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Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change

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Most prior studies have found that substituting biofuels for gasoline will reduce greenhouse gases because biofuels sequester carbon through the growth of the feedstock. These analyses have failed to count the carbon emissions that occur as farmers worldwide respond to higher prices and convert forest and grassland to new cropland to replace the grain (or cropland) diverted to biofuels. By using a worldwide agricultural model to estimate emissions from land-use change, we found that corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years. Biofuels from switchgrass, if grown on U.S. corn lands, increase emissions by 50%. This result raises concerns about large biofuel mandates and highlights the value of using waste products.

Most life-cycle studies have found that replacing gasoline with ethanol modestly reduces greenhouse gases (GHGs) if made from corn and substantially if made from cellulose or sugarcane (*1–7*). These studies compare emissions from the separate steps of growing or mining the feedstocks (such as corn or crude oil), refining them into fuel, and burning the fuel in the vehicle. In these stages alone (Table 1), corn and cellulosic ethanol emissions exceed or match those from fossil fuels and therefore produce no greenhouse benefits. But because growing biofuel feedstocks removes carbon dioxide from the atmosphere, biofuels can in theory reduce GHGs relative to fossil fuels. Studies assign biofuels a credit for this sequestration effect, which we call the feedstock carbon uptake credit. It is typically large enough that overall GHG emissions from biofuels are lower than those from fossil fuels, which do not receive such a credit because they take their carbon from the ground.

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For most biofuels, growing the feedstock requires land, so the credit represents the carbon benefit of devoting land to biofuels. Unfortunately, by excluding emissions from land-use change, most previous accountings were one-sided because they counted the carbon benefits of using land for biofuels but not the carbon costs, the carbon storage and sequestration sacrificed by diverting land from its existing uses. Without biofuels, the extent of cropland reflects the demand for food and fiber. To produce biofuels, farmers can directly plow up more forest or grassland, which releases to the atmosphere much of the carbon previously stored in plants and soils through decomposition or fire. The loss of maturing forests and grasslands also foregoes ongoing carbon sequestration as plants grow each year, and this foregone sequestration is the equivalent of additional emissions. Alternatively, farmers can divert existing crops or croplands into biofuels, which causes similar emissions indirectly. The diversion triggers higher crop prices, and farmers around the world respond by clearing more forest and grassland to replace crops for feed and food. Studies have confirmed that higher soybean prices accelerate clearing of Brazilian rainforest (*8*). Projected corn ethanol in 2016 would use 43% of the U.S. corn land harvested for grain in 2004 (*1*), overwhelmingly for livestock (*9*), requiring big land-use changes to replace that grain.

Because existing land uses already provide carbon benefits in storage and sequestration (or, in the case of cropland, carbohydrates, proteins, and fats), dedicating land to biofuels can potentially reduce GHGs only if doing so increases the carbon benefit of land. Proper accountings must reflect the net impact on the carbon benefit of land, not merely count the gross benefit of using land for biofuels. Technically, to generate greenhouse benefits, the carbon generated on land to displace fossil fuels (the carbon uptake credit) must exceed the carbon storage and sequestration given up directly or indirectly by changing land uses (the emissions from land-use change) (Table 1).

Many prior studies have acknowledged but failed to count emissions from land-use change because they are difficult to quantify (*1*). One prior quantification lacked formal agricultural modeling and other features of our analysis (*1*, *10*). To estimate land-use changes, we used a worldwide model to project increases in cropland in all major temperate and sugar crops by country or region (as well as changes in dairy and livestock production) in response to a possible increase in U.S. corn ethanol of 56 billion liters above projected levels for 2016 (*11*, *12*). The model's historical supply and demand elasticities were updated to reflect the higher price regime of the past 3 years and to capture expected long-run equilibrium behavior (*1*). The analysis identifies key factors that determine the change in cropland.

1) New crops do not have to replace all corn diverted to ethanol because the ethanol by-product, dry distillers' grains, replaces roughly one-third of the animal feed otherwise diverted.

2) As fuel demand for corn increases and soybean and wheat lands switch to corn, prices increase by 40%, 20%, and 17% for corn, soybeans, and wheat, respectively. These increases modestly depress demand for meat and other grain products beside ethanol, so a small percentage of diverted grain is never replaced.

3) As more American croplands support ethanol, U.S. agricultural exports decline sharply (compared to what they would otherwise be at the time) (corn by 62%, wheat by 31%, soybeans by 28%, pork by 18%, and chicken by 12%).

4) When other countries replace U.S. exports, farmers must generally cultivate more land per ton of crop because of lower yields.

