Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses

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Releases of greenhouse gases (GHG) from indirect land-use change triggered by crop-based biofuels have taken center stage in the debate over the role of biofuels in climate policy and energy security. This article analyzes these releases for maize ethanol produced in the United States. Factoring market-mediated responses and by-product use into our analysis reduces cropland conversion by 72% from the land used for the ethanol feedstock. Consequently, the associated GHG release estimated in our framework is 800 grams of carbon dioxide per megajoule (MJ); 27 grams per MJ per year, over 30 years of ethanol production, or roughly a quarter of the only other published estimate of releases attributable to changes in indirect land use. Nonetheless, 800 grams are enough to cancel out the benefits that corn ethanol has on global warming, thereby limiting its potential contribution in the context of California's Low Carbon Fuel Standard.

Keywords: biofuels, ethanol, land-use change, greenhouse gas emissions, market-mediated effects

In April 2009, the California Air Resources Board adopted the Low Carbon Fuel Standard (LCFS) (Farrell et al. 2007a, 2007b, CARB 2009), and in May of the same year, the US Environmental Protection Agency issued the Energy Independence and Security Act (USEPA 2009a). These actions signal that greenhouse gas (GHG) releases from indirect (or induced) land-use change (ILUC) triggered by crop-based biofuels have moved from scientific debate to consequential public policy. The predominant transportation biofuel in the United States is maize ethanol, and it will remain so for the near future. To date, the only peer-reviewed estimate of emissions due to ILUC from the production of maize ethanol is about 3000 grams (g) of carbon dioxide (CO_2) equivalent discharge per annual megajoule (MJ) of maize ethanol production capacity (Searchinger et al. 2008), or 100 g per MJ if allocated over 30 years of production. *Direct* releases of GHG also occur during the cultivation and industrial processing of maize ethanol. Estimates of these, not including ILUC, are about 60 to 65 g of CO_2 equivalent per MJ (CARB 2009), although improvements in process technologies (Wang et al. 2007, Plevin and Mueller 2008) and farming practices (Kim et al. 2009) may lower this value.

To illustrate the importance of these numbers, consider that California's LCFS requires motor fuel carbon intensity be reduced 10%, or for gasoline, from 96 g per MJ to 86 g per MJ. If ethanol is blended at 20%—twice the current legal limit—the ethanol's total global warming index, including ILUC, would have to be 46 g per MJ to meet this target. The size of the ILUC effect remains highly uncertain and clearly requires additional analysis: The estimates that the California and US regulatory agencies have produced are about a quarter of the 100 g per MJ reported by Searchinger and colleagues (2008a). However, the agencies' estimates are still large enough to make maize ethanol an unattractive compliance option for mitigating current carbon intensity or meeting fuel-use mandates; they are also likely to greatly dampen enthusiasm for other biofuels from food crops.

In this article we use the global economic commodity and trade model, GTAP-BIO (Hertel et al. 2010), to provide a new, comprehensive analysis of market-mediated changes in global land use in response to the expansion of US-grown maize for ethanol. We find the increase in cultivated land associated with US-based maize ethanol to be just two-fifths of the amount estimated by Searchinger and colleagues (2008a). Still, adding our ILUC values to typical direct

BioScience 60: 223–231. ISSN 0006-3568, electronic ISSN 1525-3244. doi:10.1525/bio.2010.60.3.8

emissions gives a total carbon intensity for maize ethanol that will have to be significantly reduced through better process technology (Wang et al. 2007, Plevin and Mueller 2008), a fleet capable of using much higher ethanol blend levels, and an extremely long period of maize cultivation, if maize ethanol is to contribute usefully to GHG reductions in transportation.

Vehicle fuel policies for global warming stabilization pose the question, “If a unit of energy is obtained from fuel A rather than fuel B, how much less greenhouse gas will be emitted?” The answer, in units of grams of CO_2 equivalent per MJ, should include indirect releases anywhere on the planet—because releases everywhere are mixed, and their warming effects are diffuse—caused by predictable responses of the world’s production system to the change in fuel use. Among the most important of these is the release of CO_2 when biofuels’ demand for feedstock triggers a succession of land-use changes that cause forest and other ecosystems with high carbon stocks (often far from where the biofuel is grown) to be converted to cultivation (Searchinger et al. 2008a). These stocks are usually burned or decay, although some, typically less than 10% of the total, may be sequestered in timber products or as charcoal in soil. In the following sections we describe changes due to expanded ethanol production, triggered by initial diversion of a unit of maize farmland in the United States from food to fuel, and following through to the various changes in agricultural practices and land conversion around the world that result in ILUC.

