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Measuring the Indirect Land-Use Change Associated With Increased Biofuel Feedstock Production

A Review of Modeling Efforts

Report to Congress

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Abstract

The House Report 111-181 accompanying H.R. 2997, the 2010 Agriculture, Rural Development, Food and Drug Administration, and Related Agencies Appropriations Bill, requested the USDA's Economic Research Service (ERS) in conjunction with the Office of the Chief Economist, to conduct a study of land-use changes for renewable fuels and feedstocks used to produce them. This report summarizes the current state of knowledge of the drivers of land-use change and describes the analytic methods used to estimate the impact of biofuel feedstock production on land use. The models used to assess policy impacts have incorporated some of the major uncertainties inherent in making projections of future conditions, but some uncertainties will continue to exist. The larger the impact of domestic biofuels feedstock production on commodity prices and the availability of exports, the larger the international land-use effects are likely to be. The amount of pressure placed on land internationally will depend in part on how much of the land needed for biofuel production is met through an expansion of agricultural land in the United States. If crop yield per acre increases through more intensive management or new crop varieties, then less land is needed to grow a particular amount of that crop.

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Measuring the Indirect Land-Use Change Associated With Increased Biofuel Feedstock Production: A Review of Modeling Efforts

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Executive Summary

In recent years, concerns have been raised about potential domestic and international land-use changes that might be associated with scaling up biofuel feedstock production. Increased competition for productive land and the resulting shifts in land use to produce food, feed, fiber, and fuel have potential impacts on greenhouse gas emissions, biodiversity, and water quality. The House Report 111-181 accompanying H.R. 2997, the 2010 Agriculture, Rural Development, Food and Drug Administration, and Related Agencies Appropriations Bill, requested the USDA's Economic Research Service (ERS) in conjunction with the Office of the Chief Economist, to conduct a study of land-use changes for renewable fuels and feedstocks used to produce them. This report is a response to that request, and it summarizes the current state of knowledge of the drivers of land-use change and the role of biofuel production in affecting land-use change. The analytical frameworks that have been used to address land-use impacts of increased biofuels production are presented, and the estimation task is explored in more detail. The objective was to survey the literature in a neutral, objective way. There was no intention to suggest that USDA does or does not agree with any assumptions or model results.

In the United States, the most advanced efforts to integrate consideration of land-use related impacts into policy have been associated with the Energy Independence and Security Act (EISA) of 2007 and policies such as the California Low Carbon Fuel Standard (LCFS). The analyses used for these policies require making projections about future values of domestic and international crop supply and demand, population growth, economic conditions, and land-use policies. Each element is a driver of land-use change, and the future value for them is uncertain. Uncertainty is an unavoidable aspect of policy-impact modeling that makes projections into the future. This report explores how some of the major uncertainties have been incorporated within models of land-use change, and how the estimates have changed over time. The publishing of research results has stimulated discussion of basic assumptions, parameters, and increased model transparency.

Continued research and modeling efforts will narrow the bands of uncertainty associated with projections of land-use change and domestic policy. New models, model refinements, and improved data will all help increase the precision with which input parameters are estimated and behavioral relationships are represented. Still, the successful integration of science and policy must come with the recognition that future projections will always carry some degree of uncertainty suggesting that it will need to be accommodated in policy design.

Highlights of the study:

- **The larger the impact of domestic biofuels feedstock production on commodity prices and the availability of exports, the larger the international land-use repercussions are likely to be.** Given the size of U.S. agriculture's influence on international markets, producers and consumers overseas regularly react to market or policy-related events in the United States. Price signals are the critical link between the behavior of the domestic agricultural sector and the induced land-use response of other countries.
- **The amount of pressure placed on land internationally will depend in part on how much of the land needed for biofuel production is met through an expansion of agricultural land in the United States.** The allocation of current cropland among different crops is based on expected returns in the next growing season. Land conversion between broad land-use categories can be both costly and irreversible and is therefore driven by longer-term economic factors.
- **If crop yield per acre increases through more intensive management or new crop varieties, then less land is needed to grow a particular amount of that crop.** Estimates of the land required for feedstock production or the crops that are displaced are highly sensitive to estimates of future crop yields on both existing and converted land.

I. Introduction

What is the issue?

In recent years, concerns have been raised about the magnitude of land-use change that could be generated by scaling up biofuel feedstock production. The reliance on use of the U.S. agricultural land base to provide fuel as well as food, feed, and fiber will lead to increased competition for productive agricultural land, shifts in land use among different crops, and, in some cases, conversion of land from other uses into agricultural production.

Land-use change in this case refers to the conversion of land from some other use for the production of biofuel feedstock or for some portion of the production displaced by expanding biofuel feedstock production. The concern first arose during life-cycle analyses (LCA) of the greenhouse gas (GHG) emissions due to increased production of biofuels. Early LCA research for GHG accounting emphasized the importance of considering the underlying land-use changes that might be associated with increased feedstock production. Furthermore, because the climate change impact of GHG emissions depends on the aggregate of emissions worldwide, not the location of the emissions, land-related emissions around the world must be accounted for if they are induced by biofuels production. Initial estimates of potential carbon release from global land-use changes suggested that so much carbon dioxide would be released under some land conversion scenarios that biofuel feedstocks would have to be produced on that land for hundreds of years as a way to compensate (Searchinger et al., 2008a; Fargione et al., 2008). These findings drew attention to the methods used to generate such numbers, and propelled the land-use issue into the forefront of the biofuels debate.

Economists have a long history of policy analysis in agriculture, though most land-use analyses are limited in scope to the impact of various domestic or international trade policies or technologies on existing domestic cropland resources. In contrast, studies attempting to quantify the broader land-use implications of biofuels production and biofuels policy, including competition among land-use sectors and market-induced repercussions worldwide, have appeared only in the last 2-3 years. To date, the most advanced efforts to integrate consideration of land-use-related GHG emissions into policy have been associated with California's Low Carbon Fuel Standard (LCFS), along with various efforts by member nations of the European Union (EU) to establish sustainability standards for biofuels, including the U.K.'s Renewable Transport Fuel Obligation (RTFO), and analyses associated with the U.S. Energy Independence and Security Act (EISA) of 2007.[1]

The regulatory requirements for GHG effects stipulated by the LCFS and EISA have greatly accelerated the development of tools necessary to perform life-cycle analyses of the GHG effects of biofuel production and to address questions related to land-use change induced by biofuels production. Such analyses require making projections about future values of domestic and international crop supply and demand, however, as well as broader assumptions regarding projected economic and population growth and development behavior. Analyses involving expectations about the future are inherently uncertain. Analytical methods exist for dealing with uncertainty in decisionmaking, but it is critical to understand the source of uncertainties in quantitative analysis to best determine how to manage them.

This report

During the fiscal year 2010 appropriations process, the House Appropriations Committee directed "the Secretary of Agriculture through the Department of Agriculture's Economic Research Service, in conjunction with the Office of the Chief Economist, to do an independent study of significant indirect land-use changes for renewable fuels and the feedstocks used to produce them."[2] This study was conducted in response to that request. It summarizes the current state of knowledge of the drivers of land-use change and the role of biofuel production in affecting land-use change. It also details the analytical frameworks used to address land-use impacts of increased biofuels production, and the modeling procedures. The objective was to survey the literature in a neutral, objective way. There was no intention to suggest that USDA does or does not agree with any assumptions or model results.

Modeling the future land-use implications of major changes in global market conditions is fraught with many uncertainties, but the assumptions that are used to address these uncertainties significantly affect the results with respect to estimating the environmental impacts associated with changes. In accounting for GHG emissions, for instance, the results differ greatly depending on whether virgin forest or pasture is converted to

[1]EISA section 201 amends section 211(o)(1) of the Clean Air Act to provide a new definition of "lifecycle greenhouse gas emissions" that includes "direct emissions and significant indirect emissions such as significant emissions from land use changes.

[2] Full text: http://thomas.loc.gov/cgi-bin/cpquery/T?&report=hr181&dbname=111&). Passed June 18, 2009.

increase the availability of cropland. Associated impacts on biodiversity and environmental quality from changes in nutrient, pesticide, and tillage use also will depend on the type of land that is converted.

Scientific methods for estimating the impacts of land conversion are improving to the point that estimates can be made if the type and location of the land-use change is known. Because the underlying stressor–the land-use change itself–is common across environmental dimensions; however, this study focuses on efforts to estimate the extent and location of land-use changes, not on efforts to estimate the resulting GHG or other environmental impacts of those changes.

Many studies of land-use change have been published in the past few years. The analytic approaches used in these studies have been expanded and refined over time, and the underlying assumptions used are now more clearly understood than in earlier studies. Some of the uncertainties associated with predicting indirect land-use change have been narrowed, while others are being examined to identify critical data gaps that are impeding development of more precise estimates.

Although most of the studies that are cited in the following review address the indirect land-use effects of corn-based ethanol production, the principles of land-use change remain the same for advanced biofuels production from other feedstocks. Corn ethanol results are used to illustrate the dynamics of land-use change because corn is currently the major biofuel feedstock in the U.S., the parameters of corn production are known, and models of global trade in corn are well established. Soybean use for biodiesel has also been studied, but the amount of soybean crop diverted to fuel production has been relatively small compared with that of corn. Recent breakthroughs in cellulosic conversion technologies promise a wider range of feedstocks for ethanol production and the potential for production of "drop in" fuels that would substitute directly for gasoline. In addition, bioenergy feedstocks may become important inputs in the generation of heat and electricity with minimal need for conversion to liquid fuel. [3] While the relative importance of particular drivers may change depending on feedstock, the underlying drivers of land-use change that are presented in this report will hold for any bioenergy feedstock (or any activity) that competes for agricultural land.

[3] For a more thorough discussion of increased biofuel production, see the Biomass Research and Development Board (2008) report, *Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications, and the Role of Research*. USDA's OCE and ERS (along with other USDA Agencies, EPA, and DOE) participated in this report.

II. Biofuels, GHG Emissions, and Land-Use Change

What is the current state and future growth of biofuels production?

In 1925, Henry Ford told a reporter "The fuel of the future is going to come from fruit like that sumac out by the road, or from apples, weeds, sawdust—almost anything. There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for a hundred years." Ford initially designed his Model T to run on a mixture of alcohol and gasoline, but the advent of inexpensive petroleum products, together with Prohibition's strict limitations on ethanol production, redirected development of the automobile industry towards hydrocarbon, rather than carbohydrate, combustion. Despite a transitory resurgence during WWII, when oil was scarce, the use of ethanol as a motor fuel remained in the shadows until the 1970s.

In the last 30 years, however, several factors have reinvigorated interest in ethanol:

- The Arab oil embargo, which highlighted the Nation's economic vulnerability to oil imports from unstable regimes and the need to diversify U.S. energy sources.
- Increased demand for gasoline oxygenates, which were mandated by the Clean Air Act to decrease smog-related vehicular emissions, and the discovery of adverse health and environmental impacts associated with other performance-related fuel additives such as lead, benzene, and MTBE.[4]
- The ability of ethanol production to stimulate agricultural markets, offering a potential market-based alternative to farm-support programs.
- The concern that GHG emissions from fossil fuel combustion are a key causal factor for climate change.
- The improved cost-effectiveness of ethanol production.

Moreover, the evolution of technology to produce biofuel from cellulose, which is in the demonstration stage and appears to be on the cusp of commercialization, has the potential to expand the spectrum of biomass raw materials that can be converted to biofuels.

To catalyze expansion of renewable fuels markets in the United States, Congress included in the Energy Policy Act of 2005 (EPAct) a Federal Renewable Fuel Standard (RFS) that mandated increased blending of renewable fuels into the U.S. fuel supply. In response to both increased interest in biofuels and increased concern about the potential GHG emissions associated with the production and use of conventional biofuels, the RFS was expanded and modified in 2007 to include a breakdown of fuel types, together with threshold levels of GHG emission reductions that the fuel types must meet to be considered qualifying renewable fuels under RFS II (Figure 1).

[4] Section 1504 of the Energy Policy Act of 2005 eliminated the requirement that reformulated gasoline (RFG) contain minimum levels of oxygenates. Current air quality requirements can usually be met without the use of oxygenates, and the associated demand for RFG oxygenates is much smaller than it was prior to the EPAct.

The sequential blending mandates, in conjunction with a tax credit that has been available to blenders who blend renewable fuels into gasoline or diesel, has been successful at accelerating development of the ethanol industry within the United States. Figure 2 shows the growth in U.S. corn and other starch-based ethanol production since 1992 as well as the forecast for growth of total ethanol production, from both starch and cellulose, to 2035 based on the latest long-term forecast from the Energy Information Administration (Annual Energy Outlook (AEO) 2010). The U.S. Department of Energy (DOE)-Energy Information Administration (EIA) projection of a brief plateau at roughly 15 billion gallons over the next decade reflects the limits placed on the volume of non-advanced ethanol that may qualify for credits under the RFS in the EISA; production levels eventually rise again due to mandated minimum levels of cellulosic biofuel under the RFS and projected improvements in the profitability of cellulosic ethanol.[5]

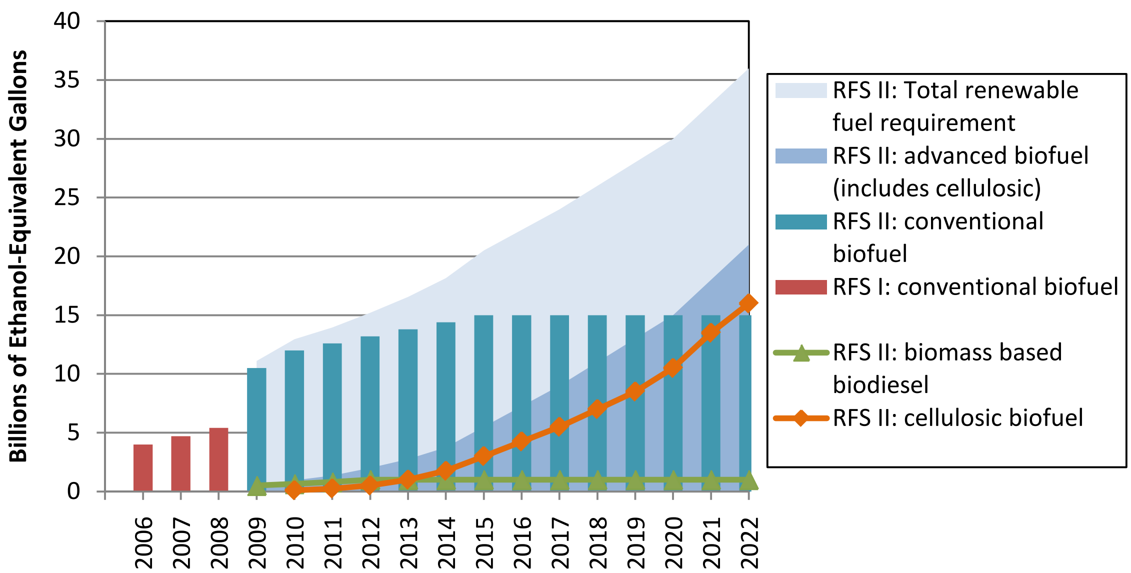


Figure 1: Renewable Fuel Standard requirements in the United States (billions of ethanol-equivalent gallons). Source: Renewable Fuels Association and Energy Information Administration.

