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Supporting Online Materials for: Global Land Use and Greenhouse Gas Emissions Impacts of Maize Ethanol: The Role of Market-Mediated Responses

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1. Current Legislative Context

Among current legislative approaches to the issue of biofuels and sustainability, see:

United States:
Section 202 of the 2007 Energy Independence and Security Act (EISA) requires 36 billion gallons of renewable fuel by 2022. Of that total, 15 billion gallons may be 'conventional', or corn-based ethanol. The renewable fuel standard under EISA includes life cycle GHG reduction performance requirements that include emissions from indirect land change. The US EPA's notice of proposed rule-making (NPRM) and draft regulatory impact analysis, released in May 2009, are available at http://www.epa.gov/OMSWWW/renewablefuels/.

United Kingdom:
As part of the Gallagher Review, the independent Renewable Fuels Agency in the UK has recommended that the current Renewable Fuel Transport Obligation (RTFO) target for 2008/09 (2.5% by volume) should be retained, but the proposed rate of increase in biofuels be reduced to 0.5% (by volume) per annum rising to a maximum of 5% by volume by 2013/14. This compares with the RTFO's current target trajectory of 5% by 2010. The review concluded that while uncertainty and data limitations prevent accurate estimation of the GHG emissions from biofuels-induced land use change, there is substantial risk that expanding biofuels production would lead to land conversion and greater GHG emissions.
http://www.dft.gov.uk/rfa/reportsandpublications/reviewoftheindirecteffectsofbiofuels/executivesummary.cfm

State of California:
In April 2009, the California Air Resources Board (CARB) approved rulemaking for state's Low Carbon Fuel Standard (LCFS). The LCFS requires at least a 10% reduction in life cycle GHG emissions from the state's transportation fuels by 2020. CARB based its estimates of emissions from indirect land use change on the modeling described herein and on additional modeling in GTAP by authors Golub and Hertel. Detailed information on the LCFS is available at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

2. Methodological Overview

To estimate the climate effects of market-mediated land use changes resulting from biofuels expansion, we combined economic modeling results with assumptions about the types of ecosystems affected, and the carbon fluxes from changes to those ecosystems.

The steps followed in our analysis are:

1. Select an increment to biofuels production levels.

2. "Shock" GTAP to force the desired increase in biofuel production, resulting in an estimate of the land area converted among cropland, forestry, and pasture use in various regions of the world.
3. Map the economic land area changes indicated by GTAP to existing ecosystem types.
4. Estimate the changes in carbon stocks and carbon sequestration owing to ecosystem conversions.
5. Compute a scalar value with which to compare the global warming intensities of the biofuel and its petroleum-based alternative.

To model indirect land use change emissions, we combine two models: (i) GTAP, which provides estimates of changes in area dedicated to forestry, pasture, and cropping by agro-ecological zone, and (ii) a carbon accounting model that estimates the emissions from land use conversion, based on Searchinger, Heimlich et al. (2008b) with modifications described below. We have combined the two models by importing regional emission factors generated by the carbon accounting model into GTAP. This facilitates complete analysis within one modeling framework and greatly simplifies the systematic sensitivity analysis described below. Our metric for LUC emissions is g CO_2 y per MJ , which measures a GHG discharge associated with maize ethanol production.

3. Modeling Approach

To estimate indirect land use change due to ethanol production in the US, we utilize a computable general equilibrium model (CGE). In this section, we provide: 1) a discussion of CGE models in general, 2) a brief description of the standard GTAP model, 3) a brief description of specific version of GTAP used in this work, followed by a discussion of several model-specific features relevant to this study.

3.1. General equilibrium modeling

General equilibrium, which dates back to Leon Walras (1834-1910), is one of the crowning intellectual achievements of economics. It recognizes that there are many markets and that they interact in complex ways so that loosely speaking, everything depends on everything else. Demand for any one good depends on the prices of all other goods and on income. Income, in turn, depends on wages, profits, and rents, which depend on technology, factor supplies and production, the last of which, in its turn, depends on sales (i.e., demand). Prices depend on wages and profits and vice versa.

To make such an insight useful, economists have to be able to simplify it sufficiently to derive predictions and conclusions. Theorists typically do this by slashing the dimensionality, say to just two goods, two factors and two countries, and often focusing on just a few parts of the system. An alternative approach is to keep the complex structure but to simplify the characterization of economic behavior and solve the whole system numerically rather than algebraically. This is the approach of Computable General Equilibrium (CGE) modeling. CGE models specify all their economic relationships in mathematical terms and put them together in a form that allows the model to predict the change in variables such as prices, output and economic welfare resulting from a change in economic policies, given information about technology (the inputs required to produce a unit of output), policies and consumer preferences. They do this by seeking prices at which supply equals demand in every market – goods, factors, foreign exchange. One of the great strengths of CGE models is that they impose consistency of one's view of the world, e.g., that all exports are imported by another country, that the sum of sectors' employment does not exceed the labor force, or that all consumption is covered by production or imports. This consistency can often generate empirical insights that might otherwise be overlooked in complex policy analysis – such as the fact that ethanol mandates may result in reduced gasoline consumption when the industry is asked to pass increased costs on to consumers.

3.1 The GTAP Model

In this work we utilize a CGE model called GTAP (Hertel 1997). The mathematical relationships assumed in the GTAP model are generally rather simple, and although 'many' markets are recognized, they still have to be very aggregated –particularly for global economic analysis. The GTAP Data Base underlying the GTAP model has 57 sectors, so, for example, 'transport and communications services' appear as a single industry. In principle all the relationships in a model could be estimated from detailed data on the economy over many years. In practice, however, their number and parameterization generally outweigh the data available. In the GTAP model, only the most important relationships have been econometrically estimated. The remaining economic relationships are based on literature reviews, with a healthy dose of theory and intuition. An important limitation of CGE models is that very few of them are tested as a whole against historical experience—although GTAP is one such (Liu 2004; E. Valenzuela 2007).

CGE modeling is a very powerful tool, allowing economists to explore numerically a huge range of issues on which econometric estimation would be impossible; in particular to forecast the effects of future policy changes. The models have their limitations, however. First, CGE simulations are not unconditional predictions but rather 'thought experiments' about what the world would be like if the policy change had been operative in the assumed circumstances and year. The real world will doubtless have changed by the time we get there. Second, while CGE models are quantitative, they are not empirical in the sense of econometric modeling: they are basically theoretical, with limited possibilities for rigorous testing against experience. Third, one can readily do sensitivity analysis on the parameter values assumed for economic behavior, although less so on the data, because altering one element of the base data requires compensating changes elsewhere in order to keep the national accounts and social accounting matrix in balance. Of course, many of these criticisms apply to other types of economic modeling, and therefore, while imperfect, CGE models remain the preferred tool for analysis of economy-wide global economic issues.

3.2 GTAP-BIO-AEZ

The great strength of the standard GTAP model is the ease with which it can be modified. In this work we begin with a variant of the standard GTAP model nick-named GTAP-BIO (Hertel, Tyner et al. 2010). GTAP-BIO is modification of GTAP-E model (Burniaux 2002) designed for climate mitigation policy. Birur *et al*. modify the GTAP-E model to incorporate the potential for biofuels to substitute for petroleum products. They also alter the energy demand elasticities based on a historical validation exercise undertaken by Beckman (2008).

A very important feature of biofuel production is the role of by-products, which often compete with the feedstock in feed use. In the case of corn ethanol, the by product is called Dried Distillers Grains with Solubles (DDGS). We build on the work of Taheripour et al. (2008) in incorporating DDGS our analysis.
Finally, we model land use following Hertel et al.(2009) who introduce Agro-Ecological Zones (Lee, Hertel et al. 2009) into the GTAP model. This facilitates analysis of the competition for land within and across regions and the potential for changes in land use driven by biofuel policies. The importance of introduction of AEZs – explicit treatment of global land use competition and different land types – should not be understated. Corn, for example, competes with different crops in different AEZs. The expansion of corn in the US for ethanol use has had a large impact on soybeans in US. This, in turn, has had an impact on the incentive to grow soybeans in particular AEZ in other regions (e.g., Brazil), which can lead to shifts in land use (e.g., livestock and forestry).

