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STUDY OF TRANSPORTATION FUEL LIFE CYCLE ANALYSIS: REVIEW OF ECONOMIC MODELS USED TO ASSESS LAND USE EFFECTS

July 2014

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Study of Transportation Fuel Life Cycle Analysis: Review of Economic Models Used to Assess Land Use Effects

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Terms and Abbreviations

AEZ............................Agro Economic Zone
ARB ....California Air Resources Board
ASM...........................Agricultural Sector Model
AREACHANGE........Area Change Model
ATLAS.......................Aggregate Timberland Assessment System
Btu..............................British thermal unit
bu................................Bushel
CA ....California
CAPRI........................Common Agricultural Policy Regionalised Impact Modelling System
CARD ....Center for Agricultural and Rural Development
CEPII..........................Centre D'Etudes Prospectives et D'Informations Internationals
CES ....Constant Elasticity of Substitution
CET ....Constant Elasticity of Transformation
CGE............................Computational General Equilibrium
CI................................Carbon Intensity
COSIMO ....COmmodity Simulation Model, AGLINK-COSIMO
CRP ....Conservation Reserve Program
CRC............................Coordinating Research Council
CNFAP.......................Center for National Food and Agricultural Policy
DDGS.........................Dried Distillers' Grains and Solubles
DGS............................Distillers' Grains and Solubles
Denatured...................Fuel denatured with gasoline
EISA...........................Energy Information and Security Act
EPA ............................U.S. Environmental Protection Agency
ETA............................Elasticity, an economic concept
EU ....European Union
FASOM......................Forest and Agricultural Sector Optimization Model
FAPRI ....Food and Agricultural Policy Research Institute
FAO............................Food and Agricultural Organization
FORCARB.................Forestry Carbon
GATT ....General Agreement on Tariffs and Trade
GDP............................Gross Domestic Product
GIS ....Geographic Information Systems
GTAP ....Global Trade and Analysis Project
GHG...........................Greenhouse gas
GREET.......................Greenhouse gas, Regulated Emissions and Energy Use
in Transportation (Argonne National Laboratory's well-to-wheels model)
GWP...........................Global warming potential
ha................................Hectare
IFPRI..........................International Food Policy Research Institute
IMPACT ....International Model for Policy Analysis of Agricultural Commodities and Trade

ILUC ....Indirect Land Use Change
IPCC...........................Intergovernmental Panel on Climate Change
J ....Joule
JRC.............................European Union Joint Research Center
kg................................Kilogram
lb ....Pound
LCA............................Life cycle assessment
LCFS ....Low Carbon Fuel Standard
LCI ....Life cycle inventory
LCM ....Life Cycle Module
LEITAP......................European derivative of GTAP
LHV ....Lower heating value
LUC............................Land Use Change
MAPS.........................Mapping of Agricultural Production Systems
MDT...........................million dry tons
MGY ....million gallons per year
MIRAGE....................Modeling International Relationships in Applied General Equilbrium
MJ ....Mega joule
ml ....milliliters
mmBtu........................Million Btu
NAPAP ....North American Pulp and Paper
NG..............................Natural gas
NREL ....National Renewable Energy Laboratory
OSB............................Oriented Strand Board
PS&D ....USDA Production, Supply & Distribution
RBOB.........................Reformulated gasoline blendstock for oxygen blending
RED............................European Union Renewable Energy Directive
RFG ....Reformulated gasoline
RFS ....Renewable Fuel Standard (U.S.)
RPA............................Resources Planning Act
SOC............................Soil organic carbon
t/ha..............................metric tonne per hectare
TAMM ....Timber Assessment Market Model
TEM ....Terrestrial Ecosystem Model
TTW...........................Tank-to-wheels
ULSD ....Ultra low sulfur diesel
UN..............................United Nations
USDA.........................U.S. Department of Agriculture
U.S. ....United States
WTO ....World Trade Organization
WTT...........................Well-to-tank
WTW..........................Well-to-wheels
WHRC........................Woods Hole Research Center
YDEL.........................Price/yield elasticity

Executive Summary

Life cycle assessments (LCA) have examined the energy inputs and greenhouse gas (GHG) emissions associated with transportation fuels since the 1980s. Estimates of the CO_2 release from land use change (LUC) associated with biofuel crop production have only recently been incorporated into policy and the broader scientific literature. Agro-economic modeling systems were improved and configured to assess the effect of changes in the agricultural policies, e.g., biofuel production, on land use change and GHG emissions. Those models are used by regulators to assess the impacts of biofuel policies on global agriculture. The objective of this study is to provide an assessment of the key factors going into LUC analysis and how those factors affect the prediction of land use change.

The four leading models used in biofuels policy were reviewed and key inputs for LUC were compared. The four models are:

1. **F**orest and **A**gricultural **S**ector **O**ptimization **M**odel (FASOM)
2. **F**ood and **A**gricultural **P**olicy **R**esearch **I**nstitute (FAPRI) model
3. **G**lobal **T**rade **A**nalysis **P**roject (GTAP)
4. **M**odeling **I**nternational **R**elationships in **A**pplied **G**eneral **E**quilbrium (MIRAGE BioFuel (BioF)) model

The MIRAGE BioF model is a recent adaptation of the GTAP database used by the European Union. The identified drivers for the estimation of land use change are crop yield (price induced yield vs. yield projections), shifting of crop production, and demand mediating effects (e.g., the demand for beef decreases with an increase in beef prices). In addition, the cumulative effect of different biofuels and biofuel policies, petroleum prices (via additional biofuel demand), and global growth affect the overall demand for agricultural commodities.

LUC Models

LUC is an important element of a biofuel's life cycle impact. It includes the direct emissions associated with agricultural land used for biofuel feedstock production and indirect emissions associated with land use change induced by a change in the economic environment. LUC models have been used for decades to assess national GHG inventories but had to be adapted to examine the impact of expanded biofuel use. Table S.1 shows LUC models that have been used by regulators in biofuel policy. Besides informing policy makers, the models are also used for academic research and are continuously improved.

There are differences in the economic modeling and carbon stock accounting among the different models. Each model calculates the expected LUC due to shocks such as biofuel policies and the resulting demand for biofuel. In GTAP and MIRAGE the shock is achieved by adjusting a hypothetical subsidy until the model predicts the desired biofuel volume. In FASOM the shock is calculated from the feedstock needed to achieve a given biofuel volume. FAPRI assesses the biofuel volume based on biofuel policies and macroeconomic variables such as the crude oil price.

Table S.1. Key Inputs to ILUC.

Model Attribute	GTAP-BIO	FASOM	FAPRI	MIRAGE-BioF
Application	CA LCFS	EPA RFS2 U.S. LUC	EPA RFS2 Outside U.S. LUC	EU RED
General vs. Partial	General	Partial: U.S. Forestry and Agriculture	Partial: Agriculture Sector	General
Geographic Coverage	World by AEZ	United States by county	World by political borders	World by AEZ (14 Regions)
Co-product Treatment for Grain Ethanol DGS	1:1 Substitute DGS for corn	Detailed feed substitution ratios for number crops	Substitution ratios same as GREET model, mix of corn and soybean meal	Detailed substitution options based on multiple feed products
Land Cover Types	Cropland, forest, pasture. Cropland-Pasture included for U.S. and Brazil only.	Cropland, Cropland-Pasture, Forest-Pasture, Rangeland, Forest, Developed, CRP	Cropland, Pasture, Forest, Barren	Cropland, Managed Forest, Pasture
Economic Sectors	57 Economic Sectors	Agriculture, Forestry	Agriculture, Biofuels, Livestock, Dairy	55 Economic Sectors
Static vs. Dynamic (single-year estimate vs. time-series estimates)	Both static and dynamic versions of GTAP exist, but the comparative static model is used more for biofuels work.	Dynamic	Dynamic	Dynamic
Trade Assumptions	Armington Elasticities	Homogeneous Goods	Homogeneous Goods	Armington Elasticities
Time Frame	2004 Database with elasticities calibrated for medium term	Projects up to 100 years with solutions every 5 years	10-15 years	2004 Database with elasticities calibrated for 2020 timeframe (RED)

All agro-economic models solve for prices that result in a supply and demand equilibrium. GTAP and MIRAGE are so-called general equilibrium models that include all sectors of the economy. FASOM and FAPRI are models including only agriculture and, in the case of FASOM, forestry. Those models are more detailed on individual agricultural commodities. GTAP, FASOM, and MIRAGE constrain the model with a limited supply of land. FAPRI is not configured with the same land limitations, although analysts that perform FAPRI runs are aware of global land availability and verify that the model does not project land use beyond the limitations of available land. All of the models project changes in land cover and predict changes in carbon stock through different carbon accounting mechanisms and carbon stock data sets. Prior Coordinating Research Council (CRC) studies have examined the sources of carbon stock data in these models.

Figure S.1 shows many of the factors affecting LUC. A first order approach to estimating LUC is to calculate the land cover required to grow a crop. Basic estimates of LUC might multiply this LUC by an assumed change in carbon stocks (such as grassland to crops) but this approximation would be inaccurate for a variety of reasons. First, biofuel production also produces co-products which replace other crops, thereby reducing LUC. Second, the type of land that is converted for new crop production is not easily determined or even modeled. Shifts in agricultural activity affect crops globally, and many new sources of land can be used to grow crops. Categories used in LUC modeling include grassland, pasture, fallow land, and forest. The changes in carbon for each land cover type differ, thus some variant of LUC modeling is necessary to predict GHG emissions associated with biofuel production.

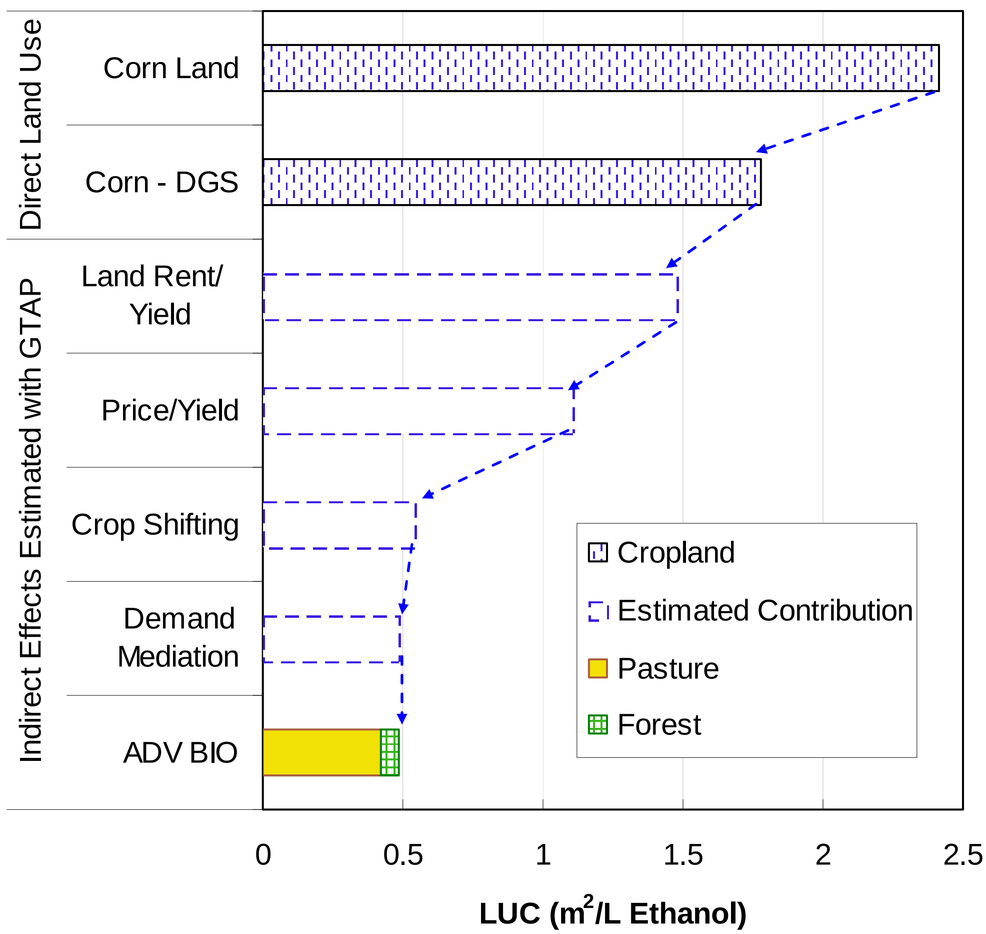

Figure S.1. Contribution of Modeling Inputs for Corn Ethanol (Rough Approximation).