[5]Ethanol industry advocates have argued that regulatory limitations on the amount of ethanol that can be blended into gasoline effectively limits the amount of ethanol that can be sold in low-level ethanol blends to 12 billion gallons per year (or roughly 10% of U.S. gasoline consumption by volume). This "blend wall" for low-level ethanol blends may create an obstacle to absorption of the regulated levels of ethanol by the market. On October 13, 2010, EPA issued a partial waiver to allow fuel and fuel additive manufacturers to introduce gasoline that contains greater than 10 volume percent (vol%) ethanol and up to 15 vol% ethanol (E15) for use in certain motor vehicles. However, extensive market penetration of E15 will require changes to state laws, recommendations from vehicle manufacturers and adoption by fuel distributors.

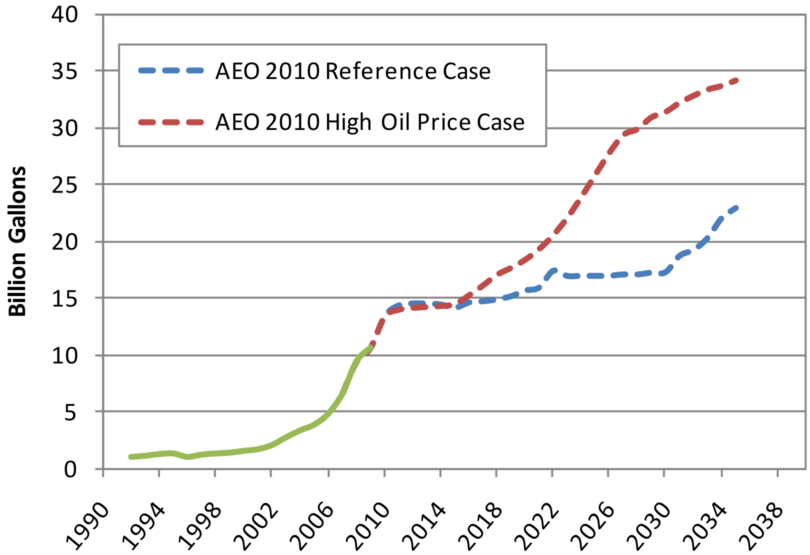


Figure 2: Historical and projected ethanol production in the U.S. (billion gallons). This graph illustrates only domestic ethanol production from starch and cellulose; it does not include projections of other biomass-based non-ethanol fuels, such as biodiesel. Source: Renewable Fuels Association and Energy Information Administration.

To meet demand for ethanol use, corn production in the United States is expected to increase from 12.9 billion bushels in 2009/10 to 14.0 billion bushels in 2015/16, with acreage planted for corn increasing from 86.4 million acres to 89.5 million acres. Over that period, yields for corn are anticipated to increase by about 5 percent, moving from 162.9 to 170.4 bushels per acre (USDA, Office of Chief Economist and World Agricultural Outlook Board, 2010).

Cellulosic biofuels

The majority of ethanol investment continues to be targeted at proven technologies—generating ethanol from corn by converting starch, a simple sugar, to alcohol. However, the congressionally mandated RFS II objectives call for 16 billion gallons of cellulosic biofuels to be produced annually by 2022. Cellulosic biofuels are based on the conversion of cellulose, a complex sugar, to alcohol. Cellulosic technologies allow the conversion of biomass feedstocks such as stalks, leaves, grasses, and even trees into ethanol. AEO 2010 projects that the cellulosic biofuels requirements under RFS II will be met by cellulosic ethanol as well as by a portfolio of new biomass-to-liquids fuels such as Fischer-Tropsch liquids, renewable (or "green") diesels, and pyrolysis oils (AEO 2010).

Cellulosic conversion technologies for the production of ethanol offer significant benefits over grain-based production of ethanol, including a higher ethanol yield per acre from a diverse array of feedstocks, the use of perennial feedstocks that require less intensive management than annual grains, and a significant reduction in the demand for fossil fuels during processing.[6] Due to the variety of potential feedstocks for cellulosic processes, it could also be possible to locate cellulosic ethanol processing plants closer to high-demand areas, lessening the need to transport ethanol from the Midwest corn-growing regions to the more populated coasts. The potential benefits of cellulosic processing are increases in land-use efficiency, reduced carbon intensity per unit of energy content, gains in cost-effectiveness, and greater flexibility in finding feedstock production pathways with a smaller environmental footprint.

Obstacles to commercial deployment of cellulosic ethanol remain, such as high production cost and the need for separate pipelines and distribution systems, though technological breakthroughs have been reported. The EPA's final rule for the RFS II adjusted the 2010 cellulosic biofuel standard down from 100 million ethanol-equivalent gallons to 6.5 million ethanol-equivalent gallons.

In the face of ongoing obstacles, uncertainties remain regarding the speed with which cellulosic ethanol production will be able to scale up and the types of feedstocks that will be available for use. The potential environmental and GHG emissions impact of cellulosic biofuels will vary depending on the choice of feedstock. While the option of using "non-food" feedstocks has been touted as one of the advantages of cellulosic ethanol production, in fact only the use of waste streams as a biomass source truly eliminates competition with food production. Corn ethanol competes with food and feed supply chains for agricultural output, and cellulosic ethanol from many biomass sources will continue to compete with food and feed supply chains for agricultural inputs, most notably land. Therefore, while greater potential per-acre ethanol yields from biomass could keep land demand down relative to a similar scale of corn ethanol production, the dynamics of the land-use impacts addressed in this report will continue to hold at some scale should large tracts of land be converted to dedicated cellulosic energy crops, such as perennial grasses or short rotation woody crops.

Greenhouse gas emissions

Demand for biofuels stems from a desire to decrease use of fossil fuels, which would lower GHG emissions as well as increase energy security for the United States. Biofuel use recycles CO_2 (a major GHG) unlike the combustion of fossil fuels, which adds CO_2 to the atmosphere. However, the GHG footprints of different biofuel feedstocks are complex.[7] The GHG requirement associated with the RFS II set in motion an extensive effort to establish a regulatory LCA methodology that would determine which fuels and production processes satisfy the GHG threshold requirements.

[6] Most ethanol processing plants currently combust coal or natural gas to generate power. Cellulosic biorefineries can generate their own power by burning non-fermentable lignin byproducts from their biomass feedstock, considerably reducing their dependence on fossil fuels.

[7] For a summary of the energy-equivalent reductions of different feedstocks compared with fossil fuels, see Biomass Research and Development Board, 2008, pp. 81-83.

Text Box 1: Life-Cycle Assessments

A life-cycle assessment (LCA) is a quantitative method of calculating the GHG balance of a biofuel (or other product) pathway, measured from production of raw materials through processing and transportation to end use. The recent expansion in the use of LCA for policy-based analysis, versus its conventional use as a product-based analysis, has prompted researchers to differentiate between "attributional" LCA analysis and "consequential" LCA analysis.

Attributional LCA analysis: Attributional LCA (aLCA) has historically evaluated the environmental impact of a product through the quantification of input and output flows of the production system based on average data and fixing the system boundaries to those flows connected to the product under study. The conventional use of LCA—providing information on the impacts of the "average" unit of product over its production pathway—has been used to compare products to one another and to identify opportunities within the production system to reduce the impacts of producing that product (Brander et al., 2008). The research questions addressed by attributional LCA analyses generally do not require that indirect production impacts be included within the scope of analysis.

Consequential LCA analysis: Consequential LCA (cLCA) evaluates the aggregate environmental impact of a change in the level of output of a product. A cLCA approach is appropriate in the case of policy analysis such as that performed for the RFS II, where the question of interest is the GHG impact of scaling up biofuels production: "cLCA models the causal relationships originating from the decision to change the output of the product, and therefore seeks to inform policy makers on the broader impacts of policies which are intended to change levels of production" (Brander et al., 2008).

The relevant scope of a cLCA analysis is therefore broader than that found in aLCA; whereas aLCA performs its analysis taking the scale of the existing production system as fixed, cLCA is specifically interested in looking at the impacts of changing the aggregate scale of production. Such impacts include effects both inside and outside the life cycle of the product itself. Production processes are linked through competition for inputs and infrastructure, for instance, so changes in the scale of production of one good will induce changes in the production of other goods that compete for common inputs. Indirect impacts therefore become a key factor in consequential LCA analysis.

While the aLCA approach is generally static and based on fixed relationships between inputs and outputs at a given point of time, a cLCA approach looks at the impacts of changing relationships, allowing for ripple effects across sectors. Expanding the scope of life-cycle analysis to include market effects requires the integration of complicated economic models to represent relevant relationships between demand for inputs, prices, elasticities, and supply chains for products and co-products. For that reason, some researchers caution that the results of consequential life-cycle analysis may be less precise than those of attributional life-cycle analysis (Brander et al, 2008), while others argue that, despite the additional uncertainty, the results are more comprehensive and complete (Schmidt, 2008).

Defining the types of land-use change arising from biofuels production

Increased demand for land to produce crops for biofuel feedstocks involves two interrelated types of land-use change—"direct" and "indirect." **Direct land-use change** refers to the conversion of land from some other use directly into biofuel feedstock production. Estimating the magnitude of direct land-use change in the country or region producing biofuel is a matter of projecting where feedstocks of different types are likely to be grown and what pre-existing land use or uses are likely to be replaced (e.g., pasture land, existing crop land, forest land or idle or degraded cropland).

Land uses displaced by feedstock production may move outside the country or region where they originated. However, **Indirect land-use change** refers to the conversion of land to produce some portion of the production displaced by expanding biofuel feedstock production. Because the aggregate demand for goods that require land for production increases as a result of increased demand for biofuel feedstocks, that initial, direct change in land use for feedstock production could trigger a cascade of off-site, induced land-use conversions elsewhere as land uses are redistributed to satisfy demand. Prices are the mediating factor between the action of increased feedstock production for biofuels and the effect of distant land-use change.

Indirect land-use changes can occur domestically or globally. For instance, increased corn production in the Midwest to supply ethanol production could induce the withdrawal of land from the Conservation Reserve Program (CRP) to grow wheat that has been displaced by the expansion of corn production for feedstocks. The conversion of CRP land to wheat is considered a domestic indirect land-use change associated with the initial increase in demand for corn for ethanol production. Sometimes, the trail from cause to effect is quite long, with many steps along the way. In the ethanol example, increased corn demand reduced soybean planting in the U.S., which reduced soy exports, which increased world soybean prices, which increased soybean planting in Brazil on land previously used to pasture beef, which increased beef prices, which increased incentives to clear Brazilian forests to increase pasture (Zilberman et al., 2010). The LCA accounting for GHG emissions is affected by the selected scope of the analysis. Changes in output in markets other than biofuel feedstock and ethanol production will occur as a result of price changes induced by increased biofuel production, and those changes in output may also have emissions implications.

Although researchers agree upon the basic concepts of direct and indirect land-use change, common usage of the terms has added confusion to the debate. "Indirect" and "international" are often used interchangeably. As noted earlier, the global land-use changes that are induced by U.S. biofuel feedstock production may be significant, but there are many drivers of international land-use change that will affect conditions abroad regardless of domestic biofuels policies.

Drivers of land-use change and implications for the agricultural sector

Increased biofuel production has had and will have effects on land use in the U.S. and the rest of the world as will any change that increases competition for agricultural land. Estimating the magnitude and location of that impact, however, is extremely challenging. In particular, estimating the indirect land-use changes that are attributable to biofuels production or policy is subject to a great deal of uncertainty. The extent of indirect land-use change is a market-mediated response that plays out internationally through global markets via changes in relative land values and commodity prices. The extent to which displaced production is replaced will depend on elasticities of supply and demand,[8] and where that production will migrate is subject to constraints imposed by national and international policies related to trade, energy, land use, forest management, etc. (Marshall, 2009). Furthermore, the difficulty of attributing off-site land-use changes to changes in feedstock production is exacerbated by the effects of simultaneous drivers of land-use change such as population change, income change and the associated changes in demand for goods such as meat and housing space, and diverse policies related to land-use management, development, trade, and other countries' biofuels policies – each of which affects the competitive advantage of different lands in different uses.

Landowners will allocate land among competing uses based on the expected net benefits of those uses, and those benefits will vary for each use depending on land quality and location. A landowner seeking to maximize profits will allocate a land parcel to the use that yields the highest expected economic return after the costs of conversion, which can include changes in machinery investments and management practices. Relative expected returns change with market conditions (commodity prices, production costs, population growth, consumer tastes, international trade, and other factors affecting the demand for land in different uses), technological advancements, and weather. The level of uncertainty surrounding future conditions will affect a landowner's assessment of expected benefits and costs.

Drivers of land-use change in the United States can be roughly categorized into those that may encourage either expansion or contraction of cropland acreage depending on market conditions, those that primarily encourage expansion, and those that primarily induce contraction of cropland acreage.

