refers to the set of land use changes that would not have happened without a marginal increase in feedstock demand. The categorization of dLUC requires knowledge about which cultivated areas are supplying which feedstock processing facilities, and depending on circumstance anywhere from 0–100% of the feedstock for a given biofuel mandate could be associated with dLUC. The answer to this question could be observed, but would not be readily susceptible to modelling. On the other hand, some quantity of iLUC will be an inevitable consequence of expanded biofuel demand. Unlike dLUC, iLUC is not readily susceptible to measurement, but the likely outcomes can be modelled (Edwards *et al.*, 2010; Njakou Djomo & Ceulemans, 2012). This modelling is possible because there are sound economic reasons to believe that increases in feedstock demand associated with biofuel mandates will cause commodity prices to rise and that these price changes will drive indirect land use changes (Edwards *et al.*, 2010; Roberts & Schlenker, 2010; Searchinger, 2010; Miranowski, 2012). In the words of Miranowski (2012):

"Anyone who has studied market and trade analysis appreciates the fact that increased demand for biofuel feedstock and related market price shocks will increase returns to cropland and thus competition for agricultural land. These market price impacts will reverberate through global commodity markets and induce both domestic and global LUC."

It is widely acknowledged that there is substantial uncertainty around iLUC emissions (e.g. Plevin *et al.*, 2010), even with sophisticated modelling available – however, the existence of uncertainty does not in itself provide justification for inaction (Di Lucia *et al.*, 2012).

Legislation in the United States (the Federal Renewable Fuel Standard and Californian Low Carbon Fuel Standard) already includes iLUC emissions in the lifecycle analysis of biofuels, but this is currently not the case in Europe. Although there is no regulatory framework to address iLUC in Europe, the issue is noted in both the Renewable Energy Directive[1] and the Fuel Quality Directive.[2] The Directives call upon the European Commission to "develop a concrete methodology to minimise greenhouse gas emissions caused by indirect land use changes." They further call upon the Commission to "analyse, on the basis of best available scientific evidence, in particular, the inclusion of a factor for indirect land use changes in the calculation of greenhouse gas emissions, and the need to incentivise sustainable biofuels which minimise the impact of land use change and improve biofuel sustainability with respect to indirect land use change."

This mandate on the Commission has resulted in several studies being commissioned by Directorates General of the Commission (Al-Riffai *et al.*, 2010; Edwards *et al.*, 2010; Fonseca *et al.*, 2010; Laborde, 2011), and the performance of a literature review by the Directorate General for Energy (DG Energy, 2010) as well as an impact assessment (not in the public domain at the time of writing) co-authored by the Directorates General for Energy and Climate Action. The Al-Riffai *et al.* (2010) study included modelled marginal iLUC factors for eight potential feedstock for European biofuels; the Laborde (2011) study represents an updated and enhanced version of this modelling.

With discussions ongoing over the appropriate way to address iLUC in European legislation, it is timely to investigate the likely emissions consequences of iLUC under different potential European policy scenarios. The European Commission has proposed for consultation four different approaches to the iLUC problem:

- Monitor the situation, but do nothing yet;
- Reduce the maximum threshold for the *direct* emissions caused by biofuels production (hence raising the threshold for the 'direct saving');
- Apply additional sustainability criteria to some or all biofuels;
- Account for iLUC in the GHG assessment.

It is not clear at this time what additional sustainability criteria would be – some possibilities are discussed in Malins (2011). Because the price signals that cause iLUC are market mediated and act internationally, in general the power of regulators, processors or farmers in either the consuming or producing country to minimize iLUC is limited except by actively increasing yields [short of intervention to effectively isolate biofuel supply from the rest of the agricultural market such as implementing the 'Responsible Cultivation Areas' system outlined by Dehue *et al.* (2010)]. The outcomes of the other three potential approaches are addressed through modelling in this article.

The modelling approach presented in this article treats the Laborde (2011) iLUC modelling using the MIRAGE model as the source for its central estimates for the likely real magnitude of iLUC emissions driven by European biofuels policy. As the relevance of the results in this article hinges on the legitimacy of this treatment, below we provide a short review of that modelling to justify the conclusion that the Laborde (2011) results can reasonably be treated as the 'best available scientific evidence', to use the language of the RED/FQD.

Laborde (2011) is not the first author to consider iLUC emissions with a European focus – the results of other modelling efforts are noted in the supporting information to this article (Table S1, Figure S1). Laborde (2011) and Al-Riffai *et al.* (2010) are however the most

[1]Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

[2]Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC.

comprehensive studies, in that they provide marginal iLUC factors for all the feedstock likely to dominate European biofuel supply. There are some studies such as Bauen *et al.* (2010) and Overmars *et al.* (2011) that have attempted to suggest iLUC factors based on non-economic approaches, in these cases causal descriptive modelling and historical analysis respectively. Although there may be arguments for using such approaches in regulatory tools (primarily the contention that these approaches can be more transparent than economic modelling approaches), we believe that economic modelling will provide the best estimation of the likely net carbon impact of biofuels expansion. This is consistent with the decision by the US Environmental Protection Agency and California Air Resources Board to implement rules based on economic modelling of land use change.

There are various factors that drive the outcomes of the economic iLUC modelling. The extent to which a given model provides a representation of these driving factors that appropriately reflects reality will determine the quality of the output results. These key factors can be grouped into the following: [3]

- Utilization of co-products;
- Demand change (reduced food consumption);
- Yield effects;
- Crop switching (the way that cultivation choices are allowed to change on existing agricultural area);
- Area response;
- Land use change emissions.

Insofar as Laborde (2011) addresses these factors in a way consistent with best practice in the field of iLUC modelling, then it is legitimate to treat the Laborde (2011) iLUC factors as the 'best available scientific evidence' for central estimates for the real magnitude of iLUC emissions. On the policy side, this characterization would support the European Commission, Parliament and Council in basing on these results their decision-making process in determining a methodology to address iLUC. The treatment of each of these factors by Laborde (2011) is therefore outlined briefly below along with an assessment of whether that treatment conforms to best practice in the field of iLUC modelling.

*Utilization of co-products*

Laborde (2011) improves on the treatment of biofuel co-products as animal feed in previous modelling efforts [e.g. Al-Riffai *et al.* (2010) with MIRAGE; Fonseca *et al.* (2010) with AGLINK-COSIMO; Tyner *et al.* (2010) with GTAP] by reflecting the protein/energy nutritional profile of different feed types. For grain ethanol, MIRAGE models wheat and maize Dried Distillers' Grains and Solubles[4] (DDGS) production. For oilseeds, MIRAGE models the oil meals from the crushing process. Note that the balance of value between oil and meal varies significantly by oilseed – for instance, the value of the oil palm crop is dominated by the value of vegetable oil, whereas the value of the soybean crop is driven by the value of meal. It is hence expected that palm area will be much more responsive to vegetable oil price than soybean area – this dynamic is also captured in MIRAGE.

For both distillers' grains and oil meals there is a significant direct displacement impact on the oil meals markets when the supply is increased, which is consistent with the higher protein content of these feeds when compared to for instance feed wheat or corn (Hazzledine *et al.*, 2011). MIRAGE also considers other ways in which increased co-product supplies influence feed markets. As supply of mid- or high- protein feedstuff increases, there is a change in the relative prices of protein and energy feeds – energy feed prices go up due to competition from biofuel producers, but protein feed prices go down due to increased supply. The result in Laborde (2011) is that the proportionate use of protein feeds for livestock increases and use of energy feeds falls. The outcomes are discussed in more detail by Malins (2011).

