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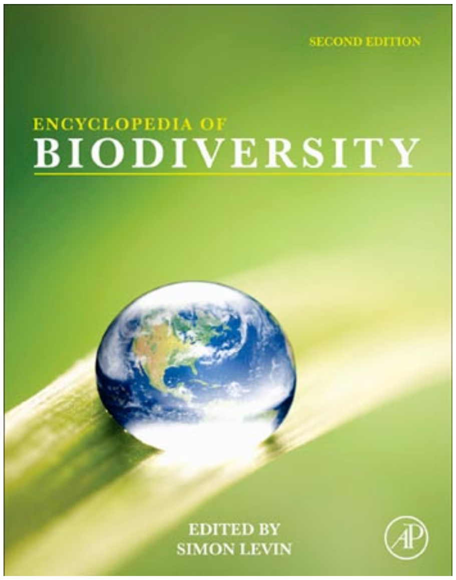

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Indirect Land Use and Greenhouse Gas Impacts of Biofuels

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Glossary

Direct land-use change (DLUC) Conversion of land from a noncrop land use to the production of bioenergy crops.
General equilibrium (GE) model Similar to a partial equilibrium (PE) model, but representing all economic sectors, generally in a highly aggregated form. GE models have greater scope but less detail (fewer products in each sector and less detail on each product) than do PE models.
Indirect land-use change (ILUC) Conversion of land from one land-use category to another, induced by the expansion of biofuel production elsewhere.
Life cycle assessment An analytic framework to assess the full environmental impacts of a product or service, from raw material extraction, through production, use, and disposal.
PE model A model of one or a few sectors of the economy that computes an equilibrium state in which supply and demand for each product equilibrate in response to some exogenously defined change, such as a tax, mandate, or loss of supply.

Overview

Biofuels can be produced from virtually any form of biomass, including purpose-grown energy crops, crop and timber residues, and wastes. Commonly used or proposed energy crops include corn, sugarcane, soybeans, rape, wheat, palm, beets, switchgrass, miscanthus, pine, and willow. Just as each crop has different energy content and life cycle consumption of fossil fuel, fertilizers, and other inputs, each crop has a different impact on the overall commodity markets for food, feed, and fiber.

When bioenergy crops are produced on productive cropland, they can displace the production of food, feed, and fiber, driving up the price of the displaced commodities. In response to the price increases, some consumers will switch to lower-priced substitutes and others will simply consume less, while farmers elsewhere will respond by replacing production of the displaced crops. Increasing crop production requires either increasing yields on existing land (intensification) or farming more land (extensification). Intensification involves the use of more inputs, such as fertilizer or water; increasing crop or livestock density; or employing better technology, such as improved genetic varieties. Extensification requires bringing additional land into crop production. If high-carbon value land, such as forest and grassland, is cleared to accommodate the additional production, enough CO_2 and other greenhouse gases (GHGs) may be released from the disturbed soil and biomass to negate the climate benefits of displacing petroleum-based fuels with biofuels. Whether and how much indirect land-use change (ILUC) occurs depends on the relative scale of each of these possible responses.

The production of biofuels from feedstocks that do not compete for land with food, feed, and fiber generally does not induce ILUC. These feedstocks include crop and forestry residues, municipal waste, and crops grown on the so-called "marginal" land that is incapable of supporting economically viable crop production. To the extent that harvesting residues reduces yield, it may result in some land clearing or additional fertilizer use. Although this land clearing and fertilizer use increases GHG emissions, the effect should be much smaller than that induced by purpose-grown energy crops.

Direct and Indirect Land-Use Change

In the context of biofuels, direct land-use change (DLUC) refers to the conversion of land from some other land-use category to the production of bioenergy crops. DLUC can provide environmental costs or benefits. For example, replacing row crops with perennial grasses will often increase soil carbon sequestration, reduce nutrient and pesticide runoff, and improve biodiversity (Davis *et al.*, 2011).

When crops replace pasture or forest, DLUC can result in substantial GHG emissions. For example, Fargione *et al.* (2008) estimate that converting lowland tropical rainforest in Indonesia and Malaysia to palm biodiesel would result in the release of about 700 Mg ha^{-1} of CO_2 for more than 50 years, resulting in a "carbon debt" that would take almost 90 years to repay through substitution of biodiesel for petroleum diesel. Only after this carbon debt is balanced would the biofuel serve as an instrument of carbon reduction. Similarly, these authors estimate that draining tropical peatland rainforest to produce palm would release about 3450 Mg ha^{-1} of CO_2, requiring more than 400 years to repay through fuel substitution. In contrast, production of biofuels from prairie biomass grown on unused or marginal cropland incurs essentially no carbon debt.