We distinguish 18 AEZs, which differ along two dimensions: growing period (6 categories of 60 day growing period intervals), and climatic zones (3 categories: tropical, temperate and boreal). Following the work of the FAO and IIASA (IIASA 2000), the length of growing period depends on temperature, precipitation, soil characteristics and topography. The suitability of each AEZ for production of alternative crops and livestock is based on currently observed practices, so that the competition for land within a given AEZ across uses is constrained to include activities that have been observed to take place in that AEZ.

3.3 The Issue of Baseline Yields

With time and improved technologies, we expect the efficiency of ethanol conversion as well as corn yields to increase, both of which will reduce the land requirements for ethanol. While ethanol conversion efficiency has not changed significantly since our base period (2001), USDA reports that corn yields had risen by 9.3% by 2007. This has a direct impact on the amount of land required to fulfill a given level of ethanol mandate – reducing the land use requirement by a factor of 8.5% in US and globally. Some have argued that higher yields in non-US regions would diminish the need to additional crop area beyond 8.5% reduction. However, this is misleading. What matters is the *ratio of US yields to RoW yields*. If yields worldwide rise at the same rate, then to find land use change in RoW required to offset the diversion of a given amount of US corn to biofuels at higher current yields, it is sufficient to multiply land use change in ROW at base period (lower) yields by inverse of growth in yields (1/1.093).[1]

Our reason for using the 2001 baseline in our analysis is that this is the latest year for which a published, publicly available global crop harvested area and yield database is available (Monfreda 2008). As we will see below, area and yields in the rest of the world are critical to our analysis of the global land use change from biofuels, so having a reliable database is essential. Of course, these yields could be "updated" via some set of projections, but this would further cloud the analysis and potentially compound the measurement errors. For this reason, we prefer the conservative approach of using the 2001 benchmark, and deflating obtained with GTAP global expansion of cropland, needed to produce additional corn ethanol, to reflect the intervening increase in feedstock yields. In the case cited above, we would deflate obtained with GTAP additional global cropland by 8.5%. This approach also has the virtue of allowing the reader to make further adjustments based on future projections of maize yields.

3.4 Intensive and Extensive Yield Responses

Our relatively simple approach to baseline yields does not mean that we do not pay close attention to yield *changes* in the wake of a biofuels program. Indeed these changes are central to our analysis, which is why we explicitly model changes in the intensive and extensive margins. As noted in the text, Keeney and Hertel (2008) review the literature on yield response to corn prices and find the simple average of recent studies results to give a yield elasticity of 0.25. This suggests that a permanent increase of 10% in the corn price, *relative to variable input prices*, would result in roughly a 2.5% rise in yields.[2] Utilizing this yield elasticity in our analysis, we obtain an average yield increase, *due to intensification*, of 2.8%, as reported in Table 2 of the text.

Turning to the extensive margin of yields there are two important contributors in our model. First, there is the change in corn yields as corn replaces other crops on existing crop land (e.g., shifting from a corn-soybean rotation to continuous corn). We can estimate this effect by referring to the differential in net returns to land in existing uses, on the assumption that land will be allocated to its highest value use. If corn production expands onto lower productivity land, then average corn yields will fall. The second extensive margin measures the change in average crop yields as cropland area is expanded into pasture, and possibly forest lands. In the absence of strong empirical evidence, we simply assume a value of 0.66 here – that is, it takes three additional acres of marginal cropland to offset the impact of diverting two hectares of current (average)

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[1] From the global market clearing condition for corn, the base period required RoW corn area is equal to global food demand, deflated by RoW yields minus the ratio of US yields to RoW yields, multiplied by the base year US corn acreage. Assuming fixed yields and fixed demand, and adjusting US corn acreage required for biofuels in light of the higher yields, all that matters is the ratio of US to RoW corn yields. If US yield had risen by 9.3% leading to 8.5% less land required for corn in US, and both US and ROW yields rise at the same rate, then RoW land use change is 100*(1-1/1.093) = 8.5% smaller.

[2] If the long run price of corn were to double, from $2/bu to $4/bu and the price of land substituting inputs merely increased by 50%, then the output-input price ratio would rise by 33% and the expected yield increase would be 0.25 * 33% = 8.25%.

cropland to biofuels production.[3] The “extensive margin” row of the US panel in Table 2 of the text reports the impact of the two extensive margins on total land requirements in the US. As can be seen, the extensive effect tends to offset the intensification effect, resulting in a *net* yield increase for coarse grains of just about 0.4%. However, the extensification effect varies widely by Agro-Ecological Zone and has an important impact on estimated changes in land cover.

3.4.1. Decomposition of the extensive yield response

Yield extensive margin is a change in crop yield as crop land expands/contracts in expense/benefit of other crops, pasture and forestry (the extensive margin). As noted above, we consider two factors here. It is impossible to directly separate the two extensification effects in the simulation because the model does not keep track of how many non-cropland hectares are converted to *a specific crop*, but rather finds net change in *total* cropland. To separate two extensification margins, we take an indirect approach. In a separate simulation, we assume that newly converted pasture and forest land has exactly the same productivity as current cropland (no fall in productivity as pasture and forests are converted to cropland). This gives us first extensive margin, which is change in yields as land shifts amongst crops. The residual (in percentage change terms) between (1) base case extensive margin that includes both effects and (2) new extensive margin that includes only change in productivity as land shifts among crops is (3) extensification effect due to expansion of cropland into pasture and forest land. Note, the yield intensive margin does not change between the base case simulation and the new simulation. The decomposed yield extensive margin is shown in Table S1.

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[3] Average productivity here is productivity of cropland within specific AEZ and region.

Table S1. Decomposition of yield extensive margin

USA

	Coarse Grains	Oilseeds	Sugarcane	Other Grains	Other Crops
	Decomposition of Yield Changes,%				
Yield	0.41	-1.20	0.40	-0.43	-1.25
Intensive	2.75	1.31	1.82	0.86	0.47
Extensive	-2.27	-2.48	-1.39	-1.28	-1.71
Total yield extensive margin	-2.27	-2.48	-1.39	-1.28	-1.71
Change in yields as land moves among crops	-1.91	-2.12	-0.89	-0.84	-1.30
Change in yields as pasture and forest land are converted to cropland	-0.37	-0.36	-0.50	-0.44	-0.42

REST OF THE WORLD

	Coarse Grains	Oilseeds	Sugarcane	Other Grains	Other Crops
	Decomposition of Yield Changes,%				
Yield	0.35	0.46	0.29	0.25	0.16
Intensive	0.26	0.32	0.19	0.18	0.10
Extensive	0.09	0.13	0.09	0.07	0.06
Total yield extensive margin	0.09	0.13	0.09	0.07	0.06
Change in yields as land moves among crops	0.19	0.20	0.21	0.11	0.15
Change in yields as pasture and forest land are converted to cropland	-0.10	-0.06	-0.11	-0.04	-0.09

3.5 Explaining the Decomposition in Figure 2

In terms of the GTAP model – indeed any well-specified economic model – the notion of resource constraints derives from the fact that the fundamental factors of production: land, labor, capital and natural resources are ultimately in fixed supply. So if any individual sector seeks to expand, it must bid these factors away from other uses. Capturing this feature explicitly is one of the major strengths of a general equilibrium model such as GTAP. However, this effect can also be "mimicked" in a partial equilibrium model such as the FAPRI model used for the Searchinger et al paper by introducing upward sloping factor supply schedules (in FAPRI's case, these are present for land used in crop production). To the extent that higher factor prices are reflected in higher product prices, and higher product prices translate into higher prices for intermediate inputs used in other sectors (e.g., the use of corn in the food processing sector), the effect of introducing resource constraints will be felt throughout the economy, thus making it more difficult to trace/pin down than things like "by-products", or "crop yield response".