LUC models also predict changing yields, both to the biofuel crop being examined as well as other crops grown globally. These yield improvements include both projected future improvements due to better farming practices (some of which may have nothing to do with an expansion in biofuels), as well as yield improvements that are due to higher prices sending a signal to the market to incentivize better farming practices, more efficient harvest, and technology improvements. An expanded use of crops for biofuels will also affect feed prices and shift the use of agricultural commodities. Certainly the production of distiller's grains with solubles (DGS) from corn ethanol production will affect feed markets. The removal of land from feed production will also cause shifts due to price mediation. Higher corn prices for example, could result in a shift from feedlot fed cattle to other sources of meat that are less feed intensive. These predicted shifts in crop usage may be the most significant factor in Figure S.1. Demand mediation, or a reduction in the demand for feed and food also reduces the overall requirement for land. Another key LUC prediction is associated with cattle stocking rates on pasture as well as the selection of forest land, marginal land or grass land. These predictions affect the carbon stock factor for LUC. Note that Figure S.1 is a notional diagram based on approximations from the input parameters.

The second phase of this project will calculate the relative contributions from leading LUC models. GTAP model runs are relatively straightforward and all of these factors can be examined with model runs. The relative contribution from other models can be assessed by examining sensitivity analyses.

Recommendations for Improving LUC Modeling

The largest uncertainties in LUC analysis are associated with the prediction of yield, especially on new and marginal land as well as the selection of land cover type. The shifting among agricultural commodities further complicates the analysis and adds a level of opacity to the modeling. Table S.2 summarizes recommendations that would improve agro economic modeling.

Table S.2. Key Data Gaps in LUC Modeling.

Data Gap	Recommendation
Transparency	• Perform Modeling Runs to Isolate Key Variables
Land cover selection and model enhancements	• Find a mechanism to add cropland pasture for areas other than U.S., Brazil to GTAP • Fallow land should be more readily accessed in GTAP • Enhance GTAP for Flexibility and Dynamic Modeling
Model validation	• Examine U.S. and global historical data
Co-products	• Improve modeling of co-products on LUC • Evaluate protein trends in developed nations • Develop approach for land cover selection in FAPRI

1. Introduction

1.1 Land Use Conversion

Many biofuel policies being adopted around the world require that any biofuel must meet specific greenhouse gas (GHG) reduction targets relative to the conventional fuels they replace. The GHG reduction is measured through life cycle assessments (LCA), which include all cradle-to-grave emissions flows (and/or other environmental impacts), starting with raw material extraction and ending with fuel consumption. The net GHG emissions are converted to a CO_2-equivalent basis and then normalized by the energy content of the fuel (e.g. CO_2e/MJ). This carbon intensity (CI) can then easily be compared amongst different fuels to assess the relative GHG emissions per unit energy.

LCAs require numerous inputs and assumptions, and are fraught with uncertainties. In particular, one area of great uncertainty and controversy is that of land use change / land use conversion (LUC). LUC occurs as land patterns are shifted from one use to another, for example, for urbanization or expansion of agriculture. Depending on the location and type of land converted, significant GHG emissions may result. There is growing concern about the effects that LUC can have on a biofuel's carbon intensity. As the demand for biofuels increase in response to fuel volume targets outlined in specific biofuel policies, more and more agricultural lands will be required. This demand may have either a direct or indirect effect on LUC. Land use can be shifted directly into biofuel crop production, or indirectly through market responses to supply and demand changes of biofuel crops and other related agricultural commodities. Resulting price fluctuations may incentivize these indirect land use changes elsewhere.

Distinguishing between indirect and direct LUC is challenging since some technologies use feedstocks that are procured from common sources such as grain elevators, while other technologies use a more dedicated source of feedstock. In all cases, the use of arable land affects the carbon flux on that land and the effect of feedstock usage globally. Thus, this report utilizes the term LUC to refer to either direct or indirect LUC. There is growing concern about the accuracy of biofuel-induced LUC emission estimates, due to the difficulties in measuring their direct relationship to increased biofuel production and use, their potentially significant impacts, and the uncertainties surrounding modeling practices.

Searchinger et al. (2008) was one of the first to introduce the concept of LUC, demonstrating severe impacts on the overall carbon intensity of biofuels. Although there is much disagreement on LUC modeling practices and results, many argue that LUC likely has a non-zero impact and should not be ignored. Regardless of the debate, regulators are developing biofuel policies that include the effects of LUC along with traditional LCA approaches: the U.S. Renewable Fuel Standard (RFS2) and California's Low Carbon Fuel Standard (LCFS) include its effects, while the European Commission is working to understand the issues to include LUC in their Renewable Energy Directive.

Because the correlation between LUC and its link to biofuel expansion cannot always be directly measured, it must be modeled. In the previous CRC E-88-2 project (Broch 2011), the modeling approaches to estimating the effects of LUC on biofuel carbon intensity (CI) were investigated.

The approach often involves linking economic models that simulate market behavior (particularly those in the agricultural sector) to predict the quantity and location of LUC with carbon stock and emission factor databases to determine net GHG emissions as illustrated in Figure 1.1

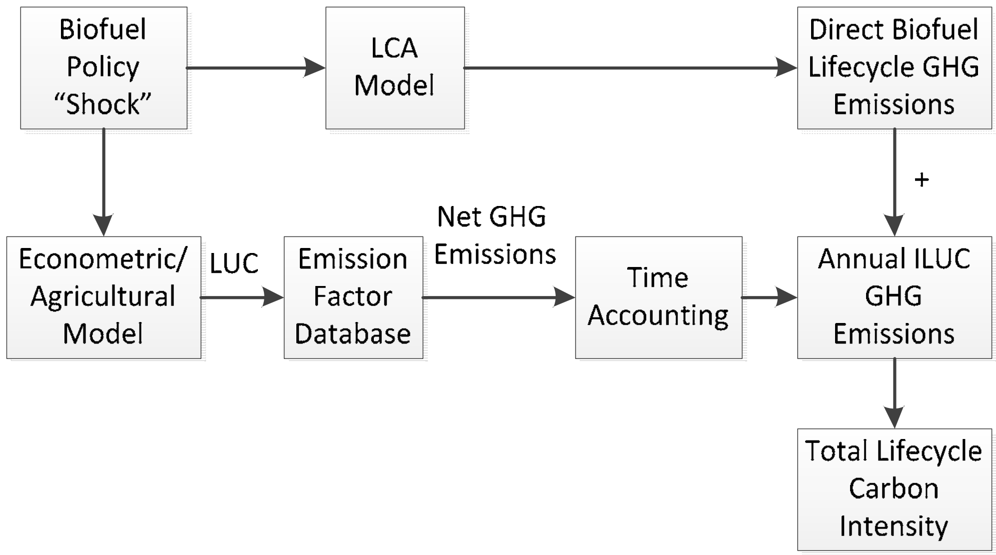

Figure 1.1. Modeling flow for determination of total biofuel lifecycle carbon intensity, including both direct and indirect effects.

Within the econometric model (in these cases, agro-economic models are used specifically for the agricultural sector), the volumetric requirement of the biofuel policy, along with other key input parameters to relate economic market and price fluctuations are used to predict the amount, location, and type of LUC. This information is used in conjunction with an emission factor database to estimate the associated GHG emissions. Emission factor databases provide estimates of the carbon stock contained within vegetation and soils within different ecosystems and regions that can be released as soils are disturbed and vegetation is removed.

1.2 Existing Estimates of LUC Emissions

Estimates of quantity and location of LUC resulting from U.S. and E.U. biofuel policy are illustrated in Figure 1.2. The figure highlights the variability in location and amount of land use change estimated, depending on the modeling approach and other assumptions. Studies not explicitly providing regional breakdowns are shown as "rest of world". The total LUC is typically estimated by an agro-economic model. Many key assumptions such as crop yield, price elasticity, and land transformation coefficients are parameters of the economic model itself, and were not investigated in detail in the previous CRC E-88-2 study. These parameters will be the subject of this follow-on study.

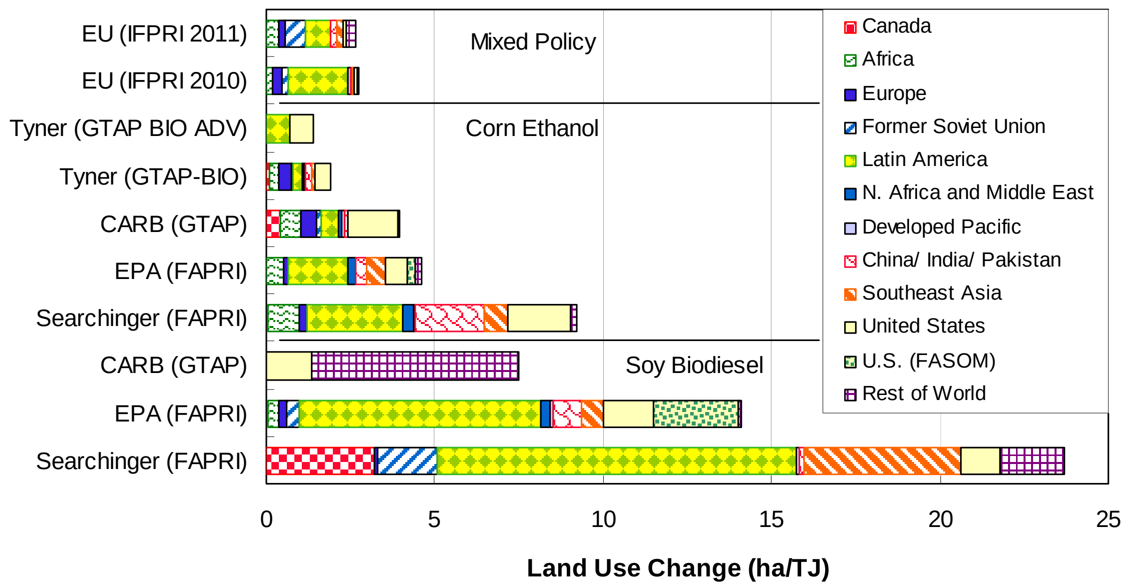

Figure 1.2. LUC model results for various models and biofuel scenarios (ha/TerraJoule).

The agro-economic models predict location and quantity of land converted as well as land cover type (e.g., forest land, pasture, fallow, etc.) These estimates are combined with carbon stock datasets such as Winrock or Woods Hole Research Center (WHRC) to arrive at LUC carbon intensity (CI) values. LUC CI estimates corresponding to the area/location estimates in Figure 1.2 are provided in Figure 1.3. The figure illustrates that even when applying the same emission factor database, very different assumptions can be applied to produce differing results. For example, the WHRC emission factor database is applied in several of the illustrated studies, with extremely differing results. Additionally, even updates to similar studies by the same authors (e.g., the International Food Policy Research Institute (IPFRI) analyses) can produce dramatically different results. This is primarily driven by land cover type assumptions in the economic models.

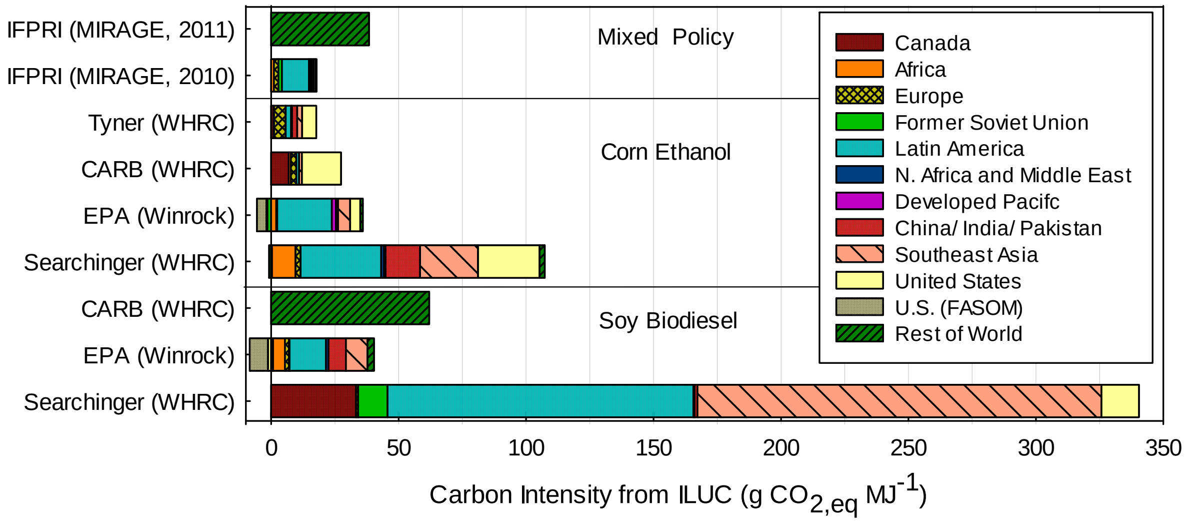

Figure 1.3. Carbon Intensity from LUC for various models and biofuel scenarios.

