



A COMPARISON OF INDUCED LAND- USE CHANGE EMISSIONS ESTIMATES FROM ENERGY CROPS

Nikita Pavlenko and Stephanie Searle

ACKNOWLEDGMENTS

This work was generously funded by the Packard Foundation and the Norwegian Agency for Development Cooperation. Thanks to Nic Lutsey, Fanta Kamakate, Chris Malins, Richard Plevin, Farzad Taheripour, Wally Tyner, Sharyn Lie, and βXin Zhao for helpful reviews.

International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | [@TheICCT](https://twitter.com/TheICCT)

© 2018 International Council on Clean Transportation

EXECUTIVE SUMMARY

Support for the first generation of biofuels derived from food crops has been controversial largely due to concerns around induced land-use change (ILUC) and their impact on food supply. In some cases, the emissions from land expansion in response to demand for these first-generation biofuels has been found to partially or wholly undermine the greenhouse gas (GHG) benefits of their use. To date, the literature on ILUC emissions from energy cropping—the cultivation of non-food woody or herbaceous crops for energy—has been sparse relative to that of first-generation biofuels made from food.

This study begins to fill this gap by performing an in-depth review of the few ILUC assessments for energy cropping conducted to date, which have exhibited substantial variance. We review model structure, assumptions, and detailed results from five prominent ILUC studies to identify factors driving differences in results. We identify three key factors in energy crop ILUC analyses that play an important role in estimating the ILUC emissions from energy cropping: yield, distribution of land types converted, and carbon stock change. Our analysis builds on previous ICCT research on energy crops as well as a literature review to provide context for the treatment of each of these factors in the reviewed modeling studies. We then evaluate each existing ILUC assessment’s methodology and assumptions to identify the extent to which the modelers’ decisions influence their results.

Figure ES-1 illustrates the wide spread in estimated ILUC emissions for energy crops that we assessed in the literature. Nearly all of the studies suggest that energy crop ILUC emissions are lower than those of food crops, but it is uncertain how much lower they are, or whether energy crop ILUC emissions are positive or negative. We evaluate a series of ILUC assessments conducted using economic models, beginning with the U.S. Environmental Protection Agency’s (EPA) 2010 assessment of switchgrass (FASOM-FAPRI); two subsequent analyses by Purdue University and Argonne National Laboratory (GTAP 1 and GTAP 2); a set of 2015 analyses using Pacific Northwest National Laboratory’s integrated assessment model (GCAM); and lastly, a 2015 assessment performed for the European Commission (GLOBIOM).

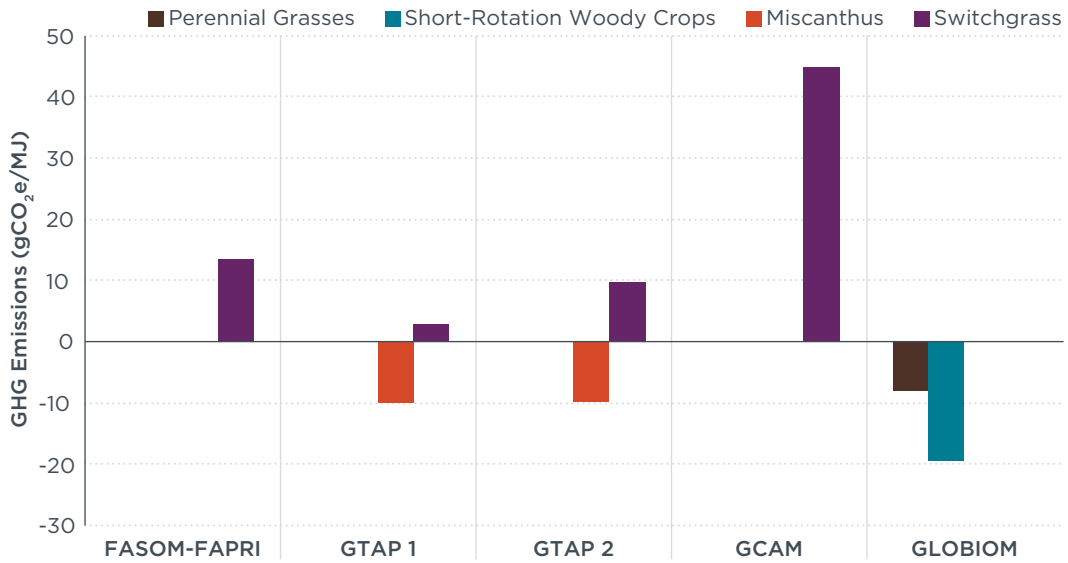


Figure ES-1. Estimated ILUC emissions from energy cropping (30-year time horizon).

Note: ILUC factors for GTAP 2 are an average of the minimum and maximum values for switchgrass and Miscanthus using Argonne National Laboratory’s carbon stock factors and including cropland pasture conversion emissions (Taheripour & Tyner, 2013). Emission factor results from the GLOBIOM modeling were converted from their original, 20-year time horizon by multiplying linearly to a 30-year time horizon for the purposes of this comparison.

Our analysis suggests that much of the variation across ILUC assessments is driven by differences in the modelers’ assumptions, although some can be attributed to model structure. We find that the most influential driver in estimated ILUC emissions associated with energy cropping across the studies appears to be the relative share of land categories converted in response to biofuel demand in each study, illustrated in Figure ES-2. Generally, the studies that predict the greatest conversion of high-carbon stock land—usually forestland—in turn estimate the highest ILUC emissions.

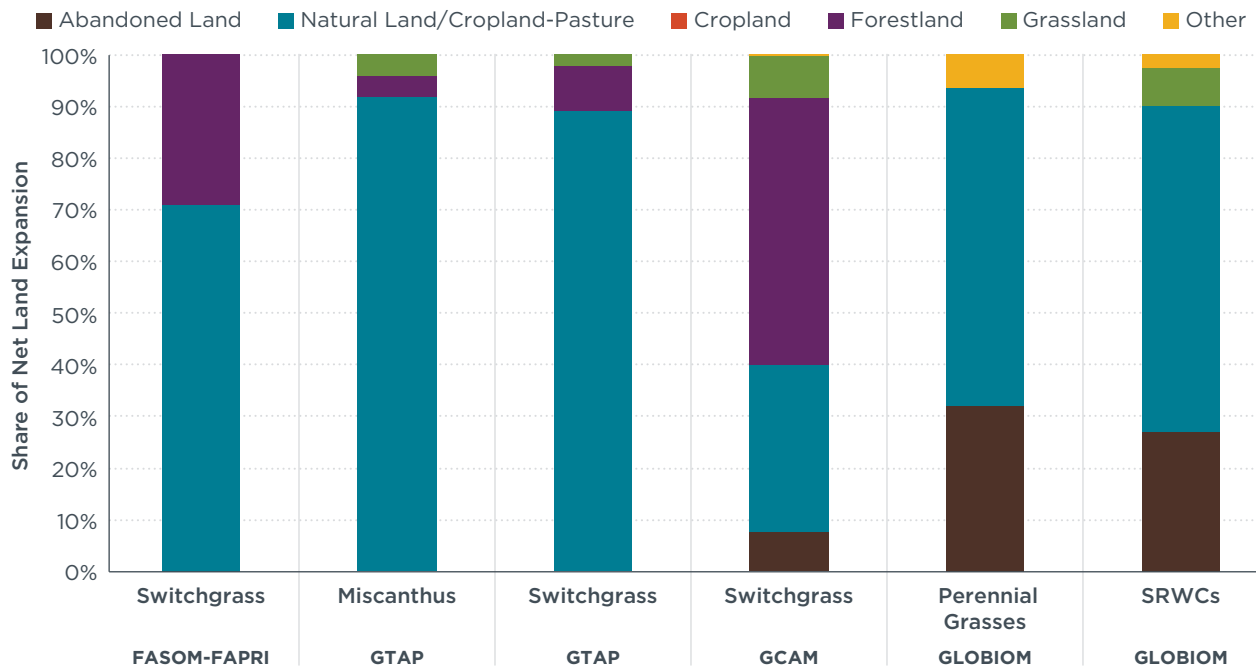


Figure ES-2. Comparison of land category as a share of net land expansion resulting from energy crop demand, by study.

Rather than recommending any one value from the studies reviewed here as indicative of energy cropping as a whole, our study instead identifies several broader trends across ILUC assessments. These trends help us to better understand how ILUC assessments can reach such varied conclusions and highlight several of the risks inherent in pursuing biofuels made from energy crops as a means of mitigating GHG emissions. We draw the following conclusions on energy crop ILUC from our analysis:

- » **Existing ILUC assessments tend to assume optimistic crop yields.** We find that nearly every ILUC assessment we review here assumes average energy crop yields at the high end of what the literature suggests are realistic for the land types on which energy crops are projected to expand. Several assessments include additional yield improvements over time. This decision reduces the total amount of land conversion necessary to meet any particular level of energy crop demand.
- » **Energy crops are unlikely to compete with food crops on a large scale given the demand expected with current policies.** Across the studies, we find that in most cases, the models predict that energy crops are not economically competitive enough to displace food crops. They tend instead to be produced on marginal lands such as lower-value abandoned agricultural lands. This results in lower carbon stock change as well as reduced disruption of food supply compared to food crops.
- » **Protecting high-carbon stock lands can mitigate energy crop ILUC emissions.** Both the GLOBIOM and the GCAM assessments illustrate the importance of forest protections on ILUC emissions. The GLOBIOM study explicitly assumes that energy crops cannot be grown on high-carbon stock land to comply with the sustainability criteria in European Union (EU) policy; this assumption contributes to the very low ILUC emission estimates from this study. In contrast, removing all implicit forestland protection in the GCAM ILUC assessments strongly increases forest conversion and increases GHG emissions. Land conversion restrictions for energy cropping could thus be important to mitigating the risk of direct conversion of high-carbon stock land.
- » **Soil carbon sequestration on marginal lands may be a significant source of uncertainty in ILUC modeling.** With the exception of EPA's assessment, we find that all of the analyses reviewed here assume that energy crop cultivation on marginal lands and cropland generates significant soil carbon sequestration, strongly reducing estimated ILUC emissions from energy crops. Although this assumption is supported by soil process models, there is little empirical evidence on soil carbon impacts of energy crops grown on abandoned agricultural land or other marginal lands. This is thus still an area of considerable uncertainty that could substantially affect ILUC estimates.

These findings indicate that there is still high uncertainty associated with estimating ILUC from energy cropping, particularly as it is a nascent industry with a minimal existing economic footprint to assess. Overall, it is still likely that energy crops offer greater GHG reductions and other environmental benefits compared to most food feedstocks used for biofuel. However, our understanding of energy cropping could be improved through the use of more realistic assumptions for energy crop cultivation based on field data as well. Furthermore, the potential risk of forestland conversion and the high emissions that would be associated with that remains unclear and is not adequately addressed in most modeling studies. Given these factors, we recommend that biofuel policies include robust sustainability criteria for feedstocks to ensure that energy cropping minimizes the displacement of high-carbon lands.

TABLE OF CONTENTS

Executive summary	i
Introduction	1
Components of energy crop ILUC	4
Feedstock yield	4
Land conversion	7
Carbon stock change	9
Review of ILUC estimates	12
FASOM-FAPRI ILUC assessment	12
GTAP ILUC assessments	17
GCAM ILUC assessments	21
GLOBIOM ILUC assessment	24
Analysis of ILUC results	28
Conclusion	34
References	36

INTRODUCTION

The global response to climate change necessitates substantial cuts to greenhouse gas (GHG) emissions. Sectors such as power generation, transportation, land use, and agriculture all must make large-scale changes to limit global temperature increases to 2° C and mitigate the worst impacts of a changing climate. As part of the strategy to transition away from fossil fuels, biofuels could play an important role by providing similar performance and functionality as their fossil counterparts at a lower carbon intensity. Although a transition to low-carbon biofuels could play a critical role of the decarbonization of the transportation sector, not all biofuels provide the same level of carbon reductions—or in some cases any carbon reductions at all.

The carbon intensity of a biofuel consists of the total GHG emissions from both its direct and indirect life-cycle components; if that total is less than its fossil fuel counterpart, that biofuel would provide a reduction in carbon intensity when it replaces that fossil fuel.¹ Two direct components of the biofuel life cycle govern the carbon intensity of a given pathway: first, the energy and emissions generated from growing and collecting the feedstock chosen to produce that fuel (e.g., corn for corn ethanol), and second, the impact of the processing technologies used to convert that feedstock into a finished product. Direct life-cycle emissions also include the impacts of converting a given plot of land from its previous use toward biofuel feedstock production, also called direct land-use change (DLUC). DLUC emissions can include the one-time emissions from soil disturbance, clearance of above-ground vegetation, and use of fertilizer on land used to grow biofuel feedstocks. Food crops such as corn often use substantial inputs of fertilizers, chemicals, and water, which are necessary to support high yields but further contribute to direct emissions. The indirect components of the life cycle, on the other hand, comprise the emissions from behavioral responses to policies and market demand attributable to that fuel. When food crops are diverted toward fuel, the shortfall in food production will generally result in increased prices of those food commodities, and as a result incentivize increased land conversion or intensification of cultivated land elsewhere. In contrast to DLUC, induced land-use change (ILUC) emissions may occur far away from where the feedstock in question is grown. Because these emissions occur as a result of increased feedstock demand, these land conversion emissions are considered attributable to that fuel policy.

Addressing ILUC within fuel policies can be controversial. ILUC accounting has been included within U.S. policies, including the federal Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS). On the other hand, both the first Renewable Energy Directive (RED) and Fuel Quality Directive (FQD), which established renewable energy targets and carbon intensity targets, respectively, in the European Union (EU) did not address ILUC emissions in their GHG calculation methodologies. As a measure to address ILUC, the 2015 ILUC Directive amended the RED to limit the share of land-based biofuels to 7% of the EU's 2020 renewable energy targets, in addition to a 0.5% sub-target for advanced biofuels from a list of non-food sources. The European Commission's proposal for a recast RED for the period 2021–2030 caps the amount of food-based biofuels that can contribute to the cross-sector renewable energy target, and does not allow food feedstocks to contribute at all to the transportation-specific energy target (European Commission, 2016).

1 The practice of combining the attributional, direct life-cycle assessment emissions for a given fuel with the indirect, consequential emissions associated with changes in fuel demand is used to inform carbon intensity (CI) standards in several jurisdictions. Plevin et al. (2015) argues that this approach may oversimplify the actual emissions.

As the body of knowledge on the impacts of food-based feedstocks has grown, questions remain about the magnitude of ILUC emissions. ILUC emissions are estimated using economic models that project the extent of land expansion in response to fuel policies. This method of estimating indirect effects has been controversial due to its reliance on economic models that produce results with an inevitable level of uncertainty, but it still has consensus within the scientific community as the best existing approach for estimating ILUC. Relative to other methods, economic modeling has fewer drawbacks and is still more credible than simply assuming that ILUC emissions are zero (e.g., Golub & Hertel, 2012). Estimating a market response to biofuel demand relies on a series of assumptions about demand for various agricultural commodities, future commodity prices, and improvement in crop yields. A number of ILUC modeling studies already have been conducted for first-generation biomass feedstocks such as corn, soybeans and canola, using a variety of models and assumptions. Estimates of the ILUC emissions of biofuel feedstocks such as corn, soybeans, and palm oil range from 8 gCO₂e to as high as 231 gCO₂e per MJ of finished fuel (Taheripour & Tyner, 2013; Valin et al., 2015). Although the results vary, it is evident that ILUC emissions for many food-based feedstocks greatly diminish their GHG reduction potential relative to fossil fuels.

Despite the abundance of estimates on the ILUC impact of food-based feedstocks, however, there are relatively few estimates of the ILUC response to increasing use of energy crops. Figure 1 shows the wide range of estimates of ILUC emissions from several key energy crops: switchgrass, Miscanthus, and short-rotation woody crops (SRWC). The available studies indicate that energy crops have lower ILUC impacts than food crops, but with relatively few data points and a wide distribution of results, there remains substantial uncertainty on this subject.