In the central figure in this paper, Figure 2, the presence of "resource constraints" is reflected in all GTAP experiments shown with the exception of the very first one. In the first experiment, it is assumed that all resources are available in infinite supply. Therefore none of the factor or commodity prices change in response to higher demand for land triggered by corn ethanol expansion. It is assumed that the increase in ethanol production to the level of 15 billion gallons per year can be achieved with no change in any prices whatsoever. While this is an absurd assumption, it is a useful decomposition device and permits us to reproduce the number you would get if you just did the accounting and figured out how much land is needed to meet this additional demand for corn ethanol.
In the second experiment, which we call "resource constraints", we introduce upward sloped supply curves. The upward sloped supply curves are still there as we move from experiment 2 to the subsequent experiments. In the second experiment, while we allow prices to change as demand for scarce resources rises, we limit agents' ability to respond to higher prices. This is a useful tool for further decomposing the estimated response to the ethanol expansion.

Specifically, we do not allow:

- R1) food consumption to diminish in response to higher food prices;
- R2) crop producers to intensify production to boost yields in response to increased returns;
- R3) production of ethanol co-product, so livestock producers cannot substitute biofuel co-products for grains in animal feed; however, livestock producers can substitute other feedstuffs for higher priced coarse grains, and they do so.
- R4) Finally, we do not allow any decline in land productivity as forests and pasture are converted to crops.

We relax restrictions R1 – R4 one at a time in the experiments labeled 3-6. Why do we do this? To show the importance of each of these four effects separately. Here, it is important to note that it is likely if we relax constraints in a different order, the size of each effect would be different. The point is that all of these factors influence the price responsiveness of supply and demand in the economy and therefore interact with one another in determining the market-mediated response to biofuels.

In Figure 2 of the paper, the first experiment reports the gross land requirement (no market response) needed to produce the additional biofuel which equals 15.2 million hectares. Second, the resource constraints, experiment shows the reduction in land use when agents react to increased prices but in a limited way due to R1 – R4. Especially pertinent to land use, we observe the following responses to higher prices:

a) livestock producers can use less land, both directly through reduced grazing as pasture rents rise, and indirectly through the purchase of other feedstuffs that are less land intensive as coarse grains prices rise;
b) forest producers can use less land and more other value added inputs as forest land rents rise;
c) consumer demand on non-food land based products (like forestry products) is sensitive to prices; forestry and forestry products are also intermediate inputs into many non-food sectors and demand for these inputs moves together with demand for final product (forestry and forestry products are used in fix proportion to output in these sectors), which intern is sensitive to prices.

All three effects (a)-(c) are present in all experiments presented in figure 2, EXCEPT the first experiment where prices do not change. Again, due to the interplay between the forces of supply and demand, the price changes will be different across six experiments in Figure 2. If the additional land requirement drops by 26% between first (gross land requirement) and second (resource constraints) experiment, it does not necessarily mean that reduction in demand for land in our final experiment due to a, b and c above is also 26%. The effects across the experiments in Figure 2 are not additive because price changes across the experiments differ due to the interactions between these different effects. It would be desirable to conduct an additional set of experiments to isolate the relative importance of items (a) – (c) in the aggregate reduction in land requirements between the first and second bars of Figure 2. However, the model does not have a general equilibrium solution without these three effects present simultaneously. So, further decomposition is impossible.

4. Additional Results on Global Land Use Change

Table S2 reports land cover changes for the world as a whole. As with the US, pasture land falls in all regions of the world, but forest land rises or is unchanged in the less productive regions where it competes less directly with crop production. Overall, forest cover in RoW falls by just 0.25 Mha, while pasture land falls by nearly 2.4 Mha.

Table S2 Land Cover Changes (Mha)

	US vs. Rest of World (non-US regions)	
Land cover type	US	ROW
cropland	1.59	2.6
pasture	1.05	-2.35
forest	- 0.54	-0.25

	ROW disaggregated				
	Canada	EU	Brazil	Japan	China
cropland	0.45	0.45	0.30	0.01	0.04
pasture	-0.15	-0.16	-0.24	0.00	-0.13
forest	-0.29	-0.29	-0.06	-0.01	0.09

	ROW					
	India	LAEn Exp	RofLatAme rica	EEuropeFSU	RofEurope	MENA
cropland	0.05	0.18	0.06	0.16	0.07	0.08
pasture	-0.02	-0.18	-0.14	-0.44	-0.05	-0.08
forest	-0.03	0.00	0.08	0.27	-0.02	0.00

	ROW					
	SSAEnExp	RofS SA	SASIAEEX	RoHIA	RoASIA	Oceania
cropland	0.54	0.09	-0.01	0.00	0.03	0.11
pasture	-0.53	-0.09	-0.01	0.00	-0.02	-0.11
forest	-0.01	0.00	0.03	0.00	-0.01	0.00

Source: Authors' Calculations

Market-Mediated Effects: Global Summary Table S3 offers a global summary of the market mediated effects of increasing corn ethanol production in the US from 6.63GL to the target of 56.8 GL. Table S3 decomposes the change in global crop production into yield and area components and further decomposes the yield component into the intensive and extensive margins. The final column of Table S3 reports the change in direct and indirect food consumption. This is simply global production, less energy uses of crop products for liquid fuels.

The global economy will respond to a biofuels program that diverts crop land from food (and fiber) by increasing yields and by reducing consumption. Based on the results in the first panel of Table S3, we observe a global intensification of crop production, with the greatest intensification occurring for coarse grains and oilseeds. However, global yields decline at the extensive margin for all crops other than sugar, with the largest drops for coarse grains, oilseeds and other agriculture. Consequently, total yields rise less for these crops, with other agricultural yields actually declining slightly.

Table S3. Decomposition of Global Land Use Change, by Crop (% change)

Crop	Yield			Area	Production	Nonfuel Consumption
	Intensive	Extensive	Total			
Coarse Grains	1.05	-0.68	0.36	5.45	5.85	-5.28
Oilseeds	0.49	-0.31	0.18	-0.09	0.13	0.14
Sugarcane	0.26	0.03	0.29	-0.50	-0.22	-0.22
OthGrains	0.22	-0.01	0.21	-0.52	-0.31	-0.31
OthAgri	0.17	-0.26	-0.09	-0.20	-0.24	-0.24

Source: Authors' Calculations

Area expansion dominates the production increase for coarse grains, sugar crops, other grains and other agriculture, while higher oilseed yields dominate the area decline in the case of that crop category, so that total production rises. This rise in production facilitates increased (indirect) consumption of oilseeds through their use as a substitute for coarse grains in livestock feeding. Meanwhile, coarse grains consumption falls sharply as DDGS and other feedstuffs replace the use of this feedstock in livestock production. Consumption of sugar crops, other grains and other agriculture all fall, implying lower food consumption for households.

Given the potential importance of consumption impacts we explore these in greater detail in the next section of the SOM, taking account not only of direct consumption of bulk products, but also considering consumption of livestock and processed food products.

A Closer Look at the Consumption Impacts: Table S4 reports changes in food prices and consumption for all food categories in the US and globally. We find that US coarse grains prices rise by about 16% (7% rise is the global average) for the 50 GL y^{-1} ethanol increase. This leads to reductions in consumption for coarse grains and many other agricultural and food products. Direct consumption of coarse grains is only modestly affected in the US (-0.9%), owing to price-inelastic demand. Despite a smaller price rise, consumption of livestock products (more price-sensitive) falls by more. In the world as a whole, consumption of all food falls. While lower food consumption may not translate directly into nutritional deficits amongst wealthy households, any decline in consumption can have a severe impact for households that are already malnourished.