1.3 Report Organization

The issue of biofuel-related LUC remains uncertain. Many studies have attempted to demystify the analyses (Edwards, Broch, Tyner); however, the core modeling drivers are difficult to grasp, especially for non-economists. This study attempts to explain how the various agro-economic models work, identifies the key drivers impacting results, and recommends future areas of work to improve the art of LUC modeling. The study team consists of experts in the main LUC models currently utilized to support fuel policy. The results are provided in the following sections:

2. Economic Modeling Primer
3. LUC Models
4. Identification of Key Modeling Drivers
5. Recommendations

An effort to quantify the impact of the key modeling drivers by re-running the models will be completed when authorized.

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2. Economic Modeling Primer

Environmental policymakers and alternative fuel producers generally have expertise in energy and emissions engineering, but only basic knowledge of economic theory. The rise of biofuels and resulting concerns about indirect land use change have required the use of computational economic models. This section of the report is intended to be a primer on economic modeling. The first section lays out the economic concepts underpinning all economic modeling. The second section describes special considerations for economic modeling of land use.

2.1 Basics of Economic Modeling

Economic models are an abstract representation of reality and focus only on the variables and aspects that are necessary for economic analysis. There are uncountable economic variables, consumers, and producers that interact in complex ways. To model all these interactions is impossible and thus, economists identify the most important variables and incorporate them in models. Standard economic models rely on a set of assumptions that are universal and make predictions of economic behavior possible. The key assumptions of economic modeling are utility maximization of the consumer and profit maximization of the producer.

2.1.1 Utility and Profit Maximization

A fundamental requirement of economic modeling is that agents will always act to maximize utility and profit. Economists use the abstract concept of "utility" to describe the "happiness" or "satisfaction" derived from consuming goods. Maximization of utility means that the consumer will maximize the value derived from consuming goods given his available income; the consumer will purchase a bundle of goods that gives the highest utility given his or her budget constraint. However, there is also the concept of decreasing marginal utility, i.e., happiness/satisfaction increases with an additional unit consumed of a good but at a decreasing rate. For example, assume the utility function of a consumer from consuming positive quantities of good x can be written as

$$U(x) = x^{0.5}$$

where the exponent 0.5 illustrates the slope of the derivatives. The utility function of a consumer can be used to derive the demand function for goods. This in turn can be used to derive elasticity.

The increase in utility with increased consumption is given by the fact that the first derivative of the utility is a positive value, but at a decreasing rate because the second derivative of the utility function is negative:

$$\frac{dU(x)}{dx} = 0.5x^{-0.5} > 0$$

$$\frac{d^2U(x)}{dx^2} = -0.25x^{-1.5} < 0$$

Although abstract for many economics students, the concept of utility maximization allows economists to predict the behavior of consumers and more importantly, derive their demand function for a particular good. The demand function can be a function of price (P), price of substitutes (P_S), price of complements (P_C), income (I), and other factors such as advertising, tastes, taxes, weather, and so on. The demand function for a good Q may be written as:

$$Q_D = f(P, P_S, P_C, I, \ldots)$$

The equivalent concept for firms is called profit maximization and is usually easier to understand because "profit" is a more tangible concept than "utility". A firm's profit is positive when the total revenues received for selling a quantity of goods exceeds total costs to produce the goods. When profit is maximized, firms produce the quantity of goods that maximize the difference between revenues and costs. Figure 2.1 provides an example of costs and revenue as a function of a firm's output. The maximum profit occurs at the production level where the difference between total revenue and total cost is the largest.

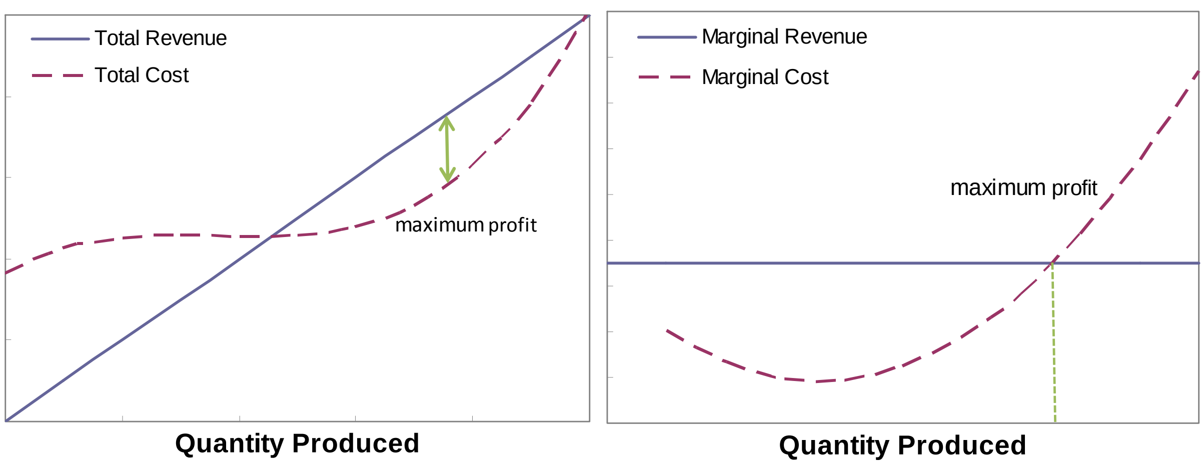

Figure 2.1. Example of Producer Profit Maximization.

A more sophisticated way to consider profit maximization is with marginal profit. Marginal profit is the difference between marginal revenue and marginal cost, or the difference between what is earned from producing the next unit less the cost required to produce it. If marginal cost is greater than marginal revenue, then marginal profit is negative and the firm loses money on the next unit produced. If marginal cost is less than marginal revenue, then marginal profit is positive and the firm makes a profit on the next unit produced. The ideal production level occurs when marginal profit is zero. At this level, marginal cost equals marginal revenue (total revenue less total cost is maximized), which maximizes return on investment.

The profit maximization requirement provides two important results: the supply curve for the item produced and the firm's demand function for labor, land and materials. A general supply function can be written as:

$$Q_S = f(P, P_R, W, T, \ldots)$$

where the quantity supplied (Q_S) is a function of output price (P), price of inputs (P_R), wages (W), technology (T), and possibly other factors such as taxes and subsidies.

2.1.2 Basic Economic Flows

Figure 2.2 is a representation of an economic flow model showing four agents: producers, consumers, the government and the rest of the world. The agents interact in two markets: goods market (produced by firms) and input markets (produced by firms and households). Table 2.1 summarizes the flows among the actors. As can be seen, households purchase goods (while maximizing utility) according to their demand functions. Producers provide goods (while maximizing economic profit) according to their supply functions.

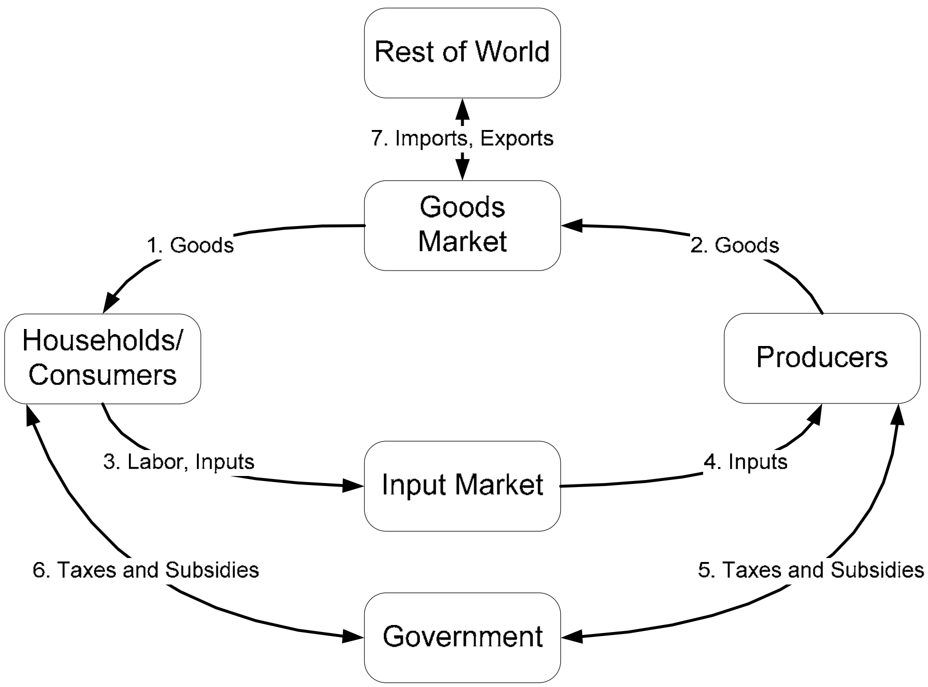

Figure 2.2. Basic Economic Flow Model.

For a particular country, trading with the rest of the world is often expressed in net exports, i.e., exports minus imports. Note that in equilibrium, all the monetary flows in the economy need to be balanced. In a closed economy (an economy that does not trade with the rest of the world), household spending plus savings need to equal income. For an open economy, the sum of the net exports of all countries needs to add up to zero, i.e., every item that is exported needs to be imported somewhere else. This type of market equilibrium condition is part of any trade model (whether partial or general equilibrium) that analyzes and predicts trade flows. Households provide labor, land and capital to the inputs market; in return households receive wages, rent and interest from producers using their inputs. These returns can be used to purchase goods in the goods market. The government collects taxes and distributes subsidies/payments to households and producers. The goods market can import and export goods from the rest of the world.

Table 2.1. Relationships in the Basic Economic Flow Model

Flow	Activity
1	Households (maximizing utility) purchase goods from the goods market according to their demand functions
2	Producers (maximizing profit) supply goods to the goods market according to their supply functions
3	Households provide labor, land and capital to the input market based on wage, rent and interest rate levels. Income received by households can be spent in the goods market.
4	Producers procure labor, land and capital from the inputs market. They also procure intermediate goods from other firms in the inputs market.
5 & 6	The government collects taxes from producers and households and redistributes subsidies to producers and households.
7	Imports and exports to the rest of the world.

2.1.3 Equilibrium

Equilibrium defines a situation in which economic agents have no incentive to change their behavior because supply equals demand. For example, assume a market where supply exceeds demand. In this situation, the price for the good in question is too high in the sense that consumers do not want to buy the good. Rather than not selling the good at all, the producer will decrease the price which in turn leads consumers to buy more of the good. The price will be reduced to a point where quantity demanded is equal to the quantity supplied. This situation represents market equilibrium. If there is disequilibrium in the market then the assumptions of utility and profit maximization are violated in some market(s).

Equilibrium exists when all goods produced by firms are completely absorbed by other sectors (households, other firms, government). Conversely the amount of factors owned by the other sectors (labor, land, etc.) is completely absorbed by the firms. When both of these conditions are met, the economy would be in equilibrium. This condition is referred to as the “market clearing” condition.

One important condition to reach a long-run equilibrium in a dynamic context is zero economic profit; expenditures must be exactly balanced by the value of the incomes. Households and producers are held to the zero economic profit condition. This means that all household revenues (wages, rents, interest) are spent on the purchase of goods and services. For producers, the sum of total revenue from production of goods must all be allocated to households (e.g., in the form of wages, interest payments, or rent), other firms for intermediate inputs, or to the government in the form of taxes. In equilibrium, producers and households make zero economic profit.