Overall, the treatment of co-products in Laborde (2011) represents best practice in the field, being for instance an improvement over the treatment in GTAP modelling (in which the energy/protein balance is not reflected) or AGLINK-COSIMO modelling (in which the displacement of energy and protein feeds has been exogenously specified based on USDA data that are unlikely to provide a good characterization of European co-product markets).

*Demand change (reduced food consumption)*

When agricultural commodity prices rise, people will consume less food. Laborde (2011) uses region specific commodity demand elasticities based on USDA data (Laborde & Valin, 2010). Food demand elasticity in Laborde (2011) was reduced compared to Al-Riffai *et al.* (2010) by restricting changes from the USDA elasticity

[3]This listing reflects but is not identical to listings of key factors identified by previous studies e.g. RFA (2008); Edwards *et al.* (2010); Marshall *et al.* (2011).

[4]There are other variations on the use of this material, such as Wet Distillers' Grains and Solubles (WDGS) and corn gluten meal, but as all these co-products are used similarly as animal feed we shall not dwell on the distinctions and assume that when we say DDGS we are referring to all of these products.

 *GCB Bioenergy*, doi: 10.1111/j.1757-1707.2012.01207.x

values in the dynamic framework. Laborde (2011) investigates the importance of food consumption change in the model by running an alternative scenario in which it is kept constant.[5] In this scenario, the carbon intensity of the mandate as a whole (across all biofuels) increases by about 20% to an average of 46 g $CO_2$e $MJ^{-1}$. Given that not only the area response but also other responses (e.g. yield) will change when the food demand response is switched off, this suggests that perhaps one-third or so of feedstock for biofuels comes from reduced food consumption. This is consistent with econometric work by Roberts & Schlenker (2010). The result is also comparable to the result of the same experiment performed by Tyner *et al.* (2010) and Hertel *et al.* (2010).

The use of demand elasticities based on USDA data is an appropriate approach, and the magnitude of the food demand reduction effect is comparable to other studies and the econometric literature. Hence it is concluded that Laborde (2011) is consistent with best practice on this factor.

### *Yield response*

MIRAGE allows three primary yield responses, two that represent yields increasing due to increased farm revenue opportunities – factor intensification and input intensification – and a marginal yield effect representing the likelihood that previously uncultivated land has relatively poor agricultural characteristics.

The representation of input intensification and factor intensification are improved compared to Al-Riffai *et al.* (2010), with a more precise factor disaggregation. The sum of the input and factor intensification effects is calibrated by varying the factor intensification elasticity to generate an average global yield-on-price elasticity of 0.2, with a lower value (0.15) in Europe and high value (0.3) for the developing world. This developing world value is intended to include the potential for double cropping in developing regions, and to reflect the larger gap to technically achievable yields in the developing world. The overall intensification elasticities are based on the conclusions of the CARB Expert Workgroup on elasticities (Babcock *et al.*, 2010), and hence similar to the yield-on-price elasticities implemented in GTAP modelling used to regulate by the California Air Resources Board, which referenced Keeney & Hertel (2009). The value of 0.2 has been criticized by Berry (2011), and is too high to be consistent with the results of econometric historical analysis by Berry & Schlenker (2011). Nevertheless, while it may be more optimistic than is supported by available historical data, the strength of the yield response in Laborde (2011) is consistent with other modelling efforts and at least some expert opinion.

Laborde (2011) sets a ratio of 0.75 between the yield for a given crop in a given region on land newly brought into production at the margin, and the average yield in that region for that crop. This falls between the (lower) ratio used in GTAP modelling for CARB and the (higher) value derived from the 'Terrestrial Ecosystem Model (TEM)' by Tyner *et al.* (2010). There is little consensus in the literature on this parameter at this time – there is a fuller discussion of this point in Malins (2011). Although the evidence is not clear, Laborde (2011) notes that the parameter has a limited and ambiguous effect on the modelled outcomes.

The assumptions on yield elasticity are relatively weakly supported by data, compared for instance to the co-product treatment or demand elasticities. Nevertheless, Laborde (2011) has a more refined treatment of the inputs and factors than other economic models, and uses values consistent with other modelling and within the ranges considered in the literature, and is hence consistent with best practice in the field on yield modelling.

### *Crop switching*

'Crop switching' is used as a catch all including all the ways in which cropping choices on the existed cultivated area are allowed to change in the model, such as 'elasticity of substitution among imports from different sectors' and, 'the ease with which land moves between alternative uses' (Marshall *et al.*, 2011). The nested constant elasticity of substitution and transformation structure of MIRAGE is similar to the structure used in other general equilibrium models such as GTAP and LEITAP. MIRAGE as implemented by Laborde (2011) has a well-disaggregated agricultural and biofuels sector (for a GE model) – for instance, unlike GTAP (as implemented for the modelling under California's Low Carbon Fuel Standard) it disaggregates key vegetable oils, while it has a more comprehensive regional coverage than AGLINK-COSIMO as implemented by Fonseca *et al.* (2010).

Some areas of MIRAGE would clearly allow a more sophisticated assessment, notably the limited resolution in the 'other oilseeds' and 'other crop' aggregates, which are important to the model results, but where the aggregation may potentially undermine the credibility of the outcomes. A partial equilibrium treatment would allow better crop resolution; however, general equilibrium has its own advantages and hence using GE models is widely considered reasonable in addressing iLUC questions. MIRAGE compares well to other GE models,

[5]The use of products as inputs for food processing is still allowed to vary – e.g. the use of oils in processed foods could change, or the quantity of flour in processed food could be reduced.

has good resolution of the key sectors and provides a sophisticated treatment of crop substitution, and switching; i.e. it conforms to current best practice in this area.

*Area response to price*

The area response to price in Al-Riffai *et al.* (2010) is determined largely by the interplay of the CES and CET functions in the nest structure with comparative land rents in the various regions. Laborde (2011) notes the paucity of data on substitution and transformation elasticities, and also notes that this system (the standard CGE approach) resulted in some rather heterogeneous outcomes in Al-Riffai *et al.* (2010). Laborde (2011) therefore introduces an alternative calibration with the aim of achieving greater consistency with land price elasticities in the literature and from the FAPRI model. For the elasticity of extension of the total managed area into 'pristine' natural environments, Laborde (2011) uses 0.01 in developed countries, whereas for developing countries it is 0.04. By applying an elasticity to overall area, Laborde (2011) bypasses the difficult issue of allocating a rent to pristine land. These elasticities for expansion into unmanaged land are somewhat below the elasticity of transformation of managed land types (0.25 for all regions). This land extension elasticity is an innovation in MIRAGE compared to the GTAP model, where total managed land expansion is not permitted.

Overall, the area response now seems to be reasonably calibrated, and the MIRAGE treatment has advantages over the GTAP approach. It thus seems reasonable to conclude that the treatment of area response is consistent with (and arguably setting) best practice in the field.