Before proceeding, it should be noted that time is very important in our analysis, an issue explored in O’Hare and colleagues (2009). If a biofuel with direct GHG emissions lower than those from fossil fuel is produced over a long enough time horizon, this initial discharge will eventually be offset (Fargione et al. 2008). However, if production ends after only a few years, the ILUC swamps any advantage the biofuel has insofar as global warming is concerned. We estimate the discharge caused by increasing annual production capacity in megajoules, and we emphasize that the assumed production period for the biofuel being analyzed proportionally affects the estimated GHG emissions per megajoule. Dividing the initial ILUC by 20 instead of 30, representing a 20-year production period, increases the per-megajoule value implied by our 800 g initial discharge by a factor of 50%, to about 40 g CO_2 per MJ.

Estimation of ecosystems converted and associated carbon emissions

We model the expansion of US maize ethanol use from 2001 levels to the 2015 mandated level of 56.7 gigaliters (GL) per year by forcing 50.15 GL of additional ethanol production, with the higher costs passed forward to consumers in the form of higher fuel prices. (As the volume of production increases, so too does the ILUC impact [Tyner et al. 2009].) Looking at the average effect over the entire 50.15 GL, the predicted ILUC is higher than for the first increment, but lower than for the final increment to ethanol production. The version of GTAP that we used identifies land-cover changes within 18 agroecological zones (AEZs) defined by rainfall and temperature (Lee et al. 2009), as well as 18 trading regions. The first panel of figure 1 summarizes the continental pattern of land conversion induced by increased ethanol production. Globally, cropland cover increases by 3.8 million hectares (Mha). In the majority of AEZs, cropland increases at the expense of both pasture and forests. However, some of this decrease in forested area is compensated for elsewhere, as both forestry and cropland increase at

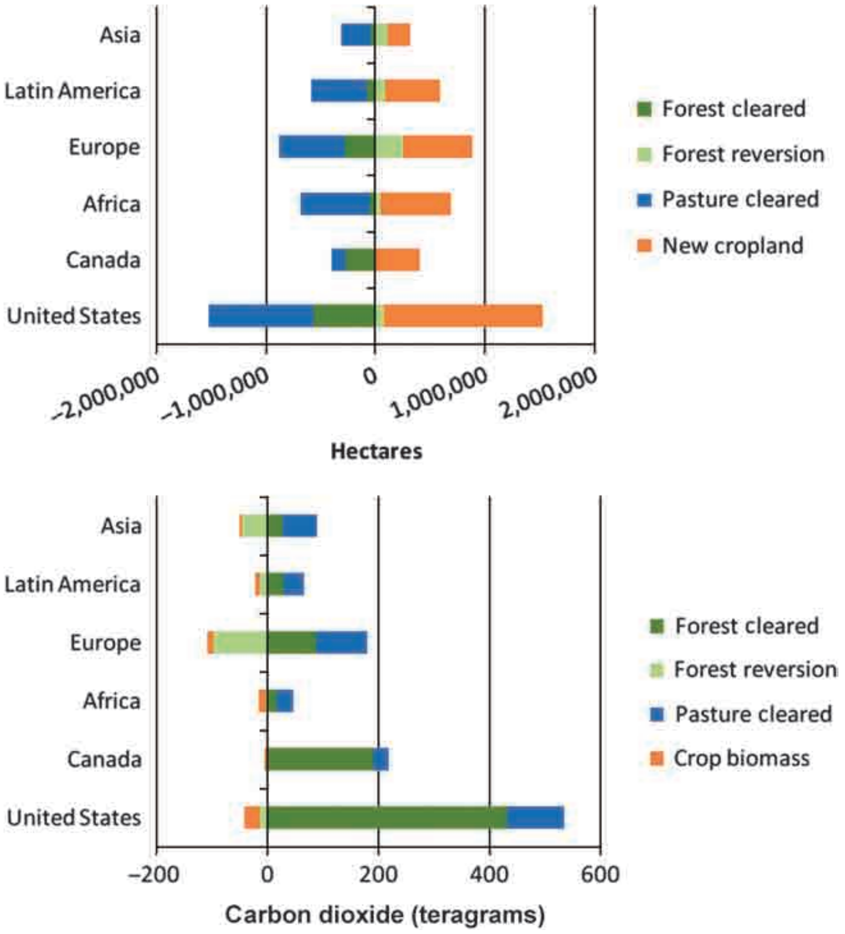

Figure 1. Global land conversion and associated greenhouse gas emissions due to increased maize ethanol production of 50.15 gigaliters per year at 2007 yields, by region.

the expense of pasture in some AEZs. We estimate that most cropland conversion arises within the United States, followed by its dominant export competitors and trading partners. In contrast to Searchinger and colleagues (2008a), we estimate far less conversion in some of the large but relatively closed agricultural economies, such as India. This geographic approach to trade is supported by the recent econometric work of Villoria (2009), who rejects the integrated world market hypothesis implicit in the analysis of Searchinger and colleagues (2008a). It should be noted that, independent of the modeling framework, international trade plays a key role in the ILUC impacts of biofuels (Searchinger et al. 2009).