The zero economic profit condition should not be confused with the zero accounting profit. Accounting profit is defined as revenue minus cost:

$$\textit{Accounting Profit} = \textit{Revenue} - \textit{Cost}$$

Economists include an additional cost in the equation known as opportunity cost, i.e.,

Economic Profit = Revenue - Cost - Opportunity Cost

Opportunity cost is the value of the best alternative use of a resource. Any activity has an opportunity cost associated with it. Suppose John is the manager and owner of a clothing store that generates accounting profits of $50,000 per year. If John was not working at his own clothing store, he could be working at a department store for $55,000. So his opportunity cost is $55,000 (his best alternative) and thus, his economic profit is actually a loss of $5,000. The same concept applies to other aspects of economic activity. Suppose an investor considers building a new ethanol facility. If the economic profit is positive, then there is an incentive to invest because the revenue is higher than the accounting profit minus the opportunity cost. Once the plant begins operating, the additional production of ethanol reduces market prices and thus, reduces revenue. In equilibrium, the economic profit is zero because there is no incentive to open or close an additional plant. Zero economic profit ensures that all economic agents are exactly compensated for their opportunity costs.

2.1.4 Key Modeling Concepts

These foregoing key principles (maximization of utility and profit, zero economic profit, income balance and market clearance) are the basis for all economic models. Money itself is not a commodity, but all commodities are denominated in a common monetary unit to allow for trading and payments. An equilibrium model essentially solves a set of equations such that the supply and demand functions for each product in each sector intersect. Because there is no closed form analytical solution, the model iteratively solves the equations until it converges to a solution. The following paragraphs provide discussions on key computational equilibrium modeling concepts.

Static vs. Dynamic

Models that provide results (prices and quantities for each product) at one equilibrium point are referred to as static models. In a comparative static analysis, the static model is run multiple times with different values for model inputs for the variable of interest; the equilibrium results from each run are compared. Modelers refer to external values as exogenous variables while values that are calculated within the model are referred to as endogenous. The GTAP model is an example of a static model. The GTAP model utilizes a database for a set year (2004 or 2007). By setting the exogenous inputs (such as population or income) for a future year, the results are said to reflect prices and quantities in the future year. Dynamic models provide data for equilibrium at intervals over a range of time, so that the transition from one equilibrium point to the next is captured. The FAPRI and FASOM models are dynamic models; the user specifies exogenous variables over time and the model provides equilibrium quantities and results at specified intervals.

General Equilibrium vs. Partial Equilibrium

There are many types of consumers and many firms engaged in different economic sectors. Sectors can include agriculture, energy, water, transportation, manufacturing, financial, government, construction, machinery, etc. Moreover, many of the sectors interact with other sectors. For example, fertilizer manufacturing uses energy, the transportation sector uses biofuel derived from corn, the financial sector provides loans to farmers for investment, and so on. General equilibrium models include supply and demand functions for all products in all sectors of the economy, assuming profit and utility maximizing behaviors. Partial equilibrium models include some sectors with the rest of the sectors assumed to be fixed outside of the model (exogenous). Partial equilibrium models can represent more economic sectors or represent a portion of the economy such as an agricultural sector. General equilibrium models solve the global economy; so, a grouping of detail within sectors is necessary to facilitate model calculations. Partial equilibrium models exclude sectors that are not of key importance to the model. For example, when considering the market for agricultural products, government decisions on tax policy or what the labor market does are not important.

Partial equilibrium models used to evaluate land use do not consider other industries in the model whereas general equilibrium models are able to capture those effects. For example, the FAPRI model is a partial equilibrium model; it does not include the forest sector or the pasture sector (with the exception of Brazil) in its modeling for land use. We would expect that if returns to forestry are increasing (or decreasing) over time that this would affect the opportunity cost of land. The FAPRI model does not impose any force (apart from the natural availability of land which is currently not binding) which would make it more difficult for the agricultural sector to expand on land.

Elasticities

An important concept in economics and equilibrium modeling is the concept of elasticity. Elasticity is defined as the percentage change in one variable as the result of a percentage change in another variable. Elasticity is a unit free measure. For example, a demand elasticity of -0.3 means that the quantity demanded will decrease by -0.3 × 1% = -0.3% after a price increase of 1%. The advantage of elasticities is that the complete demand curve does not need to be known. Important elasticities in economic models are derived based on historic estimates. A graphical example of a constant elasticity demand curve is given in Figure 2.3.

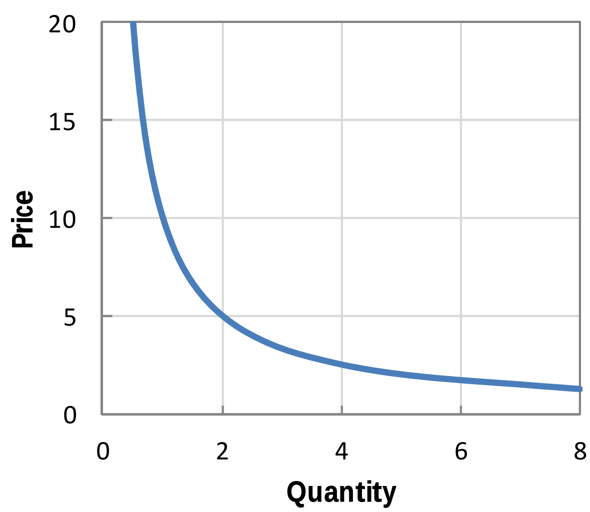

Figure 2.3. Example of a constant elasticity demand function.

Every good that has many substitutes faces an elastic demand. A good that is necessary to survive is inelastic, i.e., the quantity demanded does not change much when the price changes. Examples of inelastic commodities are milk and gasoline where consumer response to a change in price is relatively modest. In the case of gasoline, consumers have commute patterns and cars that are not easily modified in the near term. In the long run, the response to price can be more elastic if driving patterns and automobile efficiency changes. An example of an elastic product is economy cars. Here consumers may make a decision based on only a few hundred dollars in price.

In addition to demand elasticity, there is the Constant Elasticity of Substitution (CES) function. The CES measures how easy or difficult one input in a production process can be replaced or substituted by another input. For example, in a two input production technology, if input one is decreased by 1%, then the other input needs to be increased by x%, no matter how many units are produced and no matter which input combination is used.

The Armington assumption (Armington, 1969) is also an elasticity of substitution. Armington elasticities differentiate goods by country of origin and introduce repeatability in the trade flows (Edwards, et al., 2010). Armington trade elasticities represent the behavior when nations do not always seek the lowest price, sometimes they continue to trade with certain nations even though the price of goods may be a little higher than elsewhere. For economic models that use Armington elasticities, land use change is concentrated in countries where biofuel production takes place because feedstock from other countries is not as easily substitutable for domestic feedstock. This leads to the implication that less land use change takes place outside of the country where biofuels are produced. For example, if the United States increases its corn ethanol production significantly, then most land use change takes place in the United States because corn in the rest of the world is not as readily traded with corn in the United States and thus cannot serve as easily as a substitute. Models that do not take Armington elasticities into account treat goods movement as homogeneous or undifferentiated by national boundaries.

Some general equilibrium models use a constant elasticity of transformation (CET) function to allocate land to different uses (Li et al., 2012). GTAP-BIO uses two stages: In the first stage, land is allocated among cropland, pasture, and forest. In a second stage, cropland is allocated to the different crops. The elasticity parameter indicates how much land use in a particular category increases (in percent) given a percentage increase in the land rent. One disadvantage of this approach is that ha across land use do not sum up to the ha available. To correct this distortion, the CET constrains the land allocated to agriculture to be equal to the total amount of land available (Li et al., 2012).

2.2 Special Considerations for Modeling Land Use

Classical economics considers three production factors to produce economic output: capital, labor and land. Ricardo (1817) introduced the concept of land rent being based on the quality of the land, e.g., its productivity and location. Put simply, good quality land is not available in sufficient quantity to cover demand. Thus, the commodity prices need to be high enough to cover the production cost of the last unit of low quality land that is in production to meet the demand. This leads to higher rent for owners of high quality land. Von Thünen (1826) defined the value of land as a function of distance to a market or city. Land rent decreases with distance from the market because of higher transportation costs.

Land as an economic factor has generally been neglected in economic analysis since the beginning of the industrial revolution, because capital and labor were the dominant factors of production (Hertel et al., 2009). Capital and technological progress were deemed more important factors in adding value to society than land. With climate change and energy security emerging as issues of concern in the U.S. and globally, the importance of land in economic analysis is returning. On one hand, agriculture and forestry are responsible for almost one third of anthropogenic GHG emissions estimated by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 2007). On the other hand, energy security as well as climate change mitigation concerns and strategies need to incorporate the agricultural (including bioenergy) and forestry sectors. For this reason, understanding the economic decisions that drive land use and land use change are important.

As presented above, the basis for all economic analysis is that economic agents are assumed to be rational and profit (or utility) maximizing. Like any other economic agent, landowners set marginal revenue to marginal cost to determine the profit maximizing output and input quantities. For example, a landowner can use the inputs, "land" and "fertilizer" to produce the output "crop". The landowner determines whether the cost of an additional unit of input (the marginal cost), is higher or lower than the additional revenue from output (marginal revenue) produced by that additional unit of input. If the marginal revenue is higher than the marginal cost, the model will assume the landowner utilizes the additional land and fertilizer to produce the extra crop. As shown earlier in Figure 2.2, the optimum inputs and outputs will correspond to the point at which marginal cost equals marginal revenue.

What makes land different from other inputs is that the amount of land is a fixed resource. For example, suppose a landowner allocates land to two uses A and B. If the return from A increases, he/she has the incentive to produce more from use A. There are three possibilities to do so:

1. Land in category B can be converted to use A which would reduce the amount of B produced. This is often referred to as "displacement".
2. Landowners can increase inputs other than land to increase production of A from a particular plot of land, (for example increasing fertilizer use). This is referred to as intensification.
3. Expanding land use A into land that was not used for either A or B initially. This is referred to as extensification.

These three possibilities lead us to the concepts of "intensive margin" and "extensive margin". The intensive margin refers to the point where it is not optimal to increase inputs on a plot of land. At the extensive margin, it is not optimal for the landowner to increase land by an additional unit because the cost of the additional land is higher than the expected revenue for production of A.

There are three examples in the context of global agriculture which demonstrate the points made above. Searchinger et al. (2008) illustrates that if returns (revenue) from corn increase because of ethanol demand, more landowners/farmers will allocate their land towards corn production. In the U.S., this leads to a shift from a corn-soybean rotation to a corn-corn-soybean rotation, i.e., land is taken away from soybeans. The paper projects that the rest of the world sees increased commodity prices and starts to expand cropland at the extensive margin. In other words, it is cheaper to expand cropland than to increase the inputs on the cropland already used. At the same time, an expansion at the intensive margin (intensification) can be observed for Brazilian livestock (Barona et al., 2010). The authors report that between 2000 and 2006, stocking density in Brazil increased from 0.74 to 1.17 livestock units per ha.

Another feature that separates agriculture from other sectors is that neither the output nor the prices are known to the farmer at the decision time (time of planting). At the time of planting, the farmer maximizes the *expected* net returns, i.e., expected revenue minus expected cost (Barr et al., 2011). If a farmer expects the price of one commodity to increase or be high in the future, he/she will allocate more land to that commodity. The risk for the farmer today is greatly reduced by the existence of future markets which make it possible for the farmer to hedge the risk. For computational reasons, uncertainty is not included in the partial and general equilibrium models considered. Uncertainty mostly affects the storage and hedging decisions of farmers. The models generally assume that farmers have perfect foresight. Since we are usually interested in the delta between with and without biofuels, the absence of explicit treatment of uncertainty is not likely to affect estimates.

Another important issue when modeling land use is referred to as decreasing returns to scale. Land quality is heterogeneous, with higher quality land put into production first. To evaluate land use change from biofuel expansion, the crop yield on the new land (extensive land) must be known. If the yield on the new acres is significantly lower than on the existing land (intensive land), then more cropland needs to be put in production for the same amount of biofuels. Decreasing returns to scale (lower yield on extensive acres) lead to nonlinearities in model outcomes. Specifically, as biofuel production increases, the land requirement per unit of biofuel also increases. This is true for the extensive margin, but at the same time, in some models, there is a price yield elasticity that leads to higher yields on existing acreage – called the intensive margin. In this case the extensive and intensive effects at least partially offset each other.

One advantage of general equilibrium models is that all land sectors are included (e.g., pasture, grassland, conservation reserve program (CRP) forest, etc.) and the land is allocated to the highest profitable use. Partial equilibrium models such as the FAPRI model must rely on assumptions where new cropland comes from. The current version of the FAPRI model assumes a proportional allocation based on the existing land cover. For example, if a parcel has a 30-60-10 share of forest, cropland, and grassland respectively, then an increase in cropland on that parcel will take three fourths from forest and one fourth from grassland. Accurately measuring land use change on a global basis is very difficult (Dumortier, et al., 2011, 2012; Barona et al., 2010). Annual remote sensing, i.e., satellite data, would be necessary to accurately track land use change on a real time basis.