Examples of land-use change drivers that can induce expansion or contraction of cropland acreage:

- **Crop prices** can influence the amount of land planted to various crops because they affect the relative profitability of crops and farm income.

[8] Economists define elasticity as the responsiveness of the quantity demanded (supplied) of a good or service to a change in its price. More precisely, it gives the percentage change in quantity demanded (supplied) in response to a 1-percent change in price (holding constant all the other determinants of demand (supply). When demand (supply) is elastic (greater than one), demand (supply) is very sensitive to price. The fewer substitutes that exist for a good, the lower the price elasticity will be (the less responsive demand will be to a price change). Time is also a consideration in determining both consumer and producer price responsiveness for many items. The longer people have to make adjustments, the more adjustments they will make.

- **Changes in input costs** can also affect profitability. For example, use of land for cropping often requires application of fertilizers. Fluctuations in fertilizer costs can change the returns to cropping relative to other land uses. They can also affect decisions to grow particular crops because some crops require greater application of agricultural chemicals relative to other crops.
- **Technological change**, such as the introduction of yield-increasing crop varieties can increase the net benefits on a given piece of land and may reduce the demand for expansion of acreage. Some innovations, such as drought resistant seeds or pressurized irrigation systems, can induce expansion onto lands with lower quality soils.

Examples of land-use change drivers that primarily encourage expansion include:

- **Agricultural policies that increase expected returns and reduce the inherent risk associated with agricultural production** can increase the relative benefits of that land use. Such policies include commodity support programs and the Federal crop insurance program.
- **Energy policies, such as the Renewable Fuel Standard, that stimulate demand for existing commodities or create a market for new agricultural products,** such as perennial energy crops, can change the relative benefits of land use.

Examples of land-use change drivers primarily inducing contraction in cropland acreage:

- **Urbanization and pressure for commercial, residential, and industrial development** can increase the demand for land and reduce the relative benefits of keeping land in agricultural uses.
- **Conservation policies that mitigate or reverse the environmental impacts of conversion** can increase the benefits of retiring land from agricultural production. Since 1985, the CRP has been the largest driver of cropland changes (Lubowski et al., 2006).
- **Conservation policies that protect vulnerable natural resources from conversion to cropland or higher intensity uses** can offer benefits to farmers. Such policies include the Grassland Reserve Program and the Wetland Reserve Program.

Because future patterns of land use will depend on complex interactions among all of these forces, projecting future landscapes, and the degree to which they will be impacted by changes in a single driver, is very difficult. Broadening and increasing the portfolio of food, feed, fiber, and energy products from domestic agriculture will increase the amount of land required to produce those products and change domestic patterns of production. The response in terms of domestic land use will be sensitive to the wide array of factors described above.

Global perspective

U.S. agriculture is an integral part of global commodity markets, and changes in domestic production will impact how global demands for food, feed, and fiber are met. If competition for U.S. land reduces the availability of commodities for export, for instance, global markets will create the incentive, through higher prices, for those commodities to be produced elsewhere. Estimating the patterns of land-use change that will enable that increased production internationally is the crux of the indirect land-use change issue. Because agricultural expansion is one of the key drivers of land-use change and deforestation in many developing countries, there is little question that some international land-use change will result from domestic shifts in production. The debate intensifies, however, around the question of extent and location of those changes. Policies within a country that affect migration (population shifts) and associated land-use change can include road construction, colonization policies, agricultural subsidies, and tax incentives (Angelsen and Kaimowitz, 1999). While estimating future land-use change in a single, relatively data-rich country such as the United States is difficult, estimating waves of land-use change that propagate internationally through complex global commodity markets is even more challenging.

III. Methodologies for Estimating the Future Land-Use Change Associated With Biofuels Production

As discussed previously, land-use change is influenced by a number of factors, and the interactions between these factors are complex. Because experiments cannot be carried out to determine the consequences of policy or market changes, alternative means must be used. Mathematical models that attempt to estimate and test the interrelationships between factors are often used to quantify these relationships.

A quantitative economic model is a mathematical representation of how agents in a system behave under a set of hypothesized relationships informed by both theory and empirical evidence. A model serves as a proxy for what one cannot actually observe. In agricultural sector models that attempt to model land-use change, the agents are often producers of agricultural commodities and livestock, biofuel producers, and Government policy makers. A model is used to indicate, numerically, how the aggregate behavior of the agents will change if some facet of the production environment changes, such as through an increase in biofuel production mandates.

Because one cannot have perfect foresight about variables related to future weather, policy, and demand conditions, or many other factors that govern land-use decisions, the output of a model should not be taken as an immutable prediction of how the future will unfold. To isolate the effects of the variable of interest—in this case biofuel production—from the many other potential sources of uncertainty when projecting future land-change, modeling efforts usually measure the land-use impacts attributed to biofuel feedstock production as the difference between two future modeled, or projected, scenarios. Between those scenarios—a baseline projection and a “scaled up biofuels” projection—the only variable that differs is the change in biofuel production volume. The resulting difference in land use is therefore attributed to the biofuel policy mandating increased production. For example, the USDA World Agricultural Outlook Board coordinates a multiagency process that projects agricultural supply and demand 10 years out based on explicit assumptions about world markets, yields, and agricultural trade and environmental policies. This baseline is used in several studies as a projection against which to assess policy scenarios.

Because the two future scenarios share a set of common assumptions about exogenous future land-use drivers such as GDP and weather pattern, the estimate of land-use change derived this way does not reflect additional uncertainty surrounding what weather patterns are likely to be. Changes to these common data or assumptions, however, will change the resulting estimates, and, depending on the sensitivity of the model to those elements, may have a significant influence on the output. An important component of such analyses are therefore “sensitivity analyses” to determine whether the land-use change estimates respond significantly as input parameters and data are changed. These analytic frameworks can be used to assess the sensitivity of results to assumptions such as yield growth and future prices. It is important for any modeling study to be transparent about the assumptions used and the degree of confidence in the accuracy of input data.

Text Box 2: Model Frameworks

The first step in assessing quantitative and qualitative land-use impacts associated with a policy that will affect agriculture and forestry production decisions is choosing an analytical framework. There are several types of quantitative models that are used, and none can claim to be the ideal tool for assessing land-use change; each type of model has advantages and limitations.

Partial Equilibrium Models

Partial equilibrium (PE) models feature a detailed representation of agricultural (and/or forestry) production for a country or region. They typically utilize observed data to determine the amount of inputs required to produce a unit of a given product. The representation of production and land use can be highly detailed, allowing for variations in crop rotation, tillage, fertilizer application, and other variations in farm-level production decisions. Such models are “partial” in the sense that they focus on a subset of economic sectors and do not link explicitly to other sectors of the economy. Depending on the ways in which crop, livestock and forestry sectors are modeled, substitution between inputs may or may not be allowed. Partial equilibrium models can track movement of and competition for inputs such as labor, water, energy and fertilizer within the modeled sector(s), but economy-wide competition is beyond the scope of most PE models. Export and import of agricultural products and inputs are usually modeled in a relatively simple manner.

Partial equilibrium models that have been used to assess land-use change in agriculture include the Regional Environmental and Agricultural Production model (REAP), maintained by the USDA’s ERS, and the Forestry and Agricultural Sector Optimization Model (FASOM), at Texas A&M University. Both of these models focus on domestic crop production. The Food and Agricultural Policy Research Institute (FAPRI) maintains a family of econometric agricultural models that are coordinated to produce domestic and international agricultural production projections. The FAPRI models address only the agricultural sector and in aggregate can be described as a non-spatial, partial equilibrium agricultural sector model that covers both domestic and international production.

General Equilibrium Models

Computable general equilibrium (CGE) models are a class of economic models that use observed economic data to estimate how an economy might react to changes in policy, technology, or other external factors. CGE models attempt to portray an entire economic system (national or global) by accounting for interactions between all productive sectors, labor, flow of goods and capital between sectors (or countries), and government policies. The tradeoff for the expansion of modeling scope is often a loss in modeling detail for particular sectors such as agriculture. Furthermore, most existing global and regional

CGE frameworks are not structured to model land-use alternatives and the associated emissions sources and mitigation opportunities. This work has been hindered by a lack of data – specifically, consistent global land resource and non-CO_2 GHG emissions databases linked to underlying economic activity and GHG emissions and sequestration drivers (Hertel et al. 2009). Examples of CGE models used to evaluate land-use change impacts in agriculture are the Global Trade Analysis Project (GTAP), housed at Purdue University, and the Integrated Model to Assess the Global Environment (IMAGE) of the Netherlands Environmental Assessment Agency.

While CGE models feature a full accounting of the economic flows between production sectors, they have not been used widely to model land-use change at the regional level. The recent research emphasis on the importance of land and land constraints in GHG analysis of policy, products, and trade is changing that. Recent modifications to the GTAP model have included creation of a land-use module that allows GTAP-Bio to represent the global competition for land among land-use sectors (Golub et al., 2009).

Dynamic vs. Static Models

A static model addresses the impacts on production for a single year. While there are dynamic elements to agricultural production that are a function of the previous year's crop, such as commodity storage and crop yields, these elements can often be handled adequately in a static model through the use of averages or capitalized values. Dynamic optimization models explicitly model the evolution of the production environment over a range of time and can attempt to optimize over a multi-year pathway.[1] Dynamic models, for instance, are frequently used to model the forestry sector, with its long rotation times and fractional annual harvest.

Static models generally solve much faster than dynamic models and are useful in simulating a large number of policy shocks as uncertain inputs are varied. Dynamic models can be much more computation-intensive and are more sophisticated in analyzing transition effects and the effects on later periods of a decision made today under different states of the world.

A robust projection of the domestic and international land-use implications of biofuel feedstock production requires an integrated modeling system that is capable of providing answers to a lengthy list of complex and interrelated questions:

- How much feedstock will be required to meet projected biofuel demand?
- How much land will be required to produce that much feedstock?
- Where will land for feedstock production come from?
    - What will be the methods and costs of feedstock production?
    - What are the available sources of land, beyond existing cropland, for feedstock production?
    - How competitive will feedstock production be with existing land uses such as other crops, pasture, and forestry?

    - What additional obstacles exist to farmer adoption of feedstock production?
    - What are the environmental implications of changing land uses?
- What will be the impacts of changing patterns of domestic production on international commodity prices?
- Which countries will respond to changing international prices with changes in agricultural production patterns?
- What lands within those countries will be affected by changing patterns of production? If output is increased, what types of land will be converted into production?

No single model currently exists that can answer such a broad list of questions for feedstock production in the United States. Analyses at this scale generally tie together models that can answer the domestic questions related to production and macroeconomic impacts with other models that evaluate how international markets respond to regional changes in production and macroeconomic impacts. While such economic models have been under development for decades, the introduction of an explicit land-use component into the economic framework is a relatively recent addition. The link to land use in these models has been complicated by a lack of sufficient, consistent, and comparable data regarding existing land uses and historical patterns of land-use change for the United States and worldwide.

The sophisticated integration of models required to estimate biofuels-related land-use change highlights the complexity of the forecasting task. Models capturing the land-use change dynamics described earlier must make projections about future values of parameters ranging from farm production practices for crops that are not yet grown commercially, to expected growth in existing crop productivity, to projected responsiveness of world markets to changes in crop prices under specific global economic growth scenarios, and to enforcement of land-use policies in other countries.

Future values for parameters such as these are not yet known, so judgments and assumptions must be made as to the likely values these uncertain data will take. Each assumption, whether made explicitly or implicitly in the structure and data of the model, will influence the outcome to some degree, though the extent to which they influence land use results varies, with some parameters generating significantly more variability across their plausible ranges than others.

There is a long history of research on analytical methods for exploring and illustrating uncertainty in analytical contexts such as this one; model-based analysis is particularly well-suited to indepth exploration of how outcomes vary as the range of possible input values and value combinations is explored. The results of such analyses are used to refine outcome estimates over time in multiple ways:

- Identifying the scope of analysis that encompasses and elaborates on the most significant variables in generating outcomes and outcome variability;
- Reducing uncertainty surrounding those variables where uncertainty is a function of missing or coarse information; and

- Managing or bounding the uncertainty around those variables that are inherently uncertain because they are unobservable, such as future projections.

The evolution of the indirect land-use change modeling efforts has made progress along each of these pathways. Before describing the status and evolution of that analytical effort, the following section briefly reviews the major sources of uncertainty in this analytical context.

IV. Sources of Uncertainty in Model Methodologies and Assumptions

The sources of uncertainty in modeling the indirect land-use change associated with biofuels production have been roughly grouped into five categories:

1. The uncertainty associated with the demand for land for feedstock production;
2. The uncertainty associated with the supply of land in the United States;
3. The uncertainty associated with responses of domestic and international markets to feedstock production;
4. The uncertainty associated with the magnitude of land-use changes in those countries responding to international price signals; and
5. Other uncertainties in modeling indirect land-use change.

Assumptions made about the uncertain future not only affect the model results directly but also determine the baseline from which change is measured. Although a few models measure change from current conditions (attributing the total change to biofuel feedstock production), most project the likely conditions at some future date with and without the activity or policy of interest. The difference between the baseline and scenario analysis is meant to capture the policy effect. For example, the USDA World Agricultural Outlook Board coordinates a multiagency process that projects agricultural supply and demand 10 years out based on explicit assumptions about world markets, yields, and agricultural trade and environmental policies. This baseline is used in several studies to assess policy scenarios and the sensitivities of the results to the underlying assumptions embedded in the model.

The sections that follow explore some of the assumptions that are significant in generating variability around estimates of land-use change associated with future biofuel feedstock production.

Uncertainty associated with the demand for land for feedstock production

As demand for land for biofuel production rises, competition for that land will intensify and the effects of indirect land conversion will likely grow as well. Several factors influence direct feedstock demand for land, including feedstock yield assumptions and substitutability of biofuel coproducts for other products that require land as an input. Any bioenergy feedstock that has the potential to be grown on agricultural land can be considered a competitor for that land. The type of land on which it will be grown and the current use that it will displace will depend on the resource requirements of the feedstock and the relative profitability of that feedstock compared to the current use. One of the most important determinants of profitability is the yield that can be produced per acre.