As noted in the text, we sought to isolate the "nutritional cost" of corn ethanol by re-running the model holding consumption fixed with a series of country-by-commodity subsidies. In this case, we find that twice as much forest is converted to farming, and emissions from LUC increase by 50%, to 1127 g CO_2 y MJ^{-1} of capacity. Therefore, any efforts to mitigate adverse nutritional impacts will boost the GWI of the biofuel.

Table S4: Food price and consumption effects of a 57 GL y^{-1} increase in US maize ethanol production.

Food Consumption Category	"Current Policy" Experiment (reduction in food consumption)				Fixed Food Consumption	
	US		Global		US	Global
	Market Price, % change	Consumption Quantity, % change	Global Exports Price, % change	Consumption Quantity, % change, weighted by market values across regions	Market Price, % change	Global Exports Price, % change
Coarse Grains	16.33	-0.9	7.22	-0.35	17.64	8.04
Other Grains	3.7	-0.3	1.73	-0.2	4.46	2.29
Oilseeds	6.22	-0.44	3.27	-0.18	7.18	3.95
Sugarcane	8.64	-0.56	0.91	-0.09	10.44	1.37
Livestock	2.4	-1.24	0.63	-0.23	2.73	0.82
Other Food Products	0.41	-0.3	0.21	-0.18	0.46	0.29
Processed Livestock	0.85	-0.5	0.16	-0.20	0.95	0.21
Other Agriculture	2.71	-1.15	0.69	-0.33	3.24	0.99

Discussion of the changes in other grains output and harvested area

In the model, the "Other grains" aggregate includes 2 (of total 57) standard GTAP sectors: paddy rice and wheat. Direct use of other grains is important for private consumption in only a few regions (column 3, Table S5). So, the reduction in private consumption of other grains plays a small role in total output reduction. And the decline in private consumption itself is not large (column 7, Table S5).

The use of rice in animal feed is common in Asia, whereas feed-wheat is more common in other regions of the world. Table S5 below shows use of other grains by region. Thus, livestock, "other food and feed", and "other agriculture" (including processed rice) are three large purchasers of other grains. In the processed foods sectors and other agriculture there is no substitution allowed among intermediate inputs. So, use of other grains moves up or down (in some regions up, in other regions down) together with output in these sectors. In livestock, we allow for many substitution possibilities with other animal feed ingredients. The direction of substitution depends on relative prices of these ingredients.

The price of the DDGS & maize composite goes up, but price of other grains goes up too (though less). This results in some reduction of DDGS & maize AND a reduction in other grains, and an increase of oilseeds and soymeals in animal feed in the majority of regions. The reduction in direct use of other grains in animal feed is shown column 8, Table S5.

Table S5 Use of other grains, by region

Region	Export share of output	Private consumption share of output	All industry share of output	Livestock sector share of output	Other food and feed and other agriculture sectors share of output	Change in private consumption, %
1	2	3	4	5	6	7
USA	0.56	0.04	0.40	0.04	0.33	-0.30
CAN	0.91	0.01	0.08	0.03	0.05	-0.27
EU27	0.25	0.05	0.70	0.23	0.32	-0.19
BRAZIL	0.00	0.02	0.98	0.02	0.89	-0.27
JAPAN	0.05	0.01	0.93	0.01	0.91	-0.09
CHIHKG	0.00	0.06	0.94	0.47	0.32	-0.07
INDIA	0.02	0.63	0.34	0.01	0.23	-0.02
LAEEX	0.41	0.01	0.57	0.01	0.48	-0.51
RoLAC	0.05	0.14	0.81	0.03	0.57	-0.34
EEFSUEX	0.04	0.12	0.84	0.33	0.16	-0.25
RoE	0.11	0.24	0.64	0.23	0.29	-0.14
MEASTNAEX	0.01	0.77	0.22	0.02	0.10	-0.44
SSAEX	0.00	0.03	0.96	0.00	0.87	-0.19
RoAFR	0.03	0.57	0.40	0.01	0.33	-0.13
SASIAEEX	0.00	0.04	0.96	0.02	0.89	-0.14
RoHIA	0.00	0.07	0.93	0.08	0.78	-0.15
RoASIA	0.01	0.20	0.79	0.05	0.64	-0.07
Oceania	0.67	0.02	0.31	0.05	0.18	-0.21

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Table S6 shows supply side of other grains: changes in area, production and yields, and decomposition of yields changes. US share in global other grains harvested area is 0.16. Remember that this sector includes both wheat and paddy rice. Paddy rice yields are much higher than for wheat. This explains why the 0.16 share in harvested area translates to only 0.06 share of global output for US. On the other hand, in China the 0.02 share of global harvested area corresponds to 0.26 share of global production due to very high rice yeilds (columns 2 and 3, Table S6).

The reduction in US harvested area is large, as is the reduction in output (about 9 percent, Table S6). The export share in US output is large (0.56). Through this trade channel, the reduction in US output leads to other grains area expansion in other regions. But as shown in Table S6, column 5, expansion in RoW area is small in percentage terms.

Given the facts that:

a) The other grains sector in US comprises mostly lower yielding wheat, and
b) In other regions – particularly Asia -- the other grains sector is mostly higher yielding rice,

one hectare lost in US requires less than one hectare in rice focused regions, like India, to replace lost grains. Of course, this compositional effect could be eliminated by disaggregating rice and wheat, and this is recommended for future studies.

Finally, Table S6 also offers a change in other grains yields (column 6), decomposed into intensive (other grains yields are sensitive to own price) and extensive margins (columns 7 and 8). The extensive margin is decomposed into change in yield due to land conversion among crops (column 9) and change in yield due to expansion of cropland into forests and pasture. The latter, by assumption, is negative in all regions. With the exception of the US, other grains yields are increasing in all regions. This is driven by the responsiveness of other grains yield to own price (positive in all regions), but in many regions it is also driven by the impact on average yields of crop-shifting (column 9). So, not only yield sensitivity to prices drives non replacement of other grains area, but also land conversion among crops.

Table S6 Other grains yield and harvested area

Region	Share in global other grains harvested area	Share in global other grains production	Change in production, %	Change in harvested area, %	Change in yield, %	Change in yield due to intensification, %	Change in yield due to extensification %, both margins together	Change in yield as maize replaces other crops on existing cropland, %	Change in yield as cropland expands into forestry and pasture, %
1	2	3	4	5	6	7	8	9	10
USA	0.16	0.06	-9.42	-9.29	-0.43	0.86	-1.28	-0.84	-0.44
CAN	0.04	0.02	0.41	0.39	0.13	0.41	-0.28	0.12	-0.40
EU27	0.14	0.11	0.35	0.25	0.15	0.26	-0.11	0.02	-0.14
BRAZIL	0.02	0.01	0.26	0.02	0.70	0.32	0.38	0.55	-0.17
JAPAN	0.01	0.01	0.61	0.35	0.27	0.23	0.04	0.11	-0.07
CHIHKG	0.02	0.26	0.14	-0.19	0.33	0.13	0.20	0.21	-0.01
INDIA	0.07	0.17	0.21	0.12	0.09	0.12	-0.03	-0.02	-0.01
LAEEX	0.05	0.02	0.08	-0.68	0.63	0.42	0.21	0.32	-0.11
RoLAC	0.03	0.01	0.89	0.22	0.67	0.36	0.31	0.39	-0.08
EEFSUEX	0.25	0.06	0.23	0.04	0.16	0.13	0.02	0.06	-0.04
RoE	0.01	0.02	0.96	0.69	0.30	0.19	0.10	0.20	-0.09
MEASTNAEX	0.02	0.03	0.90	0.50	0.33	0.12	0.20	0.29	-0.08
SSAEX	0.05	0.01	1.03	0.93	0.08	0.15	-0.08	0.08	-0.15
RoAFR	0.01	0.00	0.76	0.33	0.47	0.23	0.24	0.44	-0.20
SASIAEEX	0.02	0.10	0.16	-0.25	0.38	0.23	0.14	0.13	0.01
RoHIA	0.00	0.01	0.24	-0.10	0.34	0.19	0.15	0.15	0.00
RoASIA	0.01	0.10	0.28	0.05	0.18	0.20	-0.03	-0.02	-0.01
Oceania	0.10	0.01	0.53	0.05	0.49	0.32	0.16	0.28	-0.12
World	1.00	1.00	-0.31	-1.38	0.21	0.22	-0.01	0.06	-0.07