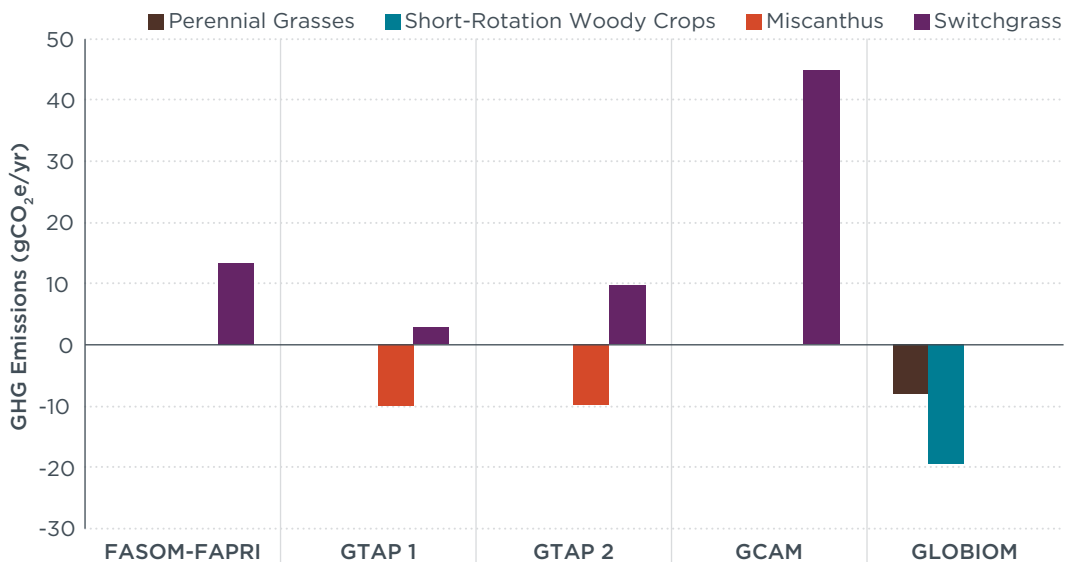


Figure 1. Estimated ILUC emissions from energy cropping (30-year time horizon).

Note: ILUC factors for GTAP 2 are an average of the minimum and maximum values for switchgrass and Miscanthus using Argonne National Laboratory's carbon stock factors and including cropland pasture conversion emissions (Taheripour & Tyner, 2013). Emission factor results from the GLOBIOM modeling were converted from their original, 20-year time horizon by multiplying linearly to a 30-year time horizon for the purposes of this comparison.

The purpose of this report is to assess the literature and model results estimating the ILUC response to dedicated energy cropping to better understand the role that energy crops should play in biofuels policy. First, we review the literature basis for key factors that are influential in determining the magnitude of energy crop ILUC emissions. We then review the assumptions in each of the reviewed modeling studies that are relevant to these key factors, and critique those assumptions in the context of our literature review. This report's conclusions and recommendations are intended to contribute to the discussion of the role for energy crops in future biofuels policy to ensure that fuel policies can make meaningful contributions to long-term transportation decarbonization.

COMPONENTS OF ENERGY CROP ILUC

Estimates of ILUC emissions result from a set of market and behavioral interactions within economic models that rely on several key inputs, including characteristics of the feedstock itself (e.g., yield), land conversion (i.e., which land will transition to energy cropping), and the carbon stock of land used to grow crops. This section provides an overview of three key factors that contribute to a given energy crop's ILUC estimate and how each affects the final ILUC emissions value.

Across various studies and economic models, the process of assessing ILUC is broadly similar. First, the modelers make an assumption on the scale of the demand shock (i.e., how much new biofuel must be produced) and the type of agricultural feedstock that will be used to meet that demand (in this case, a specific crop). If there is an existing use for the feedstock (as with food crops), the consumption of existing supplies may shift as the quantities previously used for food transition to fuels—this is not a factor for energy crops because there is no significant existing market for energy crops with non-energy uses. The increase in demand may cause production to increase on existing cultivated land by increasing yield through changes to agricultural practices. Lastly, cultivation will expand onto other land in order to meet the remaining demand.

An important factor in estimating ILUC is the degree to which the demand shock is met through maximizing the supply of feedstock from a fixed amount of land (intensification) versus increasing production by expanding the area of land cultivated (extensification). Changes can also occur in the production and consumption of other commodities. The purpose of using an economic model in this type of analysis is to simultaneously assess the interactions of all these factors.

To quantify the ILUC response, each model estimates how the market reacts to the demand shock, both in terms of agricultural expansion to meet the demand directly, as well as indirect responses. The market response is then compared to a baseline scenario in which the demand shock never occurred. The difference between these two scenarios then tells modelers not only how much land-use change occurs in response to the demand shock, but where in the world it is occurring and on what type of land. From there, the shifts in land use are paired with data on carbon stocks for initial and final land uses to determine the net impact on land-use change emissions.

Despite similar approaches, different ILUC studies use different assumptions about key parameters and structural assumptions that feed into the modeling—leading to results that can vary significantly. Differences in model structure also contribute to variation in results.

FEEDSTOCK YIELD

Feedstock yield refers to the amount of crop produced from a given unit of land in a given year. For energy crop ILUC, feedstock yield is an especially critical assumption because the rate of land expansion is more closely correlated to yield than for food crops. This is because energy crops are minimally harvested at the present time and thus necessitate direct land expansion in response to a demand shock, whereas food crops used for biofuel can be diverted from existing land in order to meet that demand shock. Golub and Hertel (2012) identify yield assumptions as potentially the largest contributing factor to ILUC uncertainty. Not only does the feedstock's yield affect the

magnitude of the final emission factor, but so do the yield assumptions for other crops in the model. Increasing yields is one form of intensification. Intensification can also occur as a result of increasing the number of crops grown on one plot of land in a year (i.e., double cropping or multicropping).

Yield—both in actively managed land and at the margins (i.e., on newly converted land)—can vary widely based on the crop in question, but even a single crop's expected yield also will vary based on additional factors, including climate, land quality, and management practices (e.g., crop rotation). This section is intended to summarize typical yields expected for several of the most common energy crops, assess the factors contributing to variation in yields, and provide context for yield assumptions in assessments of energy crop ILUC.

Searle and Malins (2014) argue there are reasons to believe that reported energy crop yields are overstated. The expected yields from energy crops can vary widely based on assumptions of agricultural practices and location, and it is easy for best-case estimates of energy crop yield to be taken out of context. Empirical studies sometimes report yield values achieved in small test plots, which tend to be higher than at commercial scale for a variety of reasons, including losses with drying and harvesting inefficiency under real-world conditions (Searle & Malins, 2014). Additionally, edge effects, where the productivity of crops increases at the edge of plantations with greater light availability, can result in artificially high yields measured on small plots (Searle & Malins, 2014). Most estimates of energy crop yield do not take the potential yield impact of scaling up production to commercial scale into account, even though when taken together these effects may significantly reduce production relative to test plots (Searle & Malins, 2014). Commercial yields also may be lower than those measured on experimental plots if energy crops are grown on land that is marginal for agricultural production.

Allen et al. (2014) estimate ranges of energy crop yields across several different climatic zones for abandoned agricultural land in the EU, relying in part upon the results from Searle and Malins (2014). The results of this review are shown in Figure 2, suggesting a range of 3 to 15 dry tonnes per hectare (t/ha) across all six feedstocks. Given the wide range of possible yields in the review, it is important to emphasize the role that land quality can play on expected yields. The lower end of the range is reflective of lower-quality abandoned land in the EU, whereas the upper end reflects higher quality abandoned land.

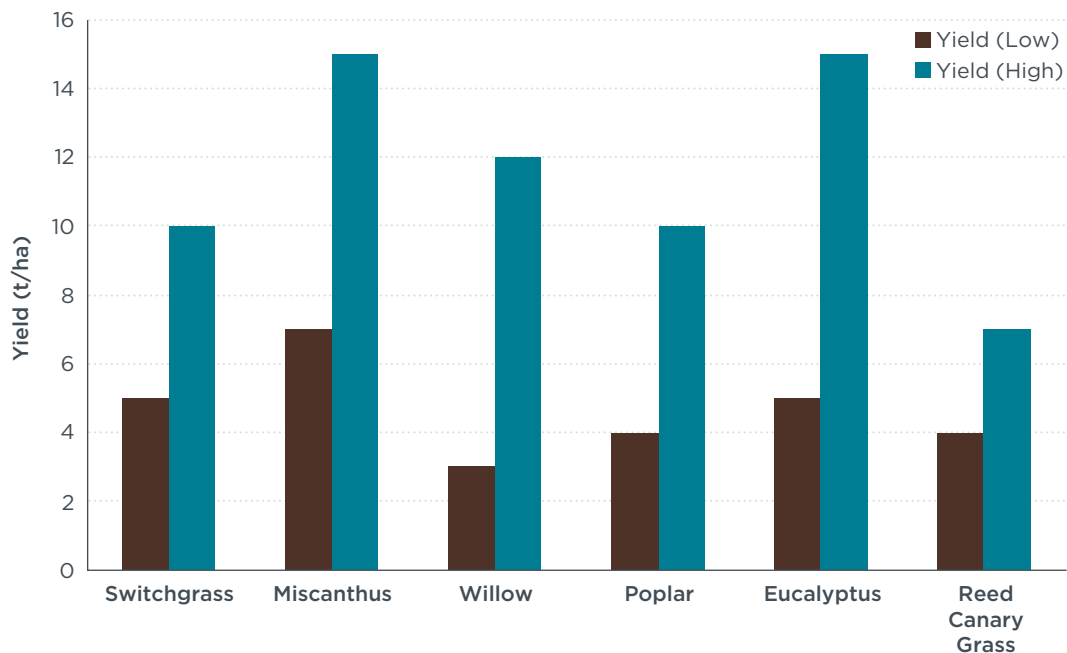


Figure 2. Expected energy crop yields at commercial scale in Europe (t/ha).

Note: Adapted from Allen et al. (2014)

As the role of energy crops is anticipated to expand in the coming years, a key consideration in forward-looking ILUC analyses is the potential for future improvement in yields toward 2030. Because energy crops to date have not been commercialized to the same extent as food crops, some studies such as one from the U.S. Department of Energy (DOE, 2016) assume that they have more potential for yield improvements than food crops. Energy crops, in theory, could experience even higher yield increases than food crops such as corn in the coming years if the technological advances that have improved corn yields are realized in a short period of time. Despite this optimism, Searle and Malins (2014) highlight several factors that suggest yield improvement for energy crops is likely to be much slower than for food crops:

- » Even in optimistic scenarios, energy crops are likely to have a much smaller overall market than food crops, with correspondingly lower market pressure to improve yield.
- » Perennial energy crops take much longer to reach maturity than annual crops, such as corn, which translates into a lengthier breeding process, because high-yielding breeding combinations take longer to identify.
- » Energy crops tend to be less responsive to fertilizer than food crops, so energy crop yields will not improve with fertilizer application beyond a certain point.

Overall, the literature suggests three important points that should inform ILUC assessments for energy cropping: (a) the expected yields from energy crops vary significantly based on their location and management practices; (b) the recorded yields from test plots are not necessarily indicative of the expected yields from commercial plantations on marginal land with lower productivity; and (c) yield improvements for energy crops may be constrained relative to the observed, historic yield improvements for food-based crops.

LAND CONVERSION

A critical issue at the heart of the debate on the ILUC emissions from energy crops is the question of which land types would be used to cultivate energy crops and the extent to which these crops would displace existing land uses. For biofuels made from food crops, the added demand from biofuels policies tends to shift existing food crop production from human consumption toward the fuel sector, creating a shortfall in food supply that generates indirect pressure on land. In contrast, energy crops are not produced in significant quantities worldwide and largely do not have existing markets outside of biofuels. Therefore, any increase in energy crop demand is likely to stimulate either cropland expansion to meet the new demand, or cause displacement of existing production of other crops. Thus, energy crops can be expected to primarily cause DLUC. DLUC is not necessarily better or worse than ILUC—its emissions impact is driven primarily by the difference in carbon stock between its previous use and the carbon stock of energy crops. For lands with low initial carbon stocks, there is some evidence that the GHG emissions from energy cropping would be minimal or even negative (see section on carbon stock change, below).

Although it is clear that in general using marginal land for energy crop cultivation would avoid emissions from the conversion of high-carbon forestland and grassland, in practice, the definition of marginal land is unclear. Literally speaking, marginal land is the most likely land type to change uses in response to economic factors and local considerations (Shortall, 2013). Depending on the context, the term marginal land is sometimes used to refer to fallow land, abandoned agricultural land (whether agricultural production ceased recently or decades ago), or contaminated land that is unfit for food production. Data on these land types are inconsistent across countries, and it is therefore difficult to assess the availability of marginal land for energy cropping on a regional or global basis (Allen et al., 2015). Economic models must create land categories and make assumptions about what types of land could fall into the marginal land or similar category. Land categories can and do overlap—any attempt to definitively sort land area into categories based on both its ecological characteristics and commercial use will be an oversimplification. Acknowledging the wide variety of land types that constitute marginal land can include one or a combination of the following land categories:

- » **Abandoned land:** This land category is used by GLOBIOM and includes recently-abandoned cropland and cropland temporarily lying fallow. This land has been abandoned sometime between 2000 and the present within the EU land database used in GLOBIOM.
- » **Natural land:** This land category is used by GLOBIOM and includes land not classified as cropland, grassland, or forest in the initial land cover data of GLOBIOM. Land that previously was used for agriculture but abandoned prior to 2000 is included within this category.
- » **Cropland pasture:** Cropland pasture is a land category defined by the U.S. Department of Agriculture (USDA) and is more commonly used in U.S.-focused ILUC assessments. It is included in GTAP and FASOM. According to the USDA's definition, cropland pasture is considered within long-term crop rotation and includes land that previously was used by agriculture within the last 100 years. However, it has more recently been either abandoned or used for livestock grazing, although it could be used for cropping in the near term without additional improvement (USDA, 2017).

This category has some overlap with GLOBIOM's Natural Land and Abandoned Land categories, depending on how long ago the land had been used for cultivation. It also overlaps somewhat with GTAP's Pasture category.

- » **Pasture:** This land category has some overlap with grassland, although in this case it refers to open land used primarily for livestock grazing. It is actively managed to support livestock production and typically contains forage specifically cultivated for livestock. GLOBIOM does not include a pastureland category, combining this land type with grassland.
- » **Grassland:** In most models, this land category refers to open land occupied primarily by forage plants and perennial grasses. This category of land does not contain forest, but is not sufficiently cleared for agriculture and tends to have higher carbon stock and biodiversity than pasture. In GLOBIOM, however, the grassland category includes land in active use for livestock grazing.
- » **Unmanaged forestland:** This category of land contains both primary and secondary forest growth and has higher carbon stocks than grassland, but may not be protected from land conversion or have an associated economic use.

Whether energy crops are grown on marginal land or displace food and fiber crops on existing agricultural land depends on their economic competitiveness. Petrenko and Searle (2016) assessed the profitability of energy cropping relative to growing food crops in Europe by comparing the expected yields and production costs of four energy crops to those of existing agricultural commodities in several EU countries. The results indicate that, in the absence of policy support, energy crops are less profitable than the most common food crops in each of the countries, and up to 10 times less profitable than the top produced crop in the same country. Even for the few cases where energy crops are more profitable than rye and oats—minor crops produced in much lower quantities than wheat, for example—the study postulates that farmers may still be hesitant to make the long-term changes to their production systems necessary to cultivate energy crops. This suggests that a very strong policy value would be necessary to induce farmers to replace food production with energy crops on a large scale.

It may be more economical in general to produce energy crops on marginal land. By definition, marginal land is not sufficiently productive to support food and fiber crop production, but energy crops tend to remain productive on low quality land relative to food crops. Perennial grasses and some types of short rotation woody crops tend to be more drought-tolerant and require less fertilizer than food crops (Searle, Petrenko, Baz, & Malins, 2016; Searle & Malins, 2014). For example, DOE's *2016 Billion-Ton Report* estimates that tens of millions of acres of set aside land in the United States could produce energy crops with reasonable yields.

Some types of land, such as forestlands, may have protections outside of biofuels policies that often are restricted in their conversion through conservation areas and parks. Even non-protected forests may also be more difficult or expensive to convert than grassland or abandoned cropland because the forest must be cleared first. Managed forestland with an active economic use is only available for land conversion if the new use exceeds its existing economic rent (e.g., timber).

However, energy crops conceivably could be cultivated on high-biodiversity, high-carbon stock lands if there were no policy restrictions in place on land conversion and if it was economical to do so. In the EU, the RED sustainability criteria require that no eligible

biofuel can come from crops grown on land that was forest in 2008. This requirement is actively enforced and requires certification to prove that the biofuel feedstock was not produced on land that recently had high-carbon stock. In the United States, the RFS requires that all eligible biofuel feedstock must be grown on land that was used for agriculture in 2007. However, this requirement is not strictly enforced. The U.S. Environmental Protection Agency (EPA) uses the “aggregate compliance” approach to monitor compliance with the land conversion restriction for the RFS, simply comparing total cropland area in the United States in any particular year to the total cropland area in 2007.² Biofuel producers are not required to demonstrate that their feedstock does not cause direct land-use change. The conversion of forest or other types of natural land to biofuel feedstock is thus possible in the United States for the domestic biofuel market.