Yields: A crop variety has a "yield potential" that represents the expected yield if all conditions are perfect. The yield potential can be changed through research (or mutation). Actual yields are an outcome of environmental conditions and the choices made by the producer about the use of agricultural practices and inputs such as tillage, irrigation, and fertilizer. If crop yield per acre increases through more intensive management or new crop varieties, then less land is needed to grow a particular amount of that crop. This is true for bioenergy feedstocks and any crops that they displace. Estimates of the land required for feedstock production are therefore highly sensitive to estimates of future crop yields on both existing and newly converted land.

Estimating future crop yields on newly converted lands is complicated by uncertainty about the productivity of land that has not yet been converted. Unfortunately, there is little empirical evidence to guide modelers in selecting the appropriate value for estimating the productivity of converted land. In most regions, existing crops are already on the most productive agriculture land, so yields on newly converted lands would likely be lower than on existing cropland.[9] New crop varieties or more intensive input use may mitigate such yield losses. The expected productivity of new land in agriculture is a major determinant of how much new land will be required to accommodate increased demand for biofuel feedstock or any use that competes for land.

The uncertainty about yield on land converted today to a new use is compounded when yields are projected over time. The yield potential for most crops has grown over time due to public and private investments in plant breeding, biotechnology, and other crop improvements (Figure 3). More intensive use of existing technologies and the adoption of new technologies also can enhance productivity. Yields, for instance, can be increased in response to higher prices by more intensive use of inputs such as fertilizer (Keeney and Hertel, 2009). Greater input use or more intensive management, however, may have environmental consequences. Increased nitrogen application may result in increased direct N2O emissions, and more intensive farming practices may result in increased erosion and decreased soil carbon sequestration. If one of the underlying motivations for concern about indirect land use is concern about GHG emissions, then such potential tradeoffs between use of land and use of other inputs to increase production must be acknowledged and incorporated into a comprehensive analysis. This concern extends to cellulosic feedstocks; although cellulosic feedstocks such as perennial grasses can be grown with fewer inputs than a crop such as corn, yields can be improved through the use of fertilizer, and added nutrients will be applied if increased revenues outweigh the costs.

Pest-resistant and herbicide-tolerant biotechnology-derived varieties of corn, cotton, and soybeans have been adopted extensively by farmers in the United States, but acceptance has not been as widespread in other parts of the world. Current biotechnology research is focused on traits such as drought tolerance that would increase yield potential for many crops. Biotechnology research will be employed in the development of bioenergy feedstocks as well as traditional agricultural commodities. Whether the recent trend in yield growth will continue unchanged, increase, or decrease is a matter of agronomic limits and research investments (Heisey, 2009). Estimates of the rate of yield growth may also differ across crops and locations. Productivity performance across countries and regions has not been uniform (Fuglie, 2010).

[9] There may be regions where newly converted cropland is as productive as existing cropland (e.g., parts of Brazil), but those cases may be the exception. Furthermore, converted areas may be more productive in the short run than in the long run. Estimates of land-use demand will greatly benefit from improved data on the productivity of converted land for cropland worldwide.

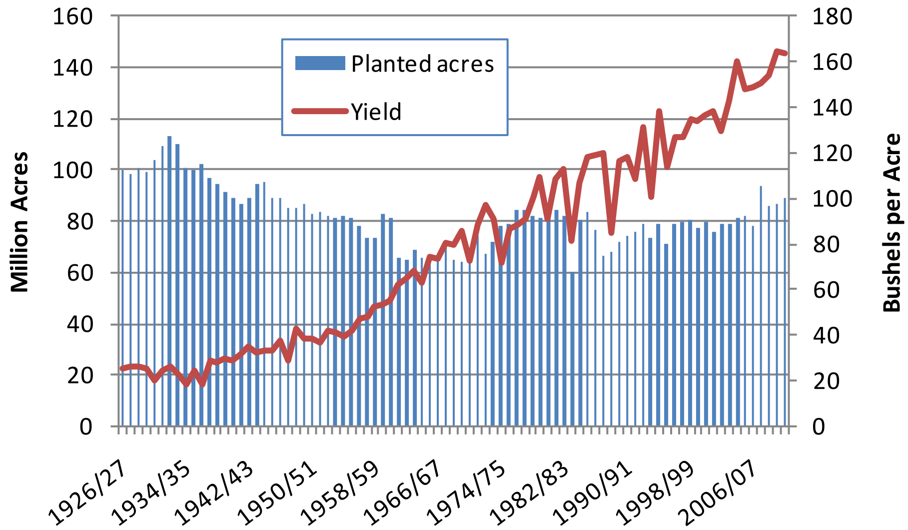
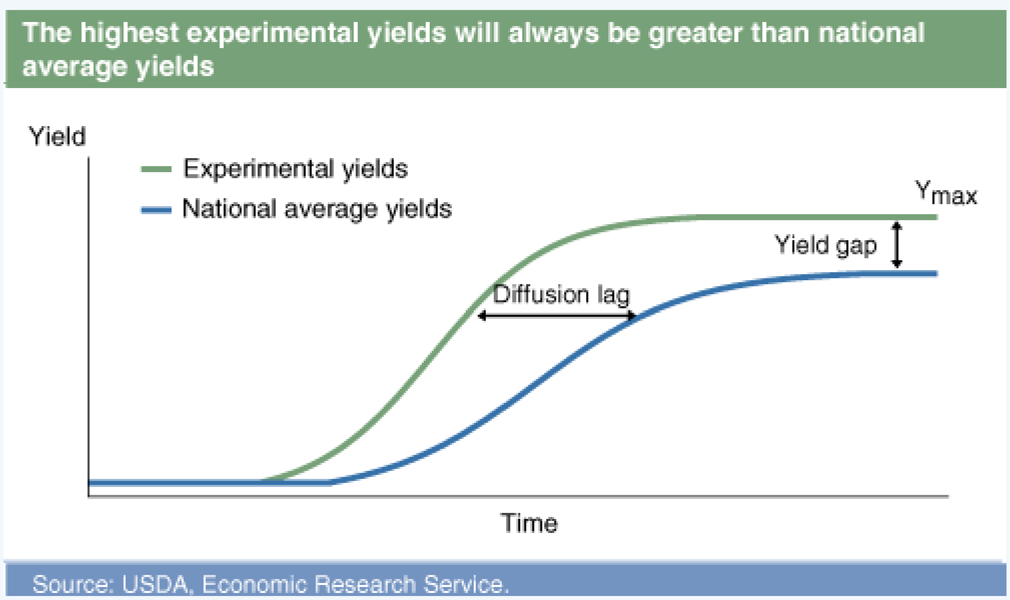


Figure 3: Yield increases for corn over time in the United States. Source: USDA, Office of the Chief Economist and World Agricultural Outlook Board, 2010.

Text Box 3: Scientific Advances, Economic Factors, and Biological Limits Determine Crop Yields Over Very Long Periods of Time

The very long-run trajectory of yields for a major field crop like corn usually begins with a phase in which yields are flat. Yields then increase over a long time with the application of science to agriculture. Finally, yields might reach some theoretical maximum based on the plant's capacity to capture available sunlight, efficiently convert it to biomass, and partition that biomass into grain. The resulting simple S-shaped graph may conceal a number of important factors. First, flat yields may not always signal periods of technological stagnation. Mechanical technology may have lowered the labor inputs into land preparation, cultivation, or harvesting. Different crop varieties may have maintained yields that would have otherwise deteriorated because of pests and diseases, or allowed expansion of commercial crop production into different growing zones. Second, the yield trajectory over time and maximum attainable yield nationwide will differ from results on small-scale experimental plots. It takes time for new corn technology to move from scientific plots to commercial application by farmers, and additional time may be required to adapt corn technology to less favorable growing regions. Furthermore, maximum yields on experimental plots will differ from yields in farmers' fields because a greater number of detrimental factors can be controlled on small experimental plots, and farmers must consider economic costs and benefits, which are less relevant in trials aimed at maximizing yields.



Coproducts from biofuels production may mitigate land-use pressures: Because ethanol diverts corn from the livestock sector, it is often perceived to be a competitor, rather than a supplier, in the livestock feed market. Ethanol dry mill production produces a coproduct called distillers' dried grains (DDGs), which can substitute for corn as feed, thereby reducing the amount of corn required by the livestock sector. The greater the substitutability between DDGs and corn, the fewer total cropland acres will be needed to supply both the ethanol and livestock sectors.

Dietary considerations place constraints on the amount of DDGs that can be used in livestock diets. Furthermore, marketing challenges remain due to variability in nutrient composition, issues related to product storage and transport, and food safety concerns (Malcolm et al., 2009). Nevertheless, research currently being conducted on how animal feed rations can be modified to make use of DDGs will lead to an improved understanding of how and to what extent DDGs can substitute for feed products, thereby offsetting some of the increased land demand necessary for corn production.

Uncertainty associated with the supply of land in the United States

The amount of pressure placed on land internationally will depend in part on how much of the land needed for biofuel production is met through an expansion of agricultural land in the United States. Agricultural production models for the United States have a long history of estimating the movement of land allocation among different crops on existing cropland based on changes in expected return. Land conversion between broad land-use categories, however, such as from forest to pastureland or cropland, can be both costly and irreversible and is therefore driven by longer-term economic factors. For example, Midwest farmers can readily move cropland between corn and soybeans when the relative profitability of those crops change. In contrast, the conversion of forest acreage to cropland represents a long-term change with high transition costs: such a decision must consider the relative profitability between agricultural and forestry commodities for many years into the future.

The uncertainty of the future values of prices and costs will affect an owner's expectation of long-term profits from any alternative. In addition, the partial irreversibility of some land-use changes gives rise to option values that increase the incentive to keep land in its current use (Stavins, 1999).[10] Using an option model, Song, Zhao, and Swinton (2009) found that landowners would be more reluctant to convert land from annual to perennial crops. The irreversibility of some land-use changes coupled with uncertainty about future economic returns can act as a brake on land conversion. Farmers hesitate to convert land because they value the "option" or "flexibility" for future land-use decisions that is preserved when land is maintained in its current use. Isik and Yang (2004) also found that such option values play a significant role in farmer decisions to retire land and that they reduce the probability of farmer participation in land retirement programs. Other factors may significantly affect land conversion decisions in a particular area or country, such as national or regional conservation and preservation policies and programs.

[10] Option value is the gain from being able to learn about future benefits that would be precluded by the conversion of land to an irreversible or partially irreversible use–the gain from retaining the option to continue with the current use and/or change uses in the future (Fisher and Hanemann, 1990).

Uncertainty associated with the responses of domestic and international markets to feedstock production

If biofuel feedstock production disrupts domestic production of other crops through competition for land or other inputs, market prices of existing crops will be affected, which will send signals internationally that may result in changes to production patterns abroad. Increased commodity prices in 2007 sparked a debate about the effects of corn-based ethanol production on consumer food prices. The “food versus fuel” discussion demonstrated the lack of consensus on the extent to which use of a portion of the Nation’s corn for ethanol production impacts the prices of finished food products, as well as the prices and export availability of the ethanol feedstock and other commodities (Trostle, 2008; Leibtag, 2008). This price signal, however, is the critical link between the behavior of the domestic agricultural sector and the induced land-use response projected for other agricultural exporters.

Given the size of U.S. agriculture’s influence on international markets, producers and consumers overseas regularly react to market or policy-related events in the United States. Domestic adjustments in production and crop mix may change incentives for foreign producers to supply their own markets or the world market, by bringing new land into agricultural production. The larger the impact of domestic biofuels production on price and availability of exports (of both the feedstock and, through land competition, all other commodities), the larger the international land-use repercussions of that domestic biofuel production are likely to be. The strength of the signal sent to markets around the world is therefore highly dependent on the domestic land supply issue already described.

The nature and magnitude of the international market response to increased prices hinges on both the production and consumption response. The consumption response is reflected in estimates of the price elasticity of demand for agricultural commodities. This variable captures what happens to world demand for food and feed crops, including crops fed to animals for meat/dairy production, when their prices increase on the world market. Assumptions of inelastic demand, where food and feed consumptions are relatively unresponsive to price, lead to larger estimates of land use impact than when it is assumed that food consumption will decline sharply as food and feed prices rise; a relatively more elastic demand for agricultural commodity good production means that in aggregate, fuel production on agricultural land “crowds out” food production to a certain extent. There are consumer welfare implications associated with the increased prices and reduced consumption; Roberts and Schelenker (2010) econometrically estimate commodity demand elasticity and the consumer welfare losses associated with reduced consumption due to biofuels-driven price increases.

Predictions of international production responses to domestic market changes often rely on one of two assumptions concerning the economic mechanism by which goods are traded between countries. The first assumption asserts that trade generally occurs in response to a single world price that results from the production and consumption decisions of individuals around the world. Thus, after controlling for transportation costs and border-related barriers, only those producers that can profitably sell at the world price will participate in the world market, irrespective of their location or their past relationships with buyers.

The second assumption, first proposed by Armington (1969), contends that, in addition to prices, bilateral relationships between traders do matter and that consumers distinguish from which country their goods originate. Under the Armington assumption, an analyst must rely on a quantitative estimate of the strength of the bilateral trade relationship. Though models may be limited to a single assumption about trade structure, the two frameworks are not mutually exclusive; a realistic trade response may be best represented using an Armington assumption in the short term, but allowing for evolution toward a "single world price" structure in the long term.

Uncertainty associated with the magnitude of land-use change in those countries responding to international price signals

Each country participating in the global market has its own characteristics with respect to current land use, land quality, resource availability, legal framework, demographics, infrastructure, international relations and economic conditions. All of these factors must be considered when analyzing the effects of changes in agricultural prices on the allocation of land in a particular country.

Using trade analysis to estimate the responses of international markets in such cases generally involves predicting changes in exports and imports of specific countries or regions under the new production scenario. The next step in tracking indirect land-use change is to associate those changes in production with the underlying land-use changes in each country that would be required to meet new export and import patterns. This requires a calculation of how much land would be required to meet the changing export/import patterns and a projection of where that land would come from. The amount of land converted into agriculture, and its original coverage (e.g., forests, pasture, or idle land), can critically determine the one-time release of carbon emissions attributable to land-conversion impacts. The challenge, therefore, is identifying where land conversion will occur, and which type of land will get converted.