On a global scale, land degradation plays an important role in land expansion, i.e., some idle cropland might be too degraded to come back into production and hence, expansion in natural vegetation is unavoidable. To include land degradation, assumptions must be made regarding loss of top soil from wind and/or water erosion, loss of nutrients and/or organic matter, salinization, and pollution, and the degree to which these affect cultivation potential. Existing models do not take land degradation into account.

2.3 Model Attributes Affecting LUC

Many factors in agro-economic modeling affect LUC. The most significant drivers directly affect the demand for land, land cover type, or feed substitution effects that affect the demand for crops. These parameters include:

- Projections for crop yields
- Elasticity factors that project crop yield improvements
- Elasticity that affects feed use, including beef versus poultry consumption as well as DGS substituting for corn or corn and soy
- Elasticity factors that affect land choice, including conversion of forest land, which has the highest carbon stocks; use of marginal land, which has low carbon stocks; and higher cattle stocking rates, which free up pasture to be used for crop production.

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von Thünen, J. H. **1826**. Der isolirte Staat in Beziehung auf Landwirthschaft und National okonomie, oder Untersuchungen uber den Einfluss, den die Getreidepreise, der Reichthum des Bodens und die Abgaben auf den Ackerbau aus¨uben.

3. LUC Models

A variety of LUC models are used in fuel LCA policy. The models were developed as agro-economic models to support a variety of objectives, including trade analysis, U.S. GHG inventory analysis, and agricultural economics, to name a few. This section describes the details of each of the main models employed to quantify LUC in response to biofuel demand. For each model we review the history, developers, policies/regulations it has supported (associated model versions), and distinguishing features of modeling methods using the concepts introduced in Section 2. Section 3.1 describes the general attributes of the LUC models examined in this study. Section 3.2 discusses model configurations for the models examined. Sections 3.3 through 3.6 describe the history and uses, distinguishing features and key computational drivers for each of the models evaluated. This report focuses on how economic models quantify the amount, location and land cover type of LUC in response to increased demand for biofuel. The carbon accounting post-processing is not addressed; nevertheless, a brief summary of how each of the models quantifies carbon emissions from estimated LUC is provided in Section 3.7.

3.1 Key LUC Model Inputs and Outputs

Table 3.1 shows the general attributes of the LUC models examined in this study. The calculation method, source of economic data, and carbon stock accounting are identified. Each model calculates the expected LUC due to a change of demand in biofuel usage (or shock). The method for implementing the shock differs between the general equilibrium models (GTAP and MIRAGE) and FASOM and FAPRI. In GTAP and MIRAGE the shock is achieved by adjusting a hypothetical subsidy until the model predicts the desired biofuel volume. In FASOM the shock is simply in calculated from the feedstock needed to achieve the biofuel volume. FAPRI can also apply calculations where the shock is calculated internally from a subsidy. The agro economic models solve a supply/demand equilibrium that takes into account changes in feed prices and shifts among feed. In GTAP and MIRAGE, the economic activity translates to all of the sectors in the economy. FASOM and FAPRI include more detail on individual agricultural commodities. GTAP, FASOM, and MIRAGE constrain the model with a limited supply of land. FAPRI is not configured with the same land limitations, although analysts that perform FAPRI runs are aware of global land availability and verify that the model does not project land use beyond the limitations of available land. All of the models project changes in land cover. The LUCs are used to predict changes in carbon stock through different carbon accounting mechanisms and carbon stock data sets. Prior CRC studies have examined the carbon stock data in these models (Unnasch 2011, Broch 2012).

Table 3.1. Comparison of Agro-Economic Model Inputs and Outputs

Model Attribute	GTAP	FASOM	FAPRI	MIRAGE-BioF
Model Input (Shock)	The biofuel shock is a quantity shock; e.g., 3 to 15 bil. gal. It is accomplished by swapping the subsidy for the quantity making the subsidy endogenous and quantity exogenous	Exogenously specify biofuel volumes above the baseline at each point in time that an equilibrium solution is desired.	Exogenously adjust either petroleum prices or biofuel subsidies until the desired biofuel quantity is achieved.	The biofuel shock is a quantity shock. Quantity is made exogenous and the biofuel subsidy becomes endogenous.
Model Calculation	Solves for price and quantity when supply equals demand in each of the economic sectors (including the biofuel sectors) by AEZ.	Solves for price and quantity in 5-yr increments when supply equals demand for each ag and forestry commodity at the county level.	Solves for prices that clear the market, i.e., equalizing supply to demand, in each region and each commodity market.	Solves for price and quantity when supply equals demand in each of the economic sectors (including the biofuel sectors) by AEZ.
Model Outputs	Change in land cover type (e.g. pasture to crop) by AEZ	Emissions of land use + crop GHG changes + livestock GHG changes in g/MJ for the entire U.S.	Change in agricultural land by crop and geographic region	Change in land cover type (e.g. pasture to crop) by AEZ
Carbon Accounting	LUC multiplied by carbon stock factors (Woods Hole and variations of) either in the model or off-model	Soil: CENTURY Models net CO_2, N_2O and CH_4 endogenous to the model due to estimated LUC	LUC combined with either (1) marginal land cover type change from MODIS Satellite Data combined with WINROCK carbon stock factors or (2) IPCC parameters.	Endogenous managed LUC combined with marginal land cover type change from MODIS Satellite Data combined with WINROCK carbon stock factors.

3.2 Key LUC Model Scope and Structure

Table 3.2 identifies the model configurations including model type, regions, trade assumptions, and timeframe. GTAP BIO and MIRAGE are both general equilibrium models based on the GTAP database. MIRAGE uses an expanded set of agricultural industries and biofuel sectors. Both GTAP and MIRAGE take into account global economic factors. For example, these models will respond to the interactions between petroleum prices and consumer demand, while FASOM and FAPRI focus on agricultural commodities. The regional focus of the LUC models is quite different. GTAP and MIRAGE estimate land cover types within agro economic zones (AEZ). The AEZs take into account land cover type. FASOM analyzes farming activity on a U.S. county level basis while FAPRI estimates the country where LUC will occur. The U.S. Environmental Protection Agency's (EPA) use of the FAPRI model applies satellite data to estimate the changes in land cover type.

Table 3.2. Comparison of Agro-Economic Model Scope and Structure

Model Attribute	GTAP-BIO	FASOM	FAPRI	MIRAGE-BioF
General vs. Partial	General	Partial: U.S. Forestry and Agriculture	Partial: Agriculture Sector	General
Geographic Coverage	World by AEZ	United States by county	World by political borders	World by AEZ (14 Regions)
Land Cover Types	Cropland, forest, pasture. Cropland-Pasture included for U.S. and Brazil only.	Cropland, Cropland-Pasture, Forest-Pasture, Rangeland, Forest, Developed, CRP	Cropland, Pasture, Forest, Barren	Cropland, Managed Forest, Pasture
Economic Sectors	57 Economic Sectors	Agriculture, Forestry	Agriculture, Biofuels, Livestock, Dairy	55 Economic Sectors
Static vs. Dynamic	Both static and dynamic versions of GTAP exist, but the comparative static model is used more for biofuels work.	Dynamic	Dynamic	Dynamic
Trade Assumptions	Armington Elasticities	Homogeneous Goods	Homogeneous Goods	Armington Elasticities
Time Frame	2004 Database with elasticities calibrated for medium term (e.g., 5-8 years)	Projects up to 100 years with solutions every 5 years	10-15 years	2004 Database with elasticities calibrated for 2020 timeframe (RED)

3.3 GTAP

The Global Trade Analysis Project (GTAP) is a global network of researchers and policymakers conducting quantitative analysis of international policy issues. GTAP's goal is to improve the quality of quantitative analysis of global economic issues within an economy-wide framework. Since its launch in 1992, GTAP has become the common "language" for analysis of global economic policy issues; GTAP-based results are influential in decision making around the world in trade, climate change, energy, and the environment. The centerpiece of the model is the GTAP Data Base, a fully documented, publicly available global data base which contains complete bilateral trade information, transport and protection linkages. The following section provides an overview of the model’s history and uses, describe the structure of the model, and discuss key drivers in the quantification of land use change.

3.3.1 History and Uses

As indicated above, GTAP came into existence in 1992 and was widely used for trade policy analysis leading up to the completion of the General Agreement on Tariffs and Trade (GATT[1]) negotiations and has also been widely used to estimate impacts of bilateral and regional trade agreements. This model was first published in 1997 by Cambridge University Press (Hertel,

[1] In 1994 GATT was replaced by the World Trade Organization.

1997). It has since garnered more than 2,800 citations on Google Scholar, and it has formed the foundation for many more GTAP technical papers and thousands of papers and government reports around the world.[2] The current release, the GTAP 8 Data Base, contains dual reference years of 2004 and 2007 as well as 129 regions for all 57 GTAP commodities.

GTAP also has two standard versions of the model – comparative static and dynamic. The comparative static version is by far the most widely used. It provides estimates of the impacts of a wide variety of shocks applied to the model. These shocks can be trade policy changes, technology changes, biofuels demands, or many others. The estimates are *ceteris paribus*, meaning that the results estimate what will happen if nothing changes but the shocks that are applied to the model. In the real world, of course, lots of things are changing at the same time. For that reason, comparative static GTAP will not replicate real world changes, since it estimates what would have happened if only the applied shocks had changed. Thus, GTAP estimates the impacts on the global economy if the only change is the applied shock. It thereby isolates the impact of the shocks for everything else going on in the economy. Commonly applied shocks are changes in factor productivity, population, and the like. The dynamic version of GTAP marches the economy through time with exogenous shocks applied in each period. A modeler can apply as many shocks as desired, and the model can still calculate the outcome. However, if the purpose is to investigate the effect of a particular policy, the model should only change the policy parameter in question. Dynamic or time dependent shocks could include the ramp up to a policy target rather than a one time event.

In addition to the two generic GTAP models (comparative static and dynamic), there are many special version GTAP models created for specific kinds of analysis. Use of GTAP for energy and environmental issues came about in the second decade of GTAP's existence. Relevant to this report, there is the GTAP-BIO (Hertel, 2010; Hertel, Tyner, and Birur, 2010; Taheripour, et al., 2010; Taheripour, Hertel, and Tyner, 2011; Tyner and Taheripour, 2012), which was created at Purdue for analysis of conventional biofuels and the GTAP-BIO-ADV model that also includes cellulosic biofuels (Taheripour and Tyner 2011, 2013; Taheripour et al. 2012). At this writing, these are both comparative static models with dynamic versions are also under development.

GTAP-BIO was developed for use by the California Air Resources Board (ARB) to estimate LUC emissions resulting from the LCFS. It includes the following first generation biofuels: ethanol from corn and sugarcane and biodiesel from soybeans, rapeseed and palm oil. Inclusion of each of these biofuels required addition of an industry to use the raw material to produce the biofuel. The model also includes the effects of corn ethanol and oilseed biodiesel co-products. GTAP-Bio underpinned the ARB 2009 LCFS LUC analysis and was also utilized to some extent by EPA in their analysis of the land use change impacts of biofuels mandates.

Three feedstocks have recently been added to GTAP: corn stover, miscanthus, and switchgrass. Each of these feedstocks can be converted to ethanol or to a drop-in fuel modeled as bio-gasoline. These biofuels are not competitive and must be shocked individually. In addition to the addition of the cellulosic biofuel feedstocks and associated biofuel industries (Taheripour and Tyner, 2012; Taheripour, Tyner, and Wang, 2011; Taheripour et al. 2012; Tyner, Brechbill, and

[2] This paragraph is largely taken from an internal note prepared by Tom Hertel (2012).

Perkis, 2010), the following additional changes were introduced into GTAP-BIO and GTAP-BIO-ADV: more flexible cropland switching, regional land transformation parameters, updated elasticity (ETA) values and more granularity (Taheripour et al. 2012), and a new land cover nesting structure with forest separated from cropland and pasture (Taheripour and Tyner 2013). These enhancements are described in more detail in the next section. In general, the earlier estimates of land use change were higher than more recent estimates as model improvements were added. Table 3.3 provides the original LUC estimates for the LCFS and more recent estimates from GTAP-BIO-ADV. Figure 3.1 shows the evolution over time of corn ethanol land use change estimates. The group 1, 2, and 3 estimates are from the Purdue report to Argonne National Labs (Tyner, et al. 2011). Clearly, induced land use change estimates have fallen considerably since the original Searchinger work (Searchinger, et al., 2008).

