Characterizing uncertainty in emissions from biofuel-induced indirect land use change

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Summary

Estimates of the greenhouse gas (GHG) emissions from land use change induced by the expansion of biofuel production are highly uncertain and will remain so for the foreseeable future. By propagating parameter uncertainty through a simple, 9-parameter model of indirect land use change (ILUC), we show that a plausible range for ILUC emissions from corn ethanol production in the US is between 25 and 150 g CO_2e MJ^{-1}. These results support the inclusion of ILUC emissions in fuel GHG regulations despite uncertainty about their exact size, and at a level higher than currently proposed in Low Carbon Fuel Standard and Renewable Fuel Standard regulations .

Modeling emissions from indirect land use change

New greenhouse gas (GHG) policies for transportation fuels have required counting GHG emissions that result when price changes in biofuel feedstock markets induce land use changes elsewhere. For example, the US Energy Independence and Security Act of 2007 (EISA) includes "significant indirect emissions such as significant emissions from land use changes" (United States Congress 2007). This requirement was adopted verbatim into the California LCFS (OAL 2010).

Several modeling studies have estimated ILUC emissions from US corn ethanol, as shown in Table 1.

Table 1. Published estimates of ILUC emissions induced by expansion of corn ethanol in the US and EU. All studies are reported with ILUC emissions amortized over 30 years of production for comparison. To normalize any value to 20 years of production, add 50%. (Based on Plevin, O'Hare et al. In review)

Study	Target year	Shock size (10^9 L)	ILUC factor (g CO_2e MJ^{-1})	Range (g CO_2e MJ^{-1})
Searchinger et al. (2008)	2016	56	104	20 – 200[a]
Hertel et al. (2010)	2001[b]	50	27	15 – 90[c]
Dumortier et al. (2009)	2018/19	30	n/a	21 – 118[d]
USEPA (2010)	2012	7.5	81	62 – 104[e]
	2017	14	58	43 – 76[e]
	2022	10	34	25 – 45[e]
Al-Riffai et al. (2010)	2020[f]	0.47	36	36 – 53[g]
Tyner et al. (2010)	2015	7.6	14	14 – 18[h]

[a] Calculated from reported sensitivity results.
[b] Based on the GTAP-6 2001 database, adjusted for 10% greater corn yield in 2010.
[c] Based on a combination of high and low values for various economic model parameters.
[d] Based on evaluating alternative model assumptions.
[e] 95% CI around mean considering only the uncertainty in satellite data analysis and carbon accounting.

[f] Based on the GTAP-7 2004 database, using the model to project out to 2020.
[g] Effect of additional 10^6 GJ after meeting 5.6% mandate. Higher value is for greater trade liberalization.
[h] Based on 2006 data constructed from 2001 GTAP database. Low value includes yield and population growth.

None of these studies has attempted a complete characterization of uncertainty in model results, relying instead on local sensitivity analyses to examine model response to changes in one or a few key parameters. Even the study by Hertel et al. (2010), which used the Systematic Sensitivity Analysis feature of the GTAP model, treated relatively few economic parameters as uncertain, and did not examine uncertainty related to model structure (functional forms, levels of regional and sectoral aggregation, choice of closure).

We exercise a *reduced-form model of ILUC*[1] (RFMI) (equation (1) comprising the nine parameters listed in Table 2 in a Monte Carlo simulation to produce an output frequency distribution characterizing uncertainty in values for ILUC emissions in g CO_2e MJ^{-1}.

(1)
$$ILUC = \frac{\frac{NDF}{FY} \times \sum_{i=F,G,W} EF_i \times F_i}{PP}$$

From the form of equation (1) it is apparent that if the terms in the numerator have wide error bars and the denominator has relatively narrow error bars, the resulting distribution will have a right tail. In general, multiplying uncertain, positive values produces a roughly lognormal distribution, i.e., bounded on the left by zero, with a long right tail.

Table 2. Parameters and ranges explored using the reduced-form model for US corn ethanol. (Based on Plevin, O'Hare et al. In review)

Parameter	Description	Units	Low	High
FY	Fuel yield	L ha^{-1} y^{-1}	3500	4500
NDF	Net displacement factor		25%	80%
EF_F	$EmissionFactor_{forest}$	Mg CO_2 ha^{-1}	350	650
EF_G	$EmissionFactor_{grass}$	Mg CO_2 ha^{-1}	75	200
EF_W	$EmissionFactor_{wetland}$	Mg CO_2 ha^{-1}	1000	3000
F_F	Fraction: forest		15%	50%
F_G	Fraction: grassland		*1 – (forest + wetland) fractions)*	
F_W	Fraction: wetland		0%	2%
PP	Production period	y	15	45

[1] ILUC is the most uncertain component, and the most politically salient dimension, of biofuels' total global warming effect.

Fuel yield (*FY*) is the amount of biofuel produced annually per hectare of feedstock production. Land net displacement factor (*NDF*) is the ratio of (a) hectares of land brought into crop production anywhere in the world to replace agricultural land used by biofuel feedstocks, to (b) the hectares dedicated directly to additional biofuel feedstocks. *NDF* includes the combined effects of (i) price-induced yield increases, (ii) relative productivity of land converted to cropping, (iii) price-induced reductions in food consumption, and (iv) substitution of crop products by biofuel co-products, such as distillers' grains replacing corn as animal feed.