*Land conversion emissions factors*

MIRAGE calculates the net quantity of land expansion and the carbon emissions associated with that land expansion separately. It endogenously determines changes in area of land under active management – managed forests and pastures – whereas for the net expansion of 'exploited land' it used the Winrock MODIS land use change database developed for the US Environmental Protection Agency for the Renewable Fuel Standard 2 rulemaking (Harris *et al*., 2009). Carbon emissions per hectare of land conversion in each category based on IPCC tier 1 values according to Bouët *et al.* (2010) – the emissions factors by AEZ and land type are listed in Appendix II of Laborde (2011). Emissions from peat decomposition are based on the study by Edwards *et al.* (2010). The Laborde (2011) results were also fed into a more sophisticated spatial allocation methodology (Hiederer *et al*., 2010) by Marelli *et al.* (2011). The results of this exercise are similar to the results of applying MODIS + IPCC tier 1, which suggests that the Laborde (2011) approach gives reasonable outcomes.

The Laborde (2011) treatment of land use changes is more advanced in some respects than the treatments implemented in GTAP (where conversion of unmanaged land is impossible) or FAPRI (which is more reliant on the exogenous Winrock data). It is not by any means as sophisticated as the model developed by Hiederer *et al.* (2010), but pending a more systematic review by the community of that model (and given the similarity of the outcomes) the Laborde treatment seems reasonable. Laborde (2011) is certainly competitive in this respect with other published iLUC modelling exercises.

*MIRAGE as a basis for modelling*

In all the areas discussed above, although improvement in MIRAGE's treatment of certain agricultural issues might be possible or desirable, the Laborde (2011) approach compares favourably to other CGE modelling, whereas any major shortcomings compared to PE approaches are a general characteristic of the model class, and not indicative of flaws with MIRAGE specifically. Delzeit *et al.* (2011) describe the Laborde (2011) work thus:

"The MIRAGE model by IFPRI used to address land use change caused by the European biofuel mandate represents a sophisticated modelling approach in the field of CGE modelling. It uses up-to-date data inputs and new methodological way to treat land and land use emissions on a global scale. The studies from 2010 and 2011 both transparently report the assumptions made and critical parameters chosen."

It is therefore concluded that it is indeed appropriate to characterize the MIRAGE work by Laborde (2011) as the 'best available scientific evidence' in the language of the Directives. Hence, the modelling approach presented herein is reasonable and provides useful insights to the policy question at hand, i.e. whether the introduction of iLUC factors into the Renewable Energy Directive could be expected to deliver significant climate change mitigation benefits?

## Materials and methods

This article uses a simplified model of the impacts of possible European biofuel sustainability policies on biofuel supply to provide a probabilistic assessment of the likely emissions consequences of the introduction of iLUC factors. The structure of the model is mathematically defined below; it is based on the following assumptions and simplifications:

- In the absence of any limitations due to sustainability criteria, the feedstock fractions predicted by Laborde (2011) for

2020 are taken as the best estimate of the feedstock that will be used to meet an expanding biofuel mandate under RED/FQD.

- In the absence of limitations due to sustainability criteria, the balance of fuels used to meet the European mandate will be 72 to 28 biodiesel to ethanol, consistent with the National Renewable Energy Action Plans (NREAPS). If some biodiesel pathways are made non-compliant due to assumed sustainability criteria (e.g. iLUC factors), the ratio is allowed to shift towards 50 : 50. If no biodiesel pathways are available, it is assumed that only ethanol will be used.
- It is assumed that if the default CI for a given pathway is too high to qualify under a given policy scenario, producers will take measures to reduce their CI to comply, if such reductions are feasible. Such measures could include enhanced processing plant efficiency, CI optimized application of fertilizer, switching to biomass for power and/or adopting CCS.
- It is assumed that there will be some cost/other barriers associated with achieving additional carbon savings below default, and therefore fractional demand for a given feedstock is reduced if it would not meet the thresholds based on the default CI. The model does not make any detailed assumptions about the nature or magnitude of these costs and barriers.
- If a feedstock is ineligible in a given policy scenario due to missing the carbon savings threshold, even when plausible improvements are taken into account, then that feedstock is not used in the model.
- The model does not assess the overall availability and/or cost of fuels. In particular, it makes no judgement about whether a 10% energy target is feasible in a given policy scenario. The model outcomes are carbon savings *per megajoule of biofuel delivered.*
- It is assumed that the reportable direct emissions for a given fuel under RED/FQD are representative of the real direct emissions of that fuel.
- It is assumed that if iLUC factors are introduced into the legislation they will be based on Laborde (2011).
- It is assumed that the marginal iLUC factors provided by Laborde (2011) are the best available estimates of the real iLUC likely from each feedstock pathway used (see above).
- Recognizing the intrinsic uncertainty in iLUC modelling (Plevin *et al.*, 2010; Laborde, 2011) the model runs many trials in which the 'real' magnitude of iLUC emissions is varied stochastically based on the Laborde (2011) values as central estimates. This means that the assumed actual carbon implications of biofuel expansion in each trial are in general not identical to the iLUC factors enshrined in a given policy option.

The model produces an emissions intensity value for the final year of the policy, 2020 – the year for which the iLUC factors in Laborde (2011) are calculated. There is no attempt to analyse carbon savings (or emissions increases) that might occur in the interim period given different policy options. A consequence of this is that the model does not and could not assess the carbon implications of temporary grandfathering. The model is defined mathematically as follows.

For each feedstock pathway $f$, the model has three input carbon intensity values - the default emissions $E_{d_f}$ from the Renewable Energy Directive, the typical emissions $E_{t_f}$ from the Renewable Energy Directive and the marginal indirect land use change emissions $i_{m,f}$ calculated by a given iLUC model m. The model does not attempt to consider uncertainty in the LCA of direct emissions effects from biofuels, so $E_{d_f}$ and $E_{t_f}$ are fixed. To allow for uncertainty in the assessment of indirect emissions, $i_{m,f}$ are used as the basis for stochastic variation. For each trial $j$, where $j \in [1, N]$ for $N$ the number of trials, we define the estimate of the real iLUC emissions for each trial $\tilde{i}_{m,f,j}$ as

$$\tilde{i}_{m,f,j} = \text{Nor}\{i_{m,f} \times V_o \times V_f, \sigma_f\}_j \quad (1)$$

where Nor$\{x, y\}$denotes a normal distribution with mean $x$ and standard deviation $y$, $V_o$ the overall deviance of the real iLUC from the modeled iLUC is defined as follows

$$V_o = \text{Nor}\{1, \sigma_{V_o}\} \quad (2)$$

and is the same across all feedstocks $f$ for a given trial $j$, and $V_f$ the variance of the real iLUC for a given feedstock type (oilseeds, cereals, sugar, cellulosic) is defined as follows

$$V_f = \text{Nor}\{1, \sigma_{V_f}\} \quad (3)$$

where

$$\sigma_{V_f} = \begin{cases} \sigma_{\text{oilseeds}} & \textit{if} \quad f \in [\text{palm, rapeseed, soybean, sunflower}], \\ \sigma_{\text{cereals}} & \textit{if} \quad f \in [\text{corn, wheat}], \\ \sigma_{\text{sugars}} & \textit{if} \quad f \in [\text{sugarbeet, sugarcane}]. \end{cases} \quad (4)$$