All of the land-use drivers described here are relevant in the international context, but in varying degrees. As in the U.S., land prices, development pressure, access to markets and transportation costs, and opportunity costs associated with alternative uses of land need to be included in the model, along with information on the effectiveness of national, regional and local land-use policies such as protected areas and conversion set asides. Lack of sufficient data makes it especially difficult to model or project future land-use change in foreign countries. Researchers must therefore make a number of simplifying assumptions about how land-use change within the country is likely to occur in the future under business as usual (the baseline) as well as how that baseline scenario will change under the biofuels feedstock production scenario. Cross-country assumptions that U.S. biofuel policies will have the same type of impact on land use within each country may result in misleading conclusions because each country has a unique set of resource endowments, institutions, trade relationships, and economic drivers (Angelsen and Kaimowitz, 1999).

Other uncertainties in modeling indirect land-use change

Many forces of varying magnitude will affect future conditions that, in turn, will affect the extent of indirect land-use change. For example, extreme weather events, natural disasters, political instability or conflict, and technological breakthroughs all have the potential to alter global supply and demand for agricultural products. One of the biggest determinants for biofuel feedstock production is the energy market, which includes the supply and demand for fossil fuel as well as all renewable energy sources.

Some uncertainties in modeling indirect land-use changes that will not be explicitly addressed in this report are associated with global energy markets and the interactions between energy demand and population growth, economic growth, and income generation more broadly. Biofuel feedstock production depends on the demand for renewable energy. Higher gasoline prices in recent years decreased the U.S. public's demand for energy in general and increased its demand for alternative energy sources. As was observed after the "oil crisis" of 1973, however, the public interest in energy efficiency and alternative energy can fade quickly when fossil fuel prices fall.

The long-term viability of renewable energy markets will depend on renewable energy being cost competitive with fossil fuels. Large investments are being made to lower biofuel production costs. However, it has been noted that relatively low energy prices can have the unintended effect of increasing energy use (the "rebound effect") and potentially increasing GHG emissions (Alfredsson, 2004; Beckman et al., forthcoming 2011).

Assumptions about future energy prices, including the impacts of such prices on economic growth and income generation, are therefore critical variables within the models that are used to estimate indirect land-use change. A related issue will be the direct competition in the provision of biofuels if domestic demand sufficiently increases. It is predicted that countries such as Brazil and Indonesia are likely to convert more land to biofuel production to supply U.S. renewable fuel needs (Fargione et al., 2008).

Another uncertainty associated with modeling energy markets that include both fossil and renewable fuels is predicting technological breakthroughs that can affect either supply or demand for one or more energy sources. Large investments are currently being made to improve cellulosic conversion so as to widen the range of bioenergy feedstocks that can profitably be used as fuel. However, research is also underway to develop technologies to process coal, tar sands, and oil shale with reduced emissions. Hydrogen power may be on the horizon, which, depending on the price, would affect demand for both bioenergy crops and fossil fuels. On the other hand, improvements in feedstock to fuel conversion efficiencies would increase the relative advantages of biomass-based fuels. Since such technological breakthroughs cannot be predicted with certainty, many models include assumptions about innovation rates that lower production costs over time. As with the crop yield increases described earlier, innovation depends on research investments that may or may not pay off. No assumption about a steady rate of technological improvement can capture the impacts of a "game-changing" breakthrough.

V. Modeling Efforts and Results to Date

Interest in measuring the scale of indirect land-use change attributable to biofuel production largely arose from concern about the potential GHG implications of such conversions. In January 2008, Dr. Alex Farrell, then director of the Transportation Sustainability Research Center at UC Berkeley, presented to the California Air Resources Board (CARB) Low Carbon Fuel Standard (LCFS) Program an illustration of potential indirect GHG impacts from biofuels production in the U.S. that would arise from indirect land-use change in other countries. That analysis, which was the first to attract major interest in the subject, presented what Farrell described as “crude upper limit estimates” on the GHG emissions associated with land-use change for biofuels production (Farrell and O’Hare, 2008). To get his extreme “worst case” scenarios, he made the assumption that an acre of bioenergy feedstock production will result in an acre of land conversion and coupled it with the assumption that the land lost will come from the highest carbon land use available for conversion. This resulted in estimates that an acre of corn production for ethanol in the United States would ultimately lead to an acre of tropical rainforest conversion, at conversion costs that go as high as 826 gCO_2e/MJ of energy from corn ethanol.[11] Less carbon-intensive scenarios where the analysis assumed that lower-carbon temperate grasslands, rather than tropical forests, are converted for corn production (while maintaining the 1:1 acreage conversion assumption) result in significantly lower estimates of 140 gCO_2e/MJ.

The evolution of estimation procedures since then has largely focused on identifying and improving the precision with which key variables–such as anticipated future crop yields and source, carbon-intensity, and productivity of new land brought into production internationally–can be represented in modeling efforts. In particular, the integration of land use into traditional economic models of production and trade, and the accompanying capacity to estimate the indirect land-use impacts of domestic production, has rapidly increased in sophistication in response to CARB and EPA’s regulatory requirement to measure the GHG impact of biofuel production. Table 1 presents the results from several recent modeling efforts that estimate the effects of ethanol production on global land use. These studies attempt to quantify the market response in the United States and in other countries to increases in commodity prices due to increases in biofuel production. These studies also quantify the GHG emissions from these market responses and attribute these emissions to biofuel production. The table is not meant to be comprehensive but shows a selected range of estimates. Other models, such as MIT’s Emissions Prediction and Policy Analysis model, have also been used to examine indirect land-use change impacts (Gurgel et al., 2007; Melillo et al., 2009).

[11] Assuming that the non-land-use-related carbon savings from corn ethanol is a 20 percent reduction from gasoline (19 gCO2/MJ), this conversion cost would require approximately 866 years of corn ethanol production to pay back. This number, though spectacular, is meant only to illustrate the rough magnitude of potential impact, as it is based on a set of unlikely “worst case” assumptions.

Table 1: Estimates of land-use change and emissions related to land-use change associated with biofuel production.

Study	Modeling framework	Increase in ethanol production	Change in Global Land Use	Change in Global Land Use	CO2 equivalent emissions
		Billion gallons per year	Million acres	Million acres per bil. gal per year	Grams CO2e per MJ of ethanol per year 1/
Searchinger et al., 2008a 2/	FAPRI/ CARD	14.8	26.73	1.81	104
Fabiosa et al., 2009 3/	FAPRI/ CARD	1.174	1.923	1.638	na
California (CARB) 2009	GTAP	13.25	9.62	0.726	30
EPA proposed rule for RFS II (corn ethanol 4/)	FASOM/ FAPRI/ GREET	2.6 (12.4 to 15.0) (p. 422, RIA)	4.4 (table 2.9-3, RIA)	1.692	60.4
EPA Final Rule for RFS II (Corn Ethanol 4/)	FASOM/ FAPRI/ GREET	2.7 (12.3 to 15.0) (p. 311, RIA)	1.95 (table 2.4-29, RIA)	.722	30.3
Hertel et al., 2010	GTAP-BIO	15	9.4	.628	27
Tyner et al. 2010 5/	GTAP (scenario 3)				
2001 to 2006		3.085	1.155	.374	17.3
2006 to 7 BG		2.145	.577	.269	12.9
7 to 9 BG		2	.581	.291	13.4
9 to 11 BG		2	.607	.304	13.6
11 to 13 BG		2	.655	.327	14.3
13 to 15 BG		2	.684	.342	14.5
2001 to 15 BG		13.23	4.258	.322	14.5
EU JRC-IE (Edwards et al., 2010) 6/					
	LEITAP			4.08	151.11
	AGLINK			2.41	89.32
	GTAP			.78	28.83 (62)
	IMPACT			.51	17.5

Na=not applicable.
1/ The carbon content of fuels, or the aggregate LCA emissions associated with production, including land-use change impacts, is often expressed relative to energy content so the carbon to energy ratio (gCO_2e/MJ) can be compared across fuels. A wide variety of methods and assumptions are used by the studies in converting land-use change impacts into associated estimates of carbon emissions; an explanation of such methods is beyond the scope of this report but critical to a full understanding of the carbon intensity estimates and why they differ among studies.
2/ Searchinger et al. reported their results in terms of a 55.92-billion-liter increase in ethanol production, which resulted in a 10.8-million-hectare change in global land use.
3/ Based on a 10-percent increase in U.S. ethanol use using 10-year averages of U.S. ethanol use and world crop area taken from the 2007 FAPRI baseline. Impact multiplier of 0.009 taken from Fabiosa et al. (2009), Table 2.
4/ Figures refer to international indirect land-use change only.

5/ Conversion to megajoules (MJ) of ethanol assumes each gallon of ethanol contains 76,330 Btu's of energy and each Btu is equal to 0.00105 MJ. Tyner et al (2010) derive results separately for multiple categories of scale of production, or billion gallons (BG) per year.
6/ The reported emissions figures associated with estimated land-use change are based on a central carbon stock estimate of 40 tC/ha of conversion and a 20-year carbon payback horizon. The JRC-IE report illustrates error bars around that estimate based on a range of 10-95 tC/ha. In the case of the GTAP model results, the JRC-IE calculated an additional emissions estimate based on a table of regional emissions factors that more finely reflects projections of different types of regional land conversion (with varying carbon stocks); the resulting emissions estimate is shown in parentheses.

While it is conceptually useful to distinguish between indirect and direct land use impacts in discussing the impacts of biofuel policy, modeling efforts often present an aggregate land-use impact estimate and do not attempt to distinguish between the two. Modeling frameworks may not be spatially explicit enough to directly associate increased commodity production with specific parcels of land, so they are unable to specify whether converted land goes to feedstock production (direct impact) or to other crops displaced by feedstocks (indirect impact). As specified under EISA, both types of impacts are critical components in determining the full land-use impact of a biofuel policy, so the aggregate estimate is an appropriate indicator for a comprehensive analysis of the land-use impacts.

The aggregate land-use impact estimates shown in Table 1 vary for a number of reasons. Some of the estimates are derived using modeling structures with different ways of representing relationships and different boundaries of analysis. Furthermore, these models are often based on, or incorporate, differences in assumptions about the many variables described earlier that can affect land-use estimates. Even where a path of values over time for a particular variable has a relatively narrow band of uncertainty, researchers may make different assumptions about the year in which the estimates are derived. The year of comparison is important in determining what technologies are assumed to be in place, such as those governing crop yields and ethanol yields per unit of feedstock. The section that follows describes in more detail the specific difference among the research efforts illustrated and how they lead to varying estimates of land-use impact.

A chronology of indirect land-use change estimates

In the February 2008 issue of *Science,* Searchinger et al. (2008a) published an influential early study of the effects of biofuel production on indirect GHG emissions. That study built on the Farrell et al. (2008) premise but used a more analytically rigorous estimation method to determine the land-use impacts of using corn for ethanol in the United States. The researchers used a worldwide agricultural trade model to explore how aggregate corn acreage diverted to ethanol feedstock production in the United States would translate into increased land use in the United States and elsewhere. Using a multi-market, multi-commodity international model of agricultural markets called the FAPRI (Food and Agricultural Policy Research Institute) model, Searchinger et al. assessed the land-use change and GHG implications of increasing corn ethanol production in the United States by 14.8 billion gallons. They projected that an additional 26.7 million acres of land would be brought into crop production worldwide (1.8 million acres per billion gallons of ethanol). The impact of domestic ethanol production was transmitted into global markets largely through price and export impacts on corn, wheat, and soybeans; prices were increased by 40 percent, 20 percent and 17 percent, respectively, while exports were estimated to decline by 62 percent, 31 percent, and 28 percent.[12]

As with all such estimates, Searchinger's (2008b) land-use change estimates are highly sensitive to the set of underlying assumptions used, including:

- Historical patterns of land conversion are used to estimate land conversion probabilities internationally (Searchinger used data collected at the Woods Hole Research Center estimating the proportion of newly converted cropland coming from different forest and grassland pools in different regions of the world).
- The analysis assumed that yields would continue to rise as they have in the past, but no additional price-induced yield increases were considered. (It was assumed that the impact of such increases would be cancelled out by greater use of lower-productivity marginal lands in production).
- The analysis employs a partial-equilibrium, one-world price model to generate projections on worldwide indirect land-use change. From their model, significant, market-driven, acreage responses emerge in China and India.

When the researchers change assumptions about land productivity and conversion efficiency, the estimated magnitude of land conversion and the resulting GHG pay-back period, are significantly reduced. The authors, however, also argue that their land conversion estimates may be low, due to an assumption that conversion of grassland has no further indirect impact (as grazing cattle are pushed into forest, for instance) (Searchinger, 2008b).

The increased concern about indirect land-use issues engendered by the initial studies by Farrell and O'Hare (2008) and Searchinger et al. (2008a) led researchers to use refined or adjusted estimation procedures to address some of the criticisms of that original analysis and provide additional perspective on the complexity of the issue. Gibbs et al. (2008) use a spatially explicit data set of crop locations and yields to explore in more detail the influence of changing crop yields and advances in conversion technology on biofuels-related land conversion. Although they demonstrate that land demand can be substantially reduced with yield and technology improvements, the authors echo Searchinger's finding that when biofuel production triggers conversion of tropical forests, the estimated payback times for GHG emissions remain on the order of 30-300 years.