In contrast to DLUC, ILUC occurs when bioenergy crops displace other crops, triggering the conversion to cropland of lands, somewhere on the globe, to replace some portion of the displaced crops (Searchinger *et al.*, 2008; Hertel *et al.*, 2010; Al-Riffai *et al.*, 2010). This result occurs because agricultural land is a constrained resource and the demand for food and feed is somewhat insensitive to changes in price (Kløverpris *et al.*, 2008). ILUC is a market-mediated phenomenon: The effects are transmitted through global markets linked by commodity substitutability and the competition for land (Laurance, 2007). Owing to the challenges of modeling global economic behavior, the location and magnitude of

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ILUC, and thus the GHG emissions induced by crop-based biofuels, are highly uncertain (Plevin *et al.*, 2010).

Although ILUC emissions are uncertain and likely to remain so due to the assumptions that drive different models, understanding ILUC is critical to understanding whether biofuel production increases or decreases GHG emissions relative to using petroleum-based fuels (Edwards *et al.*, 2010). In most life cycle analyses of the GHG emissions from biofuels, the emission of CO_2 from the combustion of biogenic carbon is considered "carbon neutral" because the biomass was formed from atmospheric CO_2 during photosynthesis (Rabl *et al.*, 2007). However, this carbon neutrality holds only if the biomass production would not have occurred in the absence of biofuel production. If the carbon would have been sequestered and remained so in the absence of biofuel production, releasing this carbon as CO_2 through biofuel combustion is not carbon neutral; it adds to the stock of CO_2 in the atmosphere (Searchinger *et al.*, 2009). To calculate whether biofuel production uses net "additional" biomass requires considering whether feedstock production results in crop displacement and land clearing. So another way of viewing ILUC uncertainty is that if it cannot be proved that ILUC has not occurred, it should not be assumed that a biofuel is carbon neutral (Searchinger, 2010).

Estimating the CO_2 Emissions from ILUC

Although DLUC can be observed and the effects measured, the indirect effects of biofuel expansion are triggered through price changes in global markets and as such are unobservable (Nassar *et al.*, 2011). Estimating ILUC, therefore, requires the use of models. Because the main linkages are economic, economic models have generally been used to estimate ILUC.

Agricultural extensification is recognized as a leading proximate cause of deforestation (Gibbs *et al.*, 2010; Nassar *et al.*, 2011); however, economic effects are only one of the several interacting drivers of land conversion (Geist and Lambin, 2002; Pfaff *et al.*, 2007). Other driving forces include social processes, such as human population growth and migration, and national policies affecting agriculture, land use, and economic development (Geist and Lambin, 2002), as well as cultural, technological, and institutional issues, all interacting in complex relationships (Schaeffer *et al.*, 2005). In this context, deforestation is best understood as an emergent characteristic of a complex system, with a range of proximate and ultimate causes. Given this complexity, the ability to predict ILUC from a single driver such as increases in commodity prices may be quite limited, and thus a core assumption underlying ILUC modeling is called into question, resulting in model uncertainty that is difficult to quantify.

The economic analyses of ILUC performed to date have assumed that a marginal increase in LUC in any region can be estimated from supply and demand functions for commodities and land, despite the presence of other drivers. **Figure 1** illustrates the steps typically used to estimate ILUC emissions from biofuels expansion. When biofuels are produced on former cropland, a cascade of displacements and substitutions may occur. These interactions are estimated using an economic model (step a), which projects changes in economic uses of land, such as cropping, pasture, and forestry. As economic models are not generally spatially explicit, changes in economic uses must be mapped onto specific land cover types (step b). Next, the carbon emissions from conversion of the identified land cover types to its projected new use (step c) are estimated. Finally, for use in biofuel regulations, the estimated ILUC emissions are typically associated with a quantity of biofuel production, resulting in an ILUC emission factor denominated in gram CO_2 per megajoule (step d). Each of these steps is discussed further below.