CARBON STOCK CHANGE

Generally, as land shifts from one use to another, the carbon stock of that land—referring to the embedded carbon in the existing biomass and in the soil—changes in response to its new use. Ecosystems such as forests, which contain substantial biodiversity as well as ecosystem services, also contain some of the largest carbon stocks owing to their high concentrations of vegetation. In contrast, cropland and recently abandoned agricultural land tends to have substantially less vegetation than forestland and thus have far lower carbon stocks. Grassland and pasture tend to have significantly higher soil carbon levels than cropland, and over time the carbon stocks of abandoned land can be expected to converge with those of grassland or forest (Guo & Gifford, 2002; Murty, Kirschbaum, McMurtrie, & McGilvray, 2002; Don et al., 2011). Peatlands, which have very high soil carbon stocks, can occur in conjunction with other land types and can generate very high CO₂ emissions if disturbed during land conversion (Page et al., 2011).

The land-use change emissions from energy cropping are strongly sensitive to assumptions about which type of land is used for cultivating new energy crops, as well as the initial carbon stock of that land prior to cultivation. The assumptions here affect the direct emissions resulting from the conversion of land for energy cropping as well as indirect emissions resulting from land-use change when energy crops displace other crops. Generally, the carbon stocks of land are depleted through human uses (e.g., agriculture) and undisturbed lands such as forests and grasslands have a higher carbon stock. Converting land from one use to another, such as for agriculture, generally results in one-time release of stored carbon. Conversely, if disturbed land can regrow natural biomass, it regains a portion of its depleted carbon stocks over time (Guo & Gifford, 2002; Murty et al., 2002; Don et al., 2011).

Searle et al. (2016) develops a literature review of soil carbon changes when perennial grasses and SRWCs are cultivated on cropland and marginal land. The literature review suggests that perennial grasses consistently sequester carbon in cropland by generating high below-ground biomass in conjunction with reduced land disturbance relative to annual crops. There is little evidence on soil carbon changes with energy crops on abandoned agricultural land; however, according to a small number of empirical studies, perennial grasses appear to sequester carbon on former cropland faster than soil carbon naturally increases when cropland is abandoned. If we infer soil carbon sequestration for energy crops grown on abandoned cropland as the difference in soil carbon change rates between energy crops on cropland and natural regrowth on abandoned land, we

2 40 CFR Part 80

can estimate a range of 0.2 to 1.1 tC/ha, but this estimate carries high uncertainty due to the limited number of observations. Similarly, Searle et al. (2016) found no direct evidence on soil carbon changes for SRWCs planted on abandoned land, but there is some evidence that SRWCs tend to increase soil carbon on cropland more quickly than natural regrowth. One study found that poplar, willow, and black locust sequester soil carbon more quickly than conversion to meadow or perennial energy grasses (Ceotto & Di Candilo, 2011).

A recent meta-analysis reinforces these conclusions by modeling carbon inputs to soil and turnover rates. Agostini et al. (2015) draws together a variety of experimental data on perennial grasses and SRWCs to assess uncertainties in the soil carbon stock changes associated with energy cropping. The study concludes that in the short term, both crop types (1.14-1.88 tC/ha/yr for grasses and 0.63-0.72 tC/ha/yr for woody crops) exceed the baseline of 0.25 tC/ha/yr of carbon sequestration from setting arable land aside.

Although available evidence suggests that energy crops are likely to increase soil carbon on abandoned cropland compared to natural regrowth, there is not sufficient empirical evidence to draw firm conclusions. Furthermore, it is not clear that the cultivation of these crops on converted grassland would provide any soil carbon benefit. On average, the studies reviewed in Searle et al. (2016) suggest that no net soil carbon change may be expected from the conversion of grassland to grassy energy crops, but grassland conversion to SRWC is likely to result in a net soil carbon loss. The conversion of forest to energy crops is not specifically reviewed in Searle et al. (2016), but similar results might be expected as for soil carbon change with grassland conversion.

Figure 3 shows ranges of values for the expected soil carbon storage from energy cropping on marginal lands from two separate literature reviews, Searle et al. (2016) and Agostini et al. (2015). The range of possible values can vary widely depending on the feedstock, the study and the geographic region. There is generally more certainty about soil carbon storage changes from energy cropping on existing cropland, which tends to have low existing carbon stocks and is a more uniform land category. For grassland, which is relatively high in carbon, energy cropping was found to be a net emitter of carbon relative to leaving the land undisturbed.

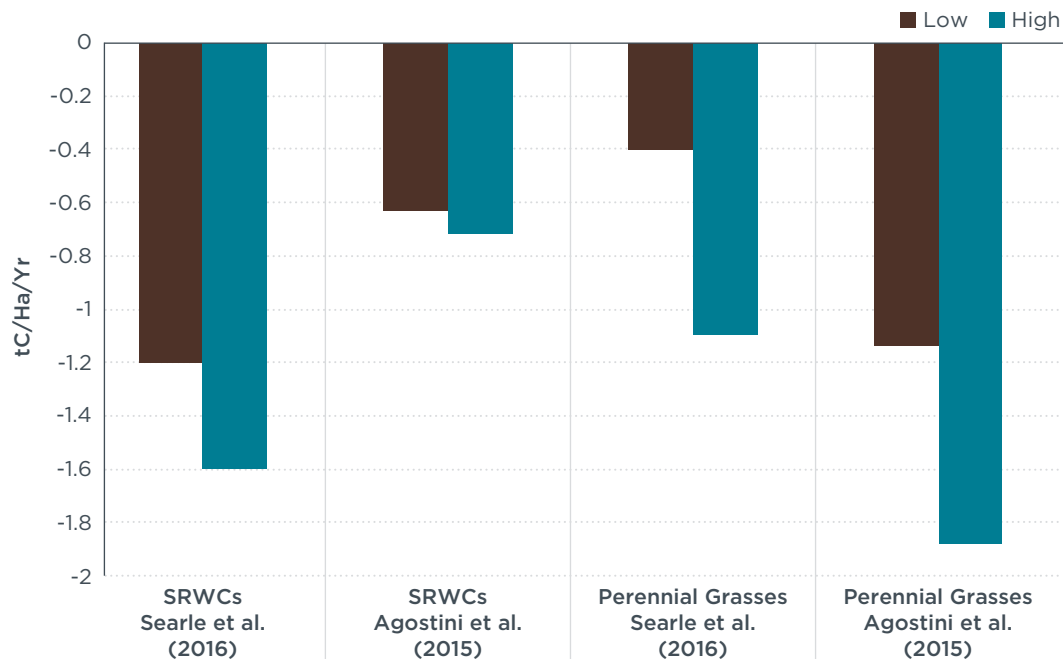


Figure 3. Soil carbon sequestration from energy crops on marginal land.

The above-ground density of vegetation also contributes to the total carbon stock of a plot of land. Forestland, for example, has the highest carbon stock of the different land categories due to its high density of above-ground vegetation. In contrast, land that has been abandoned or otherwise depleted often has minimal above-ground vegetation and thus has lower biomass stocks. Land clearance for energy cropping would release the carbon content of that land immediately, thus creating a carbon debt that would need to be paid off through carbon sequestration and mitigating emissions elsewhere, generally on a time horizon of 20 to 30 years. Given the range of representative yields for bioenergy crops indicated in the literature, these biomass stock ranges suggest that the one-time clearance of forest biomass would likely take decades to offset with energy cropping and would be a poor decision from a climatic perspective. However, grasslands or agricultural lands with lower initial biomass stocks—such as those which had been recently abandoned—could be offset by energy crops with a higher annual productivity (Searle et al., 2016).

Land conversion to energy cropping also causes “foregone sequestration,” which refers to the opportunity cost associated with the clearance of vegetation that would have continued to grow and sequester carbon over time had the land not been cleared. This effect occurs when a land with high biomass stocks and rates of afforestation (i.e., vegetation growth) is cleared and replaced with a lower biomass stock, such as the conversion of a forest to a cropland. The annual carbon sequestration that would have occurred is then summed up over the time horizon of the analysis, generally 20 or 30 years, and then attributed to the ILUC emissions. Foregone sequestration influences energy cropping emissions in cases where the energy crops displace high-carbon stock lands.

REVIEW OF ILUC ESTIMATES

This section provides an overview of studies that have estimated ILUC emissions from energy crops using economic models, either a computable general equilibrium model (CGE) such as GTAP or a partial-equilibrium model (PE) such as FASOM or GLOBIOM. These studies evaluate the impact of an exogenous demand shock for cellulosic biofuel derived from switchgrass and Miscanthus, although one study, Valin et al. (2015), modeled generic perennial grasses and SRWCs. Our analysis is presented chronologically, from EPA's original ILUC analysis for the RFS in 2010 through to the 2015 GLOBIOM analysis conducted in support of the EU's proposed RED II.

To compare the results for each study, we first describe each study's methodology for estimating ILUC and highlight decisions or assumptions that impact that study's final results. From there, we review the treatment of the three key factors discussed in the previous section in each model. First, we assess the study's yield assumptions. The total land conversion in each study is then broken out into different land categories to assess where each analysis predicts that land is being converted, and the implied carbon stock change for that conversion to energy cropping.

FASOM-FAPRI ILUC ASSESSMENT

In its impact assessment for the RFS, the EPA estimated the ILUC emissions from cellulosic ethanol derived from switchgrass grown in the United States (U.S. Environmental Protection Agency [EPA], 2010). The modeling effort predates the other analyses discussed in this report and was performed using a combination of two partial equilibrium models: the Food and Agricultural Policy Research Institute (FAPRI) model and the Forestry and Agricultural Sector Optimization Model (FASOM). The FASOM model has greater resolution of the agriculture sector at the domestic level and is used to develop estimates of ILUC at the U.S.-level. Those results were then used in the international-facing FAPRI model to assess the international response to changes in U.S. agriculture. Together, the two models combine to estimate the net global ILUC emissions from the use of switchgrass-derived cellulosic ethanol in response to the RFS mandates.

EPA (2010) models the impact of supplying 7.9 billion gallons of switchgrass ethanol produced within the United States, consistent with the original statutory volume of 16 billion ethanol-equivalent gallons of cellulosic biofuel by 2022 in the Energy Independence and Security Act (EISA) of 2007, of which a substantial share was projected to come from energy crops. The required volumes for cellulosic ethanol have since been revised downward annually to account for consistent shortfalls in the production of cellulosic ethanol (EPA, 2017). In the modeling, a mix of different fuels (e.g., corn ethanol, corn stover ethanol, soy biodiesel) is used to meet the RFS volume mandates. To calculate the net impact of ILUC for only switchgrass cellulosic ethanol, EPA estimates the emissions from a scenario where all fuels except switchgrass are used to meet the RFS mandate and then subtracts that value from the emissions estimate for the baseline 2022 scenario where the full mix of mandated fuels is produced in 2022, isolating the impact of switchgrass production.

Compared to the other ILUC analyses presented in this report, the EPA effort is an exception in several notable ways:

- » The analysis was conducted using a combination of two models. FASOM provides detailed, agricultural and forestry-sector land-use change estimates at a domestic level, whereas FAPRI estimates the international LUC shifts in response to the domestic changes estimated in FASOM.
- » FASOM uses cost-optimization that factors in the crop yields for various regions as well as the cost of transportation to hypothetical cellulosic ethanol facilities. This increases regional variation in the cost-effectiveness of energy cropping by introducing additional factors beyond the cost and availability of land resources.
- » FASOM does not differentiate yields between existing cropland and new land, whereas other models generally account for a yield penalty for production on newly converted land (Malins, Searle, & Pavlenko, 2015). Instead, FASOM assumes an additional economic cost with converting new land to improve it to be as productive as existing cropland.³
- » EPA's analysis assumes 100-million-gallon-scale cellulosic ethanol facilities, which would be very large facilities. This assumption likely results in energy crop production in concentrated, rather than fragmented, areas to supply such a large biorefinery within reasonable transport distance, and may result in greater displacement of agricultural land in high yielding areas such as the corn belt. It is possible that more concentrated production areas would occur on displaced agricultural land as marginal land may be more fragmented.
- » EPA's study includes a full consequential analysis of the RFS-induced shifts in crop production. Unlike most other studies, which include only the ILUC emissions from land conversion, EPA also estimates the other emissions that result from changes in agricultural practices, including agricultural equipment use, fertilizer emissions, methane emissions from rice straw decomposition, and livestock emissions. For example, where existing cropland cultivation is displaced by energy crops, the emissions from the previous agricultural practices are then reduced as well. For international land expansion, this approach also factors in the added direct emissions from the additional agricultural practices.

EPA's analysis predicts displacement of existing crops by energy cropping that is much higher than the level of displacement predicted by the other modeling studies reviewed here. This analysis can thus be considered a more conservative scenario of the potential indirect impacts of energy crops. Figure 4 provides an overview of the ILUC emissions from this approach, broken out into domestic and international emissions. For the purposes of consistency with the other studies, the ILUC emissions from switchgrass production are considered here to be the sum of the domestic and international land-use change. Although EPA's analysis quantifies the shifts in direct upstream production emissions in response to the land-use change caused by the demand shock, we do not take into account those specific emission sources in our comparison. Assessments of LUC-only emissions typically consider direct emissions from agriculture to be an attributional source of emissions rather than a consequential effect.

³ Personal communication with EPA OTAQ, 2017.

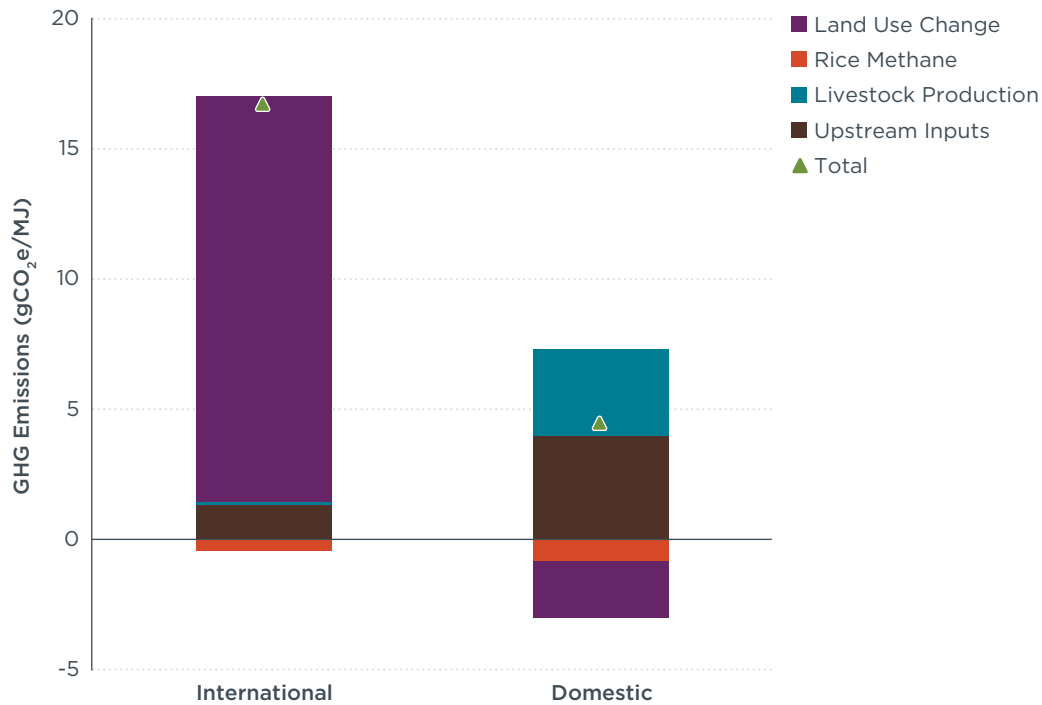


Figure 4. Overview of domestic and international emissions from switchgrass ethanol, 2022.

Source: EPA, 2010.