To examine the global warming implications of these land conversions, we developed an emission factor for each type of transition predicted in each region: forest to crop, pasture to crop, and pasture to forest. These emission factors account for changes in above- and belowground carbon stocks, as well as changes in 30-year carbon sequestration by ecosystems that are actively gaining carbon (we do not account for changes in climate-relevant biophysical land-surface properties, such as albedo or latent heat flux). Applying these factors to the land-use changes predicted by GTAP, we arrive at 870 teragrams of CO2 emissions, which is 800 g per MJ of increased annual ethanol production. Aboveground biomass loss accounts for most of these emissions in the first few years after land conversion, whereas oxidation of soil carbon and avoided sequestration can continue for decades. The second panel of figure 1 shows emissions by region and land conversion type. Carbon sequestered in crop biomass is also shown. The lion's share of emissions occurs in the United States and Canada, where a greater proportion of the forest is expected to be cleared for crops.

Forest area increases with greater maize production in some places (figure 1), mostly in Europe and Asia, where climatic conditions provide a comparative advantage for forests over crops displaced by biofuel production. Significant additional cropland expansion occurs in Africa and Latin America, but mostly from pasture, which contains much less carbon than do forest ecosystems. In Europe, we use a lower emission factor for deforestation because cropland is already reverting to forest, and biofuel cropland demand merely slows this process. The result is avoided (slow) sequestration rather than (rapid) release of aboveground carbon.

Using straight-line amortization over 30 years of production at current fuel yields (following Searchinger et al. 2008a) results in ILUC emissions of 27 g CO_2 per MJ. This is roughly one-fourth the value estimated by Searchinger and colleagues (104 g CO_2 per MJ). Nonetheless, adding our lower estimate of emissions to the 65 g CO_2 per MJ direct emissions from typical US maize ethanol production would nearly eliminate carbon benefit of this biofuel relative to typical gasoline (94 to 96 g per MJ; Farrell et al. 2006, Wang 2007), which should perhaps encourage some ethanol producers to transition to more climate-friendly technologies (Plevin and Mueller 2008). These values suggest a "carbon payback time" (Gibbs et al. 2008, Fargione et al. 2008) of 28 years.

The GTAP model estimates changes in the economic use of land (i.e., among forest, cropland, and pasture uses). In general, however, many ecosystems (specific types of forest, grassland, savannah, or wetland)—each with a unique profile of carbon stocks and sequestration rates—within a given region might be converted to or from these economic uses. To estimate which ecosystems are likely to be converted in a given region and the associated carbon emissions, we adapted the model developed by Searchinger and colleagues (2008a), which relies on data compiled by the Woods Hole Research Institute (described in detail in Searchinger et al. 2008b). We describe here only the basic concept and our modifications to that framework.

The model divides the globe into 11 regions: Europe; developed Pacific; former Soviet Union; North Africa/Middle East; Canada; United States; Latin America; South and South East Asia; Africa; India, China, Pakistan; and the rest of the world (ROW). In each region, up to five ecosystem types are identified for each of which we estimate above- and belowground carbon stocks, along with the carbon fluxes associated with converting these ecosystems to cropping or permitting these ecosystems to recover from other uses. In addition, for each region we estimate the historical rates of conversion to agriculture of each ecosystem type. Thus, the ecosystem and carbon data underlying our emission factors is of coarser resolution than the AEZ level at which the GTAP model estimates land conversion; our analysis could be refined, however, if higher resolution global data were available.

We modified Searchinger and colleagues' (2008a) approach as follows:

- For ecosystems converted to cropping, we assume that the replacement cropping system stores 5 megagrams (Mg) C per hectare in the first year (see table 5.9 in IPCC 2006).
- We assume that 10% of forest biomass is sequestered in either timber products or charcoal in soil, and that the remaining 90% is oxidized to CO_2.
- We ignore non-CO_2 emissions (IPCC 2006, p. 5.29).

These changes result in slightly lower ILUC emission factors than shown in Searchinger and colleagues (2008a; for details, see the supplementary material at *www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160*).

The Searchinger model treats emissions in Europe and the former Soviet Union in a special way, assuming that cropland is already in a process of reversion to forests in those regions. Thus, additional cropland resulting from biofuel expansion merely slows this reversion and avoids the sequestration that otherwise would have occurred. Searchinger and colleagues' data provides estimates of carbon sequestration in regrowing forests, as well as carbon sequestration rates within existing forests and grasslands.

Rather than calculate a single emission factor for all conversion to cropland in a particular region, we determined separate emission factors for each of the dominant transitions predicted by GTAP. In our analysis, three types of conversion dominate: forest to cropland, pasture to cropland,

and pasture to forest. Thus for each AEZ, we generated three emission factors. The forest reversion factor was used for AEZs with a positive change in forests, and the deforestation factor was used for AEZs with a negative change in forests. To do this, we classified each of the ecosystems described in the Woods Hole data as either forest or pasture, and generated historically weighted conversion averages within those categories. For the forest reversion factor, we adapted the method used to calculate foregone sequestration in regenerating forests in Europe and the former Soviet Union, as described in the supplementary material (*www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160*).