In a subsequent analysis of the degree to which ethanol production in the United States would drive agricultural land-use change in other countries, Keeney and Hertel (2009) also focus on the sensitivity of yield-gain assumptions, but they add a consideration of bilateral trade patterns into their estimates of global supply response. This analysis uses a modified version of GTAP—a CGE model that considers production, consumption and trade of goods and services by region and globally across multiple sectors. Over the past

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[12] Searchinger et al. (2008a) calculated that the land-use change associated with corn-based ethanol has a carbon impact in the range of 103 gCO_2eq/MJ. These emissions alone were larger than the estimated emissions from gasoline (92 gCO_2eq/MJ). In contrast, when emissions from land-use change were not included in the estimate of GHG content, corn-starch based ethanol reduced GHG emissions by 20 percent compared to gasoline.

several years, a team of researchers at Purdue University has refined and updated the GTAP model on an ongoing basis to support analysis of land-use change in response to biofuels policy. To capture the competition for land between land-use sectors, the GTAP model was augmented with a land-use module (GTAP-AEZ) that models the expansion of cropland and its distribution among different agricultural activities based on the price elasticity of yield and the ratio of productivities of marginal and average lands (Tyner et al., 2009). Other model modifications provided further refinement of the energy sector, including the three major biofuels (corn ethanol, sugarcane ethanol and biodiesel) and energy sector demand and supply elasticities that have been re-estimated and calibrated to 2006 data (Beckman and Hertel, 2009)

Keeney and Hertel (2009) conclude that assumptions about the responsiveness of U.S. yields to price are critical in determining the magnitude of acreage conversion in the rest of the world (ROW); when yields do not respond to price (as assumed by Searchinger), ROW acreage conversions are much higher. Using a range of yield elasticities that they describe as "plausible" based on past work and current agricultural conditions, they find that after 5 years, nearly 30 percent of the increased corn output can be met through yield increases rather than through acreage conversions with indirect repercussions. This study and several that followed have therefore concluded that yield-increasing technology plays a key role as a land substitute in analyses of the land demands of ethanol expansion. Assumptions about how/whether yields will continue to increase, and the role of biotechnology in boosting that increase, will strongly influence any estimation of future land conversion.

Keeney and Hertel (2009) also find that a consideration of bilateral trade patterns is critical in predicting patterns of acreage conversion. In a departure from the "one world price" philosophy of global response, they theorize that countries with a well-developed historical trading relationship with the U.S. are more likely to be affected, and to experience a market response, when prices and U.S. exports change (Hertel et al., 2010). Unlike the Searchinger results, which linked cropland conversion in the United States to acreage responses in Brazil, China, and India (as well as the United States), Keeney and Hertel's results project the most dramatic international acreage responses in Canada and Brazil. Because land-use policies and conversion patterns vary widely from country to country, location of acreage response can have a very important impact on associated environmental impacts of interest such as GHG emissions.

In a later study of biofuels-induced land allocation using FAPRI, Fabiosa et al. (2009) estimated that a 1 percent increase in U.S. ethanol use would result in a 0.009 percent increase in world crop area. Most of the increase in world crop area would come from an increase in world corn area as corn producers respond to projected drops in corn exports and an estimated 26 percent increase in world corn price. Brazil and South Africa would respond the most, with multipliers of 0.031 and 0.042, respectively, followed by Mexico, the United States, Thailand, and Egypt. More moderate acreage responses also would occur among other feed grains and soybeans. Based on the 10-year averages of U.S. ethanol use and world crop area taken from the 2007 FAPRI international baseline, and using the world area impact multiplier from Fabiosa et al. (2009) (0.009), the results suggest a land-use impact multiplier of 1.64 million acres per 1 billion gallons of additional ethanol use. This figure includes both the domestic and international cropland expansion expected as a result of increased ethanol production. The authors, however, add a caveat to their findings with the observation that data on the behavior of ethanol markets are limited, which makes it difficult to econometrically estimate the elasticities required by the biofuel market module. They also find their results are sensitive to the assumptions made about the ability of the livestock market to adapt to the use of DDGs in feed and the behavior of commodity stock adjustments in the short term.

Regulatory estimation efforts

The California Air Resources Board, in support of its recently adopted low carbon fuel standard, contracted with the Purdue research team to use the modified GTAP model described earlier to calculate how global patterns of land use would change globally in response to a 13.25 BGY increase in ethanol production, assuming a 2006 baseline for crop production patterns and conversion efficiency. CARB released its findings in March 2009; its results suggested each additional billion gallons of corn-starch-based ethanol would require only 726,000 acres; about 60 percent less than that suggested in Searchinger et al. (2008a).[13] Because completely different models are used to derive the results, it is difficult to directly attribute differences to specific assumptions, but Searchinger attributes some of the gap to varying assumptions about how world food demand and production would respond to increased prices (Charles, 2009). Searchinger's methodology assumed a modest response of food demand to world prices; CARB's finding of a more extreme food response buffers the land requirement impact of increased biofuel production. A more elastic food demand response, while keeping land demand low, may also exacerbate issues related to hunger and poverty (Charles, 2009).

In a parallel regulatory drive to quantify the GHG content of biofuels, the EPA integrated several models to explore the emissions from domestic and international land-use changes induced by increased renewable fuels consumption in the U.S. (See Figure 4.) For its analysis of the domestic response to biofuels production, EPA relied on the Forestry and Agriculture Sector Optimization Model (FASOM). FASOM estimated changes in domestic agricultural land use, as well as changes in domestic crop prices and crop export volumes. A parallel analysis used the integrated FAPRI models to project the responses of international agricultural markets and land use to the change in domestic activity. Because FAPRI does not address the locations and types of land that comes into production within countries, country-specific estimates of conversion types were extrapolated from Winrock estimates of land-use conversion between 2001 and 2004 derived from satellite imagery (U.S.E.P.A., 2009).

[13] Primarily as a result of this reduced acreage, CARB estimated the GHG emissions associated with land-use change were 70 percent less than those estimated by Searchinger et al. The GHG emissions due to land-use change were reduced from 104 grams of CO_2 equivalent per MJ of ethanol to 30 grams of CO_2 equivalent per MJ of ethanol.

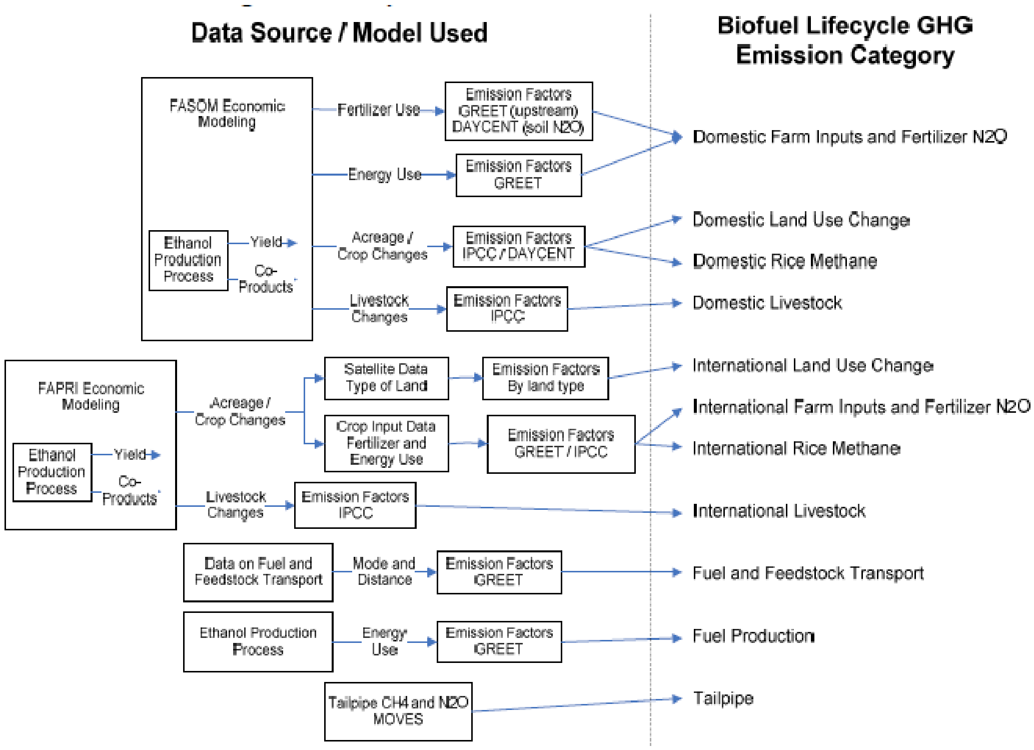

Figure 4: EPA system boundaries and models used. Source: Renewable Fuel Standard Program (RFS II) Regulatory Impact Analysis.

The EPA analysis produced two rounds of results for the domestic and international land-use changes associated with domestic biofuel production, corresponding to the proposed and final rules. The proposed rule was released in May 2009. The GHG emissions associated with international indirect land-use change were found to be a significant component of the overall GHG content of all of the biofuels analyzed; one set of results for corn ethanol is shown in Figure 5. According to these preliminary estimates, none of the corn ethanol production pathways satisfy the requirement that conventional corn ethanol reduce GHG emissions by 20 percent relative to gasoline to qualify under the Renewable Fuel Standard.

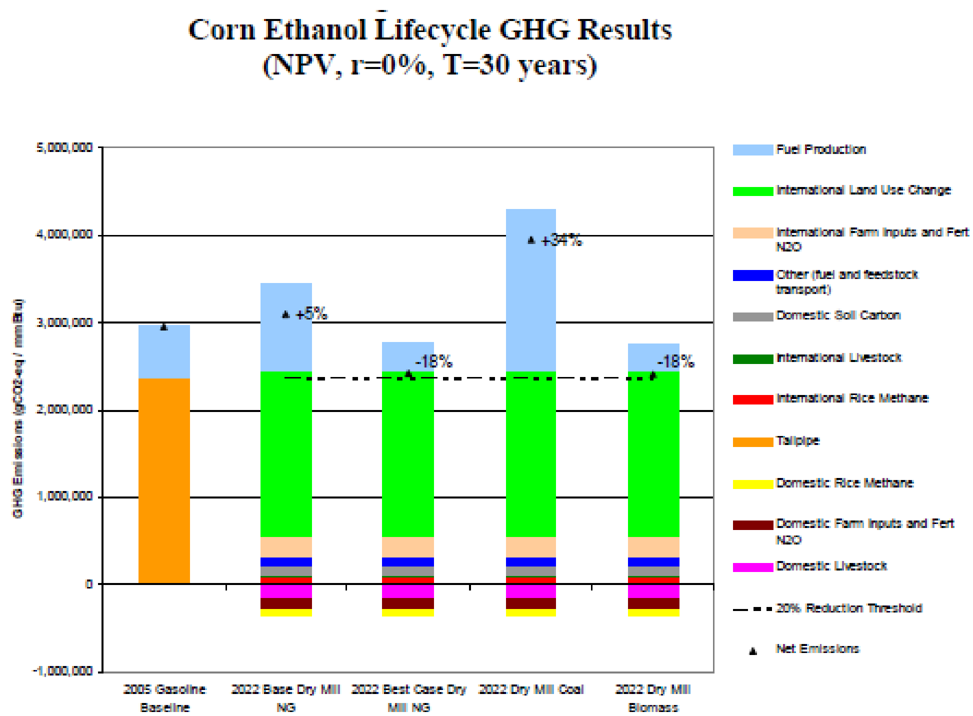

Figure 5: Corn ethanol life-cycle GHG results calculated for the 30-year, 0 percent discount rate scenario. Source: EPA Draft Regulatory Impact Analysis: Changes to Renewable Fuel Standard Program, http://www.epa.gov/otaq/renewablefuels/420d09001.pdf

Acknowledging the complexity and uncertainty inherent in deriving these numbers, EPA solicited public and expert feedback on the proposed rule throughout an extended 120-day public comment period and through use of an independent peer review process. The specific components of the methodology targeted for peer review were:

1. Land-use modeling, focusing on the use of satellite data to estimate land conversion probabilities and EPA's proposed land conversion GHG emission factors;
2. Methods to account for time in weighting GHG emissions and savings;
3. Methodology for calculating the GHG emissions from foreign crop production, including both the models and the data/assumptions used; and
4. The integration of the various models required to provide overall lifecycle GHG estimates.

A summary and compilation of the peer review results and the extensive public comments are available on the EPA website.[14] Table 2 gives a short description of the major changes between the proposed and final rules for RFS II.

In response to public and expert input during the public comment period, and to the availability of more recent data than were available during the proposed rule development, EPA made a number of changes to the assumptions and methodology

[14] http://www.epa.gov/otaq/renewablefuels/420r10003.pdf

underlying its life-cycle analysis (U.S.E.P.A., 2009). As a result, their estimates for international indirect land-use change associated with domestic biofuel production dropped from 1.692 acres per 1000 gallons of ethanol to .722 acres per 1000 gallons of ethanol.

Table 2: Updates between proposed and final rules for RFS II

Updates to domestic agricultural sector modeling

- Incorporated results from the FASOM forestry module as well as the cropland module
- Added new land classifications: cropland, cropland-pasture, rangeland, forest-pasture, forest, Conservation Reserve Program (CRP), developed land
- Updated emissions factors for N_2O and soil carbon
- Updated emissions factors for farm input production (fertilizer, etc.)

Updates to international agricultural sector modeling

- Incorporated a detailed Brazil module into the international model framework (including regional crop and pasture modeling)
- Added a factor representing price-induced yield changes
- Updated international agricultural GHG emission estimates
- Updated figures for Brazil's sugarcane production

Updates to biofuel processing in both domestic and international agricultural sector modeling

- Built in corn fractionation pathways (with coproduct markets, etc.)
- Adjusted DGS coproduct replacement rates to reflect more efficient use of DGS coproduct in livestock diets
- Added a coproduct credit for glycerin in biodiesel production
- Updated estimates of process energy use

Updates to land-use change modeling

- Used more recent and higher resolution satellite data with longer time coverage (2001-2007)
- Augmented satellite data with region-specific data where available (e.g., data from Brazil on pasture intensification)
- Used new soil carbon data
- Used new studies on long-term forest growth rates

Petroleum baseline updates

- Updated petroleum baseline to 2005

The most significant of the EPA changes that affected the magnitude and location of projected indirect land-use demand, were the inclusion of induced corn yield increases in response to corn price increases, increased substitutability of distillers' grains with existing corn and soybean meals in beef cattle and dairy cow diets (which reduces demand and land requirements for other meals), improved spatial and temporal resolution of satellite data used for investigating land conversion internationally and more detailed modeling of Brazil's agricultural sector and land-use policies, and inclusion of forest and idle cropland as potential sources of domestic agricultural land. While the new assumptions regarding DDG prospects and yield projections had a substantial impact on land demand, some researchers argue that it is still unclear whether the new projected estimates represent improvements over the estimates used in the proposed rule (Plevin, 2010).