Estimating Global Market Impacts

There are two main classes of economic models, partial equilibrium (PE) and computable general equilibrium (GE) models, both of which have been applied for estimating the economic and land-use effects of biofuel policies. PE models offer highly detailed representation of one or a few sectors of the economy, such as the agricultural sector; they, however, lack linkages to other sectors of the economy (Kretschmer and Peterson, 2010). GE models, in contrast, are comprehensive in their representation of the economy, reflecting feedback effects among all economic sectors; they, however, offer less detail. For example, a GE model might represent a composite "coarse grains" sector rather than individually representing the characteristics of corn, oats, barley, sorghum, and so on. Computational and data limitations force a tradeoff between detail and scope; combining the scope of GE models with the detail of PE models would result in a model that was computationally intractable. Both approaches have their proponents and detractors; neither is clearly superior for modeling ILUC.

Given the differing modeling approaches, data sets, and parameter choices, models of ILUC emissions have produced widely divergent results. **Figure 2** shows the results from several

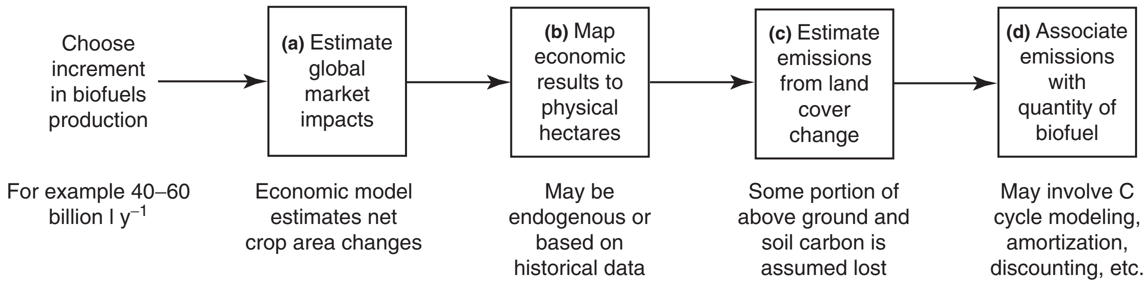

Figure 1 Schematic of indirect land-use change calculation using economic models.

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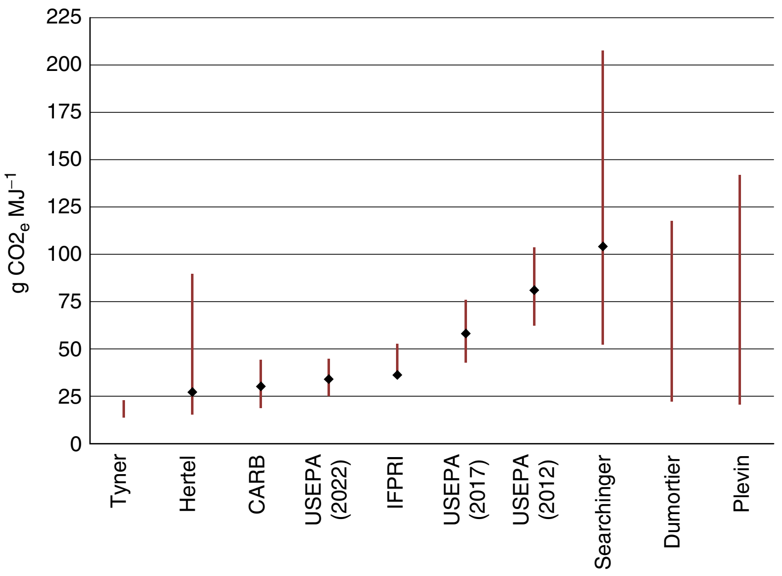

Figure 2 Ranges of results from models of ILUC emissions induced by expansion of corn ethanol production. Point estimates are indicated by the diamond where applicable. USEPA estimated ILUC emissions that would occur to meet the US Renewable Fuel Standard in each of three years: 2012, 2017, and 2022 (Tyner *et al.*, 2010; Hertel *et al.*, 2010; CARB, 2009; USEPA, 2010; IFPRI = Al-Riffai *et al.*, 2010; Searchinger *et al.*, 2008; Dumortier *et al.*, 2009, and Plevin *et al.*, 2010).

studies modeling the ILUC effects of expanded corn ethanol production. The ranges presented reflect on a variety of approaches to explore the sensitivity of ILUC emissions to various model assumptions. All of the studies shown are based on economic equilibrium modeling except for the Plevin *et al.* (2010) study, which is based on a simplified model parameterized from prior economic model results and thus incorporates model uncertainty in addition to parameter uncertainty.