Analysis of market-mediated responses

Increased biofuel production in the United States has four important effects: (1) a reduction in food consumption; (2) intensification of agricultural production, including increases in crop yields; (3) land-use change into cropping in the United States; and (4) land conversion in the ROW.

The following analysis traces the proportional influence of each of these effects on global ILUC from increased production of US maize ethanol production. We emphasize that our task is to estimate the independent effect of this increase, not to predict total land-use change (or its GHG discharge) caused by the many other factors that affect land use. It may be, for example, that technological change will boost maize yields over the period of biofuel expansion such that total maize acreage actually falls, but our analysis is directed to how much *more* it would fall without the increase in biofuel. Our estimates use a comparative static analysis relative to an observed equilibrium state (2001 data). An alternative approach—used, for example, by the US Environmental Protection Agency in its analysis for the renewable fuel standard (USEPA 2009a)—would be to project changes over time (using a wide range of additional assumptions) with and without a given quantity of biofuels production. We look forward to continued scientific comparison of these approaches.

A gross estimate of the land required for biofuel production divides the added fuel (50.15 GL per year) by the ethanol fuel yield , and then by the average 2001 US maize yield. However, market-mediated responses of producers and consumers reduce this gross land requirement to a much smaller net value for indirect land-use change (table 1). For greater clarity, the discussion below is framed as though the responses are sequential, although GTAP is solved as a simultaneous system. The discussion is couched in terms of coarse grains rather than maize because the GTAP database, upon which our analysis is constructed, combines maize (91% of US coarse grains sales) with barley, rye, oats, and sorghum.

Domestic market-mediated effects. We begin with a naive estimate of the output change using the baseline ethanol conversion factor of 2.6 gallons per bushel and baseline coarse grains yields of 335 bushels per ha, with the baseline area of 36 Mha, or about 42% of baseline production (table 1). Of course, any rise in price reduces consumption of US coarse grains, and export demand is quite price responsive. In our model, using econometrically estimated trade elasticities, the 50.15 GL per year rise in ethanol production reduces gross coarse grains exports from the United States by 17% (table 1, change in the variable). As exports constitute 27.6% of total sales in the base year, this reduces the coarse grains area requirements in the United States by about 4% (table 1, change in exports). (Reductions in exports will be made up in part by production somewhere else; see below.)

At this point, the 42% increase in output is reduced to 36%. Some domestic uses of coarse grains in the United States are also price responsive. Livestock feed dominates domestic maize use, and it matters here because a complementary product of corn ethanol production is distillers' dried grains with solubles (DDGS), a product fed to animals in place of grains and soymeal. In effect, converting a hectare's worth of corn to fuel does not consume all the feed value of maize. In our analysis, we use the work of Taheripour and colleagues (2009) to explicitly model feed-ration decisions of livestock producers and to model ethanol as a multiproduct process resulting in both ethanol and DDGS outputs; we estimate the penetration of both products into the relevant markets.

Higher coarse-grain-to-DDGS price ratios encourage both the substitution of DDGS for coarse grains and a reduction in domestic maize-based feed displaced by other feedstuffs used in livestock (table 1). Combined, these two factors result in a 42% reduction in the use of maize grain in feed, which is somewhat more than assumed in GREET (Arora et al. 2008) owing to the potential for other feedstuff substitution in response to higher coarse grain prices.

Higher livestock feed prices reduce the consumption of livestock products themselves. Other domestic uses of coarse grains (e.g., in the manufactured foods and beverages sectors) are smaller and less responsive to price, and therefore are little affected. Taking all these factors into account, the domestic demand (other than for ethanol) declines by 31% (table 1, change in the variable). Since nonethanol domestic sales account for about two-thirds of baseline coarse grains production, these market-mediated responses result in a further 17% decline in total output requirements, bringing the revised output requirement figure down from 36% to about 17%.

Switching from the demand to the supply side, we must consider the response of yields to higher market prices. If coarse grain yields on currently used land increased by 17% in response to higher maize prices, then no land would need to be converted to meet the increased demand for maize for ethanol. Some change in yields would have arisen regardless of a biofuel program (i.e., exogenous baseline yield growth) and some change arises endogenously in response to market scarcity, which has confused the debate about ILUC. We account for each of these factors by explicitly modeling the endogenous response of yields to increased biofuel production, using historical responses to market signals, while adjusting for exogenous growth in yields by deflating the *ab initio* estimated land conversion requirements (see the supplementary material for details).

Table 1. Impacts on US land use of increasing US corn ethanol production from 6.6 gigaliters to 56.7 gigaliters per year.