5. Handling Time

A salient issue in this context is the actual global warming intensities (GWIs) of various crop-based biofuels, especially maize ethanol. The issue in large part turns on so-called land cover change (LCC) effects, which are emissions of greenhouse gases and changes in biophysical land surface properties that occur because cultivation of biofuel feedstock crops displace other uses of land without eliminating the demand for food products previously derived from that land. This backward shift in the supply of other land intensive goods leads, via a causal chain operating through world food, fuel, and forestry markets, to global changes in the pattern of land use and land cover to accommodate higher overall output of land-based goods. Both USEPA and the California Air Resources Board are currently planning to recognize and count LCC effects in assigning GWI values as part of their implementation.

When these upfront emissions are simply averaged over 30 years of ethanol production, land cover emissions outweigh all other emissions in the life cycle of maize ethanol. However, this simple treatment of emissions over time makes arbitrary assumptions about the length of a biofuels program and masks the actual damages to society of climate change associated with ethanol-induced land conversion. This is because, to a first approximation, social costs at some point in the future are proportional to cumulative warming, not net emissions. Thus, using the above values, even after 167 years, the cumulative damages of elevated temperature associated with maize ethanol would exceed the cumulative damages associated with continued fossil fuel consumption. We explore this issue in depth in a companion paper (O'Hare, Plevin et al. 2009).

6. A Closer Look at Forest Reversion and Conversion

To explore the role of forest reversion, and the assumptions made about associated carbon sequestration, we performed a series of exploratory analyses, which are summarized in Table S7.

The GTAP model estimates significant pasture reversion to forestry as a consequence of US maize ethanol expansion. As cropland expands into forests in some regions, other regions partially compensate for reduced production of forestry products through reversion. However, GTAP only considers forest lands that are currently accessible as available for conversion. These accessible lands are obtained by first estimating the inaccessible forest lands and deducting them from total forest cover (Sohngen, Tennity et al. 2009). If the model were able to consider the conversion of currently inaccessible forests to productive use, this might tend to reduce the level of pasture reversion to forestry and consequently increase emissions associated with maize ethanol. The level of forest conversion to crops might also increase in this hypothetically less-constrained model because it would be even easier to shift forestry production elsewhere.

In future research, these phenomena should be addressed in an enhanced modeling framework capable of considering access costs for currently unused lands. In the context of the current analysis, however, we are able to bound the uncertainty associated with forest reversion by considering a scenario in which no forest reversion occurs and all of the pasture land that would have been converted to forest remains in pasture. As shown in table S7, this leads to a 10% increase in total emissions.

On the other hand, to the extent that reversion does occur, forests do not grow back nearly as quickly as they can be cleared, so we developed forestry reversion factors based on regional sequestration rates in re-growing forests combined with some simple assumptions about changes in soil carbon. For the forest reversion factor, we followed the method used to calculate foregone sequestration by regenerating forests in Europe and former Soviet Union. That is, we assumed that above ground biomass in pastures is replaced with 30 years worth of aboveground sequestration using carbon sequestration data from actively growing forests. Recall that the primary conversion path is from pasture to forestry, not crops to forestry, so recovered forests are assumed to gain soil carbon levels above and beyond those in pastures, but only in regions where forests actually contain more soil carbon than pastures. Specifically, we assumed that secondary forests regain 75% of the difference between the regional forest soil carbon level and the pasture soil carbon level, consistent with the assumption made in Searchinger et al regarding soil carbon gains from crops to forestry.

However, there is some empirical indication that pastures converted to forestry might actually lose soil carbon (Guo and Gifford 2002). To understand the implications of this, we examined a scenario with alternative emission factors for forest reversion. Instead of gaining soil carbon based on the difference between average forest and average pasture, we assumed that reverting forests lose 10% of soil carbon across all regions. This resulted in a 2% increase in total emissions.

Allowing for complete reversion of forests, as might occur over much longer time periods or with fast-growing plantation species, results in an 11% decrease in total emissions. . Finally, forcing all new cropland to come from forest, as a crude upper bound on the effect of more forest supply from unmanaged forest land, increases C discharge by 120%.

Table S7: Global LUC Emissions Associated with Alternative Forest Reversion and Conversion Scenarios

	Total Emissions	Percent Change from Base Case
	g CO2e / MJ	% change
Base Case	799	0%
No Forest Reversion	881	10%
10% Decline in Soil Carbon from Pasture to Forest	816	2%
Complete Forest Reversion	714	-11%
All Conversion From Forest	1747	119%

7. Sensitivity Analysis

Modeling indirect land use change emissions is an inherently uncertain venture, involving combined economic and ecosystem models that each harbor many data and epistemic uncertainties. And quantifying the full uncertainty in the projected land change emissions is difficult, as described further below.

We estimate the uncertainty in LUC emissions using the Systematic Sensitivity Analysis (SSA) capability available in GTAP. The SSA uses the Gaussian Quadrature (GQ) approach to estimate means and standard deviations of model results, as described in (Arndt 1996). For large models, the GQ method is more tractable than a full Monte Carlo analysis[4], but GQ is subject to several limitations, described in section 8. Our analysis examined the sensitivity of model results to the economic parameters described in Table S8, and to an approximate representation of the probability distributions around emissions factors, as shown in Table S9.

7.1. Parameters included in the SSA

As noted previously, our model results are sensitive to the economic parameters governing the extensive and intensive margins of land use, the acreage response to land rents and the trade elasticities. From prior study (Searchinger, Heimlich et al. 2008b), we have identified parameter value assumptions that make the most difference in estimates of iLUC, and the results here illustrate selected variations in these parameters and their consequences.

The SSA is performed with respect to the following variables and parameters:

1) yield elasticity;
2) elasticity of land transformation across uses;
3) elasticity of effective crop land with respect to harvested crop land;
4) crops and other food products trade elasticities;
5) elasticity of substitution among imports from different sectors

7.1.1. Yield elasticity

Historically, agricultural crop yields have tended to increase over time owing to scientific progress, new varieties, agronomic practice improvements, etc. The higher the average yields, the less land is required to accommodate a given amount of ethanol production. Yields also increase in response to commodity price changes.

Crops in the model are produced using various factors of production: land, capital, labor and intermediate inputs (e.g. fertilizers). The substitution among these factors is governed by a substitution parameter. When land rents are higher, cost minimizing producers will substitute away from land. The larger the elasticity of substitution between land and non-

[4] Our model solves in approximately 12 minutes. A Monte Carlo analysis using just 1,000 simulations, would take more than 8 days.

land inputs, the easier it is to boost yields. The substitution parameter in our model is calibrated to achieve desired yield responsiveness following the work of (Hertel 2007).

We use 0.25 as our central value of this parameter. This value reflects a simple average of the most recent studies of corn yield response to corn price in the US (Keeney and Hertel 2008). As those authors note, earlier studies had shown higher yield response, so there is some evidence that this value has declined with time. (This value is currently modeled with a single global parameter, yet we recognize that the effect will vary across crops, as well as across regions.) In our sensitivity analysis we consider range 0.0–0.5 for this critical parameter.