The reduction in the land-use change estimates associated with the revised RFSII assumptions had an impact on calculations used to determine whether corn ethanol satisfies the 20 percent reduction in GHG emissions required under the Renewable Fuel Standard. The final rule results for GHG emissions from ethanol production are shown in Figure 6. According to the revised estimates, in 2022 both corn ethanol production from natural-gas-powered plants and corn ethanol production from biomass-powered plants will satisfy the 20 percent reduction in GHG emissions required by the RFS. Note the significant reduction in the contribution of GHG emissions from international land-use change.

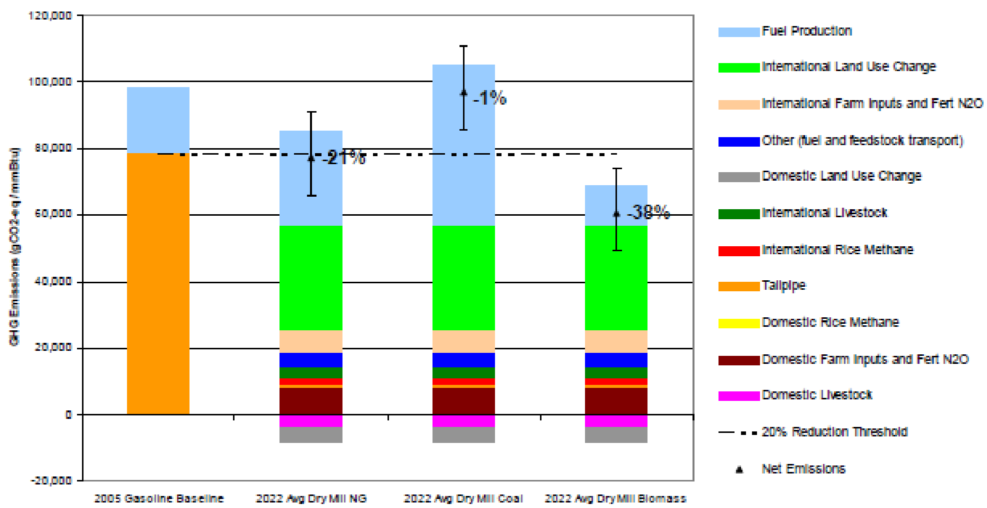

Figure 6. Results for new corn ethanol plants by fuel source and life-cycle stage for an average 2022 plant assuming 63 percent dry and 37 percent wet DDGs (with fractionation). Source: Renewable Fuel Standard (RFS II) Regulatory Impact Analysis (Final), http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

Although EPA and CARB came up with similar aggregate estimates of the indirect land-use requirements associated with domestic corn ethanol production (see Table 1), they used very different analytical structures and modeling frameworks to derive those estimates. EPA's analysis, for instance, measures the impact of biofuels policy relative to a "business as usual" case projected for the year 2022; parameter inputs, and estimated results, are assumed to reflect anticipated changes in crop yields, energy costs, and production plant efficiencies between now and 2022.[15] The CARB (2009) analysis, on the other hand, looks at land-use changes relative to a 2001 baseline year, which is the most recent year for which a complete global land-use database was available. The resulting estimates of land conversion are then corrected to account for the changes in

[15] The final year in which the RFS II renewable fuel volume mandates are phased in is 2022.

agriculture observed to occur between 2001 and present. The most significant of those adjustments captures improved corn yields, which were observed to increase by 9.5 percent between 2001 and 2009. The CARB analysis therefore represents an estimate of the biofuel impacts on land demand assuming current crop production and conversion technologies as a baseline, while the EPA analysis generates impact estimates assuming a set of anticipated future technologies as a baseline.

In addition to overarching differences in the structure of the impact analysis and the way that baselines, or business-as-usual assumptions, are defined, the two regulatory efforts used completely different modeling frameworks to quantify the land-use changes associated with biofuel production. EPA used the FASOM/FAPRI combination to evaluate land use and GHG impacts, while CARB derived its estimates using the GTAP model. To explore the robustness of its land-use estimates to modeling framework, EPA performed a series of exploratory runs using a version of GTAP that it customized to mimic as closely as possible its FASOM/FAPRI scenarios. The results of that comparison (see Figure 7) highlight some of the differences in results generated by the two modeling frameworks.

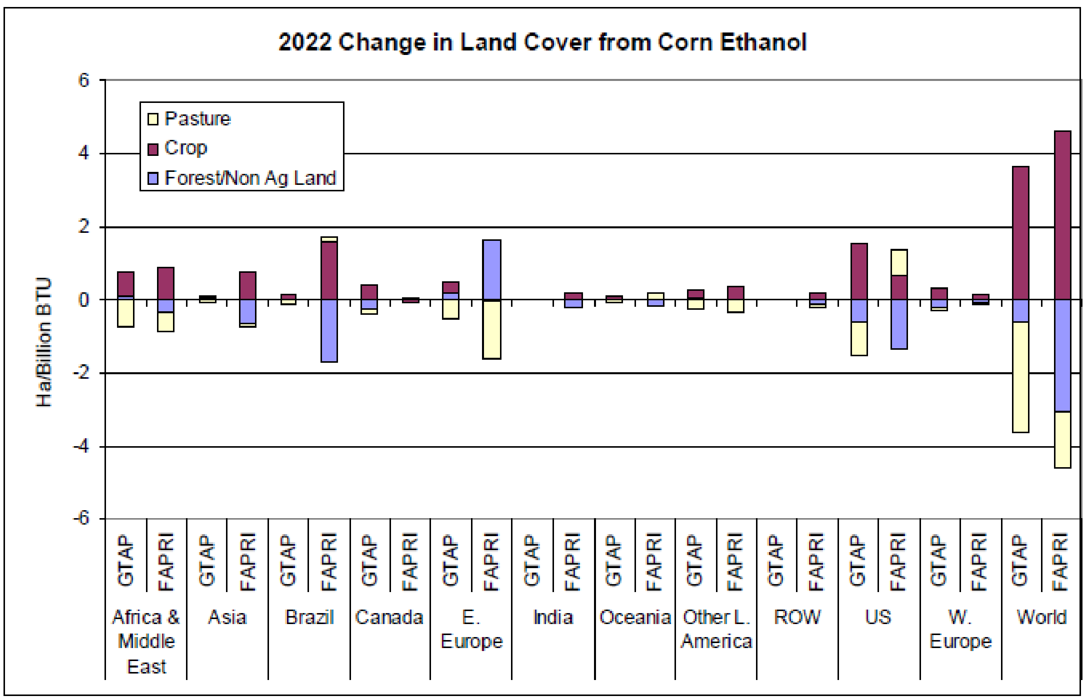

Figure 7. Changes in land cover from an increase in corn ethanol. Source: Renewable Fuel Standard (RFS II) Regulatory Impact Analysis (Final), http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

EPA's GTAP estimates suggest that, worldwide, a smaller amount of land will be converted to cropland per billion BTUs of ethanol and a greater proportion of that will come from pasture rather than forest, relative to a similar scenario derived using the FAPRI model. EPA identifies a few important factors that contribute to the difference in aggregate land demand (U.S.E.P.A., 2009):

- GTAP reflects a more optimistic assessment of the potential for intensification of agriculture as a result of higher prices, so that higher prices induced by renewable yield result in higher yields for both corn and other crops impacted by competition for land.
- GTAP is a general equilibrium model that explicitly models land demand in multiple sectors, so it captures the buffering impact on agricultural land demand that occurs when the prices of non-agricultural products rise and "push back" against the agricultural sector in its push to expand.
- The GTAP version used does not include a pool of "unmanaged" land that is available for cropland expansion. FAPRI allows land to come from a variety of sources such as grassland, savanna, shrubland, and wetlands, while GTAP assumes that all land that is not cropland or pasture is forest. If forestland is a relatively high-valued land use, that assumption could constrain the expansion of cropland acres.

The regional distribution of new cropland demand and land-cover change diverges between the two models as well. In particular, while FAPRI suggests there will be significant land-use change in Brazil, Asia, and Eastern Europe, GTAP does not. As mentioned earlier, GTAP was originally designed as a trade model, and its structure explicitly reflects historical trade relationships. GTAP results therefore have a tendency to maintain existing trade patterns and impose land-use demands on countries that have historically been major trading partners with the United States, while FAPRI results are more flexible with respect to how future trade patterns will respond to changes in global market conditions (U.S.E.P.A., 2009). Despite these differences, however, the EPA assessment of the modeling comparison concluded that "the GTAP model results were generally consistent with our FAPRI-CARD/satellite data analysis, in particular supporting the significant impact on international land use" (U.S.E.P.A., 2009).

Continuing research

Spurred by the regulatory modeling efforts, research on this topic has continued to emerge and to evolve. Hertel et al. (2010) again used the modified GTAP model to explore four market-mediated responses to increased domestic ethanol production:

1. A reduction in global food consumption;
2. An intensification of agricultural production, including increases in crop yields;
3. Land-use changes into cropping in the United States; and
4. Land conversion in the rest of the world.

To more explicitly illustrate the impacts of these critical factors, their analytical approach focused on determining the proportional influence of each of those factors on the resulting estimates of international land-use change. To isolate the land-use impacts of these individual factors, the study used an equilibrium model based on 2001 data, rather than a comparison against a forward projection of changes over time with multiple other variable forces operating on land uses simultaneously (the approach taken by EPA).

In exploring the sensitivity of their results to the factors just listed, Hertel et al. sequentially impose a series of assumptions regarding critical variables such as the yield elasticity (.25) and the relative productivity of new land brought into production (66 percent of the productivity of land currently in cropland), and calculated the impact of each additional factor on the land requirements associated with a 15 billion gallon per year increase in corn ethanol production. Figure8 illustrates the progressive effects on land demand of introducing market-mediated adjustment assumptions one at a time. The "gross" land requirement on the far left represents a case where no price or market responses are considered at all; producing corn for ethanol production requires an amount of land equal to the amount of corn required divided by the average yield. The researchers then sequentially added additional elements reflecting on particular aspects of market response and calculated the implications for land demand.

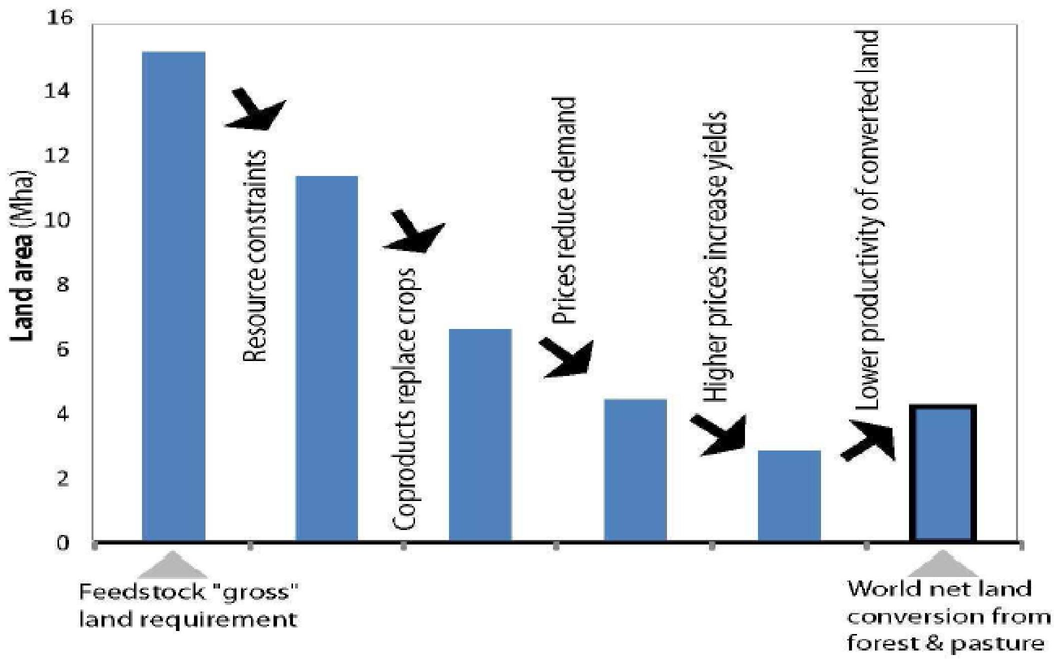

Figure 8: Estimates of indirect land-use change evolve as the scope of market-mediated impacts expands. Source: Hertel et al., 2010.

The order of the elements added into the analysis is as follows:

1. Price response arising from the introduction of constraints on the availability of suitable land, including a reduction in non-food demand and an intensification of livestock and forestry activities.
2. The ability of coproducts to substitute for feed meals and therefore reduce demand and land required for production or crops for those meals.
3. Response of world food demand to increase in prices (which is sensitive to assumptions made about price elasticity).
4. Inclusion of a yield elasticity that increases crop yields in response to price increases.
5. Assumption of a reduction in the productivity of newly converted land relative to existing cropland.

Because these factors interact in influencing land-use demand, the magnitude of impact for each factor is sensitive to the order in which market response elements are added into the analysis. Nevertheless, the figure effectively illustrates the way in which such factors contribute to the price responsiveness of supply and demand in the market and, taken together, determine the full market-mediated response to biofuels production.

When all market-mediated effects are considered, Hertel et al. (2010) found that despite a consideration of price-driven crop productivity improvements, domestic average yields of non-coarse grains and oilseeds drop as these crops are displaced from prime acreage and moved onto marginal acreage with reduced productivity. In the United States, they estimate that two-thirds of the new marginal acreage will come from forest cover, while one-third will come from pastureland. Internationally, the regions where production responds most vigorously to drops in corn exports are regions that are either significant importers of corn from the United States or that compete with U.S. corn exports in other markets, including Latin America, the EU, and China.