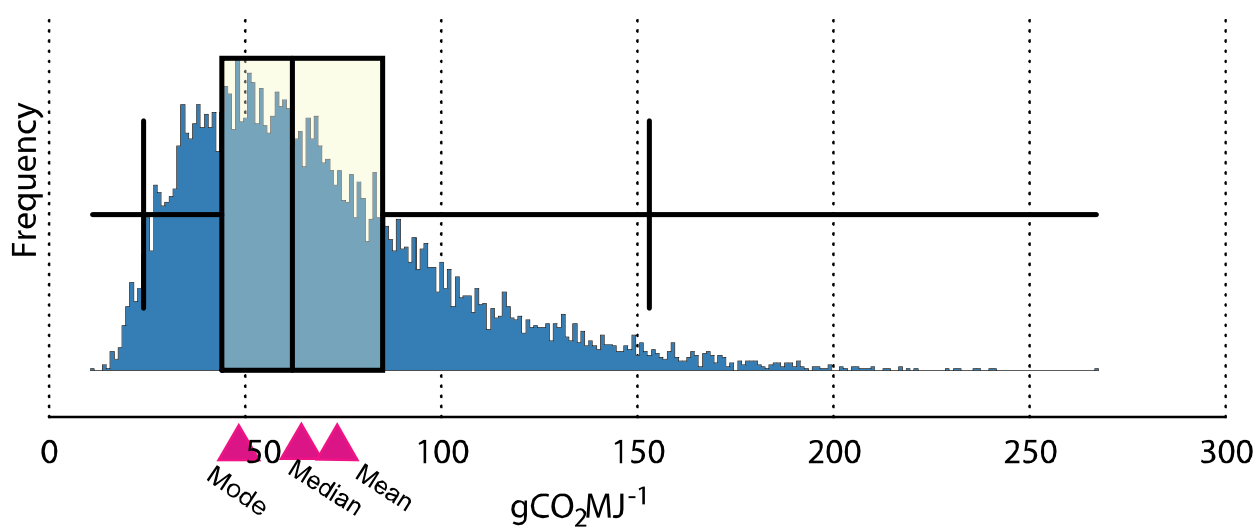
The parameters EF_F, EF_G, and EF_W represent the CO_2 emissions per hectare when forest, grassland, and wetlands, respectively, are converted to cropland. The fraction of total land conversion that occurs on former forest, grassland, and wetlands is represented in parameters F_F, F_G, and F_W, respectively. The assumed production period is represented in parameter *PP*.

Results

Representing the nine model parameters using uniform distributions bounded as shown in Table 2 resulted in the output distribution shown in Figure 1. The central 95% interval ranges from about 25 to 150 g CO_2e MJ^{-1}, with a median value of approximately 65 g CO_2e MJ^{-1}.

The distributions representing input parameters and thus the results of the Monte Carlo simulation are subjective, however similar distribution shapes are produced when the model parameters are represented using triangular or lognormal distributions (Plevin, O'Hare et al. In review). Therefore, we conclude that if these parameter ranges are plausible, then the output distribution is likewise plausible. Substantial changes in the *ranges*, however, will change the results.

Figure 1. The blue area shows the frequency distribution for indirect land use change emissions induced by US corn ethanol. Model parameters were represented as uniform distributions using the values shown in Table 1. The overlaid box-and-whiskers graph represents the same data, with the box representing the inter-quartile range (25th to 75th percentile values) and the vertical line across the box representing the median. The ends of the whiskers show the maximum and minimum values, and the crossbars identify the 2.5 and 97.5 percentile values. Notice that the low end of the IQ range is about at the mode (most likely value) of this distribution, with the mean and median both substantially higher. (Based on Plevin, O'Hare et al. In review)



Uncertainty importance analysis indicates that the land net displacement factor (*NDF* in equation 1) contributes approximately 35% of the total variance in ILUC emissions when the production period is allowed to range from 15 to 45 years. When the production period is fixed at 30 years, *NDF* accounts for about 75% of the total variance. The *NDF* is the most challenging parameter to estimate since it is a result of a system of globally linked economic markets and depends on many uncertain parameters and subjective choices in the economic models used. Barring the arrival of more precise data and better causal models of the global economy, we don't expect this uncertainty to be narrowed appreciably.

ILUC emissions should be included in regulations despite uncertainty

The requirement to estimate ILUC emissions poses significant challenges for regulators: the complexity of the global economy, a lack of sufficiently detailed data and causal models, and a dependence on assumptions about future developments prevent modeling ILUC emissions accurately. However, no study of which we are aware has produced zero or negative values for ILUC emissions. Rather, modeling studies have produced central estimates of the ILUC emissions for corn ethanol ranging from 14 to 104 g CO_2e MJ^{-1}, with sensitivity analyses showing values as high as 200 g CO_2e MJ^{-1}. The present study, which considers uncertainty in a broader set of parameters than do most studies, suggests a plausible range from 25 to 150 g CO_2e MJ^{-1}. We note that the life cycle GHG emissions of gasoline are typically estimated at 90–100 g CO_2e MJ^{-1} (CARB 2009; USEPA 2010).

The robust asymmetry of the resulting distributions for ILUC, with a long tail on the high side, force attention to the dispersion this causes among the mean, median and mode of such a distribution, and thus to the cost of error in using a given value for ILUC when the real value is different. It is a standard result in decision theory that if this cost function is linear in the absolute error, the optimal action (choice of value) is the median of the distribution; if quadratic, the mean. *Both of these are higher than the mode in all the distributions we generate*, so we argue for a regulatory value of ILUC significantly higher than the mode or "most likely" value of of a single model's results, or of an aggregate such as we analyze here. If there is reason to believe the cost of error is asymmetric around zero, further analysis and research to characterize it is very important, and a numerical solution for the optimal regulatory value of ILUC is probably required.

Excluding uncertain components from estimates of the life cycle GHG emissions of biofuels provides only specious precision, and could result in perverse policy outcomes.

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