Table 3.3. Biofuel Volume Shocks and GTAP Estimated Land Use Changes.

		CARB LCFS (GTAP-BIO)		LCFS Rev (GTAP-BIO-ADV)	
Model Parameter	**Units**	**Corn Ethanol**	**Soybean Biodiesel**	**Corn Ethanol**	**Soybean Biodiesel**
Change in Volume Modeled	bgy	13.25	0.695	11.59	0.812
Cropland Change	ha	n/a	n/a	2,126,261	143,189
Pasture Change	ha	-3,030,000	-304,000	-1,835,267	-145,369
Forest Change	ha	-860,000	-137,000	-290,637	2,179
Cropland Pasture Change	ha	n/a	n/a	1,438,468	202,759
Change w/o Cropland Pasture	ha/1000 gal	0.29	0.63	0.18	0.18
Change w/Cropland Pasture	ha/1000 gal	n/a	n/a	0.31	0.43

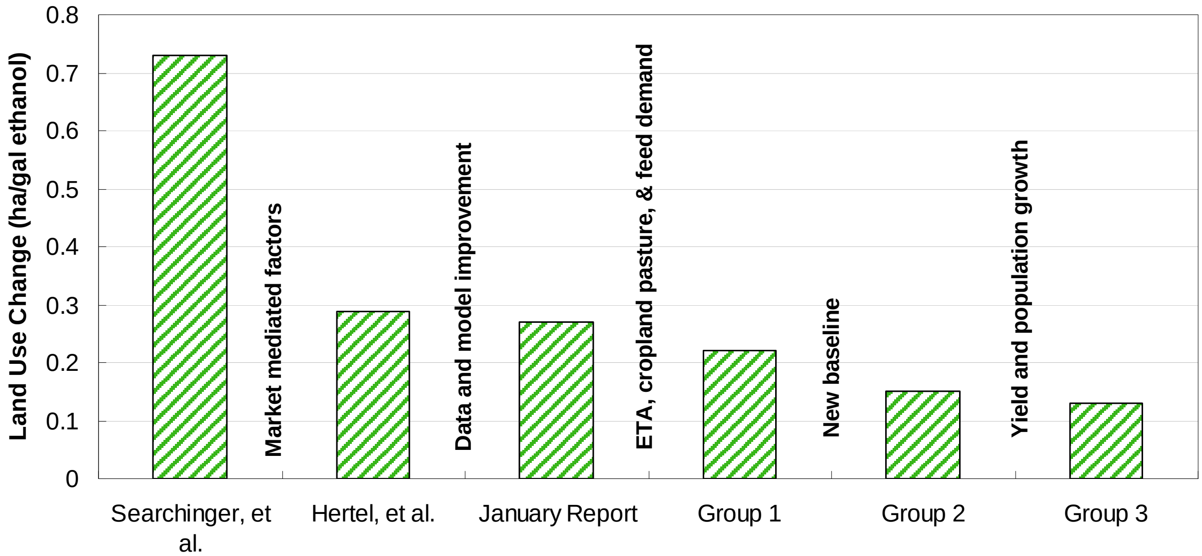

Figure 3.1. Induced Land Use Change from Corn Ethanol (m^2/liter ethanol).

3.3.2 GTAP Model Structure

Since the GTAP database was designed explicitly for use in global, applied general equilibrium analysis, it must satisfy many consistency requirements which are not exhibited in most global databases. What one country exports, another country must import. Regional economies must be on their budget constraint – once international income payments and capital flows are accounted for. Sectors must earn zero profits. Global savings must equal global net investment. And the exports of global transport services from individual countries must equal the demand for these same services, as evidenced in the international margins applied to merchandise trade flows between countries. The data set must also be accompanied by behavioral parameters if users are to be able to specify a full general equilibrium model, and these parameters depend on the data structure, as well as the underlying model. For this reason, there must be a standard GTAP model.

The GTAP database is normally updated every three years. The current release, the GTAP 8 Data Base, contains dual reference years of 2004 and 2007 as well as 129 regions for all 57 GTAP commodities. Most of the biofuels work has been done with either the 2001 or 2004 version of the data base using the comparative static version of GTAP, although some analyses have been done with the dynamic version. GTAP is considered to be a mid-term model, meaning that many of the relevant elasticities are tuned to a mid-length period of 5-8 years.

Figure 3.2 illustrates the general structure of GTAP and most computational general equilibrium (CGE) models. Households spend their income on domestic goods and imports as well as taxes. Households also save part of their incomes, which ultimately gets translated into investment. Producers use resources (land, labor, and capital) to produce goods, and the factor payments become income to households. Governments collect taxes and spend the tax receipts on domestic and imported goods and services.

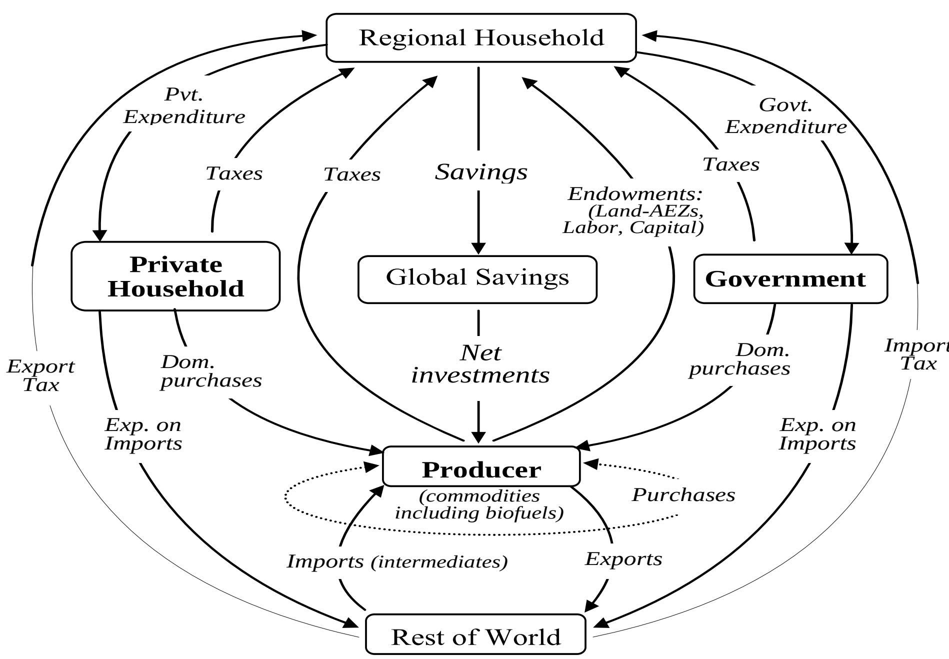

Figure 3.2. General Structure of the GTAP Model.

As shown in Figure 3.3, land endowments are divided into 18 agro-ecological zones (AEZs) around the world (Avetisyan, Baldos, and Hertel, 2011). The land cover data by land type, agro ecological zone (AEZ), and country for the year 2004 were produced by Navin Ramankutty using the Global Cropland and Pasture Data from McGill University. The version 7 GTAP Land Use Data Base was developed using the Food and Agriculture Organization of the United Nations (FAO) 2004 data on production, harvested area and price, by country and 159 FAO crop categories.

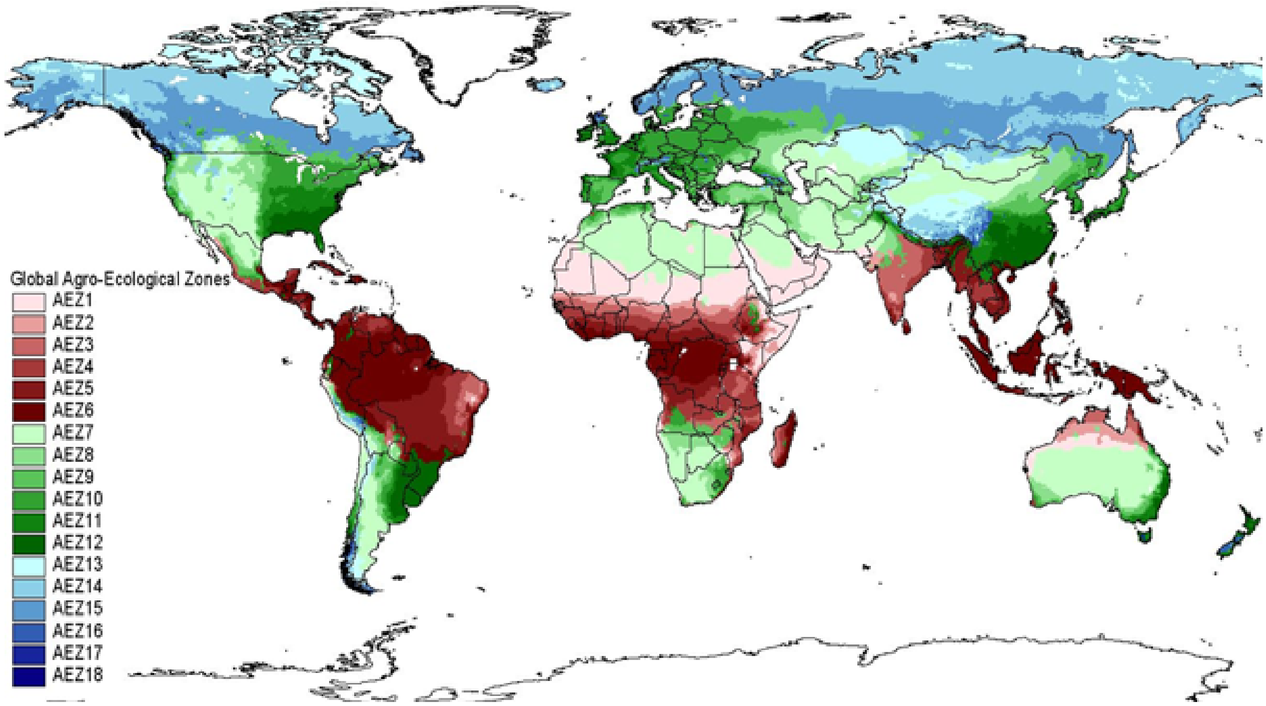

Figure 3.3. Global Agro-ecological zones in GTAP.

Figure 3.4. Major Links in the Analytical Framework for Biofuels" provides the general structure of the GTAP-BIO version of the model. Land is divided into three categories: cropland, pasture, and forest. For Brazil and the U.S., the model also includes a category called cropland pasture that is more productive than pasture but less productive than cropland. This addition is a significant revision to the previous version of the model. Land is used to produce crops that are allocated to food, feed, or biofuels. Corn ethanol and oilseed biodiesel also have byproducts that go back into the animal feed system. If there is insufficient land from cropland to meet added demands of biofuels, then land is taken from pasture, forest, or cropland pasture to produce the added crops. This land conversion that is induced by the added biofuel demand is called indirect land use change. GTAP does not differentiate between direct and indirect land use change; rather GTAP uses the term induced land use change.

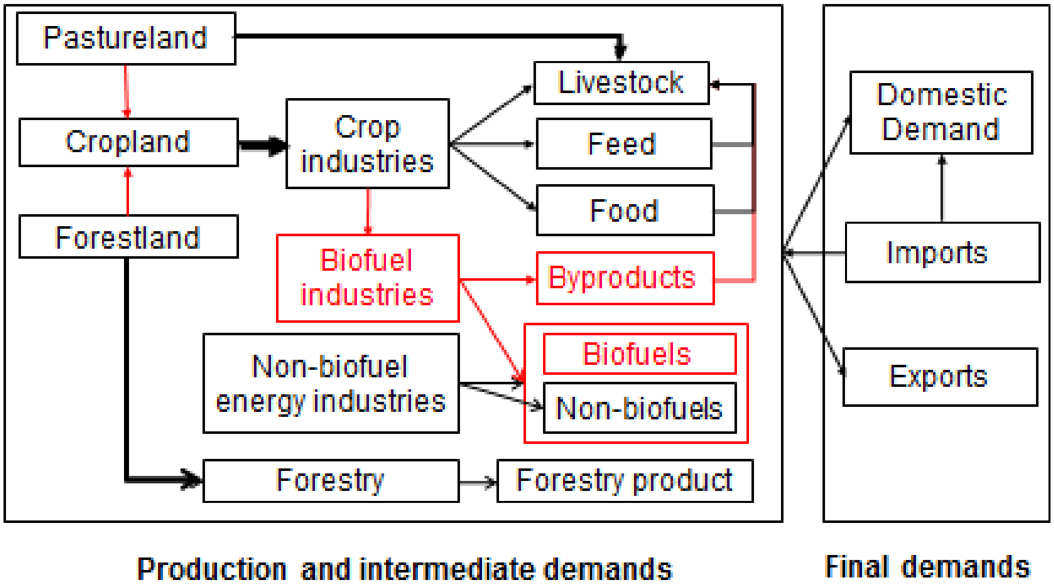

Figure 3.4. Major Links in the Analytical Framework for Biofuels.