7.1.2. Elasticity of land transformation across cropland, pasture and forestry

Empirical evidence on land rental differentials suggests that land does not move freely between alternative uses—cropland, pasture, forestry—within an AEZ. Therefore, in the model, such movement is constrained by a Constant Elasticity of Transformation (CET) frontier. Thus, within an AEZ in the CGE model, the returns to land in different uses are allowed to differ. With this structure, we can calibrate the partial equilibrium land supply response to available econometric estimates.

The absolute value of the CET parameter (0.2 in our central set of the parameters) represents the *upper bound* (the case of an infinitesimal share for that use) on the elasticity of supply to a given use of land in response to a change in its rental rate. The more dominant a given use in total land revenue, the smaller its own-price elasticity of acreage supply. The lower bound on this supply elasticity is zero (the whereby all land is already devoted to that activity). Therefore, the actual supply elasticity is dependent on the relative importance (measured by land rents share) of a given land use in the overall market for land and is therefore endogenous.

By way of example, consider the supply of land to crops when CET parameter is set to 0.2 and the share of cropland in total AEZ land rents is 0.4. If pasture and forestry land rents do not change (which is impossible in GE model unless we fix them exogenously), then 1% increase in cropland rents results in the following response in crop land area: 0.2*(1- 0.4) = 0.2*0.6 = 0.12% increase.

In the model, a nested CET structure of land supply is implemented whereby the rent-maximizing land owner first decides on the allocation of land among three land cover types, i.e. forest, cropland and grazing land, based on relative returns to land. The land owner then decides on the allocation of land between various crops, again based on relative returns in crop sectors. To set the CET parameter among three land cover types and among crops, we follow the recommendations in (Ahmed, Hertel et al. 2008). In our sensitivity analysis we consider 0.1 and 0.3 as bounds on this CET parameter.

The CET parameter governing the ease of land mobility across crops is set at 0.5. As with the land cover elasticity, this represents the upper bound on crop acreage response to an increase in the rental rate on a specific crop type. The lower bound is zero (when all crop land in an AEZ is devoted to a single crop). This CET parameter is taken from (Ahmed, Hertel et al. 2008) who base their estimate on the parameter file for the FAPRI model which, in turn underpins the analysis in Searchinger et al. (2008b). In our sensitivity analysis, we vary this between 0.1 and 0.9.

7.1.3. Elasticity of effective crop land with respect to harvested crop land

Pasture and forest lands converted to agriculture are presumed to be less productive than the average of land already in production. The argument is that if it were more productive it would probably be in use already. Again, the assumed yield from this marginal land greatly affects the land use change induced by biofuel production. Our central value for this parameter (ETA), again a global average, is 0.66. This means that marginal land brought into crop production is only two-thirds as productive as average cropland. Values of ETA ranging from 0.32 to 1.0 are considered in the sensitivity analysis. To our knowledge there are no studies presently available that estimate this key parameter. It should be a high priority for future research in this area.

In the global land use databases, there is often a large gap between crop land cover and crop land harvested area. Of course this is partly due to crop failures. However, when multiple cropping is present, this works in the opposite direction, as harvested hectares exceed cropland cover. In the US, cropland cover also includes crop land used for pasture, idle land and CRP land. Here, we assume that this difference remains unchanged (e.g., total CRP land remains fixed).

Table S8. Distributions for economic parameters used in the Systematic Sensitivity Analysis

Parameter	Sector	Central value	Std. Dev.	Absolute change, +/-	Percent change, +/-	Distribution
Elasticity of effective crop land w.r.t. harvested crop land expansion	n.a.	0.66	n.a.	0.34	n.a.	uniform
Elasticity of crop yield w.r.t. to crop price	n.a.	0.25	n.a.	0.25	n.a.	triangular
Elasticity of land transformation across cropland, pasture and forestry	n.a.	-0.2	n.a.	n.a.	80	triangular
Elasticity of land transformation across crops within cropland	n.a.	-0.5	n.a.	n.a.	80	triangular
Elasticity of substitution among imports from different sources	CrGrains	2.60	1.10	2.69	n.a.	triangular
	OthGrains	9.06	4.17	10.22	n.a.	triangular
	Oilseeds	4.90	0.80	1.96	n.a.	triangular
	Sugarcane	5.40	2.00	4.90	n.a.	triangular
	OthAgri	4.14	1.52	3.73	n.a.	triangular

7.1.4. Trade elasticities

Patterns of trade have a significant impact on the composition of land-using activities, inducing significant shifts between crops, livestock and forestry uses. Keeney and Hertel (2008) have shown that bilateral trade specification of a multi-country model is an important source of parametric uncertainty in predicting global land use change from the biofuels programs. When we simulate increased corn ethanol production in the US, more US land is devoted to corn which changes production and land use patterns in US and globally through trade channels. Changes in global land use patterns are important for our emissions per MJ calculations because the emission factors differ across regions.

How readily a shock in the US is transmitted to other countries' land markets is determined through trade elasticities. We consider how sensitive our results with respect to the elasticity of substitution among imports from different sources. In our "central" and sensitivity runs (one standard deviation below and one standard deviation above central value) we use econometric estimates reported in Table S8 and reported in (Hertel 2007).

7.1.5. Uncertainty in Carbon Fluxes

Estimates of the carbon lost upon land conversion include uncertainties in several underlying quantities: the carbon in the above-ground biomass, the carbon in the below-ground biomass (generally estimated as a percentage of the above-ground biomass), the carbon in the soil, and the fraction of these carbon stocks lost upon conversion. Estimates of the carbon lost from conversion of each ecosystem type reflect variation in field observations in different places and times of a phenomenon with intrinsic actual variation across locations. However, there is also uncertainty in how well these data represent the deforestation our analysis attempts to model. For example, the use of average carbon content of particular forest ecosystems (e.g. temperate evergreen forest) may be too coarse since the processes underlying deforestation are unlikely to randomly select forest stands for removal; rather, selection criteria may include factors such as tree density and salability which may favor conversion of certain forest stands over others (Houghton 2005). We have no data upon which to base estimates of this uncertainty within ecosystem types, and our analysis does not incorporate this factor. In addition, there are insufficient data on the carbon content of some ecosystems. Of particular note, the Searchinger *et al* (2008b) model assumes that the grasslands of the China-Pakistan-India region have the average carbon content estimated for the grasslands of Europe. We cannot quantify this epistemic uncertainty.

We estimate the uncertainty in the carbon accounting subsystem using a stochastic implementation of the computational model described in the Searchinger et al supporting materials (Searchinger, Heimlich et al. 2008a), adding probability distributions around all key point estimate assumptions, and using Crystal Ball™ to evaluate the model in a Monte Carlo simulation.[5] The result of this simulation is a set of probability distributions for the emissions

[5] A Monte Carlo simulation repeatedly recalculates the model by selecting randomly chosen values according to each input parameter's defined probability distribution and saving the designated output results. The model is run a large number of times; the frequency distribution of results defines an output probability distribution. All simulation runs in this study were performed

factors (Mg CO_2 per ha) for each region, shown in Table S5. Although the generated distributions were asymmetric, the SSA requires that parameters be assigned symmetric uniform or triangular distributions. To meet this requirement, we used the average of the bounds of the interquartile range as the central value, and half the difference between the 25th and 75th percentile values as the deviation around that central value, to assign symmetrical uniform distributions to each emissions factor. The resulting distributions are show in Table S9**.**

Table S9. Central value and deviations used in the SSA for emission factors (Mg CO_2e ha^{-1})