Although EPA’s analysis correctly notes the high variability in switchgrass yields in the literature, this study draws upon a long-term DOE study on switchgrass production for its own estimates. The DOE estimates that a substantial yield improvement is possible within 10 years. Thus, EPA assumes that an average yield of 15.1 t/ha is possible by 2022, reflecting a substantial improvement over the average yields at the time of the study. EPA’s assumption is high compared to the average estimated ranges for energy crop yields in Searle and Malins (2014) and Allen et al. (2014). The high switchgrass yield estimate is likely due in part to cultivation in higher yielding regions such as the corn belt to minimize feedstock transport costs to large biorefineries. High yields may also be appropriate in this particular study because EPA assumes that most switchgrass is grown on existing agricultural land, which is likely to support higher yields than on marginal land, although we note that EPA assumes the same yields on marginal land, implicitly assuming that crop producers improve the quality of newly converted land (Beach & McCarl, 2010; Searle & Malins, 2014).

Domestically, FASOM estimates that to produce 7.9 billion gallons of switchgrass-derived cellulosic ethanol, approximately 5.1 million hectares of land are converted to switchgrass production. This shift includes the displacement of approximately 3.5 million hectares of existing cropland, primarily corn and soybean production. This results in a net 1.6 million hectares of land diverted from other, non-agricultural uses. The newly converted land comes from a mix of idled cropland, cropland pasture, and forestland. The inclusion of idled cropland, in addition to cropland pasture, is a substantial methodological difference in the FASOM modeling compared to several of the general equilibrium models assessed in the text, and it constitutes the largest share of the land expansion occurring in response to the switchgrass demand shock. Idled land typically refers to land in short-term rotation, for example, unused for one season or one year

before returning to cultivation. Cropland pasture in EPA’s modeling and in the GTAP studies and abandoned agricultural land in Valin et al. (2015) refer to land that has been taken out of crop production for a longer and indefinite period. The other modeling studies do not explicitly include idled land as a land category. FASOM also estimates that the switchgrass slightly increases the area of domestic forest-pasture land. Figure 5 illustrates the net change in land use in response to the switchgrass shock by 2022.

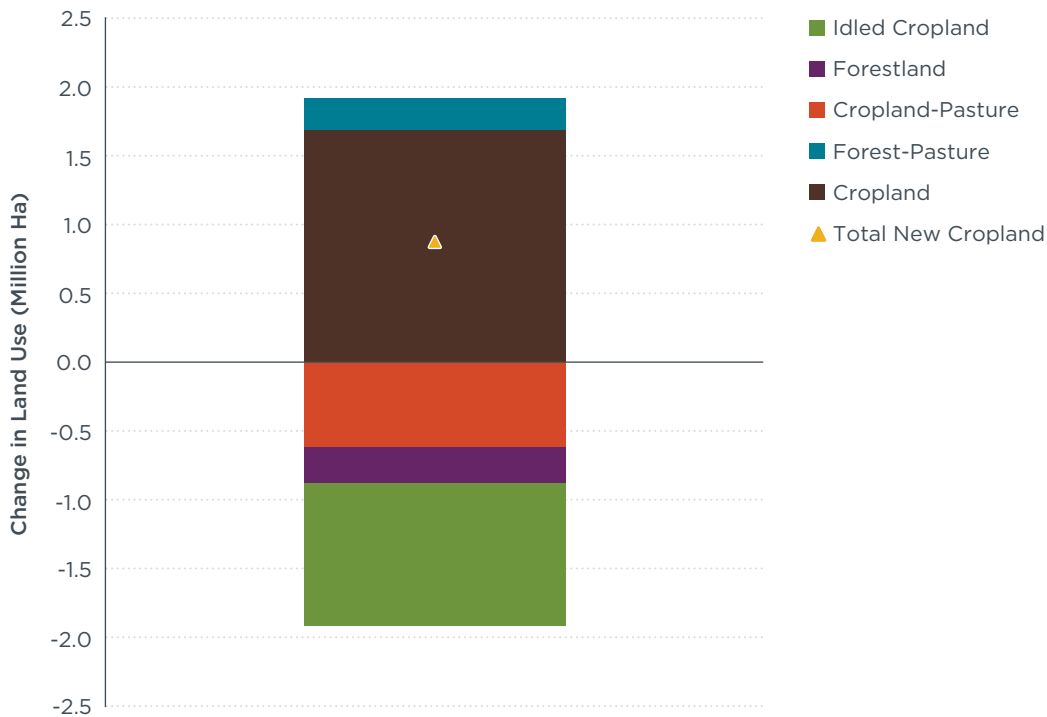


Figure 5. Change in domestic land use by type from switchgrass ethanol, 2022.

Source: EPA, 2010

In the FASOM modeling, of the 5.1 million hectares used to grow switchgrass domestically, approximately 95% (4.8 million hectares) comes from either cropland, idled cropland or cropland pasture. Therefore, the domestic impact on carbon-rich land is minimal. A substantial amount of switchgrass production occurs on existing cropland to reduce handling costs to large biorefineries. EPA (2010) assumes that much of the cellulosic ethanol production in the United States in 2022 will occur at commercial-scale 100-million-gallon biorefineries with substantial feedstock demand. In some cases, this causes the model to estimate high-density production of energy crops in an area immediately surrounding a biorefinery to reduce transport and handling costs, as energy crops, with relatively low energy content per tonne, resulting in high handling costs per gallon (Beach & McCarl, 2010).

EPA (2010) uses Daycent/CENTURY model soil emission factors for land conversion, which include a modest soil carbon increase when a switchgrass is cultivated on idled cropland and cropland pasture; this is consistent with empirical studies in the literature, but again, we note a relative paucity of evidence overall for soil carbon changes with this type of land-use change (Searle et al., 2016).

The FASOM modeling estimates net $-2.2 \text{ gCO}_2\text{e/MJ}$ emissions from domestic land-use change. Working backward from this factor, a 30-year time horizon, and the 5.1 million hectares of switchgrass cultivation, we estimate an implied average carbon stock increase of 0.1 tC/ha/yr for soil carbon. FASOM does not include soil carbon stock increases generated by switchgrass growth relative to annual cropping on existing cropland, as the model only estimates soil carbon stock changes when land transitions between uses and management practices. Therefore, the added soil carbon storage from energy crop cultivation on existing cropland is not included in EPA's assessment. This omission may understate increases in soil carbon sequestration, potentially overestimating net ILUC emissions for switchgrass.

The international impact of switchgrass production is substantially different from the domestic land-use change and the effects predicted in the other studies assessed here. To determine the international LUC in response to domestic switchgrass production, the net change in land use within the FASOM modeling is used as input for FAPRI's international agricultural framework. The model estimates that the international crop area will expand by approximately 1.4 million hectares by 2022, with the majority of the increase—approximately 900 million ha—attributed to the expansion of soybean cultivation in Brazil. Additionally, the model predicts a small decrease in international pasture land, likely from additional demand from soybean expansion in Brazil, which displaces some grazing land. EPA's FAPRI modeling estimates that the net international ILUC emissions (LUC-only) are approximately $15.6 \text{ gCO}_2\text{e/MJ}$, with more than 90% of those emissions occurring in Brazil.⁴ Although the land conversion for switchgrass is high on an absolute scale, it is lower than for first-generation, food-based biofuels per unit energy. For example, the international land conversion for soybean biodiesel (6.4 hectares per billion btu of biofuel) is approximately five times higher than the international land conversion for switchgrass (1.3 hectares per billion btu). This is largely because expanding switchgrass production displaces less food production than directly using those food crops for fuel, due to the higher yields of energy crops.

Of the net ILUC emissions EPA estimates for switchgrass, the bulk of emissions are expected to come from ILUC occurring internationally, rather than from direct land conversion in the United States. This contrasts with other studies, which attribute the bulk of emissions to DLUC. Whereas EPA assumes that the majority of domestic LUC is constrained to cropland or cropland pasture, international LUC includes significant areas of forestland and pastureland diverted to food crop production. Furthermore, due to the displacement of domestic food production, the magnitude of international LUC is higher than for other studies. The bulk of the international land conversion occurs in three Brazilian regions modeled in FAPRI, including the Amazon (predominantly forestland) and the Cerrado (including a mix of grassland and pastureland). Whereas switchgrass production on cropland in the United States sequesters carbon, the conversion of forest and pasture to annual food crop production—effectively replacing food crops in the United States that were diverted to switchgrass—results in substantial one-time carbon emissions that are not offset within the 30-year time horizon. For example, the one-time emissions from converting forest to annual crops in North Mato Grosso, Brazil, are 614 tC/ha , with a 30-year emissions value of 772 tC/ha , factoring in foregone sequestration (EPA, 2010).

4 Similar to the treatment of domestic energy cropping, EPA's analysis includes the upstream agricultural emissions for crop production internationally. For the purposes of this study, we do not consider those emissions in our comparison to other ILUC modeling studies

Overall, the EPA's analysis finds that switchgrass ethanol generates substantially lower ILUC emissions (13.4 gCO₂e/MJ) than either corn ethanol or soybean biodiesel, although this value is larger than EPA's ILUC estimate for sugarcane of 5 gCO₂e/MJ. To maintain consistency with our comparison of other studies in this report, these values exclude the shifts in agricultural production emissions caused by shifts in crop production. Although switchgrass causes greater domestic land conversion than food-based biofuels in the FASOM analysis, that land conversion results in net carbon sequestration. Furthermore, although some food crops are displaced by switchgrass, there is overall less food production displaced per unit of fuel produced than for corn or soybeans, thus moderating the international response. International land expansion, which comes largely from grasslands and forestlands, generates the bulk of the emissions for all biofuels in the EPA analysis.

GTAP ILUC ASSESSMENTS

The Global Trade Analysis Project (GTAP) model is a CGE model that simulates the global trade network and estimates the shift in global land use in response to a demand shock. Beginning with GTAP-BIO, introduced in 2008, the modelers of GTAP have introduced updates (GTAP-BIO-ADV and GTAP-BIO-ADVFUEL) that allow scenarios to model the impacts of advanced biofuel production on a more granular basis with a greater variety of agricultural products potentially used for biofuel production, such as switchgrass and Miscanthus. Two 2013 studies assess the ILUC emissions from energy cropping using land conversion data from a 2011 model run of the GTAP-BIO-ADVFUEL model (Dunn, Mueller, Kwon, & Wang, 2013; Taheripour & Tyner 2013; Taheripour, Tyner, & Wang, 2011). The 2011 LUC estimates also are incorporated into Argonne National Laboratory's (ANL) Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) model, which uses them in conjunction with ANL's most recent emission factors for land conversion (Dunn et al., 2015).

Taheripour et al. (2011) use GTAP to estimate the ILUC emissions from cellulosic ethanol produced from both switchgrass and Miscanthus in the United States. The study uses volumes similar to those of the EPA's RFS regulatory impact analysis, assuming a demand shock of 7.1 billion gallons of additional ethanol produced from either switchgrass or Miscanthus, after accounting for existing corn ethanol demand, by 2022.

Taheripour et al. (2011) assume relatively high average yields for switchgrass and Miscanthus of 10.1 and 17.5 t/ha, respectively. The ethanol demand shock necessitates approximately 9.5 and 5.1 million hectares of cropland for switchgrass ethanol and Miscanthus ethanol, respectively. Although the relative shares of land categories used to meet the new demand are slightly different between switchgrass and Miscanthus, the results are similar to those from Dunn et al. (2013). Within the study, most of the difference in the land expansion between the two crops assessed is attributable to the higher yield of Miscanthus. The majority of the new cropland in both scenarios comes from cropland pasture, with minimal estimated international land-use change occurring in response to the land pressure. A more recent analysis by Taheripour, Zhao, and Tyner (2017) use an updated version of GTAP (using an updated, 2011 database) to assess the impact of a 1-billion-gallon demand shock on Miscanthus; the land-use shifts from the 2017 analysis are very similar to the original, with the bulk of the new land for energy cropping converted from existing cropland pasture with minimal forestland conversion.

Figure 6 illustrates the total LUC that occurs in response to the demand shock in the modeling, separated into domestic and international LUC. The results suggest that little existing cropland used to produce food commodities is likely to be diverted to cellulosic ethanol feedstock production. Instead, other land consisting primarily of cropland pasture is converted to full-time cultivation. The new domestic demand has little effect on international markets, which do not have much demand for the cellulosic crops. Instead, we see a slight shift in land demand internationally for pasture, due to the loss of domestic land for livestock grazing. International LUC comprises approximately 1% of the total global land conversion for both switchgrass and Miscanthus.

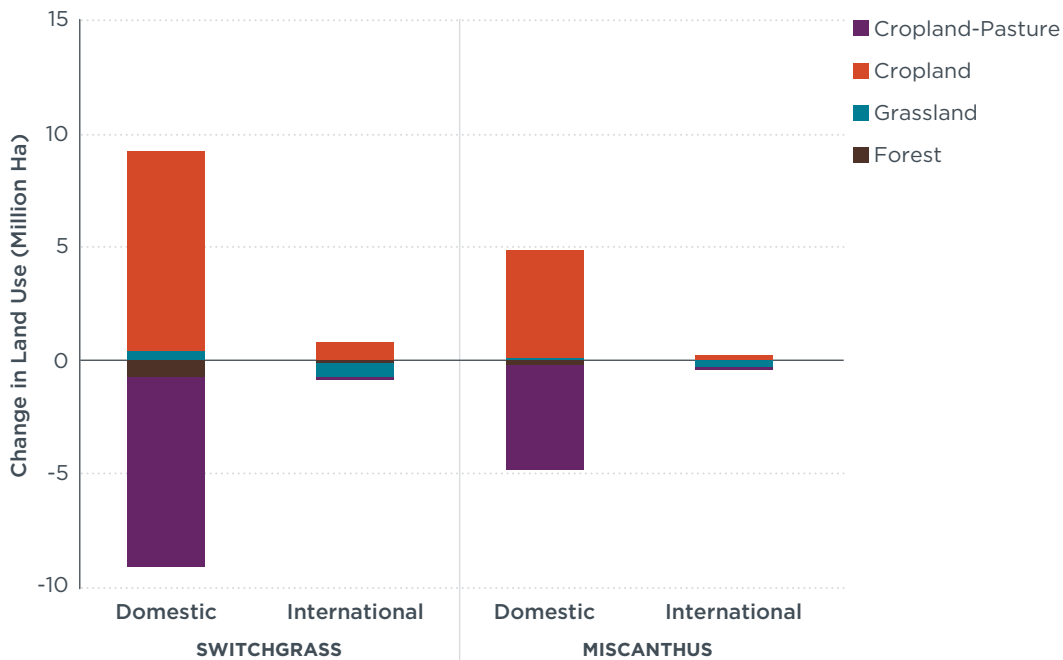


Figure 6. Total land-use conversion from switchgrass and Miscanthus ethanol, 2022.

Source: Taheripour et al., 2011.

A key consideration in GTAP assessments is the treatment of land categories and uses based on their economic value, or rent. In GTAP, land conversion between different uses is established by the model’s constant elasticity of transformation (CET) for land. This CET parameter establishes the elasticity at which one land type is converted into another, based on the comparative value of different uses of that land (Malins et al., 2015). For example, the shifts from cropland pasture to cropland are relatively elastic, because the ease of changing use and the difference in value between energy crops and pasture for livestock is small. Therefore, GTAP analyses tend to consider cropland pasture the likeliest source of new land for energy crops.

The model’s CET nesting structure makes the conversion of forestland to cropland less elastic than the conversion of either pasture or cropland pasture (Golub, Hertel and Sohngen, 2008). Finally, most forestland in the model’s land cover database is classified as inaccessible for either legal or infrastructure reasons, thus excluding it from the land supply altogether. Approximately 60% of U.S. forestland is treated as inaccessible in the most recent version of GTAP (Dunn et. al., 2015). Gibbs, Sheehan and Nelson (2010) highlight the potential risk of understating land supply in response to price due to the treatment of most forestland as inaccessible within the GTAP modelling framework.

Using the underlying data on shifts in land use from Taheripour et al. (2011), two 2013 studies estimate different ILUC emissions for both switchgrass ethanol and Miscanthus ethanol. Dunn et al. (2013) estimate that ILUC emissions for switchgrass and Miscanthus range from 2.7 to 19 gCO₂e/MJ and -10 to -2.1 gCO₂e/MJ, respectively with the lower end of those ranges representing the base case. Taheripour and Tyner (2013) evaluate the impact of using different sets of land conversion emission factors on ILUC emissions, estimating a range of 1.3 to 16.4 and -12.3 to -3.5 for switchgrass and Miscanthus, respectively, when using ANL emission factors. The single largest factors influencing both studies' final results were their assumption of carbon sequestration by energy crops on marginal lands, as well as their estimates that more than 90% of the land diverted to energy cropping comes from cropland pasture.