Variable	Unit of measure	Value	Change in individual variable (percentage)	Change in coarse grains hectares (percentage)
Adjustments in coarse grains harvested area				
Corn ethanol yield	L/Mg	387		
Change in ethanol production	GL	50		
Additional corn required	Tg	129	42	
2001 coarse grains yields	Mg/ha	8.5		
Additional equivalent area (using 2001 coarse grains yields)	Mha	15		42
Changes in output of coarse grains due to:				
Change in exports			–17	–4
Change in domestic sales			30	22
Decline in nonethanol domestic sales			–31	–17
Domestic sales to livestock			–43	–17
Livestock feed demand: Substitution of DDGS for the corn in livestock corn-based feed			–37	–15
Livestock feed demand: Reduction of livestock corn-based feed			–8	–3
Livestock feed demand: Reduction of all feed due to reduction in demand for livestock			–1	–0.4
Other domestic sales			–0.3	–0.1
Change in sales to ethanol			757	47
Final change in corn output			17	
Additional land after consideration of demand-side market forces (i.e., constant yields on land with initial productivity)	Mha	6.1		17
Additional land needed when yield increase is taken into account on land with initial productivity	Mha	5.0		14
Additional land needed after consideration of corn yield increases due to higher prices and yield decline on other cropland converted into corn	Mha	6.0		16

DDGS, distillers' dried grains with solubles.

Two competing forces are at play in the market-mediated response of yields to biofuels production, and better knowledge of them would help resolve the uncertainty surrounding all ILUC estimates. First, higher maize prices induce higher yields (the intensive margin). The size of the US yield response to maize prices appears to have diminished over time (Keeney and Hertel 2009). The most recent estimates of the yield elasticity average 0.25, which we adopt: A permanent increase of 10% in the maize price, relative to variable input prices, would result in a 2.5% rise in yields. In response to ethanol expansion, we obtain an average US yield increase, owing to intensification, of 2.8% (table 2). This means that rather than rising by 17%, the land employed by the coarse grains sector needs to rise only by about 14% (table 1).

Working in the opposite direction is the tendency for the expansion of land for maize to reduce average yields, as less productive land must be brought into production (the extensive margin). We consider two factors here. First, maize yields change as maize replaces other crops on existing cropland. This extensive margin is based on observed land rents per hectare in current use. In the United States, this expansion results in a decline in average coarse grains yields as maize production expands into land less suited for maize. A second extensive margin arises when cropland is expanded into pasture and forest lands. In the absence of strong empirical evidence (a lacuna we urge the research community to fill), we assume a central value of 0.66—that is, it takes three additional hectares of pasture- and forestland to produce what two hectares of average current croplands produce. The "extensive margin" row in table 2 shows that that these two factors combined tend to offset the effect of the intensive margin, resulting in a net yield increase for coarse grains of just about 0.4%. (Of course, the intensive margin effect varies widely by AEZ and has an important impact on estimated changes in land cover.)

Table 2. Change in harvested area, by crop, for the United States.

	Coarse grains	Oilseeds	Sugarcane	Other grains	Other crops
Decomposition of output charges (percentage)					
Output	17	–6.1	–1.7	–9.4	–1.7
Yield	0.41	–1.2	0.40	–0.43	–1.3
Area	16	–5.2	–2.1	–9.0	–0.59
Decomposition of yield changes (percentage)					
Yield	0.41	–1.2	0.40	–0.43	–1.3
Intensive margin	2.8	1.3	1.8	0.86	0.47
Extensive margin	–2.3	–2.5	–1.4	–1.3	–1.7
Harvested area (millions of hectares)	6.0	–1.6	–0.02	–2.7	–0.01

Table 3. Change in harvested area, by crop, for the rest of the world.

	Coarse grains	Oilseeds	Sugarcane	Other grains	Other crops
Decomposition of output charges (percentage)					
Output	1.0	1.4	–0.15	0.28	0.07
Yield	0.35	0.46	0.29	0.25	0.16
Area	0.69	0.98	–0.43	0.03	–0.11
Decomposition of yield changes (percentage)					
Yield	0.35	0.46	0.29	0.25	0.16
Intensive margin	0.26	0.32	0.19	0.18	0.10
Extensive margin	0.09	0.13	0.09	0.07	0.06
Harvested area (millions of hectares)	1.4	1.6	–0.10	0.20	–0.53

Thus, to obtain the US coarse grains output of 17% (table 1), a 16% increase in land is required. This amounts to a rise of about 6 Mha of land over the baseline harvested area (table 1, "value"). How will the economy meet this equilibrium increase in land devoted to coarse grains? Table 2 reports adjustments in harvested area for other US crops, triggered by the expansion of land devoted to coarse grains. This amounts to a reduction of 4.4 Mha, most of which comes from area previously devoted to oilseeds and other grains. In our analysis we ignore the effects of such crop switching on GHG emissions, focusing only on emissions from conversion of new cropland. However, crop switching in the United States does leave a significant gap in world supplies of these other products—some of which will be produced elsewhere.

As expected, the reduction in total production of these other crops in the United States is also influenced by yield changes. These also are reported in table 2. With the exception of sugar crops, average yields fall—despite the presence of an intensification effect. The reason for this decline is that the best soybean land, for example, is converted to maize, thereby lowering average soybean yields (and likewise for wheat, etc.). This extensive margin effect dominates the intensification effect and therefore results in a larger decline in US output and exports than would otherwise be the case. Indeed, the estimated declines in exports of other grains (–15%) and oilseeds (–12%) rival the percentage export reduction in coarse grains themselves, thereby contributing to increased cropland conversion in the rest of the world (table 3).