Mapping Economic Results to Physical Hectares

The GHG emissions resulting from conversion to cropping vary with land cover types and across regions (Fargione *et al.*, 2008). Estimating ILUC emissions, therefore, requires assumptions about the specific land cover types converted as a result of biofuels expansion. As most economic models are not spatially explicit, economic model results must be mapped onto land cover types to predict the emissions from land cover conversion.

One mapping approach relies on survey data or remote sensing to identify the agricultural frontier – the regions in which natural land cover has most recently been converted to agriculture. If the economic model predicts, for example, the conversion of forest to cropland in a region, some models assume that the types of forest converted will resemble the types of forest conversion previously detected in that region. That is, it is assumed that prior land conversion patterns are predictive of future patterns.

For example, Winrock International compared moderate-resolution imaging spectroradiometer (MODIS) satellite images from 2001 and 2007 to detect land-use changes (Harris *et al.*, 2009). However, as noted by the authors, comparing already-classified land cover sets from two time periods can involve high error rates as small differences can be magnified when a parcel of land changes just enough to change classification between the two data sets. A more accurate – and much more time-consuming – approach would be to compare the two images before classification and to classify the changes directly.

Another approach considered by the European Union's (EU's) Joint Research Center (JRC) uses a spatial allocation model that incorporates land cover trends detected using remote sensing with predictive information such as the distance from existing cropland and the suitability of the land for producing different crops (Hiederer *et al.*, 2010).

Estimating Emissions from Land Cover Change

The magnitude and time profile of emissions from land cover change depend on the type of land cover and the mode of clearing. Burning releases most biomass carbon immediately, mostly as CO_2, but also as black carbon (soot), organic carbon, carbon monoxide (CO), methane (CH_4), and other volatile organic compounds. Nitrous oxide (N_2O) is also generally released on burning biomass.

Estimates of the total CO_2-equivalent emissions from land conversion usually rely on the well-documented Intergovernmental Panel on Climate Change GHG inventory methods, which include estimates of the CO_2 emissions from above- and below-ground biomass, dead organic matter (dead wood and litter), and soil organic matter, as well as non-CO_2 gases from burning above-ground biomass and dead organic matter (IPCC, 2006). Models of ILUC generally also consider some number of years of foregone sequestration of carbon, that is, sequestration presumed to have occurred if not for land cover conversion.

Total emissions are estimated by multiplying the total area in each land cover type by the associated emission factors. Even for a single set of economic model results, different estimates of total emissions will result from different land cover

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allocations. For example, the JRC estimated ILUC emissions induced by the EU Renewable Fuel Directive using the MIRAGE GE model. Applying the spatial allocation model (*see* Mapping Economic Results to Physical Hectares) to the MIRAGE resulted in emissions of 168 Mg CO_2 from above- and below-ground carbon stocks, compared with the prior estimates of 43 Mg CO_2 based on the same MIRAGE results and the Winrock land allocation method (Hiederer *et al.*, 2010; Table 25, p. 106). The increased estimate of emissions results from a greater allocation of land-use changes to areas that have a high-carbon carrying capacity (e.g., forests and shrubland) in the Spatial Allocation Model.

Associating ILUC Emissions with a Quantity of Biofuel

When ILUC emissions are included in biofuel regulations, the total emissions are generally associated with a quantity of fuel production to produce a metric in g CO_2e per megajoule. The simplest approach, used by regulators in USA and EU is straight-line amortization, dividing the emissions over 20 (EU) or 30 (US) years of biofuel production (Note that for any given total for ILUC emissions, amortizing over 20, rather than 30, years increases the per-MJ value by 50%). Another approach compares the total cumulative radiative forcing from biofuels to that of gasoline and measures the difference at an arbitrary time in the future (O'Hare *et al.*, 2009). Others have suggested long time horizons, discounting either emission flows (USEPA, 2009) or damages from emissions (Delucchi, 2011). Others have suggested charging for ILUC emissions when they occur (mostly in the first year) rather than amortizing (Melillo *et al.*, 2009).

Food Price Rationing

As noted earlier, one of the effects of biofuel expansion in the resulting competition for land is an increase in food prices. In response to this increase, economic models of ILUC indicate a reduction in food consumption. Because of reduced consumption, less additional land is required than would be if food demand were unchanged. Thus in models of ILUC emissions, the reduction in food consumption appears as a GHG "benefit" (Searchinger *et al.*, 2008; Hertel *et al.*, 2010). One approach to including this social cost in the ILUC factor would be to hold food consumption constant when estimating ILUC. In one such modeling experiment, holding food consumption constant increased the ILUC factor by approximately 40% (Hertel *et al.*, 2010).