Figure 7 summarizes the land-use change emissions from both the switchgrass and the Miscanthus scenarios in Dunn et al. (2013), breaking down each land conversion category's contribution to the total emissions. The single largest factor in the final emissions value for fuels assessed is the carbon sequestration from energy cropping on cropland pasture, which adds a relatively strong negative emissions value to the overall ILUC emission factor for both feedstocks. The study uses an emission factor of approximately -0.39 tC/ha/yr and -0.58 tC/ha/yr for switchgrass and Miscanthus grown on cropland pasture, respectively. Although cropland pasture has a carbon stock change similar to abandoned land, these two land categories are not necessarily the same, as cropland pasture may have an existing use for livestock grazing. The sequestration is offset somewhat by the land conversion emissions on domestic forests and international land-use change (mostly forest into pasture), both of which comprise a very small share of the overall land conversion, but fairly high emissions on a per-hectare basis. Forestland conversion is estimated to emit a 30-year average of approximately 2.61 to 2.84 tC/ha/yr in the switchgrass and Miscanthus scenarios, respectively.

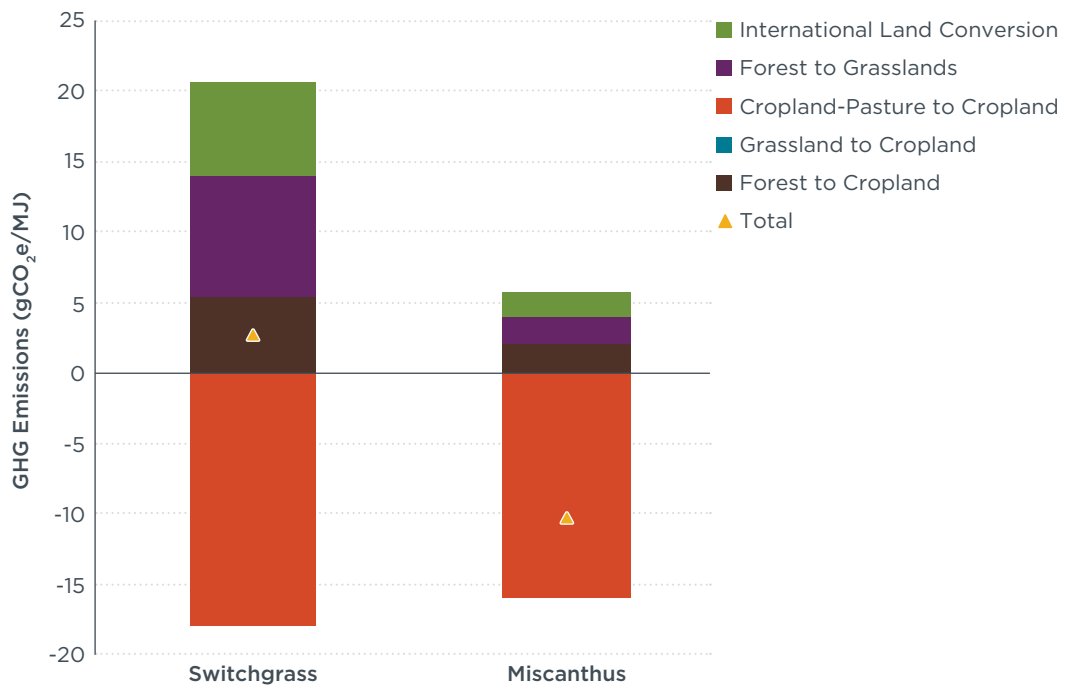


Figure 7. Land-use change emissions from switchgrass and Miscanthus cellulosic ethanol, 2022.

Source: Derived from Dunn et al., 2013.

Although the results from both 2013 studies did not contain a detailed breakdown of the carbon stock factors used to estimate ILUC emissions, we can use the CCLUB model to infer the carbon stock changes by land category. The CCLUB model of LUC emissions incorporates the land conversion data from Taheripour et al. (2011), generating different ILUC emission factors depending on several factors, most notably the choice of underlying emission factor data as well as agricultural practices and soil depth. If we use the baseline assumptions, which is to say Century Modeling for domestic land-use emissions, 30 cm soil depth, and harvested wood product assumptions, and the most recent LUC emissions data set generated through the CENTURY model, the ILUC emissions for switchgrass and Miscanthus are 7.6 gCO₂e/MJ and -10.4 gCO₂e/MJ, respectively, a result similar to Taheripour and Tyner (2013).

We used the CCLUB factors to assess the impact of each land category transformation on the total ILUC emissions for switchgrass and Miscanthus as shown in Figure 8. The land conversion factors used in the CCLUB model reflect the assumption that large-scale conversion of cropland pasture to dedicated energy cropping is the primary driver for low emissions for energy crop-derived biofuels. The model assumes that cultivating switchgrass and Miscanthus on cropland pasture sequesters approximately 0.27 tC/ha/yr and 0.56 tC/ha/yr, respectively (a weighted average across all of the agro-ecological zones [AEZs] transformed in the analysis). This response is attributable to the loss of cropland pasture domestically for livestock grazing, which results in the conversion of international forestland to pasture for grazing.

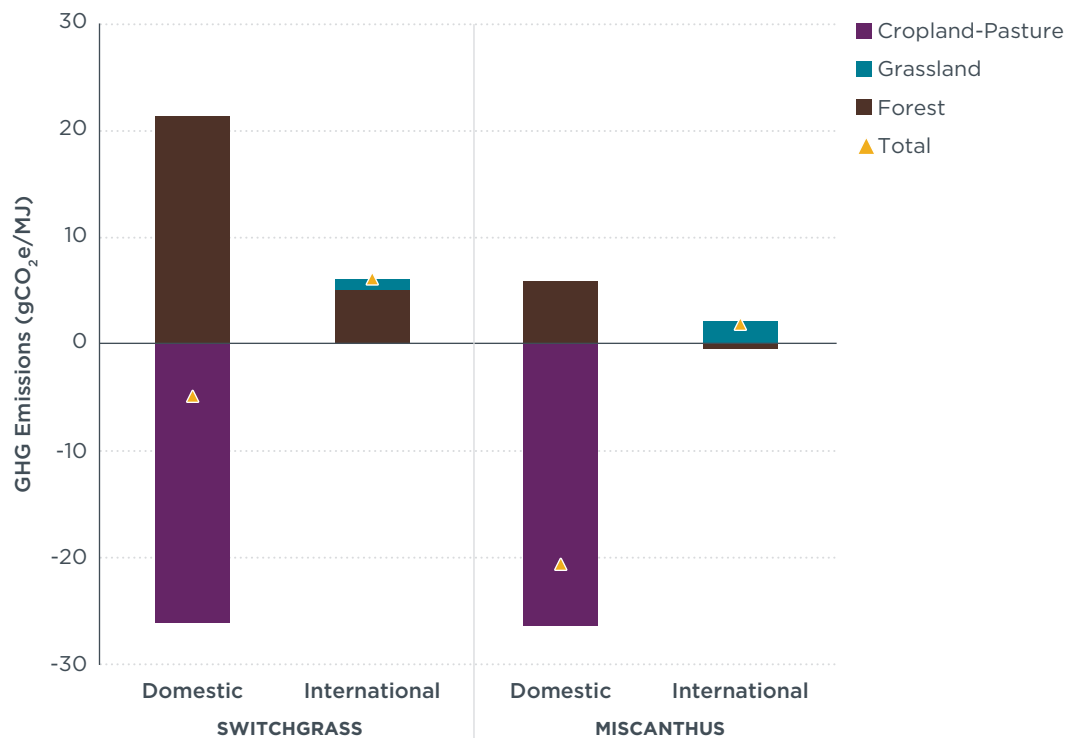


Figure 8. Domestic and international land-use change emissions from switchgrass and Miscanthus cellulosic ethanol, 2022.

Source: Derived from CCLUB model (Dunn et al., 2015)

GCAM ILUC ASSESSMENTS

Both Wise et al. (2015) and Plevin and Mishra (2015) use the Global Change Assessment Model (GCAM) to estimate the ILUC emissions from increased cellulosic biofuel production in the United States. GCAM is a partial-equilibrium integrated assessment model developed by the Pacific Northwest National Laboratory (PNNL). The model contains a climate module linked to a series of economic, energy and land-use systems. Plevin and Mishra (2015) estimate the impact of corn stover and switchgrass production using a modified projection of the EPA’s RFS volumes. The baseline scenario assumes that approximately 3 billion gallons of cellulosic ethanol and 4 billion gallons of Fischer-Tropsch biofuels are produced annually in 2020 as the reference case. To assess the impact of additional energy cropping, the study then shocks the system with a demand for 2 billion additional gallons of either corn stover or switchgrass cellulosic ethanol in 2025.

Figure 9 provides an overview of the land-use change emissions and other emissions induced by the switchgrass demand shock in the modeling. The authors estimate that the ILUC emissions from switchgrass ethanol produced in the United States range from 45 to 52 gCO₂e/MJ, depending on whether additional emissions from livestock production and rice production are included to harmonize the results with the methodology of the EPA’s 2010 RFS2 study.⁵ This study generates ILUC emission estimates on par with food crop ILUC emissions in most other studies. However, energy crop ILUC emissions in Plevin and Mishra (2015) are still far lower than those estimated by the same authors for corn using the same modelling approach.

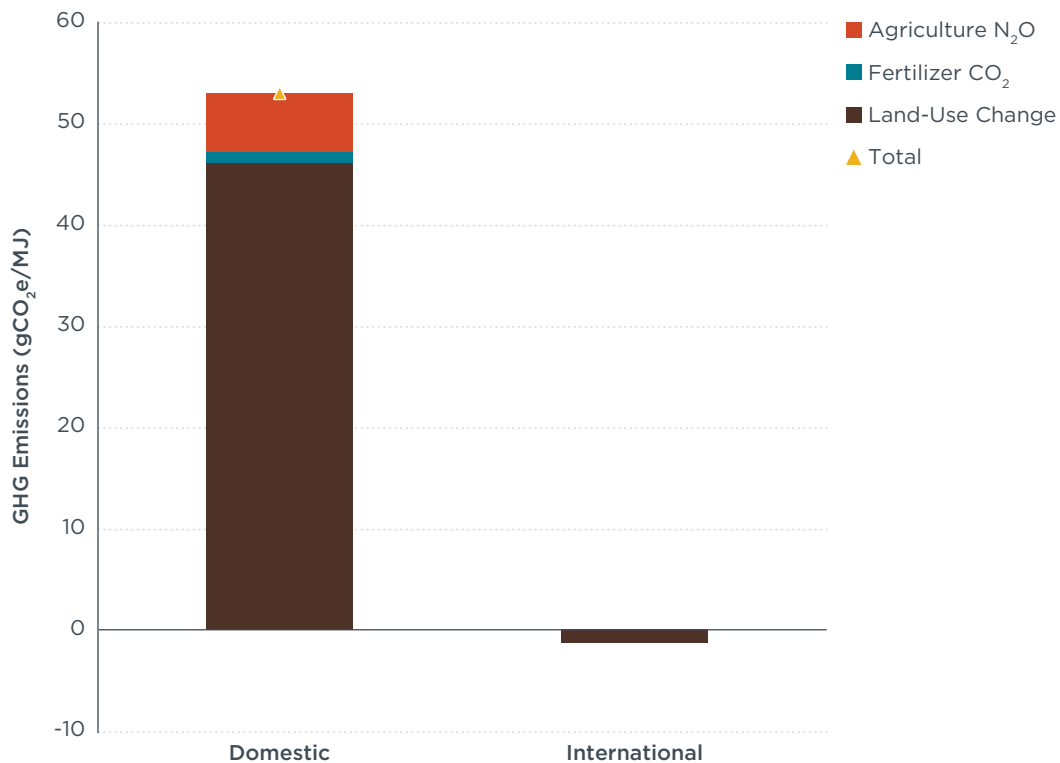


Figure 9. Domestic and international emissions from switchgrass ethanol, 2020.

Source: Plevin and Mishra (2015)

⁵ GCAM also includes the indirect, market-mediated impacts of biofuel mandates on fossil fuel consumption, creating a rebound effect due to lower fossil fuel prices and adding to the emissions attributable to the policy.

If we assume a cellulosic ethanol yield from switchgrass similar to EPA (2010), then we can infer that the GCAM modeling suggests an average switchgrass yield of more than 20 t/ha, much higher than present-day yield estimates.⁶ This assumption greatly exceeds the anticipated switchgrass yields in Searle and Malins (2014), and likely results in a much lower total amount of land converted to meet the demand shock than would be predicted using moderate yield assumptions.

The bulk of the ILUC emissions estimated by the study (45 gCO₂e/MJ) come from domestic land conversion, rather than induced international land conversion. The GCAM analysis also includes consequential direct emissions from shifts in upstream agricultural inputs, estimated using a similar approach to EPA's FASOM analysis; however, we do not consider non-LUC emissions for the purposes of this analysis. The high domestic emissions imply that the majority of the impact stems from direct land-use change, rather than from indirect effects. The GCAM modeling predicts that the switchgrass will be cultivated on high-carbon stock land, theoretically undermining its supposed carbon storage benefits. The international emissions, however, indicate that very little cropland is displaced domestically, resulting in a very small international impact.

The results from Plevin and Mishra (2015) are relatively consistent with the results from Wise et al. (2015), depending on the AEZ in which the energy cropping occurs. Wise et al. (2015) do not provide an assessment of ILUC emissions on a national scale, instead estimating the impact of switchgrass cultivation for specific AEZs. The study suggests that a national switchgrass ethanol demand would be met predominantly via cultivation on AEZ 10 (with a carbon intensity of 70 gCO₂e/MJ) and AEZ 7 (35 gCO₂e/MJ). Wise et al. (2015) suggest that in GCAM there is slightly more geographic resolution of yield than in GTAP and GLOBIOM. The study uses separate yield assumptions for each AEZ, which affects the relative land demand within each AEZ for the analysis; however, this is still largely an oversimplification of the expected yields on smaller plots of land within a given AEZ.

Figure 10 provides disaggregated emissions for the switchgrass ILUC emissions, broken out by land category and normalized by the MJ of biofuel produced. Although the bioenergy crops themselves sequester a substantial amount of carbon year-over-year, this is more than offset by one-time emissions from the conversion of forestland and pastureland to meet the switchgrass demand shock. The study estimates that switchgrass sequesters approximately 0.4 tC/ha annually on the average hectare, which is substantially less than what would be needed to offset the one-time emissions generated from the conversion of either commercial or non-commercial forests within the modeling framework. The sequestration is closer to the one-time emissions for grassland, pasture and shrubland, but still not enough to offset the land conversion emissions within a 30-year time horizon.

6 The yield was derived from study's estimate of the total hectares of land devoted to switchgrass production in 2025, EPA's assumption of a conversion factor of 93 gallons per dry tonne of switchgrass, and the demand shock of 2 billion gallons described in this study.

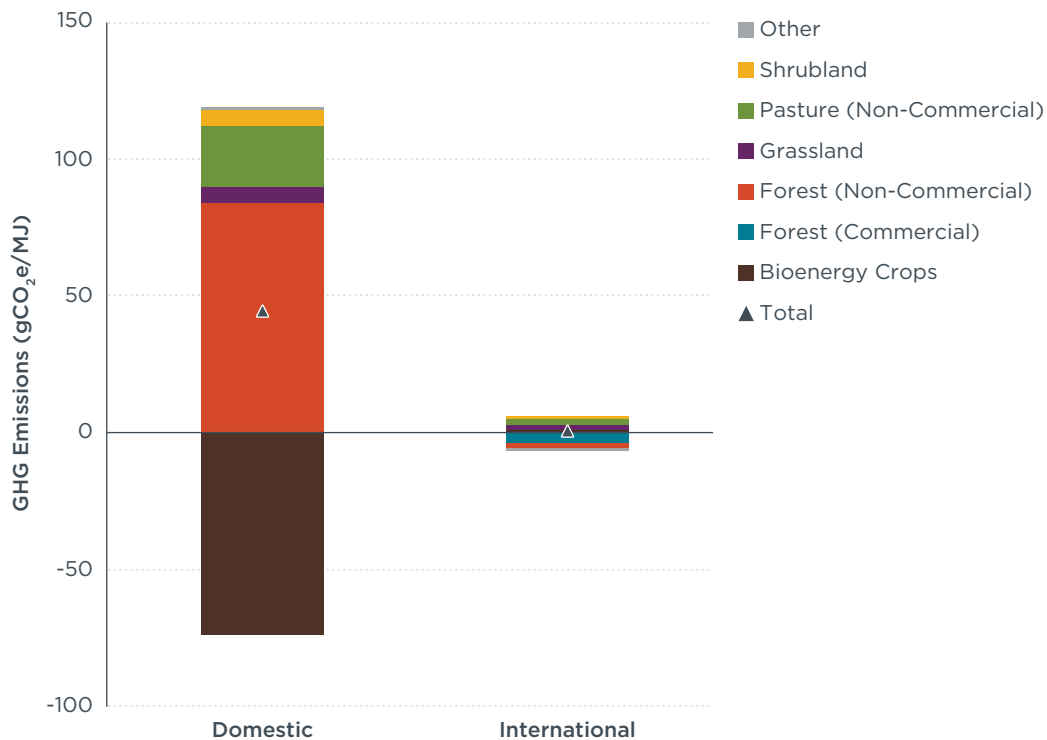


Figure 10. Breakdown of land-use change emissions from switchgrass ethanol, 2020.