The final piece of the land-use puzzle in the United States is the conversion of noncropland to crops, the dominant source of ILUC GHG emissions, and thus a focus of the debate over ethanol as a renewable fuel. With an increase of 6.0 Mha for coarse grains, and a reduction of 4.4 Mha for other crops, net cropland conversion in the United States totals 1.6 Mha, which amounts to a roughly 1% increase in total cropland. Our model is silent on the precise nature of the land transitions. We expect that most of the cropland will come from high-quality pastureland, with greater demand for pasture infringing on forest lands. Our estimates suggest that about two-thirds of the net reduction will occur in pastureland, and one-third of the net reduction (0.5 Mha) will come from forest cover. The composition of these land-cover changes vary greatly by AEZ in the United States, with pastureland declining in all AEZs, but forested lands declining only in the most productive AEZs where maize is grown.

Market-mediated effects in the rest of the world. Not surprisingly, the reduction in coarse grain exports from the United States to the rest of the world leads to higher production overseas. The aggregate increase in the rest of the world's coarse grain production is 1% (table 3), with the largest contributions coming from Latin America, the European Union, and China.

The distribution of production increases depends not only on existing capacity but also on bilateral patterns of trade. Those regions that either (a) import a significant amount of maize from the United States or (b) compete with US exports in third markets experience the largest increases in production.

In the case of noncoarse grains crops, the percentage change in production in the rest of the world varies; for oilseeds, the percentage increase (1.4) is even higher than for coarse grains. This is a consequence of US oilseeds being significantly displaced (1.6 Mha). The percentage rise in production of other grains is smaller, and that for the category ”other crops” is smaller yet. Production of sugar crops in the rest of the world actually declines as maize ethanol is substituted in the United States for imported sugar cane ethanol.

As in the United States, the increases in production in other regions are met by increases in yield and area (table 3). In the case of coarse grains and oilseeds, the increase in area is twice as important as the increase in yield, whereas in the case of other grains, the yield response is more important. In the cases of sugar crops and other crops, the area harvested actually falls, while yields grow modestly. The bottom row of table 3 reports the changes in area for the rest of the world. Overall, total cropland area expands in all regions except Southeast Asia, with further conversion of forest and pastureland to crops. Our estimated total cropland conversion is 2.6 Mha for the rest of the world—the majority of which (2.4 Mha) is net conversion from pastureland (figure 1).

Market-mediated effects summary. Figure 2 summarizes market-mediated adjustments on global cropland conversion following a 50.15 GL per year increase in production of US maize ethanol. This summary is obtained from a series of successively less-restrictive model solutions, each adding another element of the market-mediated effects. We emphasize that if the constraints were relaxed in a different order, this decomposition would probably change. The first column in figure 2 reports the gross feedstock requirement (15.2 Mha) for the 50.15 GL per year increment to US ethanol production. This would apply if resources (land, labor, and capital) were in perfectly elastic supply—an assumption typically used in life-cycle analyses—so that there were no price responses whatsoever. The finite availability of suitable land induces a price response, which in turn engenders a reduction in nonfood demand, as well as an intensification of livestock and forestry activities (crop yields are still fixed at this point, as are food demands), resulting in a reduction in cropland conversion to 11.3 Mha. The use of coproducts further reduces the demand for cropland conversion to 6.6 Mha. This is followed in figure 2 by the impact of reduced food consumption, leaving about 4.4 Mha of global cropland conversion. After that, we see that the competing effects on yields of higher prices inducing more intensive crop production on the one hand, and cropland expansion lowering yields, on the other. These effects are largely offsetting at the global level (–1.6 Mha versus +1.4 Mha). This leaves a net cropland conversion estimate of 4.2 Mha. Thus, market-mediated effects result in net land conversion of just 0.28 ha for each gross hectare of maize production diverted to fuel use. When adjusted for 2007 coarse grains yields (see the material at *www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160*), this figure is reduced to our final value of 3.8 Mha—just about two-fifths of previous estimates (Searchinger et al. 2008a).

Effects on food consumption

As noted in figure 2, reduced food consumption is an important market-mediated response to increased biofuels production. (Estimates of the resulting change in consumption are reported in table S4; *www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160.*) While lower food consumption may not translate directly into nutritional deficits among wealthy households, any decline in consumption will have a severe impact on households that are already malnourished. These consumption effects can be interpreted as the “nutritional cost” of the market-mediated response to maize ethanol. In order to isolate the size of this effect, we ran the model holding consumption fixed with a series of country-by-commodity subsidies. In this case, we