	Forestry (lost) [a]		Forestry (gained) [b]		Cropland [c]		Pasture [d]	
	mean	deviation	mean	deviation	mean	deviation	mean	deviation
1 USA	770	136	243	49	16	7	111	34
2 CAN	707	138	476	82	16	7	206	83
3 EU27	314	36	407	66	16	7	162	60
4 BRAZIL	403	68	181	39	16	7	75	20
5 JAPAN	573	80	236	25	16	7	93	15
6 CHIHKG	573	80	236	25	16	7	206	81
7 INDIA	573	80	236	25	16	7	206	81
8 LAEEX	403	68	181	39	16	7	75	20
9 RoLAC	403	68	181	39	16	7	75	20
10 EEFSUEX	324	37	433	72	16	7	165	64
11 RoE	314	36	407	66	16	7	162	60
12 MEASTNAEX	157	37	73	22	16	7	87	20
13 SSAEX	317	50	140	26	16	7	44	13
14 RoAFR	317	50	140	26	16	7	44	13
15 SASIAEEX	917	161	350	37	16	7	93	15
16 RoHIA	573	80	236	25	16	7	93	15
17 RoASIA	917	161	350	37	16	7	93	15
18 Oceania	395	99	216	53	16	7	101	24

[a] A higher carbon value reflecting the amount lost when trees are burnt and tilled for crops. These values are used in AEZs where forest is lost.
[b] A lower value reflecting the re-sequestered standing biomass and regained soil carbon above and beyond the soil carbon in pastures. These values are used in AEZs where forest is gained. Note that since almost all predicted transitions to forestry are from pasture, this makes sense. If we were seeing transitions from crops to forestry, a different factor would be appropriate. We've assumed that if commercial forest plantations are planted on existing pasture, the aboveground pasture carbon is first cleared. However, commercial plantations, may regain carbon faster than typical forest ecosystems.
[c] The small amount of aboveground biomass in annual crops
[d] The amount of carbon lost when pasture is converted to crops.

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using 6,000 iterations and Latin Hypercube Sampling (this sampling scheme provides better definition of the tails of the result distribution).

7.1.6. SSA Results for Land Cover

As described above, we implemented the Gaussian Quadrature approach to systematic sensitivity analysis, sampling from the distributions outlined in tables S5 and S6 above. This generated a mean and standard deviation for each endogenous variable in the model. For ease of presentation, we focus on the coefficient of variation (CV), which is the ratio of the latter to the former. A low CV, corresponds to an outcome in which we can place greater confidence. We adopt CV=0.5 – the value at which the mean is twice the standard deviation as a focal point in our discussions.

There are 3 land covers x 18 AEZs x 18 Regions = 972 possible land cover changes in our global model. To reduce these dimensions, we aggregate over AEZs using physical hectare shares for a given AEZ in each region. These weighted CVs are reported in figures S2-S4 for each of the land cover types.

Figure S2 reports the CV outcomes for cropland cover change, by region. From this it can be seen that the cover changes in the US and its major trading partners are fairly robust (CV<0.5). However, the changes in China and South Asia as less certain. And, in the case of the South Asian energy exporters, there is some cropland loss.

Figure S2. Weighted average CVs of cropland expansion and contraction

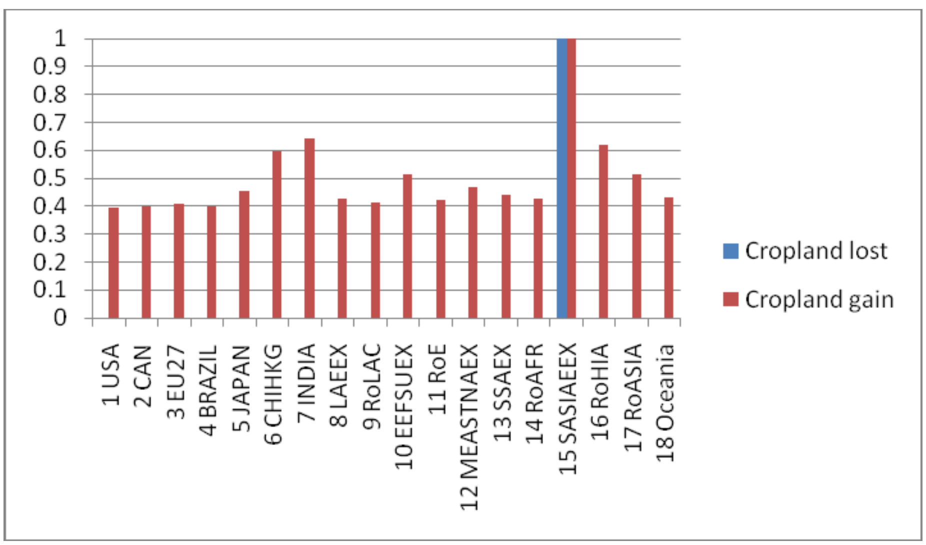
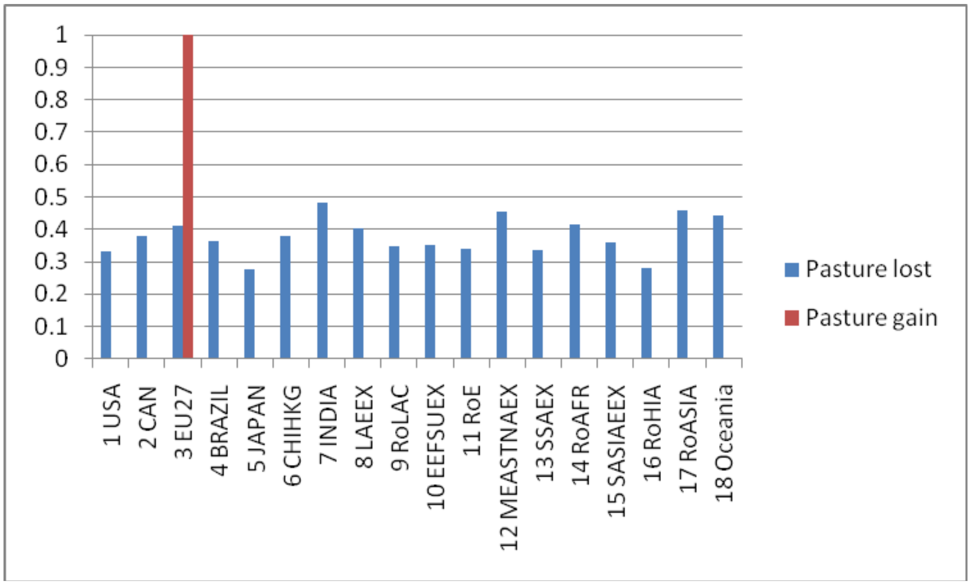


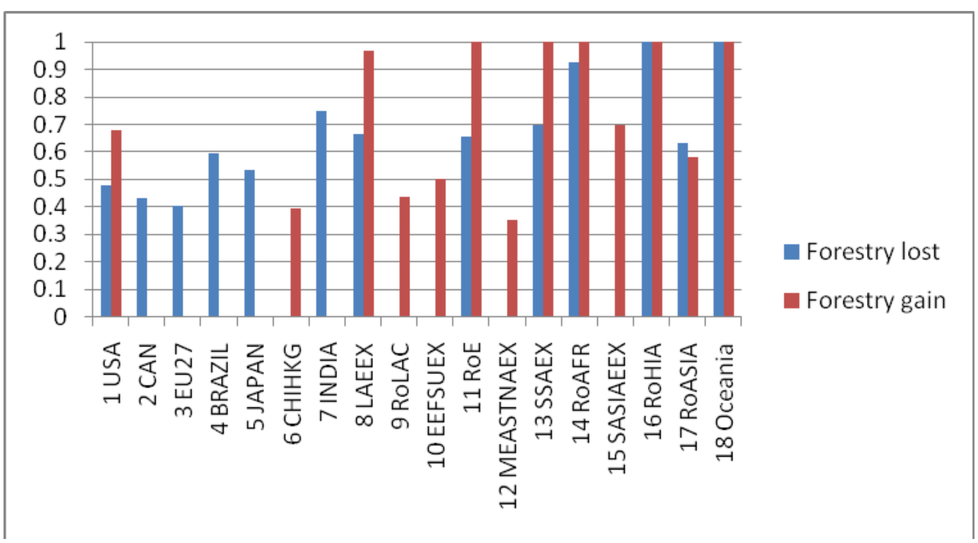
Figure S3 reports the area-weighted CVs for the 18 regions in our model. Apart from the EU, where some AEZs show increased pasture area, all of these are below 0.5 and therefore reasonably robust, by our criterion.