Source: Plevin and Mishra (2015).

The primary driver of the high emissions estimate for switchgrass is the relatively high conversion of unmanaged forestland in the United States to cropland for bioenergy. This is due in part to a decision to modify the GCAM reference scenario to remove protections for forestland. The default assumption in the model is that approximately 90% of forestland is protected, whereas the modeled scenario in Plevin and Mishra (2015) removes these protections. The shift in land allocation in response to the demand shock brings approximately 10 Mha of land into bioenergy crop production in the United States, with the greatest share of the displaced land, approximately 5 Mha, coming from U.S. non-commercial forestland.

The high degree of forestland conversion makes this study an outlier within the analyses reviewed in this report. However, the decision to remove land protections is an important methodological choice that warrants further consideration in other ILUC analyses for energy cropping. In the case of the United States, the aggregate compliance approached used to verify compliance with the land restrictions in the RFS may not be a sufficient safeguard against forest conversion to meet energy crop mandates. GTAP and the default GCAM assumptions list the majority of U.S. forestland as inaccessible for legal or infrastructure reasons, and this may understate the availability of forestland, particularly unmanaged forest. Although the assumption of zero domestic forestland protection is also unrealistic, this decision highlights the risks of encouraging biofuel use without explicit safeguards for land expansion.

Wise et al. (2015), who also use GCAM, further demonstrate the importance of forestland protection assumptions on bioenergy emissions. In that analysis, the authors estimate that implementing GCAM's assumption of 90% forestland land protection

reduces switchgrass ILUC by 55% to 70%, depending on the AEZ studied. The authors of that study confirm that GCAM provides similar results to GTAP once forestland protections are in place, suggesting that the results without forest protection are an important comparison point with studies that do not model expansion onto unmanaged land. Similarly, Plevin and Mishra (2015) determine that for scenarios in which forestland remained protected, the ILUC emissions from switchgrass range from 16 to 24 gCO₂e/MJ, a substantial decrease from the unprotected forestland main scenario. Although those estimates are still higher than those of the other ILUC analyses in our review, they are much closer—particularly to the GTAP and EPA ILUC assessments.

GLOBIOM ILUC ASSESSMENT

The most recent assessment of energy crop ILUC comes from Valin et al. (2015), which is the first study to use the International Institute for Applied Systems Analysis' (IIASA) Global Biosphere Management Model (GLOBIOM) to estimate the ILUC effect in response to EU demand for biofuels. GLOBIOM is a partial equilibrium (PE) model similar to the ones used for EPA's ILUC assessment, offering a high resolution of detail on the agricultural sector, particularly within the EU. Valin et al. (2015) estimate the ILUC response for a 2020 policy shock for a variety of feedstock-specific scenarios. The study consolidates energy crops into two categories: SRWCs (i.e., short-rotation coppice and poplar) and perennial grasses (i.e., switchgrass and Miscanthus). For both crop categories, the study assumes that 1% of transport fuel demand would be met using Fischer-Tropsch renewable diesel, equivalent to annual production of 123 PJ⁷ of renewable diesel, approximately equivalent to 23 million tonnes of oil.

The results from Valin et al. (2015) suggest that the ILUC emissions from energy cropping are substantially lower than those of food crops, whose emissions can range from 9 to 154 gCO₂e/MJ in the same modeling exercise, largely driven by deforestation and peatland disturbance.⁸ This study finds that the overall net land-use change emissions from energy crops is negative: -19 gCO₂e/MJ for SRWCs and -8 gCO₂e/MJ for perennial grasses, respectively, over a 30-year time horizon. Similar to the GTAP and GCAM studies reviewed here, Valin et al. (2015) predict minimal impacts on international land use and the most carbon-rich land categories, as well as high soil carbon sequestration by energy crops on marginal lands.

Valin et al. (2015) estimate that nearly all, which is to say more than 90%, of the new demand for SRWCs and perennial grasses is met through land conversion rather than diversion of feedstock from other sources, in part due to the low existing production of those crops in the absence of a biofuel mandate. For both crops, more than 95% of the global land conversion occurs in the EU, indicating that there is minimal international land-use change in response to increased pressure on land in the EU.

Valin et al. (2015) apply the same demand shock (123 PJ) to a variety of different food crops, agricultural and forestry residues, and energy crops, allowing us to evaluate differences in the model's response for each shock. The authors estimate substantial differences in the ILUC emissions for food crops and energy crops, particularly for oilseeds. Similar to energy crops, the GLOBIOM analysis estimates that the domestic

7 1 Petajoule of energy is equal to 1×10^{15} Joules.

8 Valin et al. (2015) is the only study assessed in this analysis that uses ILUC factors developed using a 20-year time horizon. To facilitate a consistent comparison with the other studies in this report, we converted the values from the study into a 30-year time horizon.

land conversion in the EU for rapeseed generates relatively low emissions, but the increased rapeseed demand generates international land conversion on much higher carbon stock lands, resulting in net ILUC emissions of 43.6 gCO₂e/MJ over a 30-year time horizon—much higher than for energy crops. In contrast, both the perennial grasses and SRWCs scenarios result in negligible international land conversion.

The yields in the GLOBIOM study are based on yield estimates for energy crops within the EU from the Environmental Policy Integrated Climate Model (EPIC), which models yields based on crop management system and land characteristics by spatial unit. The study's estimated yield for perennial grasses varies by climatic region: The average yield for *Miscanthus* is assumed to be 10.5 t/ha in Northern Europe, 9.2 t/ha in Central Europe; and 9 t/ha in Western Europe. The estimated average yield of switchgrass is assumed to be 7.4 t/ha in Southern Europe, 8.7 t/ha in Eastern Europe, and 10.1 t/ha in Western Europe. The yield of SRWCs is modeled as approximately 9.4 t/ha on average within the EU. These values are on the upper range of the 3 to 15 t/ha average yields for energy cropping in Allen et al. (2014), particularly the SRWCs, but are lower than the yields assumed in all the other ILUC studies reviewed here.

GLOBIOM uses a time-step approach with increasing baseline crop yields at every time step of the modeling period, such that the yields at the end of the modeling period are higher than the initial yields described above. GLOBIOM projects a linear background rate of improvement in crop yields that reflects technological improvement paired with an endogenous yield response. The endogenous yield response, which factors in how yields respond to price changes within the model, uses region-specific costs for different agricultural management practices. Assuming that each farmer wants to maximize his or her own cost-effectiveness, the model estimates the practices used to determine the extent to which yields intensify. Therefore, by the end the modeling period in 2030, the yields from energy crops have increased to 13.9 t/ha and 10.9 t/ha for perennial grasses and SRWCs, respectively.

GLOBIOM determines land availability for SRWCs for a series of individual plots of land, using a GIS analysis to determine suitable total land area for conversion. The modeling finds that most energy crop production comes from conversion of non-agricultural land. Approximately 94% and 61% of the land converted to perennial grasses and SRWCs, respectively, comes from a combination of natural land and abandoned land. Natural land includes uncategorized land, much of which has been used for agriculture but abandoned prior to 2000, whereas abandoned land includes cropland that has been abandoned after 2000. A substantial fraction of SRWC cultivation does come from displacing other crops on existing agricultural land. This generates a 240 kilotonne (kt) decline in demand for grains and a 160 kt decline in sugar crops. Perennial grasses have a slightly smaller effect on food demand, primarily reducing demand for grains.

As the land expansion to meet the demand for biofuel from perennial grasses and SRWCs comes primarily from abandoned and other natural land within the GLOBIOM estimates, the GHG impact of this land expansion within the modeling is therefore relatively low. Figure 11 provides an overview of the land-use change emissions estimated for perennial grasses and SRWCs, respectively. It is evident that one-time emissions from land conversion for both crops are relatively low, contributing less than 3 gCO₂e/MJ to total LUC emissions, although ongoing foregone sequestration contributes a larger share to the overall emissions (8.1 and 5.9 gCO₂e/MJ, respectively). The land conversion emissions are low because the converted land has relatively low biomass

stocks: Natural land and grassland in the EU is estimated to contain 9 and 3 tonnes of biomass carbon per hectare, whereas the total carbon stocks of forestland (above- and below-ground) range from 88 t/ha in the EU to as high as 120 t/ha. This assumption could plausibly underestimate biomass stocks on agricultural land abandoned decades ago (categorized as natural land) on which substantial regrowth may have occurred. An important factor behind the low ILUC emissions for energy crops in this analysis is that it assumes all biofuel production induced by the demand shock complies with the EU’s RED sustainability criteria. This requirement prevents the conversion of high-carbon stock land, such as forestland, for the purposes of bioenergy. It is likely that this methodological decision contributes to the low emissions for both perennial grasses and SRWCs by restricting their expansion to lower-carbon stock lands.

Similar to the other studies reviewed here, the remaining factor contributing to energy crops’ low ILUC emissions in the GLOBIOM assessment is the crops’ potential to sequester additional carbon. The study finds that energy crop cultivation sequesters more carbon, on balance, than is emitted. The upstream sequestration comes from two processes: (1) new agricultural biomass—the higher biomass stocks of energy crops compared to the vegetation in the previous land use—and (2) increased soil organic carbon, which results from the additional carbon storage in soils in response to cultivation changes. The study estimates that the perennial grasses, which are projected to grow primarily on abandoned and natural land, sequester approximately 0.5 tC/ha/yr in soil, whereas SRWCs sequester approximately 0.9 tC/ha/yr in soil. Amortized over a 30-year time horizon, the soil carbon storage emissions are approximately -8.1 and -22.2 gCO₂e/MJ for perennial grasses and SRWCs, respectively.

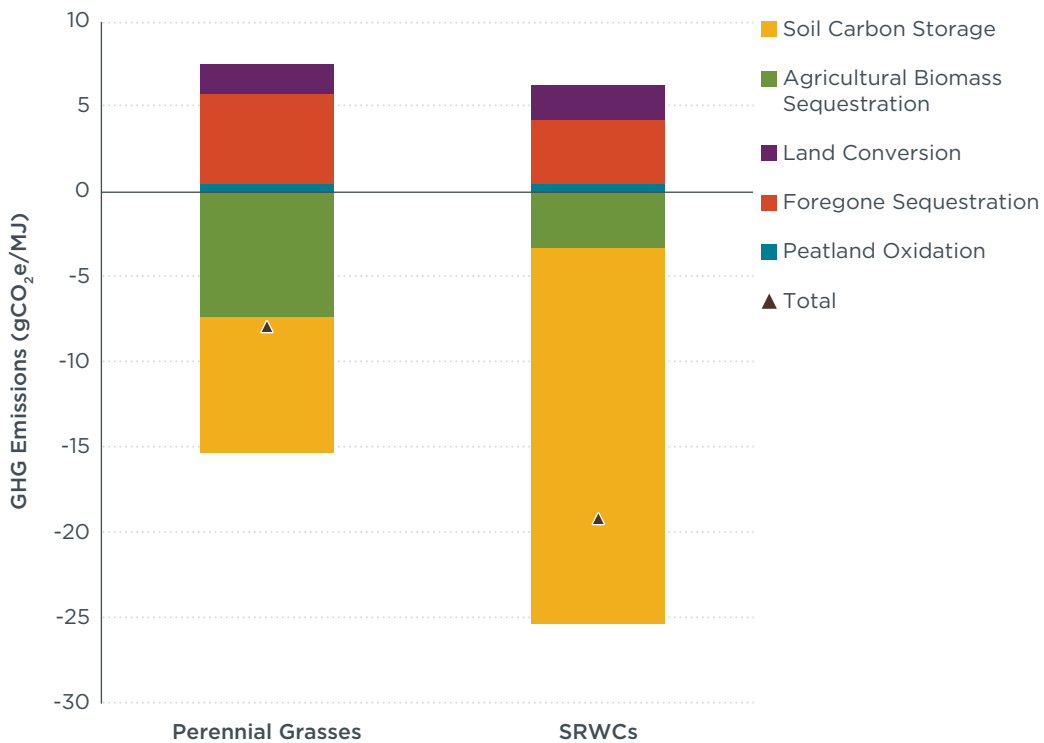


Figure 11. Overview of GLOBIOM energy cropping ILUC emissions.

The GLOBIOM modeling conducted by Valin et al. (2015) estimates that both perennial grasses and SRWCs generate net negative ILUC emissions and have the lowest emission estimates of any of the studies assessed in this paper. The primary factors driving this result are the assumption that a substantial amount of marginal land is available for energy crop expansion in Europe and that energy cropping on that land generates net carbon sequestration.

ANALYSIS OF ILUC RESULTS

The purpose of this section is to identify what the individual energy crop ILUC analyses have in common as well as to highlight how and why they differ from one another. We also compare our literature review with the assumptions and treatment of the ILUC key factors, including feedstock yield, type of land converted, and carbon stock changes. This discussion provides context for the ILUC estimates in the reviewed studies.

To get an overall sense of how the methodologies of the various studies compared, we first evaluate the total area of land expansion necessary to supply 1,000 ethanol-equivalent gallons. Land expansion in this case does not include the transition of existing cropland to energy crops, only the conversion of other land categories to cropland. This measure provides a direct point of comparison of total land-use change for a given level of biofuel demand across the studies. This exercise likely does not produce exactly the same results that would be given if each of the modeling studies were redone with the same demand shock, as the response of land-use change to demand shock may not be strictly linear. Figure 12 provides an overview of each study's land expansion intensity, separated by feedstock.

The Miscanthus land-use intensity is relatively consistent across the three studies that assess Miscanthus or perennial grasses (EPA, 2010; Valin et al., 2015; Taheripour et al., 2011), despite varying assumptions of yield and the size of the demand shocks. In contrast, the switchgrass land expansion intensity varies substantially among the studies, from a low of 0.11 ha/1000 gallons in EPA (2010) to nearly 1.4 ha/1000 gallons in the GTAP analyses. Valin et al. (2015) is the only study in this review that models the ILUC impact of SRWCs, finding a land expansion intensity at the higher end of the range of the other energy crop values assessed here.

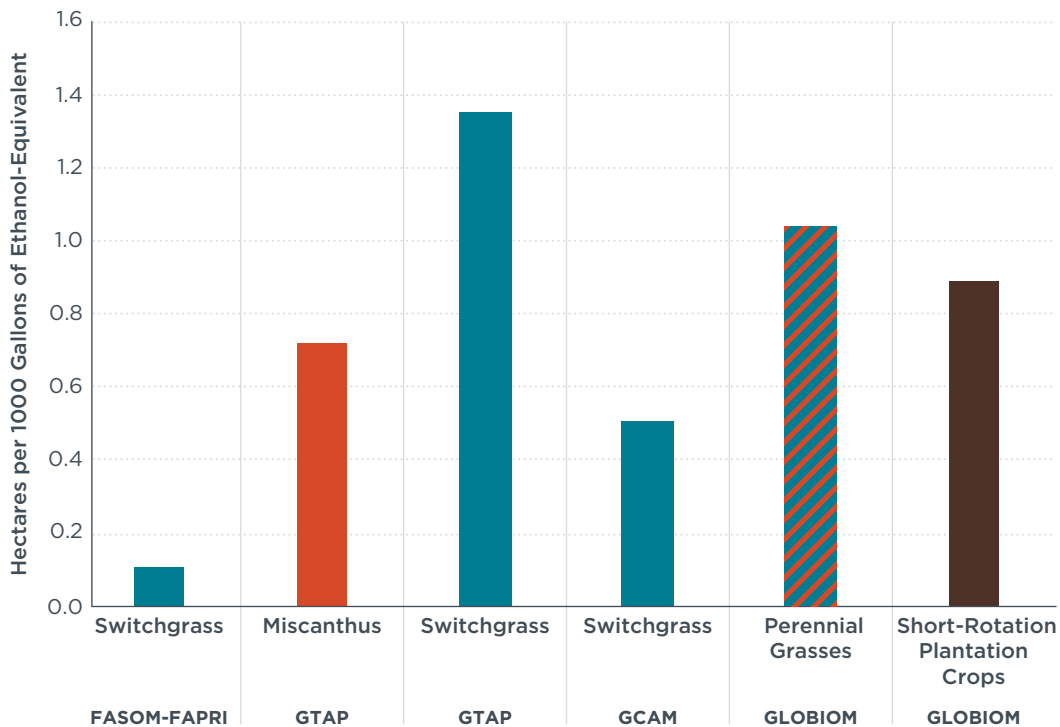


Figure 12. Comparison of land expansion intensity of energy crop production across ILUC studies.