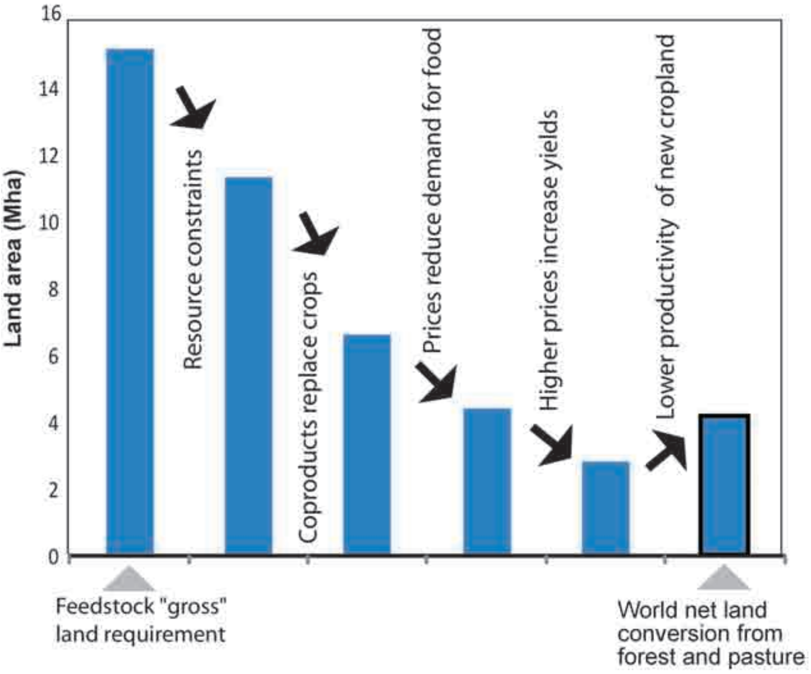

Figure 2. Market-mediated reduction in global cropland conversion from additional 50.15 gigaliters (GL) per year of maize ethanol production (millions of hectares [Mha], based on 2001 yields).

find that twice as much forest is converted to agriculture, and emissions from ILUC increase by 41%, to 1127 g CO_2 per MJ of increased annual production capacity. This estimate may be thought of as a "food-neutral" ILUC value or alternatively, as an ILUC value that translates food effects into units of GHG emissions.

Sensitivity of findings to uncertainty in model parameters and inaccessible forest

GTAP results are sensitive to several key economic parameters, and in this case, also to emission factors. Accordingly, we have undertaken systematic sensitivity analysis (SSA) through the Gaussian quadrature approach (DeVuyst and Preckel 1997, Pearson and Arndt 2000) using probability distributions for economic parameters and emission factors described in the supplementary material. This SSA is limited to parameters known to be especially relevant to our results, and therefore the full uncertainty is broader than these results indicate (for details, see *www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160*). We find the coefficient of variation associated with global ILUC (global additional cropland) to be 0.37, while that for CO_2 emissions is 0.46. We have also used variation of the most controversial yield parameters to compute bounding values for emissions, leading to lower and upper bound values on our results of 440 and 2700 g CO_2 per MJ, respectively. Accordingly, we conclude that parametric uncertainty is not by itself a justification for ruling out policy recognition of the ILUC impacts of biofuels.

Because our current model considers only those forestlands that are currently accessible and available for conversion or for forest products, we may understate total carbon releases and overstate forest reversion. As a further bounding analysis, we consider first a scenario in which no forest reversion occurs and all of the pastureland that would have been converted to forest remains in pasture (see the supplementary materials at *www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3160*). This leads to a 10% increase in total emissions. However, to the extent that reversion does occur, forests do not grow back nearly as quickly as they can be cleared. Accordingly, our emission factors for forest reversion reflect partial regeneration of potential aboveground forest biomass—30 years worth of sequestration. 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 forestland, increases carbon discharge by 120%.

Better understanding of skewness and long tails in an estimated distribution of the ILUC value will probably imply that an optimal value for the index assigned to a particular biofuel will be different from a central estimator of its ILUC effect. However, innovative research that combines economic estimates like ours with policy-analytic and risk management principles is needed before this path is clear. At present, we can say that even if our results are taken as no better than an "order-of-magnitude" estimate of the GHG consequences of biofuels-induced ILUC, they are cause for concern about the prospects of large-scale production of crop-based biofuels on prime agricultural land, particularly because the uncertainty in our estimates is not symmetric: Actual discharges may be much larger than our central value in more ways than they may be smaller, as many of the effects we observe are bounded by zero on the left. Finally, we caution that any technology that competes with other high-valued uses of resources that are inelastic in supply has the potential to induce significant market-mediated effects such as the ones we describe here. Biofuels that do not displace existing land use activities—such as those derived from wastes, residues, or algae, for example—do not share this specific feature. However, it remains to be seen whether such technologies induce other market-mediated effects of concern for the global climate.

Acknowledgments

This work was supported in part by the California Air Resources Board (CARB), the Energy Biosciences Institute (EBI), the US Environmental Protection Agency (EPA), the Energy Foundation (EF), a National Science Foundation (NSF) Graduate Research Fellowship (to R. J. P.), and EPA STAR graduate research fellowship (to A. D. J.). It does not necessarily represent the views of CARB, EBI, NSF, EF, or the EPA.