3.3.3 Key Drivers of Land Use Change Estimates in GTAP

Armington Trade Structure

GTAP is a large global model with thousands of data points and parameters. It uses an Armington trade structure, which means that trade geography and history matter. Imports and domestic goods are imperfect substitutes. The alternative is the Heckscher-Ohlin structure, which assumes that trade adjustments are very rapid and depend only on relative prices and costs. Most economists support the Armington structure, but some partial equilibrium models, particularly regional models, use the Heckscher-Ohlin approach.

CET Land Supply

The land supply nests in GTAP use a CET supply structure, illustrated in Figure 1.1 (Taheripour, Tyner, and Wang, 2011). The Ω parameters are the CET parameters. They apply at the land cover level as well as at the cropland level. The values in GTAP, like many of the parameters, have an empirical basis, but improved data are often needed. Recent work took advantage of actual global land use changes by region to update the CET parameters on a regional basis (Taheripour and Tyner, 2013). The parameters from this work are shown in Table 3.4 and are utilized in GTAP-BIO-ADV.

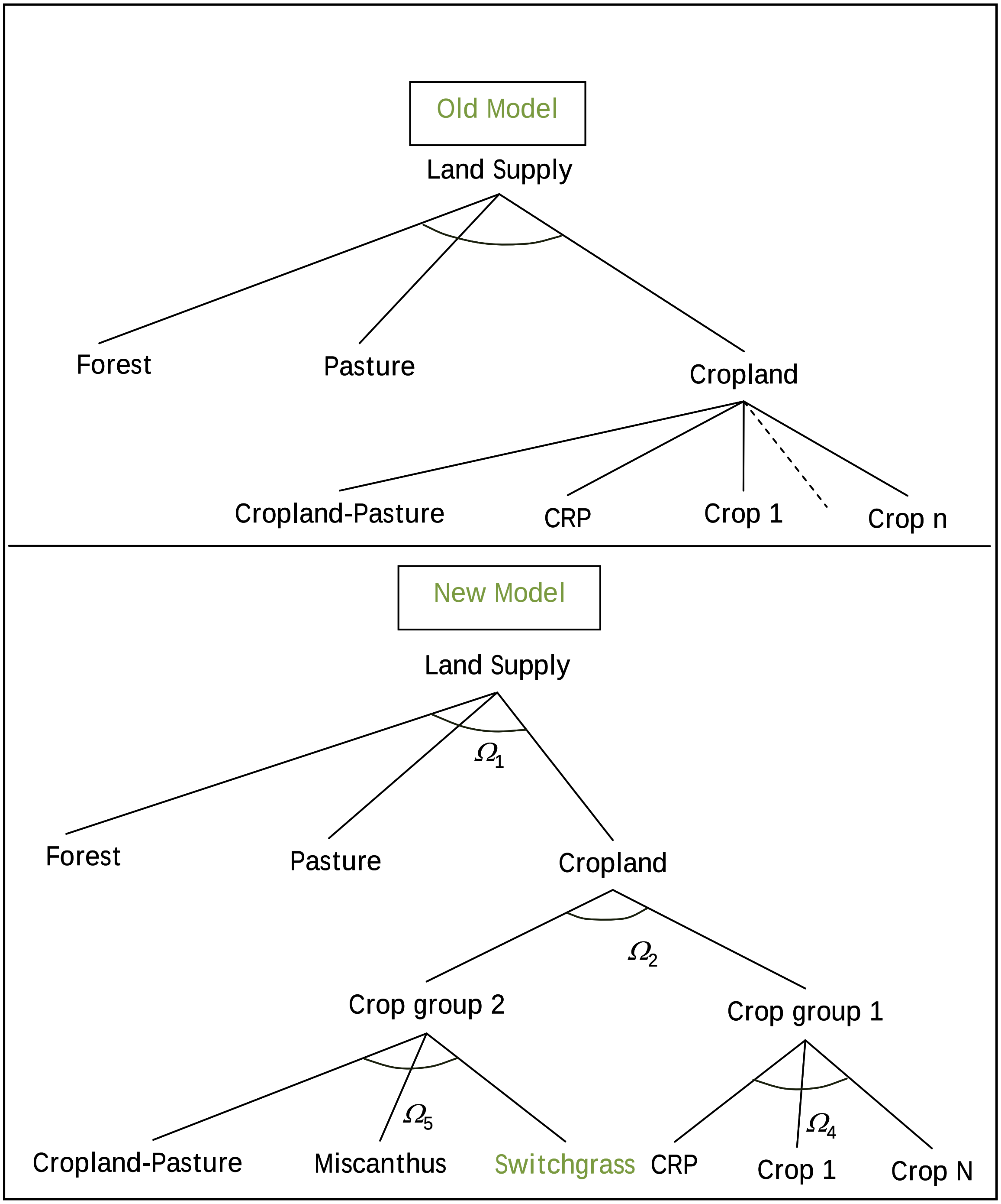

Figure 3.5. Land Cover and Land Use Activities in the Old and New GTAP-BIO-ADV.

Table 3.4. Tuned regional land cover transformation elasticities.

Regions	Rank in land cover change	Tuned ETL1	Tuned ETL1$_F$	Tuned ETL1$_P$	Tuned ETL2
Oth_Europe	Very Low	−0.02	−0.018	−0.0218	−0.25
Oceania		−0.02	−0.018	−0.0218	−0.25
CAN		−0.02	−0.018	−0.0218	−0.25
U.S.A.		−0.02	−0.018	−0.0218	−0.75
MEAS_NAfr		−0.02	−0.018	−0.0218	−0.25
Oth_CEE_CIS		−0.02	−0.018	−0.0218	−0.75
C_C_Amer		−0.02	−0.018	−0.0218	−0.25
EU27		−0.02	−0.018	−0.0218	−0.75
INDIA	Low	−0.1	−0.0909	−0.1091	−0.25
R_S_Asia		−0.1	−0.0909	−0.1091	−0.25
Russia	High	−0.2	−0.1818	−0.2182	−0.75
JAPAN		−0.2	−0.1818	−0.2182	−0.5
CHIHKG		−0.2	−0.1818	−0.2182	−0.25
E_Asia		−0.2	−0.1818	−0.2182	−0.5
BRAZIL	Very High	−0.3	−0.2727	−0.3273	−0.5
R_SE_Asia		−0.3	−0.2727	−0.3273	−0.5
Mala_Indo		−0.3	−0.2727	−0.3273	−0.25
S_o_Amer		−0.3	−0.2727	−0.3273	−0.25
S_S_AFR		−0.3	−0.2727	−0.3273	−0.5

Other Parameters and Assumptions

Another issue that has garnered some attention is the decrease in food demand with higher commodity prices brought about by biofuel shocks. The decrease in food demand, a market mediated response, results in lower land use change than would be estimated if food consumption were held constant. Some have argued that biofuels should not be "credited" with the lower land use change due to lower food consumption. Of course, this is a value judgment and beyond the realm of normative analysis. Table 3.5 shows the harvest area by crop type for selected countries. They are aggregated into the GTAP inputs by AEZ.

Following are some of the major changes that have been made to GTAP-BIO over time:

- Yield *intensification*: Yield intensification is the change in commodity yield due to changes in price. An elasticity of 0.25 is used based on Hertel, et al. (2009). The GTAP team considers this yield to reflect the best information in the economic literature. This elasticity means that a 10% increase in crop price, *relative to variable input prices*, would result in a 2.5% increase in yields.

- Yield *extensification:* Yield extensification is the change in yield due to crop land expansion into forest and pasture land as well as change in yield due to substitution among crops. GTAP measures productivity of new cropland compared to existing cropland with an elasticity referred to as ETA. In early work, GTAP used an ETA value of 0.66 for all regions across the world. A new set of regional ETAs by AEZ was developed using a process-based biogeochemistry model (Terrestrial Ecosystem Model (TEM) along with spatially referenced information on climate, elevation, soils and vegetation land use (Taheripour et al., 2012). Table 3.6 provides the new values.

- Updated energy elasticities: Earlier versions of the model were found to be too elastic when there were changes in energy prices. That is, there was too much quantity change related to price changes induced by various shocks. The model elasticities were re-calibrated to better represent real world responses.

- Improved treatment of biofuel production co-products: The modeling of the livestock sector was changed to better reflect the functioning of the livestock feed markets (Taheripour, Hertel, and Tyner, 2011).

- Separation of soybean from other oilseeds, separation of soybean oil from other vegetable oils and fats with substitution between them, and separation of soybean biodiesel from other types of biodiesel.

- Separation of palm and palm oil.

- Modified model structure for livestock sector.

- Incorporated cropland pasture as a separate land cover type for U.S. and Brazil and added CRP land in the U.S.

- Endogenous yield adjustment for cropland pasture: When cropland pasture is converted to cropland, the expectation is that farmers would make investments to render the cropland pasture more productive. These investments could range from fertilizer, improved seeds, etc. to investment in better drainage, leveling, etc.

Table 3.5. Production, Harvested Area, and Yield of Major Crops for Selected Countries.

	Crop	Brazil	Canada	China	France	Indonesia	India	Morocco	Russia	U.S.A.	S. Africa
Harvested area (1000 ha)	Barley	142	3,841	786	1,631	0	657	2,324	9,562	1,627	83
	Maize	12,411	1,072	25,467	1,821	3,357	7,430	245	870	29,798	3,204
	Millet	0	0	916	4	0	11,886	6	935	241	21
	Paddy Rice	3,733	0	28,616	20	11,923	41,907	4	125	1,346	1
	Sorghum	931	0	570	48	0	9,331	18	26	2,637	130
	Wheat	2,807	9,389	21,626	5,237	0	26,595	3,064	22,920	20,222	830
	Rapeseed	34	4,867	7,272	1,125	0	5,428	1	232	338	44
	Soybeans	21,539	1,174	9,582	59	565	7,571	1	555	29,930	135
	Sugarcane	5,632	0	1,393	0	345	3,938	13	0	380	325
Harvested production (1000 tons)	Barley	397	12,557	3,222	11,032	0	1,298	2,760	17,180	6,091	185
	Maize	41,788	8,837	130,434	16,372	11,225	14,172	224	3,516	299,914	9,710
	Millet	0	0	1,813	20	0	10,841	8	1,117	342	12
	Paddy Rice	13,277	33330	180,523	115	54,088	12,4697	30	471	10,540	3
	Sorghum	2,159	0	2,341	257	0	6,681	15	44	11,523	373
	Wheat	5,819	24,796	91,952	39,693	0	72,156	5,540	45,413	58,738	1,687
	Rapeseed	57	7,674	13,182	3,993	0	6,291	1	276	613	32
	Soybeans	49,550	3,044	17,404	147	723	6,876	1	555	85,013	220
	Sugarcane	415,206	0	91,044	0	26,750	233,862	872	0	26,320	19,095
Yield (tons/ha)	Barley	2.80	3.27	4.10	6.76	0.00	1.98	1.19	1.80	3.74	2.23
	Maize	3.37	8.24	5.12	8.99	3.34	1.91	0.91	4.04	10.06	3.03
	Millet	0.00	0.00	1.98	5.00	0.00	0.91	1.33	1.19	1.42	0.57
	Paddy Rice	3.56	0.00	6.31	5.75	4.54	2.98	7.50	3.77	7.83	3.00
	Sorghum	2.32	0.00	4.11	5.35	0.00	0.72	0.83	1.69	4.37	2.87
	Wheat	2.07	2.64	4.25	7.58	0.00	2.71	1.81	1.98	2.90	2.03
	Rapeseed	1.68	1.58	1.81	3.55	0.00	1.16	1.00	1.19	1.81	0.73
	Soybeans	2.30	2.59	1.82	2.49	1.28	0.91	1.00	1.00	2.84	1.63
	Sugarcane	73.72	0.00	65.36	0.00	77.54	59.39	67.08	0.00	69.26	58.75

Table 3.6. Regional land conversion factors (ETA) truncated to 1 (C4 crop).