Uncertainty in ILUC Emission Estimates

Despite many uncertainties and a wide range of estimates, the consensus from a suite of different economic modeling efforts is that the biofuels expansion results in net emissions from ILUC (Edwards *et al.*, 2010; Plevin *et al.*, 2010). Substantially narrowing the range will be difficult owing to the challenges of accurately modeling the response of the global economy to changes in production. Economic models tuned to historical performance are better suited in projecting small change to the *status quo* and less well-suited in modeling the effects of the rapid increase in biofuel production witnessed in the recent history and anticipated in the near future. Another challenge is the lack of spatial reasoning in economic models, requiring a variety of imperfect methods for mapping projected economic activities to specific land cover types.

One important uncertainty not considered in current economic models is the effect of climate change on agriculture. Global increases in extreme weather events suggest that existing models will underestimate future yield in some areas and overestimate yields in far more locations. Based on a probabilistic analysis of climate change and its effects on crop yields, Tebaldi and Lobell (2008) wrote: "[We] estimate the chance that global losses from climate change by 2030 will outweigh gains from CO_2 as unlikely for wheat ($<33\%$ chance), likely for barley ($>66\%$ chance) and virtually certain for maize ($>99\%$ chance). In addition, we estimate larger than 80% chance that net losses for maize will exceed 10% over this relatively short time period." Lobell and Burke (2010) noted that "although most cropping systems exhibit a clearly negative yield response to warming, the precise amount of yield loss per degree warming is often not tightly constrained, either from theory or observations." The longer the analytical horizon used to estimate the climate effects of fuels, the more important it becomes to consider the potential effects of climate on agriculture. An important nexus exists here between the economic models and long-range ecological assessments, such as the Millennium Ecosystem Assessment (http://www.maweb.org).

Approaches to Avoiding ILUC

Although estimates of ILUC emissions remain uncertain, ILUC can be reduced, and possibly avoided, by limiting competition between bioenergy feedstocks and other high-demand commodities (Schubert *et al.*, 2010, p. 210). The two main approaches are (1) to ensure that bioenergy crops do not compete with existing food and feed production, and (2) use byproducts of other production systems rather than purpose-grown crops as feedstocks.

Some bioenergy crops can be produced on a so-called "marginal" land that cannot support commercial agriculture. The most beneficial situation from a climate change perspective is to grow perennial grasses, such as switchgrass, miscanthus, or mixed prairie grasses on marginal land, where their deep root systems can enrich soil carbon and improve soil structural properties (Hill *et al.*, 2006; Blanco-Canqui, 2010).

An approach favored by the Roundtable on Sustainable Biofuels (a voluntary certification organization) is to grow bioenergy crops in responsible cultivation areas where the land use from increased bioenergy production is offset locally by intensification, such as increasing cattle stocking density or double cropping, thereby ensuring that the area maintains its prior output while producing energy crops.

The organic portion of municipal solid waste and waste from the food processing and timber industries can also be used to produce biofuels without competing with crops. Estimates of net GHG benefits of using these feedstocks for

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biofuels should consider the alternative fate of the biomass. For example, combusting biomass that would have otherwise remained intact in a dry landfill releases additional CO_2 to the atmosphere just as the burning of fossil fuels does. In other cases, the removal of biomass from landfills can reduce methane emissions, resulting in additional GHG reductions.

Crop residues can also be used as a biofuel feedstock. The collection and use of corn stover has been shown to reduce corn yield in subsequent years and to reduce the accumulation of soil carbon (Blanco-Canqui, 2010). Compensating for reduced yield can require extensification, triggering ILUC, or intensification, resulting in additional fertilizer-related N_2O emissions. From a climate change perspective, reducing soil carbon sequestration is equivalent to emitting the carbon. Blanco-Canqui estimates that only 25% of residue can be collected without adversely impacting soil properties, erosion, soil carbon sequestration, and crop production (Blanco-Canqui, 2010). Collecting such a small percentage of stover may not be economically feasible.

See also: Biodiversity in Logged and Managed Forests. Biofuels and Biodiversity: The Implications of Energy Sprawl. Deforestation and Land Clearing. Land-Use Changes and CO_2 Emissions Due to US Corn Ethanol Production. Life Cycle Analysis of Biofuels. Rainforest Loss and Change

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