The bulk of the variation in land expansion intensity observed in the above ILUC analyses is attributable to differences in yield assumptions (as seen in Figure 13). For example, the GTAP analysis finds higher land-use expansion for switchgrass than Miscanthus, which is in line with its higher assumed yield (i.e., Miscanthus has approximately double the yield, and consequently, approximately half of the land-use expansion). Plevin and Mishra (2015) estimate a land expansion intensity roughly half that of both switchgrass GTAP estimates, reflecting the authors' assumption of a switchgrass yield roughly double that in the GTAP analyses. Approximately half of the yield estimates in the studies here exceed the average expected yields from Allen et al. (2015). One of the studies with lower yields, Valin et al. (2015), had some of the highest land expansion intensities of any of the studies, suggesting that if energy crop yields are closer to those suggested by the literature (rather than the projections used for ILUC analyses), ILUC assessment may in fact be understating the possible land expansion associated with energy crops.

EPA's (2010) FASOM analysis is an outlier for land expansion intensity, as its low value in Figure 12 above is not solely attributable to that analysis' differences in yield assumptions. Whereas EPA (2010) assumes a yield similar to both GTAP analyses and Valin et al. (2015), its estimated land-use intensity is less than half that of the other studies. The EPA analysis' low land expansion intensity could stem in part from the authors' assumption that switchgrass production would occur near very large biorefineries, generating in greater agricultural land use in high-yielding areas transitioning to switchgrass production in order to minimize transport costs. Had the study instead included the conversion of greater quantities of cropland pasture in lieu of existing cropland, the FASOM land expansion intensity could have been similar in magnitude to the GTAP analyses.

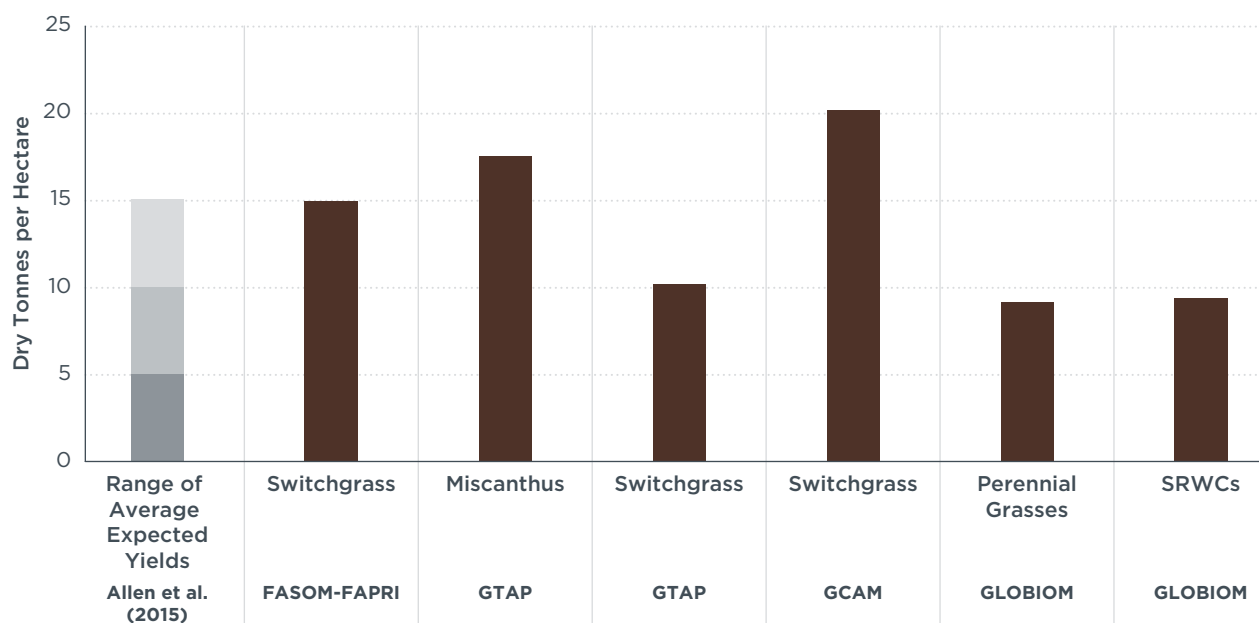


Figure 13. Average yield estimates for energy cropping across ILUC studies, relative to literature review.

The total land-use expansion in each study assessed here combines both direct and indirect LUC. For the purposes of our comparison, direct land-use change refers to the domestic land conversion that does not displace other uses (e.g., land conversion of

marginal lands and other non-croplands), whereas indirect expansion includes the land conversion (either domestic or international) that results from energy crops displacing existing agriculture and incentivizing expansion of other crops onto new land.⁹ Although the studies did not necessarily distinguish between these types of land-use change, we can infer the relative degree of indirect effects from the international land-use change area as a share of total land-use change (Figure 14). All DLUC is domestic in these studies, and most indirect land-use change occurs internationally. A smaller amount of ILUC is domestic and we cannot separate that out from DLUC in the way the results are reported. ILUC is likely partially offset by a variety of factors, including food demand reduction, crop switching, and yield increases.

Of the studies assessed in this analysis, only EPA (2010) estimates a total area of international land expansion that comprises more than 10% of the total land-use expansion. In this assessment, energy crops displace substantial amounts of corn and soybean production, resulting in international cropland expansion to supply those commodities, primarily in Brazil. In contrast, the other modeling studies reviewed here find very low amounts of international land-use change. The GTAP assessments attribute the small share of international land expansion in their analyses to demand for food crops to slight shifts in food demand at the margins of production as well as displacement of some livestock grazing.

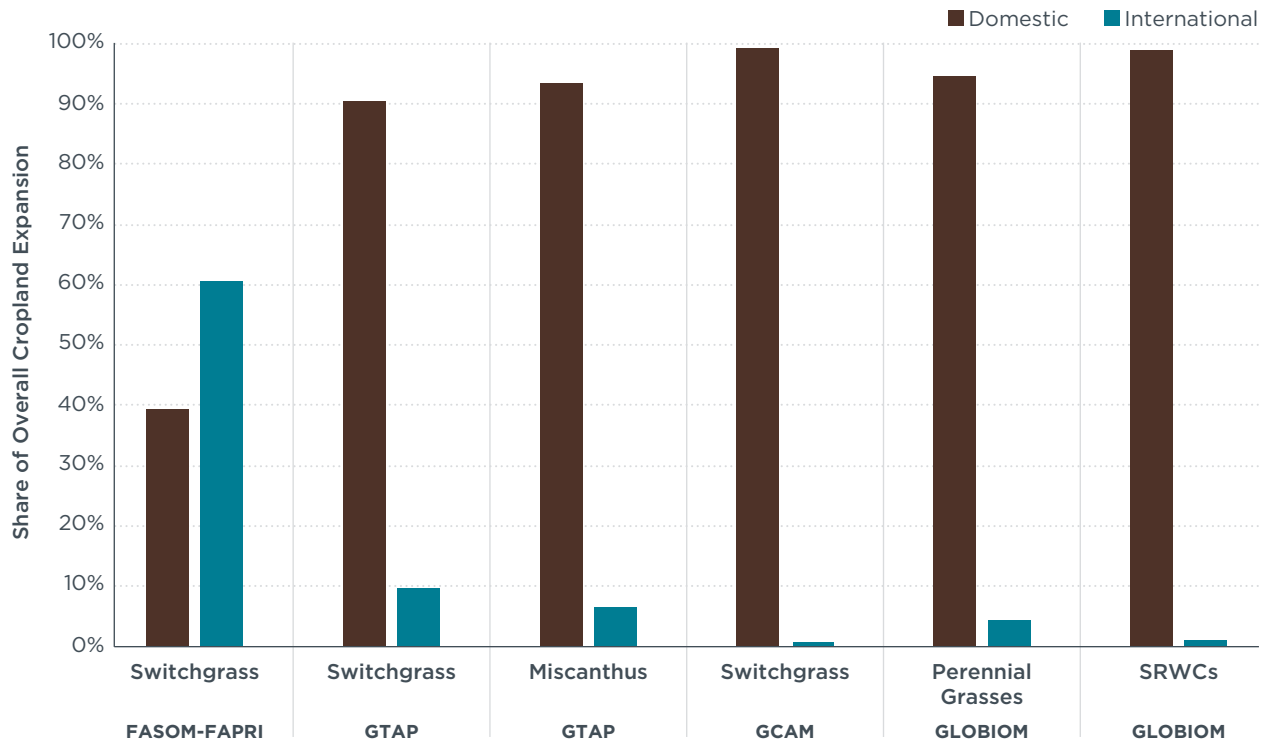


Figure 14. Relative shares of domestic and international cropland expansion across studies.

⁹ Each study assumes that energy crop biofuel mandates will translate into domestic energy crop production in the regions assessed. Although this assumption will hold true based on present-day policies, future biofuel policies and changes in biofuel markets could theoretically drive the production of cellulosic energy crops in one region for import into another.

Although the models differ in their estimates of land expansion intensity, there are larger differences in the models' projections of how energy cropping will be distributed among different land categories. This can have a large impact on the final ILUC emission factor for each analysis due to the differences in carbon stock changes for land conversion between various land categories. Figure 15 illustrates the relative amounts of each land category converted as a share of the total land expansion for each study. The GLOBIOM study and both GTAP analyses suggest that 60% to 90% of the total land demand can be met by a combination of abandoned land, natural land and cropland pasture, with relatively small amounts attributed to carbon-rich lands such as forestland.

Plevin and Mishra (2015) is the only study predicting that most land demand is met by converting more carbon-rich land categories, with approximately half of the converted land coming from forestland and nearly 10% coming from grassland. This is due to the authors' decision to model forestland as unprotected domestically, resulting in large shifts of forestland to energy cropping due to its relative ease of accessibility. In EPA's analysis, most net land-use change occurs on idle cropland or cropland pasture domestically, and pastureland, grassland and forestland internationally.

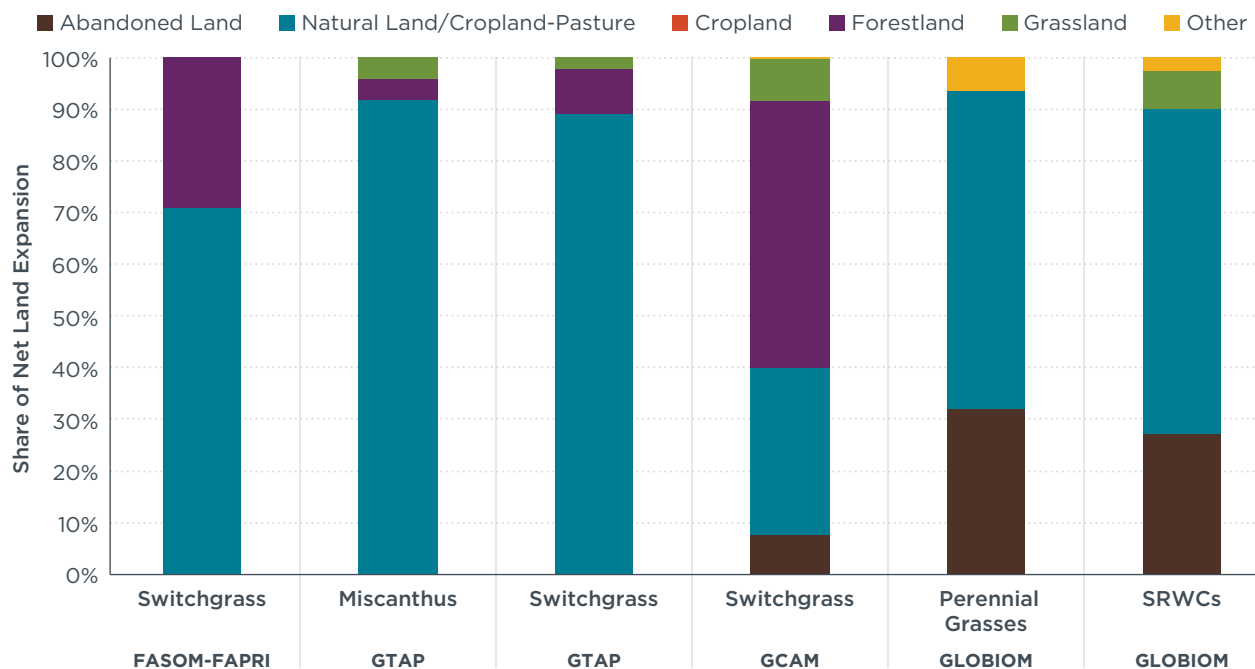


Figure 15. Comparison of land category as a share of energy crop land expansion, by study.

Note: Abandoned land refers to unmanaged land used by Valin et al. (2015).

One of the largest contributing factors to the studies' differences in how they allocate different land categories to energy cropping is their choice of economic model. GTAP is a CGE model, whereas GLOBIOM, FASOM and FAPRI are PE models. CGE models offer the advantage of including more detailed linkages between broad economic sectors (e.g., agriculture and energy), as they encompass the entire global economy. However, PE models focus on an individual sector—in this case, agriculture. PE models' level of detail facilitates more granular assessments of land use and land management. Therefore, the PE models have more detailed estimates of baseline land uses, resulting in greater resolution of unmanaged and unused land that does not necessarily have an

economic rent. These models often have more land that isn't being actively managed available for domestic land expansion, as evidenced by the high levels of natural land and abandoned land used for energy cropping in the GLOBIOM ILUC assessment.

GTAP allocates land use based on supply and demand, with land going to sectors that can support a higher price for it. The CET structure in conjunction with low prices makes cropland pasture the most likely candidate for land transformation, as the new demand for consistent, year-on-year energy cropping supports a higher price for that land than the existing use of grazing and occasional agriculture. The GCAM assessment conducted by Plevin and Mishra (2015) attempts to correct for this somewhat by modifying the underlying land protections from U.S. forestland in the model's database and allowing it to be converted; this has the effect of overstating the likely forest conversion that would occur in response to the demand shock. Unlike GTAP, which includes pasture relatively close to cropland within the model's nesting structure, GCAM separates pasture out further than forestland, citing the inclusion of many low-productivity plots of land as pasture within many land databases (Wise et al., 2015). Although this change alone does not make forestland always more likely to be converted into cropland relative to GTAP, it may contribute to GCAM's larger estimates of forest conversion to energy cropping.

The final key factor we evaluate across these studies is the expected soil carbon change from energy cropping. We find a common assumption across the studies that all the categories of energy crops assessed in the various analyses (switchgrass, Miscanthus, and SRWCs) generate net carbon sequestration when cultivated on marginal lands such as cropland pasture and abandoned land. This is the largest factor contributing to these crops' relatively low ILUC emissions relative to food crops. Figure 16 provides a comparison of the estimated soil carbon stock change on marginal lands for each study. In general, we see that the models tend to assume that switchgrass provides the lowest carbon sequestration, followed by Miscanthus, and then SRWCs. This is shown alongside the average of the range of values from the literature review within Searle et al. (2016) for abandoned cropland specifically. It is important to note that although the ILUC studies generally predict most land-use change to occur on abandoned cropland or cropland pasture, some amount of land-use change is predicted to occur on grassland and forest. Conversion of these land types to energy cropping is likely to result in either no net change or a net loss of soil carbon, respectively.