We thank Timothy Searchinger, Thomas Darlington, and other participants in CARB and EBI biofuel workshops for comment and criticism on this work, and we gratefully remember the leadership and guidance provided by the late Alex Farrell, who would have been a primary contributor to this project.

References cited

Arora S, Wu M, Wang M. 2008. Update of Distillers Grains Displacement Ratios for Corn Ethanol Life-cycle Analysis. Center for Transportation Research, Energy System Division, Argonne National Laboratory. (11 January 2010; *www.transportation.anl.gov/pdfs/AF/527.pdf*)

[CARB] California Air Resources Board. 2009. Proposed Regulation to Implement the Low Carbon Fuel Standard, vol. I: Staff Report: Initial Statement of Reasons. CARB: 374. (11 January 2010; *www.arb.ca.gov/regact/2009/lcfs09/lcfsisor1.pdf*)

DeVuyst EA, Preckel PV. 1997. Sensitivity analysis revisited: A quadrature-based approach. Journal of Policy Modeling 19: 175–185.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. Science 319: 1235–1238.

Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM. 2006. Ethanol can contibute to energy and environmental goals. Science 311: 506–508.

Farrell AE, et al. 2007a. A Low-carbon Fuel Standard for California, Part 1: Technical Analysis. University of California Press. (16 February 2010; *www.enery.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_1-FINAL.pdf*)

Farrell AE, et al. 2007b. A Low-carbon Fuel Standard for California, Part 2: Policy Analysis. University of California Press. (16 February 2010; *www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_2-FINAL.pdf*)

Gibbs HK, Johnston M, Foley JA, Holloway T, Monfreda C, Ramankutty N, Zaks D. 2008. Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. Environmental Research Letters 3: 034001.

Hertel TW, Tyner WE, Birur DK. 2010. Global impacts of biofuels. Energy Journal 31: 75–100.

[IPCC] Intergovernmental Panel on Climate Change. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 4: Agriculture, Forestry and Other Land Use. Cambridge University Press.

Keeney R, Hertel TW. 2009. Indirect land use impacts of US biofuels policies: The Importance of acreage, yield and bilateral trade responses. American Journal of Agricultural Economics 91: 895–909.

Kim S, Dale B, Jenkins R. 2009. Life cycle assessment of corn grain and corn stover in the United States. The International Journal of Life Cycle Assessment 14: 160–174.

Lee HL, Hertel TW, Rose S, Avetsiyan M. 2009. An integrated land use database for CGE analysis of climate policy options. Pages 72–88 in Hertel TW, Rose S, Tol R, eds. Economic Analysis of Land Use in Global Climate Change Policy. Routledge Press.

O'Hare M, Plevin RJ, Marin 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. doi:10.1088/1748-9326/4/2/024001

Pearson K, Arndt C. 2000. Implementing Systematic Sensitivity Analysis Using GEMPACK, GTAP. Center for Global Trade Analysis, Purdue University. Technical paper no. 3.

Plevin RJ, Mueller S. 2008. The effect of CO_2 regulations on the cost of corn ethanol production. Environmental Research Letters 3: 024003.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T-H. 2008a. Use of US croplands for biofuels increases greenhouse gases through emissions from land use change. Science 319: 1238–1240.

———. 2008b. Supporting online materials for: Use of US croplands for biofuels increases greenhouse gases through emissions from land use change. Science: 1151861.

Searchinger T, Hamburg S, Melillo J, Kammen DM, Lubowski R, Oppenheimer M, Robertson GP, Schlessinger W, Tilman GD. 2009. Fixing a critical climate accounting error. Science 326: 527–528.

Taheripour F, Hertel TW, Tyner WE. 2009. Biofuels and their byproducts. Biomass and Bioenergy. (20 January 2010; *http://dx.doi.org/10.1016/j.biombioe.2009.10.017*)

Tyner WE, Taheripour F, Baldos U. 2009. Land Use Change Carbon Emissions due to US Ethanol Production. Report to Argonne National Labs. (11 January 2010; *www.agecon.purdue.edu/papers/biofuels/Argonne-GTAP_Revision%204a.pdf*)

[USEPA] US Environmental Protection Agency. 2009. Renewable Fuel Standard Program (RFS2) Notice of Proposed Rulemaking. USEPA: 549. (11 January 2010; *www.epa.gov/OMSWWW/renewablefuels/rfs2-nprm-preamble-regs.pdf*)

Villoria N. 2009. The role of geography in determining the global land use impacts of biofuels. PhD dissertation. Purdue University, West Lafayette, Indiana. (11 January 2010; *http://web.ics.purdue.edu/~nvillori/pdf/geoclu.pdf*)

Wang M, Wu M, Huo H. 2007. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environmental Research Letters 2: 13.

Wang MQ. 2007. GREET 1.8a Spreadsheet Model. (19 January 2010; *www.transportation.anl.gov/modeling_simulation/GREET)*

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