The standard deviation $\sigma_f$ of the probability density functions for the individual feedstock $f$ is based on the uncertainty analysis in Laborde (2011). The mean and 75th percentile of the reported distributions in Laborde (2011) are used to parameterize a normal distribution for each feedstock. This captures the uncertainty that was analysed using MIRAGE – however it ignores the 'model uncertainty' (Plevin *et al.*, 2010) around whether the model makes systematic under or overestimates of iLUC factors, and it ignores other sources of uncertainty (such as the emission factors) which are characterized by Plevin *et al.* (2010). Plevin also considers production period (and hence the period over which results should be amortized) as a source of uncertainty, whereas Laborde adopts a standard amortization over 20 years based on the RED – this article adopts the same 20-year amortization. Because of this difference in scope, as well as the methodological differences, Plevin *et al.* report rather wider uncertainty intervals than Laborde – for instance, for corn Plevin *et al.* report a 95% central interval of up to 121 g $CO_2$e $MJ^{-1}$, compared to a total range of only about 20 g $CO_2$e $MJ^{-1}$ in Laborde. These additional uncertainties that are not captured in the Laborde Monte Carlo analysis are collectively represented in this article in the terms $V_o$, $V_f$, which are used to further stochastically vary the mean of the feedstock specific distribution. The first term is the same for all feedstock, representing the possibility of systematic over or underestimation across the board. The second varies by feedstock type (vegetable oils, cereals, sugars, cellulosic), representing the possibility of systematic over or underestimation of the iLUC from a given feedstock type compared to the others. These scaling factors are given normal probability distributions with mean 1 and standard deviation 0.4 for the overall variation and 0.3 for the variation by type. The use of these scaling factors gives a lognormal character to the overall probability distribution for each feedstock and a wider range in uncertainty for each feedstock than that captured in the Laborde Monte Carlo analysis. This lognormal character reflects the expectation (Plevin *et al.*, 2010) that there is a long right tail on the possible magnitude of iLUC emissions.

The model allows a given policy scenario to be defined using a small set of parameters. The basic framework is that of the Renewable Energy Directive, in which there is a defined fossil fuel comparator and fuels must achieve a given carbon saving compared to it to qualify for support. The parameters for the policy scenario are as follows:

- The fossil fuel comparator, $E_{\mathrm{fos}}$ 0.88 $\mathrm{gCO_2e\ MJ^{-1}}$ is used in this article; [6]
- The minimum required carbon saving as a percentage, $S_{\%}$;
- The model used as a basis for any iLUC factors - in this article, all iLUC factors are based on the IFPRI MIRAGE model;
- The model considered to give the best available evidence for the actual magnitude of iLUC, from which the stochastically varied real iLUC emissions are determined - in this article, the IFPRI MIRAGE model is taken as providing the best available evidence for the magnitude of iLUC emissions; [7]
- A characterization of the availability of each biofuel feedstock pathway to meet the mandate, $A_f$, detailing the comparative proportions of each feedstock that would be used to meet the mandate if there were no carbon savings threshold on compliance;
- The maximum % reduction $R_{\mathrm{max}}$ achievable in direct emissions compared to the typical direct emissions $E_{\mathrm{t}_f}$. In this article, it is assumed that significant reductions of up to 80% compared to typical performance through measures such as fertilizer reduction, renewable energy utilization and efficiency improvements would represent the best possible performance;
- The size of the iLUC factor introduced in the model compared to the iLUC emissions predicted by our chosen iLUC model, $F_{\mathrm{iLUC}}$; so $F_{\mathrm{iLUC}} = 0$ would imply that there were no regulatory iLUC factors, while $F_{\mathrm{iLUC}} = 1$ would imply that all regulatory iLUC factors were equal to $i_{\mathrm{m},f}$ In the modelling in this article, $F_{\mathrm{iLUC}}$ is always 0 or 1;
- The fraction $P_{\mathrm{biod}}$ of biofuel that would be supplied as biodiesel in the absence of a carbon threshold.

For a given trial $j$ and set of policy parameters, the model calculates the average carbon saving in the following way. Firstly, for each feedstock pathway two total carbon intensities are determined - the actual carbon intensity of the pathway given the real iLUC emissions in trial $j$, $E_{\mathrm{actual}_{f,j}}$, and the reportable carbon intensity of the pathway given the policy option being assessed, $E_{\mathrm{reportable}_f}$. $E_{\mathrm{reportable}_f}$ is calculated as

$$E_{\mathrm{reportable}_f} = E_{\mathrm{d}_f} + F_{\mathrm{iLUC}} \times i_{\mathrm{m},f} \tag{5}$$

where $E_{\mathrm{d}_f}$ is the direct emission for a feedstock pathway $f$, and is defined

$$E_{\mathrm{d}_f} = \begin{cases} E_{\mathrm{d}_f} & \mathit{if} \quad E_{\mathrm{d}_f} \leq (1 - S_{\%})E_{\mathrm{fos}} - F_{\mathrm{iLUC}} \times i_{\mathrm{m},f}, \\ E_{\mathrm{t}_f} & \mathit{if} \quad E_{\mathrm{t}_f} \leq (1 - S_{\%})E_{\mathrm{fos}} - F_{\mathrm{iLUC}} \times i_{\mathrm{m},f} < E_{\mathrm{d}_f}, \\ (1 - S_{\%}) \times E_{\mathrm{fos}} & \mathit{if} \quad (1 - R_{max})E_{\mathrm{t}_f} \leq (1 - S_{\%})E_{\mathrm{fos}} - F_{\mathrm{iLUC}} \times i_{\mathrm{m},f} < E_{\mathrm{t}_f}, \\ (1 - R_{\mathrm{max}})E_{\mathrm{t}_f} & \mathit{if} \quad (1 - S_{\%})E_{\mathrm{fos}} - F_{\mathrm{iLUC}} \times i_{\mathrm{m},f} < (1 - R_{\mathrm{max}})E_{\mathrm{t}_f}. \end{cases} \tag{6}$$

Notice that it is assumed that biofuel producers will deliver biofuels with direct carbon emissions such that $E_{\mathrm{reportable}_f}$ just beats the legal carbon saving threshold, down to some minimum achievable direct emissions $(1 - R_{\mathrm{max}})E_{\mathrm{t}_f}$. $E_{\mathrm{actual}_{f,j}}$ is calculated as

$$E_{\mathrm{actual}_{f,j}} = E_{\mathrm{d}_f} + \tilde{i}_{\mathrm{m},f,j}. \tag{7}$$

In general, the reportable carbon intensity and the actual carbon intensity are not equal to each other, so that there is a nonzero discrepancy between the reportable emissions under any given policy regime and the actual net emissions outcomes from a given policy regime,

$$\Delta E_{f,j} = E_{\mathrm{reportable}_{f,j}} - E_{\mathrm{reportable}_f} \neq 0. \tag{8}$$

If $\Delta E_{f,j} > 0$ then a given policy framework would over report the carbon benefits for a given feedstock pathway $f$ in a given trial $j$, whereas if $\Delta E_{f,j} < 0$ then a given policy framework would under report the carbon benefits.