While much of the research in this field reports out a single figure for average land-use impact, Hertel et al. (2010) analyze in more detail how the uncertainty associated with their parameter assumptions impacts their estimates of expansion and contraction of various land uses. In the supporting documentation for their research, the authors identify the following variables and parameters as the most critical ones in driving their estimates of land-use change:

1. The response of yields to price (yield elasticity);
2. The ease with which land moves between alternative uses, including cropland, pasture, and forestry (elasticity of land transformation across uses);
3. The assumed yield from marginal lands (elasticity of effective cropland with respect to harvested cropland);
4. The response of other countries' land markets to shocks in U.S. exports and prices (trade elasticities for crops and other food products); and
5. The extent to which imports can substitute for one another when one commodity or product experiences a shock (elasticity of substitution among imports from different sectors).

Their analysis suggests that the most uncertain results are the forestry conversion estimates, particularly in areas outside of the U.S., Canada, and the EU.

Hertel et al. (2010) also vary their parametric assumptions to compute bounding values for the emissions impacts associated with their land-use change analysis. The resulting lower and upper bounds, 15 and 90 gCO2 per MJ per year, suggest that the distribution of possible land-use change values is not symmetrically distributed around the average value of 27. The tail of the distribution of possible emissions values is much longer on the side of increased emissions; in other words, if actual emissions deviate from the estimated average on the low side, they may be somewhat lower than the projection, but if they deviate on the high side, they may be significantly higher than the projection. The authors therefore conclude that, "Better understanding of skewness and long tails in an estimated distribution of the ILUC value will probably imply that an optimal value for the index assigned to a particular biofuel *will be different from* a central estimator of its ILUC effect."

The most recent estimates of biofuels-related land-use change to emerge from the Purdue research team were released in April 2010 (with revised estimates released in July 2010). Tyner et al. (2010) compare the land-use implications under three different sets of parameter assumptions:

1. An analysis of impacts relative to the 2001 database;
2. An analysis of impacts relative to a 2006 database that is calculated as having evolved from the 2001 database in a world with regional changes to GDP, gross capital formation, population, biofuel production, crop yields, and forest area; and
3. An analysis of impacts relative to the 2006 baseline but with continued growth in crop yield and population for ethanol amounts corresponding to production years beyond 2006.

The land conversion requirements drop sequentially as the authors move through the scenarios, largely due to the impacts of changes in assumptions about crop yields. Scenario 2 reflects observed increases in crop yields over the period 2001-2006, while scenario 3 further assumes an annual 1 percent increase in crop yields for all crops in all regions beyond 2006. The reduced land requirements in scenario 3 reflect a set of underlying parameter assumptions that result in land-saving yield impacts dominating the increased land demand associated with increased food demand and a growing population. These results, of course, are sensitive to the underlying assumptions; there may be some debate, for instance, about whether it is reasonable to expect a 1 percent annual increase in crop yields for all crops in all regions.

The land-use change requirements results for scenario 3 are shown in Table 1; 1000 gallons of ethanol production requires an average of .32 acres of additional land. The land requirements for biofuel production are significantly lower than those found in other studies, including those performed using GTAP. The authors describe two recent modifications to the model that contribute to this reduction (Tyner et al., 2010). The first is the introduction of two new land categories into GTAP's available land pools: cropland pasture and unused cropland, including acreage enrolled in the CRP. Land brought into production from these land pools is not considered "land conversion," so using these lands reduces the amount of forest or grassland that must be converted. The second modification increased the refinement with which the productivity of marginal lands is considered in the model. In prior GTAP analyses, newly converted land is generally assumed to have 66 percent of the productivity of existing cropland. The revised model, however, uses a process-based biophysical simulation model to calculate a set of regional productivity factors at the agro-ecological zone (AEZ) level, some of which are larger than 66 percent. Over the three scenarios, the authors find that the fraction of land-use change that occurs in the United States varies between 24 and 34 percent, while the percentage of new cropland that comes from forest ranges between 25 and 33 percent.

In the summer of 2010, the European Commission's Joint Research Centre published a series of consultation documents that had been contracted to inform decisions on how indirect land use effects should be handled in implementation of the EU Renewable Energy and Fuel Quality Directives (RED/FQD). One of those documents—"Indirect Land Use Change from increased biofuels demand: Comparison of models and results for marginal biofuels production from different feedstocks"—describes the extensive modeling effort conducted, some scenarios of which looked at the impacts of U.S.

grain-based ethanol production (Edwards et al., 2010). This effort employed a range of models; some of the results of the EU analysis for U.S.-based ethanol production from maize or coarse grains are shown in Table 1.

An indepth description of the EU modeling effort, and an explanation of the results, can be found in the source document listed above. However, the report highlights the following reasons for the discrepancies between model results:

- The IFRPI-IMPACT model assumes a large price-induced yield gain across crops, which results in relatively low area changes.
- GTAP assumes significant contributions from price-induced yield gains as well, but that effect is countered by the fact that GTAP assumes lower yields for crops produced on newly converted production areas.
- Three of the models employ some type of Armington trade assumptions (GTAP, LEITAP and AGLINK) to introduce "stickiness" into the global trade response to represent transport costs, import tariffs and regulations, and information flows. This stickiness affects the extent to which crop production can be shifted to developing countries, in comparison to the integrated world market assumed by IMPACT.
- LEITAP does not account for byproduct effects, which increases land-use impacts relative to the other models.
- Significant differences exist among the models in how they calculate the area change required for an increase in crop production. Only GTAP, for instance, calculates the incremental area required based on an assumed marginal/average yield ratio (.66) that accounts for the fact that crop areas are expanding onto marginal lands with the potential for lower yields.
- Significant differences exist in the extent to which food demand declines as prices rise. LEITAP assumes very little food demand response, while the land-use change impacts predicted by both IMPACT and GTAP drop by more than 50% when their food demand response assumptions are implemented.

The EU modeling effort illustrates the spectrum of potential sources of variability and uncertainty across models and parameter assumptions. While the land-use impact estimates derived reflect this variability, all of the estimates across models, feedstocks, and type of biofuel, show significant increases in land-use requirements for crops resulting from scaled-up biofuel demand (Edwards et al., 2010).

VI. Summary and Future Research Needs

The increase of biofuel production to reduce energy dependence on fossil fuels led to concerns about unintended consequences of that activity. In particular, life-cycle analyses that accounted for greenhouse gas emissions identified the importance of considering the underlying land-use changes that might be associated with increased feedstock production. Estimating these changes, however, has been a daunting task. Mathematical models are used to indicate numerically how the aggregate behavior will change due to new conditions or policies, and they serve as a proxy for what cannot be directly observed. However, no single model currently exists that can address all of the questions related to this issue.

Uncertainty is an unavoidable aspect of policy impact modeling that makes projections into the future. There are many drivers of land-use change in the U.S. and internationally that exist regardless of biofuel policy. The assumptions embedded within the different models estimating land-use change will affect model results. In the past few years, the analytic approaches used in these studies have been expanded and the underlying assumptions have been made more transparent. Many of the differences in model estimates can be traced to differences in assumptions about:

- Crop yields and the projected elasticity of response to demand-driven price increases;
- The baseline that is used from which to measure change;
- The anticipated productivity of newly converted land and the amount of land required to meet increased production demands by region;
- The structure and flexibility of trade flows;
- The price elasticity of demand for agricultural food and feed products;
- The scope of the life-cycle assessment–including, for instance, whether the livestock and forest sectors are explicitly modeled as competitors for land.

Managing uncertainty in the context of modeling indirect land-use change has involved:

- Identifying the variables that are particularly important in contributing to the uncertainty of estimates and improving the precision with which such variables are represented with the analysis (e.g., future crop yields, the productivity of newly converted lands, and the substitutability of DDGs in livestock diets);
- Identifying relevant relationships that require more refined analysis (such as the importance of trade relations in determining likely sources of increased agricultural production);
- Understanding the nature of the remaining uncertainty, its effects on the distribution of potential outcomes, and the implications of incorporating different measures of that uncertainty into policy;
- Designing policy to ensure that existing regulations evolve as the science becomes more sophisticated.

Both EPA and CARB call for regular examination and updating of the indirect land-use impacts component of the GHG quantification methodology. EPA includes in its final rule the following stipulation: “EPA will request that the National Academy of Sciences evaluate the approach taken in this rule, the underlying science of life-cycle assessment, and in particular indirect land-use change, and make recommendations for subsequent lifecycle GHG assessments on this subject” (EPA, 2010). The CARB resolution also states, "… that the Board directs the Executive Officer to convene an expert workgroup to assist the Board in refining and improving the land use and indirect effect analysis of transportation fuels and return to the Board no later than January 1, 2011 with regulatory amendments or recommendations, if appropriate, on approaches to address issues identified” (CARB, 2009).

Establishing such mechanisms for continuous refinement is a critical element of policy design in this area. The science underpinning these regulations is an evolving discipline, and the estimates derived from it will continue to improve, as will the policy mechanisms established to handle ongoing uncertainty. Additional research on variables that have been identified as critical drivers in determining the land-use impacts of biofuels policy also will be instrumental in refining modeling capacity and estimates in this area. Research and data that can facilitate greater understanding of critical dynamics in land-use impact modeling includes:

- Improved data on land use and land cover change worldwide;
- Improved data on the extent and productivity of existing and potential cropland worldwide, including previously cleared, “degraded,” or underutilized lands;
- Greater understanding of and ability to model prospective growth in crop demand and supply by region worldwide. This includes refined analysis of development and adoption of crop productivity technologies such as biotechnology as well as impacts of income, population growth, and dietary transitions;
- Improved modeling and parameter estimates around the substitutability of biofuel coproducts in other markets, such as livestock feed markets.

Future research that addresses more explicitly the sources and magnitude of this uncertainty will be particularly useful in informing policy design. Hertel et al. (2010) set a precedent for this by highlighting the need for performing and reporting more extensive sensitivity analysis in research on land-use impacts. These authors state that a more explicit treatment of sensitivity and distributions of possible outcomes is also needed to inform a more sophisticated treatment of uncertainty within policy design itself. They suggest that central estimators such as average or median values may not be the most appropriate values to assign to land-use change or emissions estimates in cases where highly asymmetrical distributions of possible outcomes exist (Hertel et al. 2010). Further research on alternative estimators or alternative methods of capturing distributions within a policy indicator, together with research on how those methods correspond to particular attitudes toward risk and risk management, may lead to a critical development in the appropriate incorporation of inherently uncertain estimates into policy such as that related to biofuels and land-use change.

As the science of projecting land-use change evolves, USDA has an important role to play both in supporting ongoing EPA efforts and in developing additional research capacity for exploring the critical variables determining the direct and indirect land-use impacts of domestic agricultural production and the way they play out through domestic and global market interactions. Existing ERS research corroborates the upwards pressure that biofuel production puts on commodity prices and land demand (Malcolm et al. 2009) and the sensitivity of domestic bioenergy's economic and welfare impacts to uncertain projected responses within world energy markets (Gehlar et al. 2010).

In an ongoing effort to integrate more sophisticated land allocation considerations into its analyses of bioenergy production, USDA's Economic Research Service is expanding two in-house agricultural models to more explicitly represent the critical variables driving the relationship between land use and biofuels and to differentiate among potential pools of land for production. The Regional Environment and Agriculture Programming Model, a detailed domestic partial equilibrium model of cropland and livestock agriculture, is being expanded to include a forestry component and a more sophisticated treatment of competition for land and conversion among uses. The Future Agricultural Resources Model, a global general equilibrium model that was a pioneer in the movement to partition land as an economic input into different land classes, is being retooled to accommodate a dynamic forestry sector, to explicitly track energy technologies and energy accounting, and to allow for cellulosic conversion technologies that create biofuels from feedstocks such as crop residue, switchgrass, or fast-growing trees.

ERS models without explicit land-use analysis capacity are also being modified to support research related to trade and market response to biofuels production that can then be used to inform future land-use analyses. The U.S. Applied General Equilibrium (USAGE) Model includes more than 20 major importing and exporting trade partners and the data are being updated to capture the supply response of the farm sector to address bioenergy-related issues. The Partial Equilibrium Agricultural Trade Simulator (PEATSim) is being enhanced to include more domestic and international policies affecting major crop and oilseed markets, as well as oilseed product markets, sugar, livestock, and dairy.

Continued research and modeling efforts will be required to narrow the bands of uncertainty associated with projections of land-use change and domestic policy. New models, model refinements, and improved data will all help increase the precision with which input parameters are estimated and behavioral relationships are represented. Still, the successful integration of science and policy must come with the recognition that future projections will always carry some degree of uncertainty suggesting that policy design must accommodate uncertainty. As research moves forward, an explicit focus on the nature and structure of input and output uncertainty, and on the full distributions of possible outcomes and estimates that result, will facilitate improvements to policy design over time.

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Glossary of Acronyms

AEO	Annual Energy Outlook
AEZ	Agro-Ecological Zone
CARB	California Air Resources Board
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
CRP	Conservation Reserve Program
DDGs	Distillers' Dried Grains
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EPA	U.S. Environmental Protection Agency
EPACT	Energy Policy Act of 2005
ERS	USDA Economic Research Service
FAIR	Federal Agriculture Improvement and Reform
FARM	Future Agricultural Resources Model
FAPRI	Food and Agricultural Policy Research Institute
FASOM	Forestry and Agricultural Sector Optimization Model
GHG	Greenhouse Gas
GTAP	Global Trade Analysis Project
ILUC	Indirect Land Use Change
IMAGE	Integrated Model to Assess the Global Environment
LCA	Life-Cycle Analysis
LCFS	Low Carbon Fuel Standard
MJ	Megajoule
PE	Partial Equilibrium
PEATSIM	Partial Equilibrium Agricultural Trade Simulator
REAP	Regional Environmental and Agricultural Production
RIA	Regulatory Impact Analysis
RFS	Renewable Fuel Standard
RFS II	Renewable Fuel Standard - 2009
ROW	Rest of World
RTFO	Renewable Transport Fuel Obligation
USAGE	U.S. Applied General Equilibrium
USDA	U.S. Department of Agriculture