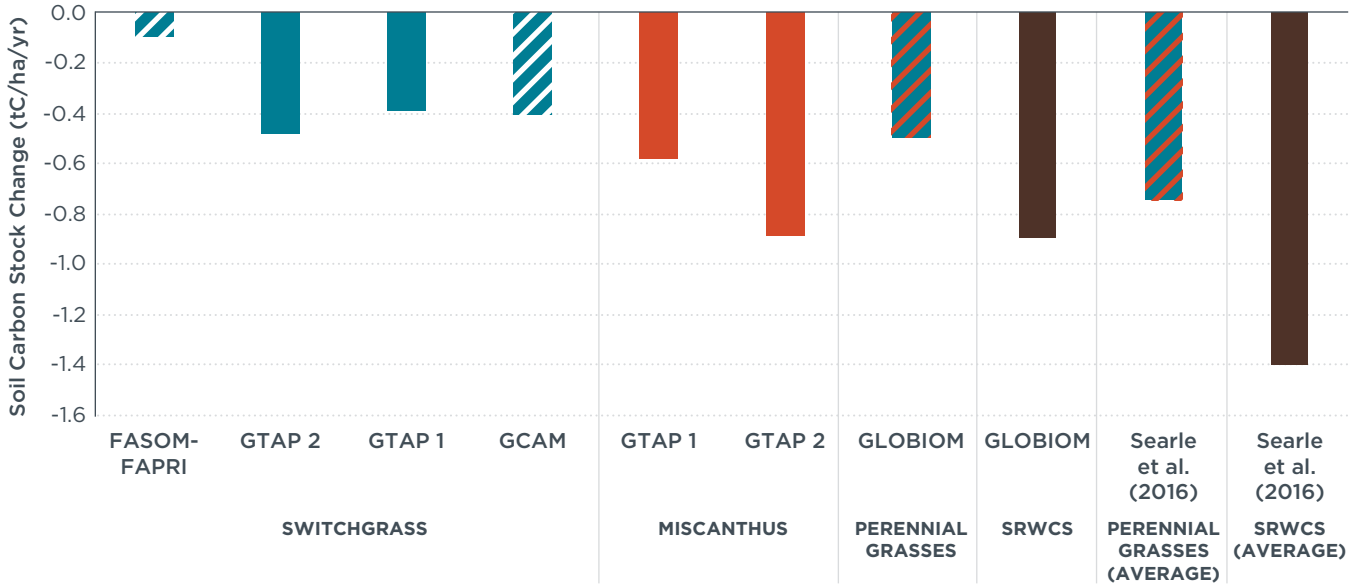


Figure 16. Comparison of energy crop soil carbon stock change on marginal lands to average values, sorted by study and crop type.

Note: Values inferred from ILUC emission factors are partially shaded. These values may include changes in biomass carbon stocks.

Across the studies assessed in this analysis, the estimated carbon sequestration from switchgrass and Miscanthus generally align with the literature review average provided by Searle et al. (2016), although they are slightly closer to zero. EPA (2010) is a notable exception, generating less than a third of the soil carbon sequestration of the other switchgrass examples. This may be in part due to fact that FASOM did not consider the soil carbon stock increases from switchgrass relative to annual cropping on existing cropland, as the model only estimates soil carbon stock changes when land transitions between uses and management practices. Taheripour and Tyner (2013) point out that prior to 2013, land-conversion emission factor databases did not accurately account for the soil carbon sequestration from perennial energy crops. Valin et al. (2015) estimate soil carbon stock changes for SRWCs that are similar to the average that we estimate from the literature review. The high rate of soil carbon sequestration assumed in Valin et al. (2015) combined with the high rate of land expansion results in an overall low ILUC estimate for perennial grasses and SRWCs compared to the other studies. Overall, assumptions about soil carbon stock change constitute one of the largest factors contributing to the low ILUC emissions for energy crops relative to food crops in that study.

CONCLUSION

This study evaluates the key factors influencing differences in results among energy cropping ILUC modeling studies. The purpose of this exercise is to provide context for those estimates by highlighting modeling assumptions that strongly influence the final results. Our analysis identifies three key factors: yield assumptions, land conversion, and carbon stock change.

We find that there is significant evidence that energy crop-derived biofuels can offer substantial carbon reductions relative to fossil fuels and that their ILUC emissions are lower than those of most food-based crops. However, the market behavior for energy crops—which have yet to reach commercialization—remains uncertain and difficult to project. Given that the structure of economic models themselves and the specifics of the scenarios differs, it would not necessarily be helpful to conclude that any individual value derived from these modeling exercises is necessarily more representative of the impacts of energy cropping than the others.

Most of the ILUC modeling studies reviewed here find that energy crop demand is unlikely to displace substantial amounts of existing cropland, reducing the extent to which energy cropping would displace food production. This is consistent with the findings from Searle et al. (2016) that energy crops are much less profitable on existing agricultural land than the top produced food crops. Most of the studies assessed here find that most of the land needed for energy cropping is expected to come from marginal lands such as cropland pasture and abandoned land. An interesting exception is EPA's analysis, which predicts substantial displacement of existing agricultural production, possibly as a result of modeling very large cellulosic biorefineries that would require concentrated feedstock production within a reasonable transport distance.

Our analysis of land expansion intensity across the studies suggests that land expansion intensity is highly correlated with yield assumptions. Most of the analyses assume that energy crop yields fall on the high end of the appropriate range found in the literature review, reducing overall land expansion. In EPA (2010), high yields may be in part due to the use of higher-yielding regions, whereas other studies mostly attribute high yields to price responses and ongoing agricultural improvements. Low land expansion does not necessarily decrease ILUC emissions if most of the land used for energy crop cultivation is abandoned cropland or cropland pasture, on which energy crops may net sequester carbon.

The composition of the land categories converted in each analysis has a greater impact on the ILUC emissions for each study than the land expansion intensity. The analyses that project the greatest land expansion tend to predict most of that land expansion on marginal lands with low carbon stocks. In contrast, the study with the lowest land expansion intensity, Plevin and Mishra (2015), had the highest ILUC estimate of any analysis, because it estimated that most of the converted land came from forests and grasslands.

The literature suggests that cultivating energy crops may lead to net soil carbon sequestration on abandoned cropland and cropland pasture. Across the studies assessed, this contributes to a strong net decrease in emissions for most cropland used directly for energy cropping, greatly reducing the land-use change impacts for switchgrass and resulting in negative ILUC factors for Miscanthus and SRWCs. Even though there is abundant evidence that energy crops sequester carbon on existing agricultural lands, the empirical evidentiary basis for assuming strong soil carbon

sequestration on marginal lands is thin. Therefore, although the ILUC assessments reviewed here largely agree with the literature, this component of energy crop ILUC still carries a high degree of uncertainty.

The completeness of land representation and assumptions of land protections may be critical for future ILUC assessments of energy crops. GTAP and GCAM exclude a portion of inaccessible forestland that in reality may be available for conversion in cases where demand is sufficiently high. The decision to remove all forestland protections in Plevin and Mishra (2015) is also unrealistic. The GLOBIOM modeling for the EU appropriately assumes that the RED sustainability criteria would apply to any biofuels produced for the EU, however, this assumption would not be realistic in the United States. Conducting a GLOBIOM assessment with a similar shock as Valin et al. (2015) in the United States could conceivably predict the conversion of higher carbon stock lands and higher ILUC emissions for energy crops.

Table 1 provides a summary of how each energy crop ILUC study aligns with the key factors assessed in the literature review. Based on several studies' assumptions on soil carbon sequestration from energy cropping and optimistic representations of the availability of forestland, we believe that some ILUC analyses here may understate ILUC emissions for energy crops. Although additional data and modeling improvements could change our understanding of the magnitude of energy crop ILUC emissions, it is still likely that energy crops offer superior GHG benefits and other environmental benefits compared to most food feedstocks used for biofuel. Overall, we find that especially when energy cropping is limited to marginal lands, it is likely that these crops can provide substantial GHG reductions relative to first-generation biofuel feedstocks. The high ILUC emissions predicted when forestland conversion is allowed highlight the importance of land protections in ensuring a sustainable bioenergy supply.

Table 1. Comparison of studies with energy crop key factors

Environmental effect on marginal land	Yield Assumptions	Land Conversion	Carbon Stock Change
Valin et al. (2015)	Within range of average expected yields	Mostly from abandoned land and natural land; marginal impact on food and livestock land use	Within range of average measured carbon stock change on marginal lands
Plevin and Mishra (2015)	Higher than average expected yields	Majority of land conversion comes from forestland and grassland	Within range of average measured carbon stock change on marginal lands
Taheripour et al. (2011); Dunn et al. (2015)	On the high end of the range of expected yields	Most energy cropping occurs on cropland pasture; marginal displacement of livestock grazing	Within range of average measured carbon stock change on marginal lands
EPA (2010)	On high range of expected yields, but also projects that higher-yielding existing cropland will be used	Most energy cropping occurs on existing cropland; substantial displacement of food crops resulting in indirect, international LUC. Some domestic land expansion onto idle cropland and cropland pasture	Substantially lower than average measured soil carbon stock change

REFERENCES

- Agostini, F., Gregory, A.S., Richter, G.M. (2015). *Carbon Sequestration by Perennial Energy Crops: Is the Jury Still Out?* *Bioenergy Res.* 2015;8:1057-1080.
- Allen, B., Kretschamen, B., Baldock, D., Menadue, H., Nanni, S., & Tucker, G. (2014). *Space for energy crops—Assessing the potential contribution to Europe's energy future*. Retrieved from Institute for European Environmental Policy website: http://www.birdlife.org/sites/default/files/attachments/IEEP_2014_Space_for_Energy_Crops_0.pdf
- Allen, B., Marechal, A., Nanni, S., Prazan, J., Baldock, D., & Hart, K. (2015). *Data sources to support land suitability assessments for bioenergy feedstocks in the EU—A review*. Retrieved from Institute for European Environmental Policy website, https://ieep.eu/uploads/articles/attachments/4ac6cfa9-fdfc-4cbc-b906-06c0d179c1cd/IEEP_2015_Land_scoping_Study.pdf?v=63664509934
- Beach, R. H., & McCarl, B. A. (2010). *U.S. agricultural and forestry impacts of the energy independence and security act: FASOM results and model description*. Retrieved from [https://yosemite.epa.gov/sab/SABPRODUCT.nsf/962FFB6750050099852577820072D.FDE/\\$File/FASOM+Report_EISA_FR.pdf](https://yosemite.epa.gov/sab/SABPRODUCT.nsf/962FFB6750050099852577820072D.FDE/$File/FASOM+Report_EISA_FR.pdf)
- Ceotto, E., & Di Candilo, M. (2011). Medium-term effect of perennial energy crops on soil organic carbon storage. *Italian Journal of Agronomy*, 6, 212-217.
- Don, A., Osborne, B., Hastings, A., Skibas, U., Carter, M., Drewer, J., Flessa, H., Freibauer, A., Hyvonen, N., Jones, M., Lanigan, G., Mander, U., Monti, A., Njakou Djomo, S., Valentine, J., Walter, K., Zegada-Lizarazu, W., & Zenone, T. (2011). Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy*, 4, 372-291.
- Dunn, J. B., Mueller, S., Kwon, H., & Wang, M. Q. (2013). Land-use change and greenhouse gas emissions from corn and cellulosic ethanol. *Biotechnology for Biofuels*, 6:51.
- Dunn J. B., Qin, Z., Mueller, S., Kwon, H., Wander, M., & Wang, M. (2015). *Carbon calculator for land use change from biofuels production (CCLUB), users' manual and technical documentation* (No. ANL/ESD/12-5 Rev. 2). Argonne National Laboratory (ANL). Retrieved from <https://greet.es.anl.gov/publications>
- European Commission. (2016). *Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*. COM (2016) 767 final/2. Retrieved from: http://eur-lex.europa.eu/procedure/EN/2016_382
- Gibbs, H., Sheehan, J., & Nelson, R. (2010). *Land cover types subgroup: Low carbon fuel standard (LCFS) indirect land use change expert work group*. Retrieved from <https://www.arb.ca.gov/fuels/lcfs/workgroups/ewg/010511-final-rpt-land-cover-types.pdf>
- Golub, A., Hertel, T.W., and Sohngen, B. (2008). *Land-Use Modeling in Recursively-Dynamic GTAP Framework*. GTAP Working Paper No. 48. Retrieved from: <https://www.gtap.agecon.purdue.edu/resources/download/3679.pdf>
- Golub, A. A., & Hertel, T. W. (2012). Modeling land-use change impacts of biofuels in the GTAP-BIO framework. *Climate Change Economics*, 3 (3). doi:10.1142/S2010007812500157

- Guo, L., & Gifford, R. (2002). Soil carbon stocks and land use change: a meta-analysis. *Global Change Biology*, 8, 345-360.
- Malins, C., Searle, S., & Pavlenko, N. (2015). *Assessment of the scale of potential indirect emissions due to higher oil use*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/Indirect_emissions_%20oil_use_201510.pdf
- Murty, D., Kirschbaum, M. F., McMurtrie, R. E. & McGilvray, H. (2002). Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, 8, 105-123.
- Page, S. E., Morrison, R., Malins, C., Hooijer, A., Rieley, J. O., & Jauhiainen, J. (2011). *Review of peat surface greenhouse gas emissions from oil palm plantations in southeast Asia* (White Paper No. 15). Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_Peat_Emissions_Sept2011.pdf
- Petrenko, C., & Searle, S. Y. (2016). *Assessing the profitability of growing dedicated energy versus food crops in four European countries*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/EU-ILUC-Case-Studies_ICCT_nov2016.pdf
- Plevin, R. J., & Mishra, G. S. (2015). *Estimates of the land-use change carbon intensity of ethanol from switchgrass and corn stover using the GCAM 4.0 model*. Retrieved from <http://static.ewg.org/reports/2015/better-biofuels-ahead/plevinreport.pdf>
- Plevin, R. J., Beckman, J., Golub, A. A., Witcover, J., O'Hare, M. (2015). Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change. *Environmental Science and Technology*, 49(5), 2656-2664.
- Searle, S. Y., & Malins, C. J. (2014). Will energy crop yields meet expectations? *Biomass and Bioenergy*, 65, 3-12.
- Searle, S., Petrenko, C., Baz, E., & Malins, C. (2016). *Crops of the biofrontier: In search of opportunities for sustainable energy cropping*. Retrieved from the International Council on Clean Transportation, <http://www.theicct.org/sites/default/files/publications/Energy%20Crop%20White%20Paper%20vF.pdf>
- Shortall, O. K. (2013). "Marginal land" for energy crops: Exploring definitions and embedded assumptions. *Energy Policy*, 62, 19-27.
- Taheripour, F., Tyner, W. E., & Wang, M. Q. (2011). *Global land use changes due to the U.S. cellulosic biofuel program simulated with the GTAP model*. Argonne National Laboratory. Retrieved from https://greet.es.anl.gov/publication-luc_ethanol
- Taheripour, F., & Tyner, W. E. (2013). Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors. *Economics Research International*. doi:10.1155/2013/315787
- Taheripour, T., Zhao, X., & Tyner, W. E. (2017). The impact of considering land intensification and updated data on biofuels land use change and emissions estimates. *Biotechnology for Biofuels*, 10, 191. doi:10.1186/s13068-017-0877-y
- Thomson, A. M., Izarrualde, R. C., West, T. O., Parrish, D. J., Tyler, D. D., & Williams, J. R. (2009). *Simulating Potential Switchgrass Production in the United States*. Pacific Northwest National Laboratory (PNNL). Retrieved from http://www.pnnl.gov/main/publications/external/technical_reports/pnnl-19072.pdf

- U.S. Department of Agriculture. (2017). *Major land uses: Glossary*. Retrieved from <https://www.ers.usda.gov/data-products/major-land-uses/glossary/#cropforpasture>
- U.S. Department of Energy. (2016). *2016 Billion-Ton Report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstocks* (ORNL/TM-2016/160). Oak Ridge, TN: Oak Ridge National Laboratory. doi:10.2172/1271651.
- U.S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. (2010). *Renewable fuel standard program (RFS2) regulatory impact analysis*. (EPA-420-R-10-006). Retrieved from <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1006DXP.txt>
- U.S. Environmental Protection Agency. (2017). *Proposed renewable fuel standards for 2017, and the biomass-based diesel volume for 2018*. Retrieved from: <https://www.epa.gov/renewable-fuel-standard-program/proposed-renewable-fuel-standards-2017-and-biomass-based-diesel>
- Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., & Hamelinck, C. (2015). *The land use change impact of biofuels consumed in the EU. Quantification of area and greenhouse gas impacts*. Retrieved from <http://www.globiom-iluc.eu/iluc-study-now-available-online/>
- Wise, M., Hodson, E. K., Mgnone, B. K., Clarke, L., Waldhoff, S., & Luckow, P. (2015). An approach to computing marginal land use change carbon intensities in policy applications. *Energy Economics*, 50, 337-347.