Having assigned actual and reportable carbon intensities to each feedstock pathway the model determines what the relative use of each feedstock pathway would be under a given policy scenario. If there were no carbon saving threshold, the fractional use to meet the mandate of each feedstock pathway $\tilde{U}_f$ would be

$$U_f = \frac{A_f}{\sum_f A_f}. \tag{9}$$

However, in general some feedstock pathways will be limited by the imposition of carbon savings thresholds. Even in a policy case with no iLUC factors ($F_{\mathrm{iLUC}} = 0$) there are likely to be limits on some pathways - for instance in the RED the default palm biodiesel pathway without methane capture does not meet the 35% carbon saving threshold for plants built post-2008 in the period 2010–2017. The model assumes that if a given feedstock pathway fails to meet the carbon saving threshold at the default carbon intensity, then producers will in general be able to implement chain of custody and/or improve their performance, and instead report the typical carbon intensity. Similarly, if the feedstock pathway does not meet the savings threshold at the typical carbon intensity then the model assumes that options will be available to reduce the carbon intensity of that pathway as much as necessary, down to the minimum achievable carbon saving $(1 - R_{\mathrm{max}})E_{\mathrm{t}_f}$. However, it is also assumed that delivering this chain of custody/improved performance will make that feedstock pathway marginally less competitive compared to the others.

[6]This is a simplification compared to the values proposed for the European Fuel Quality Directive, in which diesel is identified as marginally more carbon intensive than petrol per megajoule, but this does not significantly affect the results. This intensity is not adjusted for drivetrain efficiency.

[7]Setting the model from which iLUC factors are drawn to be different to the model considered the best available evidence would allow the model to investigate the expected consequences of using a model that we did not believe represented the best available evidence to set iLUC factors.

To determine $U_f$ the fractional use of each feedstock pathway $f$ given the selected policy regime, the availability vector is adjusted as

$$\tilde{A}_f = \begin{cases} A_f & \text{if} \quad E_{\text{reportable}_f} = E_{\text{d}_f} \\ \alpha A_f & \text{if} \quad E_{\text{reportable}_f} = E_{\text{t}_f} \\ \alpha^2 A_f & \text{if} \quad (1 - R_{\max})E_{\text{t}_f} \leq E_{\text{reportable}_f} > E_{\text{t}_f} \\ 0 & \text{if} \quad E_{\text{reportable}_f} < (1 - R_{\max})E_{\text{t}_f} \end{cases} \qquad (10)$$

where $\alpha$ is a parameter set at 0.8 for the modelling in this article. In the case where biodiesel pathways become limited by the sustainability criteria an additional condition is set that the share of biodiesel in the biofuel pool may not drop below 50% unless there are no biodiesel compliance pathways at all – a second adjustment is made to the availability vector to meet this condition,

$$\tilde{\tilde{A}}_f = \begin{cases} \tilde{A}_f & \text{if} \quad \sum_{\text{bd}} \tilde{A}_f = 0 \\ \tilde{A}_f & \text{if} \quad \frac{\sum_{\text{bd}} \tilde{A}_f}{\sum_{\text{be}} \tilde{A}_f} > 0.5 \\ \tilde{A}_f \times 0.5 \frac{\sum_f \tilde{A}_f}{\sum_{\text{be}} \tilde{A}_f} & \text{if} \quad \frac{\sum_{\text{bd}} \tilde{A}_f}{\sum_{\text{be}} \tilde{A}_f} < 0.5 \quad \text{and} \quad f \in \text{Ethanol feedstocks} \\ \tilde{A}_f \times 0.5 \frac{\sum_f \tilde{A}_f}{\sum_{\text{bd}} \tilde{A}_f} & \text{if} \quad \frac{\sum_{\text{bd}} \tilde{A}_f}{\sum_{\text{be}} \tilde{A}_f} < 0.5 \quad \text{and} \quad f \in \text{Biodiesel feedstocks} \end{cases} \qquad (11)$$

where $\sum_{\text{be}}$ is a sum over ethanol feedstock and $\sum_{\text{bd}}$ is a sum over biodiesel feedstocks. From this the use fractions are calculated

$$U_f = \frac{\tilde{\tilde{A}}_f}{\sum_f \tilde{\tilde{A}}_f} \qquad (12)$$

From the combination of use fractions and feedstock pathway carbon intensities, the model calculates the overall average carbon intensity of biofuel used given the specified policy scenario in each trial,

$$E_{\text{average}_j} = \sum_f E_{\text{actual}_{f,j}} U_f \qquad (13)$$

with the expected average carbon intensity over all $N$ trials being defined

$$\overline{E}_{\text{average}} = \frac{\sum_{f,j} E_{\text{actual}_{f,j}} U_f}{N}, \qquad (14)$$

which can also be transformed to the carbon saving in one trial and the expected carbon saving from the policy over all trials,

$$S_{\text{average}_j} = \frac{E_{\text{fos}} - CI_{\text{average}_j}}{E_{\text{fos}}} \text{ and } \overline{S}_{\text{average}} = \frac{E_{\text{fos}} - \overline{CI}_{\text{average}}}{E_{\text{fos}}} \qquad (15)$$

## Results

In this article, three policy scenarios are modelled for comparison:

- No iLUC factor, with a 50% carbon saving threshold;
- No iLUC factor, with the carbon savings threshold raised to 65%;
- iLUC factors taken directly from Laborde (2011), with a carbon savings threshold of 50%.

For each policy scenario, 1000 trials are run.

### *No iLUC factor, with a 50% carbon saving threshold*

With no iLUC factor, all feedstock listed in the Renewable Energy Directive represent viable compliance pathways. In the case of soy and rapeseed biodiesel this would require demonstrating better-than-typical emissions performance – palm biodiesel could comply with the default intensity for a plant with methane capture. Emissions are increased compared to the fossil fuel comparator in 39% of trials. The mean carbon saving across all 1000 trials for the policy as a whole is 4%, with a median carbon saving of 8%, reflecting the long right hand tail on the distribution for possible iLUC emissions. The standard deviation in the modelled carbon savings was 26%. The reportable carbon savings for the policy in this case would be 55% - that is to say that it would be expected that the success of the policy would be overstated by over 50 percentage points (reporting savings 13 times higher than the real policy savings) if the carbon emissions were reported with no accounting for indirect land use change. The distribution of savings achieved in each trial is shown in Fig. 1. In this policy scenario, the use of biodiesel would increase emissions compared to using fossil diesel.

### *No iLUC factor with minimum carbon saving threshold raised to 65%*

Raising the carbon savings threshold has been proposed as a way to manage the risk of iLUC emissions without attempting to account for them. Figure 2 shows the modelled distribution of possible carbon savings for a

 

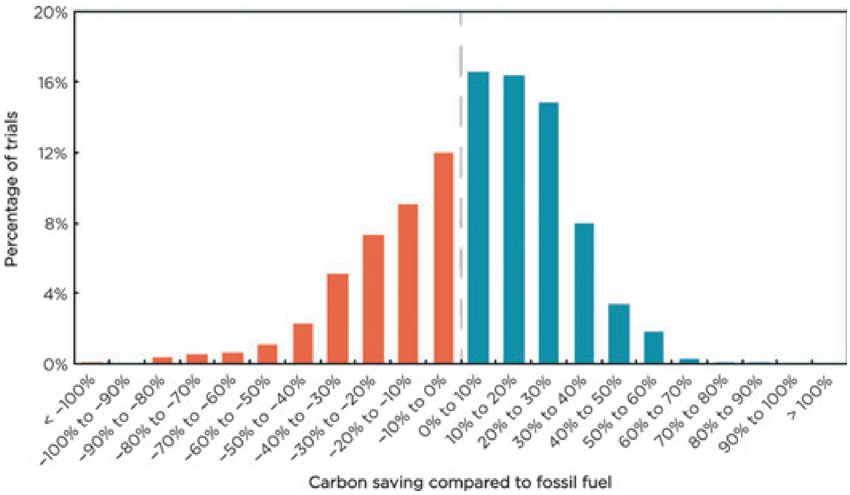


**Fig. 1** Distribution of modelled carbon savings from a policy scenario with no iLUC factors and a 50% carbon savings threshold.