Figure S3. Weighted average CVs of pasture expansion and contraction



Forestry land cover is the most uncertain component of our analysis. As discussed previously, forest lands increase in the less productive AEZs, in response to higher timber prices, while shrinking in AEZs where forestry is competitive with maize, oilseed and other grains. While the CV for forestry losses in USA, Canada and EU are less than 0.5, this is not the case with forestry losses in other regions. And forestry area gains are also quite uncertain.

Figure S4 Weighted average CVs of forestry expansion and contraction



7.1.7. SSA Results for Greenhouse Gas Emissions

In the end, we are most interested in the uncertainty associated with global GHG emissions. Here, we find that the CV associated with global emissions is 0.46, suggesting that, under the assumption of normality, a 95% confidence interval for emissions would range from 64 to 1534 g CO_2 MJ^{-1}. Most notably, this does not include zero – a value which some industry groups have suggested adopting due to the presence of too much uncertainty associated with LUC estimates.

It is also instructive to consider some "bounding runs" of the model. Here, we simply choose a combination of parameters to illustrate the sensitivity of the model to key assumptions. Table S6 reports our findings. The first row reports our base case results of 799 g CO_2 MJ^{-1}. The second row reports the case where we set the yield elasticity at its highest value (0.5) and ETA at its highest value (1.0) as well, thereby maximizing the potential for yields to offset the increased biofuels requirements. This gives a result of 444 g CO_2 MJ^{-1}. When we eliminate the potential for yield response to price, and set ETA at is lower bound of 0.32, we estimate a global emissions rate of 2702 g CO_2 MJ^{-1}.

The final two rows of Table S10 report the outcomes in special cases where we ignore other elements of the market-mediated responses. In the first case, we eliminate the potential for livestock sectors to substitute co-products for other feedstuffs. This boosts the land requirements associated with biofuels and gives an emissions outcome of 1,285 g CO_2 MJ^{-1}. Finally, we report the case, discussed above and in the text, where we hold food consumption constant globally via a set of commodity/region specific subsidies. With food consumption failing to drop, global emissions rise by 41% above the base.

Table S10. Bounding runs on the model: Global GHG emissions in g CO_2 per MJ

Base case	799
Low LUC	444
High LUC	2702
No Coproducts	1285
Constant Food Consumption	1127

7.1.8. Limitations

Both the economic and ecosystem carbon model contain several epistemic uncertainties that cannot be easily represented using the SSA or Monte Carlo methods. Some of these can be explored using discrete scenarios, however. For example, in the economic model, features susceptible to scenario analysis include the choice of functional forms used to implement the model (McKitrick 1998), the choice of model closure (Roberts 1994; Mitra-Kahn 2008), the choice of base year (Roberts 1994), the data chosen to represent the base year, and the level of sectoral and regional aggregation used (Hertel 1999). Although these can, in theory, be examined in scenario analyses, the data requirement to construct these alternatives is prohibitive. In the ecosystem model, epistemic uncertainties include the assumption that the location of the historic agricultural frontier can predict the pattern of biofuels-induced LUC, or that economic pressure alone is a valid predictor of LUC (Geist and Lambin 2002; Schaeffer, Vianna et al. 2005). These are much more difficult to analyze as our understanding of these processes is weak.

8. Discussion: caveats and cautions

The present paper describes findings in a form close to the "language" established by Searchinger (a GW index term that adds LUC to direct discharges independently of time). It does not exhaust the analysis needed for this policy area, and we have already observed three areas in which more work is needed.

As noted above, we think that a simple allocation of LUC discharge to biofuel produced over decades is not a proper representation of the GW effects of biofuel policy. Discounting discharges as though they were economic phenomena is theoretically unsound, and even this crude recognition of time value ignores both the cumulative but non-linear global warming effect of long-lived gases and the risk of irreversible calamities, a risk that increases with GHG concentrations. In parallel work, we examine more sophisticated and scientifically responsible ways to account for time in analyzing LUC, noting here that these factors properly included, because the LUC discharge distinctively occurs at the beginning of the analytic period, will only increase the GW index of crop biofuels relative to petroleum.

We have also begun to elaborate ways to recognize the intrinsic uncertainties in estimates like these so as to include the distributions appropriate for model parameters, and model uncertainties not easily described as statistical distributions of random variables. In future work we will present these results, findings that will greatly enrich the approach of showing selected key parameter values' effects used here.

Finally, we observe an additional indirect effect of a US biofuel mandate that may be relevant to policymakers, namely that forcing a fuel more expensive than gasoline into the motor fuel mix without a parallel subsidy will reduce consumption of the mix and therefore induce a reduction in total emissions from transportation in the US, while (by reducing US demand for gasoline) increasing emissions in the rest of the world. This effect needs to be estimated but is much more difficult to interpret as a biofuel GW index, as it depends on the policy by which the biofuel's use is forced, on market prices for petroleum and biofuels, and on whether any price increase should be treated as intrinsic to the biofuel policy or as a separate policy equivalent to a tax on motor fuel.

In addition to these refinements requiring conceptual advances, we note the following opportunities to refine the present estimates in more technical ways:

Other market-mediated effects on emissions: Changes in livestock intensity and quantity, and in rice farming, induce changes in methane releases that are not captured here; corn farming, especially as higher yields are sought, induces releases of N_2O that may be greatly underestimated in current studies.

Land cover transitions: GTAP does not estimate conversions of particular ecosystems to cropland. Rather it estimates conversions among different economic uses of land. Thus, part of constructing emissions factors for land conversions is determining which ecosystems are converted when pasture or forest becomes cropland. As a starting point, we have used a database from Woods Hole that provides data on historic rates of conversion from specific ecosystems to crops as well as estimates of aboveground carbon loss, below ground carbon loss, and foregone sequestration. Most of these ecosystems can be classified as forests or grasslands. Thus, we use the forestry values, weighted by their historical conversion rates by region for conversion from forestry to cropland and we use the grassland values, similarly weighted by region, for conversions from pasture cropland.

The current version of GTAP does not estimate conversions from unmanaged land to cropland. Thus the model could be overestimating conversions from forestry and pasture (since conversion of unmanaged land would take pressure off of already managed land) and underestimating conversion overall (since the conversion of unmanaged land would only occur if it was cheaper than converting managed land, meaning the total cost of land conversion would be lower than currently modeled). Unmanaged lands that are likely to be important include abandoned croplands and currently inaccessible forests.[6] In the US there has been considerable discussion about the use of CRP land for biofuels. However, USDA has stated that it plans to defend CRP acreage at the level of 32 million acres, and US-EPA analyses have accordingly kept CRP acreage unchanged, relative to baseline. In order to explore variation owing to conversion of different ecosystem types–either different ratios of forest and pasture conversion or conversion of ecosystems outside the market such as CRP–we also considered emissions scenarios in which all conversion is assumed to come from grassland pasture.

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[6] Forest land area used in this work is accessible forest land area and not managed forests. The forest accessibility is function of distance to infrastructure. Accessible forests area includes managed forests plus that part of unmanaged forests that is easily accessible.

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