Farmers would also try to boost yields through improved irrigation, drainage, and fertilizer (which have their own environmental effects), but reduced crop rotations and greater reliance on marginal lands would depress yields. Our analysis assumes that present growth trends in yields continue but that positive and negative effects on yields from biofuels balance out.

We calculated that an ethanol increase of 56 billion liters, diverting corn from 12.8 million ha of U.S. cropland, would in turn bring 10.8 million ha of additional land into cultivation. Locations would include 2.8 million ha in Brazil, 2.3 million ha in China and India, and 2.2 million ha in the United States.

Greenhouse emissions will depend on the type of lands converted. We assigned the new cropland in each region to different types of forest, savannah, or grassland on the basis of the proportion of each ecosystem converted to cultivation in the 1990s and assumed that conversion emits 25% of the carbon in soils (*13*, *14*) and all carbon in plants, which must be cleared for cultivation. For mature forests in carbon equilibrium, we only calculated emissions from the initial conversion. For growing forests, we attributed emissions to biofuels equal to the carbon those lost forests would no longer sequester over 30 years (adjusted for disturbances like fire). Our estimates of the carbon content of ecosystems compare roughly to figures cited by the Intergovernmental Panel on Climate Change (IPCC) (*15*). Our analysis does not reflect the full opportunity costs of using lands for biofuels, which include the additional carbon lands could store if managed optimally (e.g., through reforestation), but only the carbon lands would otherwise store in their existing use. Our method yielded an average GHG emission of 351 metric tons per converted hectare (CO_2 equivalent).

We allocated the total emissions for all converted land into emissions per MJ of fuel and factored them into the GREET model (Table 1). GREET provides a commonly used lifecycle analysis of GHG emissions from the different stages of biofuel and gasoline production (*3*–*5*), and its default assumptions calculate that replacing gasoline with corn ethanol reduces GHGs by 20% in the 2015 scenario excluding land-use change (*5*, *16*). As land generates more ethanol over years, the reduced emissions from its use will eventually offset the carbon debt from land-use change, which mostly occurs quickly and is limited in our analysis to emissions within 30 years. We calculated that GHG savings from corn ethanol would equalize and therefore "pay back" carbon emissions from land-use change in 167 years, meaning GHGs increase until the end of that period. Over a 30-year period, counting land-use change, GHG emissions from corn ethanol nearly double those from gasoline for each km driven (Table 1). [We chose 30 years because reductions of greenhouse gases in that period will be both difficult to achieve and important to avoid irreversible adverse effects from climate change (*17*) and because ethanol is typically viewed as a bridge to more transformative energy technologies.]

As part of our sensitivity analysis, we found that, even if corn ethanol caused no emissions except those from land-use change, overall GHGs would still increase over a 30-year period (*1*). We also hypothesized a scenario in which (i) increased ethanol and higher prices spur enough yield increases beyond current trends to supply 20% of the replacement grain; (ii) emissions per ha of converted land are only half of our estimates, and (iii) improved technology allows corn ethanol to reduce GHGs compared with gasoline by 40% excluding land-use change. In that scenario, the payback period would last 34 years, which means emissions modestly increase over a 30-year period (*1*).

By the workings of our model, the emissions from land-use change per unit of ethanol would be similar regardless of the ethanol increase analyzed. For example, a smaller ethanol increase of 30.6 billion liters had only modestly different results, with emissions from land-use change per MJ of ethanol 10% lower (*1*). Far larger biofuel increases could change the magnitude of results in unclear ways that would require modification to the model.

Although these estimates face several uncertainties, the general finding flows from three reliable projections. First, farmers will replace most of the grain diverted from food and feed by ethanol because the demand for overall food and feed, as opposed to any particular grain, is inelastic (*18*). Second, increases in cropland will provide most replacement grain because they are cost-effective and fast, the yield effects of biofuel demands are both positive and negative, and the world has many convertible acres: up to 170 million ha in Brazil alone (*19*, *20*) and perhaps 2.8 billion ha worldwide (*21*). Most significantly, the potential emissions per hectare of land conversion greatly exceed the annual greenhouse reductions per ha of biofuels. According to GREET and at 2015 yields, a ha of corn for ethanol reduces GHGs by 1.8 metric tons ha^{-1} $year^{-1}$ (CO_2 equivalent), but each ha of forest converted has up-front emissions of 604 to 1146 metric tons (varying by type and maturity), and each hectare of grassland or savannah from 75 to 305 metric tons (*1*). If new cropland replaces any substantial fraction of diverted cropland, the payback period for these up-front emissions will be long (even without counting foregone annual

Table 1. Comparison of corn ethanol and gasoline greenhouse gasses with and without land-use change by stage of production and use (grams of GHGs CO_2 equivalents per MJ of energy in fuel) (*28*). Figures in total column may not sum perfectly because of rounding in each row. Land-use change was amortized over 30 years. Dash entries indicate "not included."