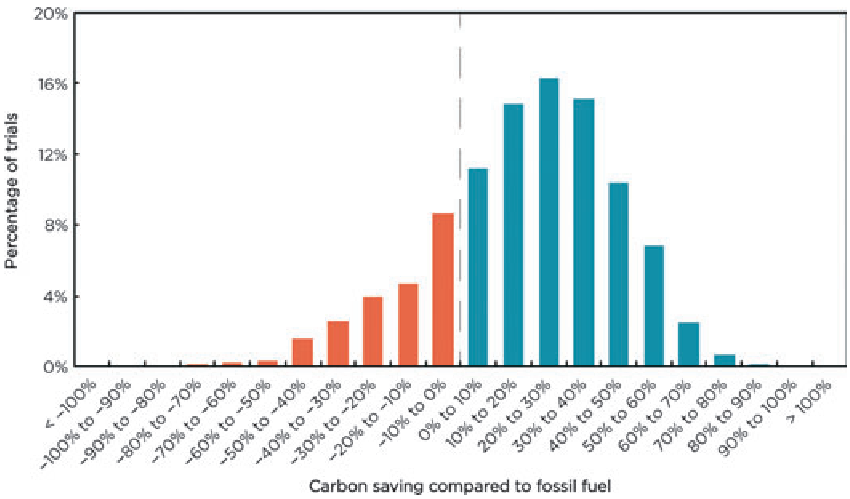


**Fig. 2** Distribution of modelled carbon savings from a policy scenario with no iLUC factors and a 65% carbon savings threshold.

65% carbon savings threshold. With this threshold, all pathways are considered possible, but for corn, sugar beet and all biodiesel feedstock better-than-typical direct emissions performance would be required. With a raised threshold, emissions are increased in only 22% of trials – an improvement over the case with a 50% carbon saving threshold, but still a 1 in 5 risk that the policy could actually increase global carbon emissions. The average carbon saving is improved to 19%, with a median carbon saving of 21%. The standard deviation is 26%. The reportable carbon savings would be 66%, so with a 65% carbon savings threshold it would be expected that the carbon benefits of the policy would be overstated by 48 percentage points. It is expected that raising the carbon savings threshold would make ethanol more appealing as a fuel compared to biodiesel, as it is likely to be easier to achieve the threshold savings for ethanol pathways.

### *iLUC factors and 50% carbon savings threshold*

Introducing an iLUC factor profoundly changes the mix of feedstock available to meet the mandate. No biodiesel feedstocks are expected to meet the threshold – 71% of compliance in this scenario is through sugar-based ethanol, with the rest from grain ethanol. It is beyond the scope of this article to assess what would be the maximum likely supply available to Europe from these sources. Note that the results are not strongly sensitive to the grain/sugar ethanol mix, as the fuels that meet the threshold are anticipated to have similar direct and indirect emissions profiles (for corn ethanol, this requires better-than-typical emissions performance).

When iLUC factors are introduced, there are no trials in which overall emissions are increased by biofuel policy. The mean carbon saving for the policy is approximately equal to the median carbon saving, 54%. In contrast to the scenario with no iLUC factors, the reportable savings are expected to match the real savings – the reportable savings value would also be 54%. The carbon saving per megajoule of fuel is expected to be 13 times higher in a policy including iLUC factors than in one with no iLUC factors. The standard deviation in the carbon savings from the policy is 8%, compared to 26% without iLUC factors - this suggests that iLUC factors would provide a marked reduction in the uncertainty around the effect of the policy. The distribution of results is shown in Fig. 3.

It is also pertinent to consider the distribution of the carbon benefit delivered by the introduction of iLUC factors, compared to trials in the scenario with a 50% carbon saving threshold and no iLUC factors. In only two of one thousand trials did the introduction of iLUC factors result in worse carbon performance than not introducing iLUC factors. On average, introducing iLUC factors improves the carbon savings from the biofuel mandate by 49%, with a median improvement of 47%. In 3% of trials, the carbon savings from the policy were increased by over 100 percentage points by introducing iLUC factors. The distribution of the carbon saving ben-

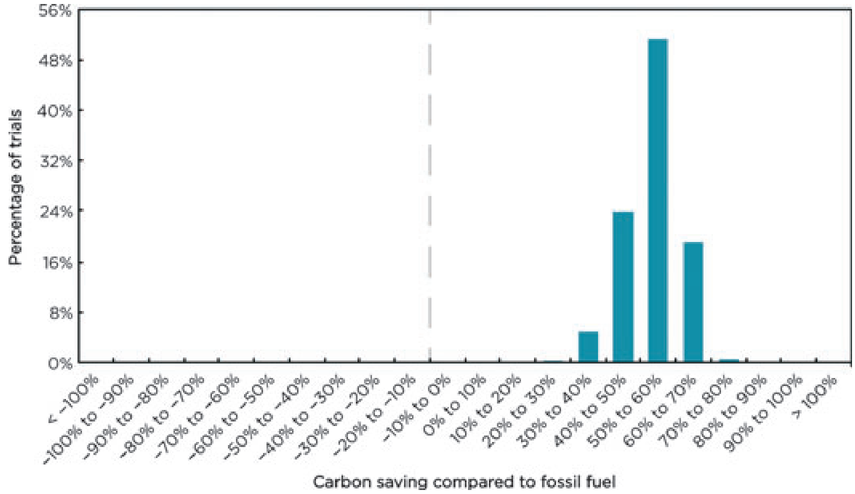


**Fig. 3** Distribution of modelled carbon savings from a policy scenario with iLUC factors and a 50% carbon savings threshold.

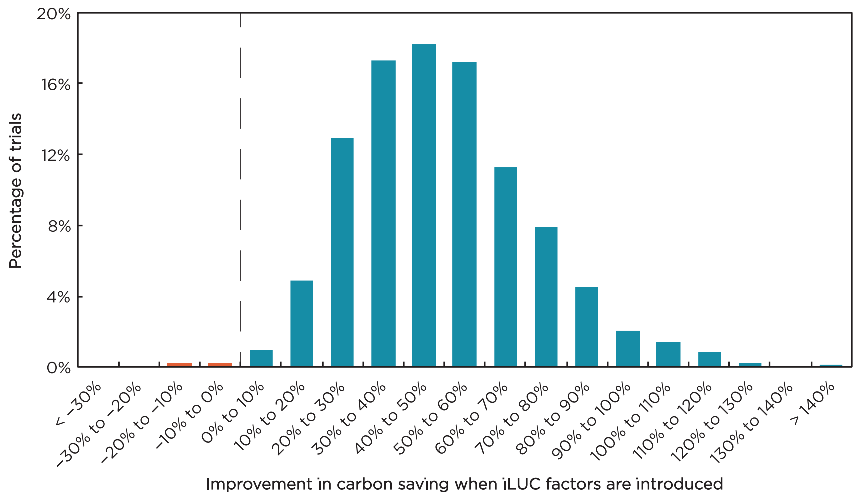


**Fig. 4** Distribution of increase in carbon saving in each trial for a policy scenario with iLUC factors compared to a policy scenario with no iLUC factors.

efit delivered by an iLUC factor compared to no iLUC factor, for each trial, is shown in Fig. 4.

## Discussion

This article presents modelling results to show that, if it is not revised to address iLUC, the Renewable Energy Directive could be expected to deliver only a 4% carbon saving compared to fossil fuel, with a 30% chance that it would actually cause a net emissions increase. All the saving from the policy is likely to come from the supply of bioethanol – biodiesel from non-waste vegetable oil is likely to have a worse carbon footprint than fossil diesel. The modelling in this article does not explicitly consider the Fuel Quality Directive, but it is reasonable to infer that without addressing iLUC that policy is also unlikely to meet its GHG mitigation goals. Given that biodiesel production is also expected to be worse for a range of other environmental indicators (e.g. acidification, eutrophication, biodiversity) (Zah *et al.*, 2007) than fossil diesel, there is no environmental basis for the EU to continue to support the supply of biodiesel (or hydrogenated vegetable oil, HVO) from non-waste vegetable oil. Production of ethanol from grains and sugars would be expected to be a more effective climate strategy. It should be noted that there are likely to be some trade-offs even to a sugar and grain-based biofuel policy in terms of increased food prices and reduced welfare (RFA, 2008), but these are not considered in this article.

The model presented here is simplified. It contains uncertainties, such as the capacity of fuel producers to improve their 'direct' emissions performance and the rate of use of different feedstocks in a given policy scenario. It would be possible to add layers of additional sophistication to this type of approach in the attempt to more thoroughly model the economics of biofuel supply – such enhancements could potentially start to allow the model to capture the costs associated with achieving better carbon reductions. It might also allow the important question of how much of the overall RED target could plausibly be met with ethanol alone to be addressed. Although such innovations would certainly change the detail of the results, the conclusion itself (that iLUC factors are likely to be effective) is considered robust, and unlikely to be affected by such enhancements.

The rest of the available scientific evidence also strongly supports the expectation that the magnitude of indirect land use change emissions will be on the same scale as the carbon benefits sought from biofuels (see for instance Dehue *et al.*, 2011; Fritsche & Wiegmann, 2011). This article explicitly recognizes that uncertainty remains in the calculation of iLUC. Some of this uncertainty may be reduced by further modelling innovations either within the MIRAGE framework, or within an alternative framework. Other aspects of the uncertainty are more fundamental, and a necessary aspect of economic modelling results. Uncertainty should not be seen as an adequate reason for regulatory inaction in this area, and these results show that even when recognizing the uncertainty of the economic research, there is still a strong case to believe that iLUC factors will be an effective policy intervention.

The analysis here follows the convention in the biofuel LCA literature of ignoring the time sensitivity of the climate to emissions. It is assumed that emissions incurred at the start of a biofuel mandate are of equivalent value to emissions savings achieved over the subsequent 20 years, i.e. there is no discounting applied on emissions. It has been argued (e.g. O'Hare *et al.*, 2009) that because land use emissions occur before savings from displacing fossil fuels are actualized that a more sophisticated time accounting would show an increased climate footprint for biofuels compared to fossil fuels, however, while it is important this question is beyond the scope of this study.

There are also several potential consequential impacts of introducing a biofuels mandate that we have not represented. Following the methodological example of California's Low Carbon Fuel Standard and Laborde (2011), we have estimated the 'real' GHG implications of a given biofuel feedstock as the sum of attributionally calculated direct emissions and consequentially calculated iLUC emissions. It has been pointed out by several authors (e.g. Creutzig *et al.*, 2012) that combining aspects of attributional and consequential analysis introduces a degree of inconsistency into any emissions intensity assessment. By hypothesis, the full increase in biofuel production, and hence biofuel processing emissions, modelled by Laborde (2011) is policy driven, and thus it seems reasonable to assume that a consequential analysis of processing emissions would give more or less the same results as the attributional calculation. In contrast, a consequential treatment of changes in agricultural emissions may well give a quite different result to an attributional assessment – in the regulatory context, this can be seen when comparing the generally lower US EPA consequential estimates of biofuel policy driven agricultural emissions to the generally higher European Commission or CARB estimated attributional values.

On the other hand, we also do not account for the fossil fuel rebound (Stoft, 2010) or for biofuel production related change in albedo (Bright *et al.*, 2012). It is generally expected that the use of biofuels will not result in a full one-to-one substitution of fossil fuels, as an increased total energy supply will tend to depress crude oil prices and increase demand, reducing the potential carbon savings from a biofuel mandate; albedo effects are likely to vary by crop and region. We look forward to future research that is able to combine the type of uncertainty aware approach attempted here with an increasingly comprehensive characterization of the full climate footprint of policy interventions to support alternative fuels. Nevertheless, the central conclusion of this article that an iLUC factor in the RED would be effective is robust given the current evidence, and would be unlikely to change even if a more comprehensive climate impact assessment were undertaken.

In this modelling there is a 94% chance that introducing iLUC factors would improve the carbon saving per unit of energy achieved by EU biofuels policy by at least 20 percentage points, with an expected benefit of 49 percentage points, i.e. iLUC factors would be expected to be a very effective policy intervention. Adding iLUC factors would also minimize the risk of negative climate effects from European biofuels policy. This result would be highly desirable under the precautionary principle. By restricting the supply of biofuels that have poor GHG performance iLUC factors would also incentivize the faster introduction of innovative technologies that would allow the production of biofuels from feedstock with minimal iLUC impacts, such as residual cellulosic material or algae. In contrast, raising the minimum carbon savings threshold would be likely to provide some limited carbon benefits, but would not prevent a substantial likelihood that EU biofuel use could increase net biofuel emissions, nor address the expected disconnect between reportable and actualized carbon emissions.

## Acknowledgements

I am grateful to the ClimateWorks Foundation for the financial support that has enabled this work. I would also like to thank David Laborde for his indulgence in responding to questions about his MIRAGE modelling work, and Stephanie Searle of the ICCT for her support in preparing the paper.

## References

Al-Riffai P, Dimaranan B, Laborde D (2010) *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*. International Food Policy Research Institute, Washington, DC, USA.

Babcock B, Gurgel A, Stowers M, Adili K 2010. Final recommendations from the elasticity values subgroup. Low Carbon Fuel Standard (LCFS) Indirect Land Use Change Expert Workgroup, Sacramento, CA, USA. Available at: http://www.arb.ca.gov/fuels/lcfs/workgroup/expert workgroup.htm (accessed 11 January 2011).

Bauen A, Chudziak C, Vad K, Watson P (2010) *A Causal Descriptive Approach to Modelling the GHG Emissions Associated with the Indirect Land Use Impacts of Biofuels*. E4Tech, London.