				Net land-use effects			
Source of fuel	Making feedstock	Refining fuel	Vehicle operation (burning fuel)	Feedstock carbon uptake from atmosphere (GREET)	Land-use change	Total GHGs	% Change in net GHGs versus gasoline
Gasoline	+4	+15	+72	0	–	+92	–
Corn ethanol (GREET)	+24	+40	+71	–62	–	+74 +135 without feedstock credit	–20% +47% without feedstock credit
Corn ethanol plus land use change	+24	+40	+71	–62	+104	+177	+93%
Biomass ethanol (GREET)	+10	+9	+71	–62	–	+27	–70%
Biomass ethanol plus land use change	+10	+9	+71	–62	+111	+138	+50%

sequestration). This result makes intuitive sense because potential biofuel benefits originate in the annual carbon uptake from growing a feedstock, but growing that feedstock will typically require up-front release of carbon previously sequestered on land over decades.

This analysis has implications for other biofuels. Cellulosic ethanol could use wastes that do not trigger land-use change. But if American corn fields of average yield were converted to switchgrass for ethanol, replacing that corn would still trigger emissions from land-use change that would take 52 years to pay back and increase emissions over 30 years by 50% (*1*).

Ethanol from Brazilian sugarcane, based on estimated GHG reductions of 86% excluding land-use changes (*6*), could pay back the up-front carbon emissions in 4 years if sugarcane only converts tropical grazing land. However, if displaced ranchers convert rainforest to grazing land, the payback period could rise to 45 years (*1*). The extraordinary productivity of Brazilian sugarcane merits special future analysis.

Even if excess croplands in the United States or Europe became available because of dramatic yield improvements beyond existing trends (*22*) or the release of agricultural reserve lands (*7*), biofuels would still not avoid emissions from land-use change. Truly excess croplands would revert either to forest or grassland and sequester carbon. Use of those lands instead for biofuels sacrifices this carbon benefit, which could exceed the carbon saved by using the same land for biofuels (*24*). In addition, even as cropland declined in Europe in recent years, changing technology and economics led cropland to expand into forest and grassland in Latin America (*24*). Higher prices triggered by biofuels will accelerate forest and grassland conversion there even if surplus croplands exist elsewhere. Most problematically, even with large increases in yields, cropland must probably consume hundreds of millions more ha of grassland and forest to feed a rising world population and meat consumption (*21*, *25*), and biofuels will only add to the demand for land.

This study highlights the value of biofuels from waste products (*26*) because they can avoid land-use change and its emissions. To avoid land-use change altogether, biofuels must use carbon that would reenter the atmosphere without doing useful work that needs to be replaced, for example, municipal waste, crop waste, and fall grass harvests from reserve lands. Algae grown in the desert or feedstocks produced on lands that generate little carbon today (*27*) might also keep land-use change emissions low, but the ability to produce biofuel feedstocks abundantly on unproductive lands remains questionable.

Because emissions from land-use change are likely to occur indirectly, proposed environmental criteria that focus only on direct land-use change (*7*) would have little effect. Barring biofuels produced directly on forest or grassland would encourage biofuel processors to rely on existing croplands, but farmers would replace crops by plowing up new lands. An effective system would have to guarantee that biofuels use a feedstock, such as a waste product, or carbon-poor lands that will not trigger large emissions from land-use change.

Counteracting increases in biofuels with controls or disincentives against land conversion would not only face great practical challenges but also have harsh social consequences. In our analysis, a diversion of 12.8 million ha, otherwise generating 10% of the world's feed grain by weight, would reduce world consumption of meat 0.9% by weight and dairy products 0.6% (fluid milk equivalents) (*1*). This effect, of which around half reflects poorer diets in developing countries, depresses emissions and has a GHG "benefit" but probably not a desirable one. Effective controls on land conversion would constrain the major source of new supply to meet increased biofuel demands, resulting in less additional cropland and higher prices as markets seek equilibrium. In that event, more greenhouse benefits would stem in reality from reduced food consumption.

Use of good cropland to expand biofuels will probably exacerbate global warming in a manner similar to directly converting forest and grasslands (*29*). As a corollary, when farmers use today's good cropland to produce food, they help to avert GHGs from land-use change.

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