Berry S (2011) *Biofuels Policy and the Empirical Inputs to GTAP Models*. Yale University Department of Economics & Cowles Foundation and NBER, New Haven, Connecticut.

Berry S, Schlenker W (2011) *White Papers*. Technical Report for the ICCT: Empirical Evidence on Crop Yield Elasticities. International Council on Clean Transportation, Washington, DC, USA.

Bouët A, Dimaranan BV, Valin H (2010) *Modeling the Global Trade and Environmental Impacts of Biofuel Policies*. International Food Policy Research Institute Discussion Paper 01018, Washington, DC, USA.

Bright RM, Cherubini F, Strømman AH (2012) Climate impacts of bioenergy: inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. *Environmental Impact Assessment Review*, **37**, 2–11.

Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O (2012) Reconciling top-down and bottom-up modeling on future bioenergy deployment. *Nature Climate Change*, **2**, 320–327.

Dehue B, Meyer S, van de Staaj J (2010) *Responsible Cultivation Areas: Identification and Certification of Feedstock Production with a Low Risk of Indirect Effects*. Ecofys, Utrecht.

Dehue B, Cornelissen S, Peters D (2011) *Indirect Effects of Biofuel Production - Overview Prepared for GBEP*. Ecofys, Utrecht.

Delzeit R, Klepper G, Lange KM (2011) *Review of IFPRI study: "Assessing the Land Use Change Consequences of European Biofuel Policies and its Uncertainties."* Study on behalf of the European Biodiesel Board by Kiel Institute for the World Economy, Kiel, Germany.

DG Energy, 2010. *The Impact of Land Use Change on Greenhouse Gas Emissions from Biofuels and Bioliquids*. An in-house review conducted for DG Energy as part of the European Commission's analytical work on indirect land use change. European Commission, Brussels, Belgium.

Di Lucia L, Ahlgren S, Ericsson K (2012) The dilemma of indirect land-use changes in EU biofuel policy – An empirical study of policy-making in the context of scientific uncertainty. *Environmental Science and Policy*, **16**, 9–19.

Edwards R, Mulligan D, Marelli L (2010) *Indirect Land Use Change from Increased Biofuels Demand: Comparison of Models and Results for Marginal Biofuels Production from Different Feedstocks*. Joint Research Centre - Institute for Energy, European Commission, Ispra, Italy.

Fonseca MB, Burrell A, Gay H, Henseler M, Kavallari A, M'Barek R, Dominguez IP, Tonini A (2010) *Impacts of the EU Biofuel Target on Agricultural Markets and Land Use: A Comparative Modelling Assessment*. (ed Burrell A). Joint Research Centre, Institute for Prospective Technological Studies, European Commission JRC IPTS, Seville, Spain.

Fritsche UR, Wiegmann K (2011) *Indirect Land Use Change and Biofuels*. Study: European Parliament, Brussels, Belgium.

Harris N, Grimland S, Brown S (2009) *Land Use Change and Emission Factors: Updates since the RFS Proposed Rule*. Winrock International, Arlington, Virginia.

Hazzledine M, Pine A, Mackinson I, Ratcliffe J (2011) Estimating displacement ratios of wheat DDGS in animal feed rations in GB. A report prepared for the ICCT, Staffordshire, UK: Premier Nutrition. In: *ICCT Working Papers*. (ed. Anil Baral), pp. 1–19. International Council on Clean Transportation, Washington, DC, USA.

Hertel TW, Golub A, Jones AD, O'Hare M, Plevin RJ, Kammen DM (2009) Supporting online materials for: global land use and greenhouse gas emissions impacts of maize ethanol: the role of market-mediated responses. *BioScience*, **60**, 223–231.

Hiederer R, Ramos F, Capitani Koeble R, Blujdea V, Gomez O, Mulligan D, Marelli L (2010) *Biofuels: A New Methodology to Estimate GHG Emissions from Global Land Use Change: A methodology Involving Spatial Allocation of Agricultural Land Demand and Estimation of $CO_2$ and $N_2O$ Emissions*. Joint Research Centre - Institute for Energy, European Commission, Ispra, Italy.

Keeney R, Hertel TW (2009) The indirect land use impacts of United States biofuel policies: the importance of acreage, yield, and bilateral trade responses. *American Journal of Agricultural Economics*, **91**, 895–909.

Laborde D (2011) *Assessing the Land Use Change Consequences of European Biofuel Policies*. International Food and Policy Research Institute, Washington, DC, USA.

Laborde D, Valin H (2010) *Modelling Land Use Change in a Global CGE: Asessing the EU Biofuel Mandates with the MIRAGE-BioF Model*. International Food Policy Research Institute, Washington, DC, USA.

Malins C (2011) Indirect land use change in Europe - Considering the policy options. In: *ICCT Working papers* (ed. Joe Schultz), pp. 1–22. International Council on Clean Transportation, Washington, DC, USA.

Marelli L, Ramos F, Hiederer R, Koeble R (2011) *Estimate of GHG Emissions from Global Land Use Change Scenarios*. Joint Research Center - Institute for Energy, European Commission, Ispra, Italy.

Marshall E, Caswell M, Malcolm S, Motamed M, Hrubovcak J, Jones C, Nickerson C (2011) *Measuring the Indirect Land-Use Change Associated with Increased Biofuel Feedstock Production: A Review of Modeling Efforts*. (ed Agriculture UDO). USDA: Washington, DC.

Miranowski JA (2012) *Greenhouse Gas Accounting: Life Cycle Analysis of Biofuels and Land Use Change*. OECD Joint Working Party on Agriculture and the Environment, Paris, France.

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

O'Hare M, Plevin RJ, Martin JI, Jones AD, Kendall A, Hopson E (2009) Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environmental Research Letters*, **4**, 024001.

Overmars KP, Stehfest E, Ros JPM, Prins AG (2011) Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data. *Environmental Science and Policy*, **14**, 248–257.

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

RFA (2008) *The Gallagher Review of the Indirect Effects of Biofuels Production*. The Renewable Fuels Agency, Hastings, East Sussex, UK.

Roberts MJ, Schlenker W (2010) Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate. National Bureau of Economic Research Working Paper Series, No. 15921. NBER, Cambridge Maaschusetts.

Searchinger TD (2010) Biofuels and the need for additional carbon. *Environmental Research Letters*, **5**, 024007.

Stoft S (2010) Renewable fuel and the global rebound effect. Global Energy Policy Center Research Papers No. 10-06. Global Energy Policy Center, Berkeley.

Tyner WE, Taheripour F, Zhuang Q, Birur DK, Baldos U (2010) *Land Use Changes and Consequent $CO_2$ Emissions due to US Corn Ethanol Production: A Comprehensive Analysis*. Dept. of Agricultural Economics, Purdue University, West Lafayette, Indiana.

Zah R, Böni H, Gauch M, Hischier R, Lehmann M, Wäger P (2007) *Life Cycle Impact Assessment of Energy Products: Environmental Impact Assessment of Biofuels. Executive Summary*. Bundesamt für Energie, Bern.

## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Emissions due to iLUC from EU-focused studies with approximate well-to-wheel fossil comparison (solid line) and 50% saving (dashed line).
**Table S1.** iLUC emissions results from models considering increased demand in Europe.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.