AEZ[2]\ Region[3]	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
1	0.00	0.00	0.91	0.00	0.00	0.00	0.93	1.00	0.95	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.68	0.61	1.00
2	0.00	0.00	0.92	0.00	0.00	0.00	0.89	1.00	0.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	1.00	1.00
3	0.00	0.00	0.93	0.00	0.00	0.00	0.86	1.00	0.90	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.89	0.74
4	0.00	1.00	0.89	0.00	0.00	1.00	0.93	1.00	0.88	0.00	0.88	0.89	1.00	0.00	0.00	0.00	0.86	0.92	0.92
5	0.00	0.00	0.93	0.00	0.00	0.90	0.98	0.88	0.90	0.00	0.90	0.91	0.98	0.00	0.00	0.00	0.00	1.00	0.96
6	0.00	0.00	0.91	0.00	0.00	0.88	0.98	0.97	0.85	0.00	0.88	0.95	0.78	0.00	0.00	0.00	0.00	1.00	0.88
7	0.73	0.00	0.00	0.89	0.00	0.80	0.90	0.59	1.00	1.00	0.00	0.00	0.43	1.00	0.98	0.00	0.46	0.80	0.65
8	0.71	0.90	0.00	0.91	0.00	1.00	0.71	0.72	0.90	1.00	0.00	0.00	0.60	0.84	0.84	0.00	0.71	0.79	0.86
9	1.00	1.00	0.00	0.85	1.00	0.98	0.88	1.00	0.91	1.00	0.00	0.00	1.00	0.94	0.82	0.00	0.77	0.84	0.93
10	0.93	0.96	0.88	0.88	0.96	0.84	1.00	0.89	1.00	0.93	0.00	1.00	0.92	0.89	0.89	0.87	0.98	0.88	0.92
11	0.96	0.83	1.00	1.00	0.94	0.95	0.90	1.00	0.87	0.84	0.00	1.00	0.79	0.89	1.00	0.00	0.00	0.77	0.96
12	0.89	0.86	0.91	0.00	0.95	0.92	0.90	1.00	0.84	0.00	0.00	1.00	1.00	0.00	0.89	0.00	0.00	1.00	0.98
13	0.92	1.00	0.00	0.55	0.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.63	0.97	0.00	0.00	0.00	0.00
14	0.51	0.89	0.00	0.80	0.00	0.92	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.90	1.00	0.95	0.00	0.00	0.00
15	0.71	0.90	0.00	0.83	1.00	1.00	1.00	0.00	0.64	1.00	0.00	1.00	1.00	0.90	1.00	0.87	0.00	0.00	1.00
16	1.00	0.89	0.00	1.00	0.00	1.00	1.00	0.00	0.92	0.00	0.00	1.00	1.00	0.85	1.00	1.00	0.00	0.00	1.00
17	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

In this table, a value of 0 means no land is available. In general, when ETA = 1, it shows that the average productivity of new land is equal to the average productivity of existing cropland. ETA values greater than 1 are also truncated to 1.
Rows are AEZs from AEZ1 to AEZ18.
Columns R1 to R19 represent the following regions, respectively: USA, EU27, Brazil, Canada, Japan, China, India, C-America, S-America, E-Asia, Mala-Indo, R-SE-Asia, R-S-Asia, Russia, E-Europe-RFSU, Other Europe, M-East-N-Africa, Sub-Saharan Africa, Oceania.

GTAP ADV BIO is configured with economic sectors for each biofuel. The sector includes all of the direct and indirect economic inputs associated with feedstock and fuel production as well as fuel distribution. The initial GTAP BIO models were developed from econometric data for the corn ethanol and sugarcane ethanol industries. The fuel production yields in Table 3.7 are derived from economic statistics and are consistent with process data from engineering studies.

Table 3.7. Feedstock Conversion Rates in GTAP.

Category	Feedstock	Biofuel Yield
Starch Ethanol	Corn	2.7 gal/ bushel
Sugarcane Ethanol	Sugarcane	24 gal/tonne
Biodiesel	Soybean Oil	11.4 pounds/ bushel
Cellulosic	Stover, Miscanthus, Switchgrass	60 gal biogasoline or 75 gal ethanol per dry ton

3.4 FASOM

The Forest and Agricultural Sector Optimization Model (FASOM) is a partial equilibrium model of forest, agriculture, and livestock for the United States. Within the model the linked agricultural and forestry sectors compete for a portion of the land base in the United States. Prices for agricultural and forest sector commodities and land are endogenously determined given demand functions and supply processes.

The FASOM model maximizes the net present value of the sum of consumers' and producers' surpluses (for each sector) with producers' surplus estimated as the net returns from forest and agricultural sector activities. Farmers and timberland owners are assumed to have perfect foresight regarding the consequences of their own behavior regarding future land use. The model provides estimates of economic welfare disaggregated by agricultural producers, timberland owners, consumers of agricultural products, and purchasers of timber.

FASOM can model the forest or agricultural sectors either independently or simultaneously. The modeling system is designed to provide information about the effects of a wide range of potential policies on carbon sequestration, market prices, land allocation, and consumer and producer welfare under alternative supply and demand scenarios and producer eligibility-participation constraints.

Key differences between FASOM and GTAP are that (1) FASOM is a partial equilibrium model while GTAP is a general equilibrium model, (2) FASOM is a dynamic model that can simulate changes over a long period of time, while GTAP is generally run in a static mode, (3) FASOM models the U.S. while GTAP models the world, and (4) FASOM contains very detailed modeling of the interaction between different types of forests, crops and livestock, where these interactions in GTAP are much more general in nature. Since the conversion of forests is the primary driver of land use change emissions, the fourth distinction is a very significant one.

The rest of this section is divided into the following subsections:

- History and Uses
- Model Structure
- Key Drivers of Land Use Change in FASOM
  - How much land is converted
  - What type of land is converted

3.4.1 History and Uses

The current version of FASOM reflects numerous model enhancements that have been made over time, dating back to the first version of the Agricultural Sector Model (ASM, Beach and McCarl, 2010). ASM has been used for analyses of renewable fuel production dating back to the late 1970s and 1980s. In addition, ASM was applied to study ozone impacts, acid rain, soil conservation policy, global climate change impacts, and GHG mitigation.

One of the drivers behind integrating ASM with forest-sector models to create FASOM was an ASM study examining issues regarding joint forestry and agricultural GHG mitigation. Attempting to reconcile forestry production possibilities with the static single-year equilibrium representation in ASM led to the recognition that the model did not adequately reflect a number of dynamic issues associated with land allocation between forestry and agriculture. Thus, the initial FASOM model was constructed to address these limitations by linking a model of the forest sector with a version of the ASM model in a dynamic framework, allowing some portion of the land base in each sector to be shifted to the alternative use. Land could transfer between sectors based on its marginal profitability in all alternative forest and agricultural uses over the time horizon of the model. Management investment decisions in both sectors, including harvest timing in forestry, were made endogenous, so they too would be based on the expected profitability of an additional dollar spent on expanding future output.

Modeling of the forest sector was based on the family of models developed to support the timber assessment component of the U.S. Forest Service's decennial Forest and Rangeland Renewable Resources Planning Act (RPA) assessment process. These models included TAMM (Timber Assessment Market Model), NAPAP (North American Pulp and Paper model), ATLAS (Aggregate Timberland Assessment System), and Area Change (AREACHANGE).

GHG accounting for CO_2 and major non-CO_2 GHGs was added into a model denoted FASOMGHG. The forest carbon accounting component of FASOM is derived from the Forestry Carbon (FORCARB) modeling system, which is an empirical model of forest carbon budgets simulated across regions, forest types, land classes, forest age classes, ownership groups, and carbon pools. The U.S. Forest Service uses FORCARB, in conjunction with their economic forest-sector models, to estimate the total amount of carbon stored in U.S. forests.

Following the inclusion of forest carbon accounting and some limited coverage of soil carbon changes associated with land use change, work began to widen the coverage of agricultural GHG sources and management possibilities for mitigating GHG. The model was expanded to account for numerous categories of GHGs and to include a set of agricultural-related GHG management possibilities. That work expanded ASM to include changes in tillage, land use exchange between pasture and crops, afforestation, nitrogen fertilization alternatives, enteric fermentation, manure management, renewable fuel offsets, fossil fuel use reduction, and changes in rice cultivation. The resulting model was labeled ASMGHG.

The dynamic modeling and forest carbon sequestration coverage included in FASOM and the agricultural coverage in ASMGHG were included as agricultural alternatives into the FASOMGHG structure. In that work, the agricultural model was expanded to have all the GHG management alternatives in ASMGHG with the additional coverage of dynamics. More recently, additional model modifications have been made to enhance FASOM's ability to provide detailed analyses of the agricultural and environmental impacts of large-scale renewable fuel production under the Energy Independence and Security Act (EISA).

Clearly FASOM can and has been used to estimate GHG impacts of many more processes than just land use change. For example, FASOM was used by EPA in the RFS2 analysis (EPA, 2010) to estimate changes in domestic agriculture, including changes in nitrogen application rates of all crops, changes in rice methane, and changes in enteric fermentation in addition to land use change. We limit our discussion here to the land use change modeling. Table 3.8 summarizes the biofuel shocks used for corn ethanol, soybean biodiesel, and switchgrass ethanol and domestic (U.S.) land use changes estimated by FASOM for the RFS2. We also show the estimated land use change emissions in kg CO_2 per million Btu of biofuel, annualized over 30 years as estimated by the EPA.

Table 3.8. Biofuel Volume Shocks and FASOM-Estimated Land Use Changes in the U.S.[a]

Biofuel	Units	Corn Ethanol	Soybean Biodiesel	Switchgrass Ethanol
Biofuel Volume	bgy	3.7	0.5	7.9
Cropland Change	million acres	0.9	1.2	2.2
Cropland Pasture Change	million acres	-0.9	-1.0	-1.5
Forest Pasture Change	million acres	0.2	0.2	0.6
Forest Change	million acres	-0.03	-0.2	-0.6
LUC	kg CO_2/mmBtu	-4.0	-8.9	-2.5

[a] International LUC estimates for EPA RFS2 analysis are shown Table 3.13

In the corn ethanol scenario, the volume of ethanol modeled was a 3.7 bgy increase. FASOM predicted that this would have resulted in 0.9 million more acres total in crops, 0.9 million less acres in cropland/pasture, 0.2 million more acres of forest/pasture, and 0.03 million less acres of private forest in the United States. The net *domestic* land use change emissions are negative, at -4.0 kg CO_2eq/mmbtu of ethanol. However, as described in the next section, the international estimates prepared with FAPRI offset the negative results modeled with FASOM leading to an over positive LUC.

We note that while cropland increased in all three cases, and forestlands decreased, the land use change emissions estimated by FASOM are actually negative. This means that domestically, the land use changes brought about by the various biofuel scenarios are actually reducing GHGs, rather than increasing GHGs. This is opposed to the conclusions of other modeling efforts such as GTAP.

3.4.2 FASOM Model Structure

Examining the dynamic effects of policies affecting the forestry and agricultural sectors requires an analytical framework that can simulate the time path of market and environmental impacts. FASOM simulates a dynamic baseline and changes from that baseline in response to changes in public policy or other factors. FASOM combines models of agricultural crop and livestock production, renewable fuels production, livestock feeding, agricultural processing, log production, forest processing, carbon sequestration, GHG emissions, wood product markets, agricultural markets, GHG payments, and land use to capture the mix of biophysical and economic processes that will determine the technical, economic, and environmental implications of changes in policies. FASOM covers private timberlands and all agricultural activity across the lower 48 United States, broken into 11 market regions. Finally, FASOM tracks five forest product categories and more than 2,000 production possibilities for field crops, livestock, and renewable fuel.

FASOM assumes profit-maximizing behavior by landowners. Landowners are assumed to have perfect foresight and base decisions in a given period on the net present value of the future returns to alternative activities. For instance, the decision to continue growing a stand rather than harvesting it now is based on a comparison of the net present value of timber harvests from future periods versus the net present value of harvesting now and replanting (or not replanting and shifting the land to agricultural use). Similarly, landowners make a decision to keep their land in agriculture vs. afforestation based on a comparison of the net present value of returns in agriculture and forestry. Land can also move between cropland and pasture depending on relative returns. This process establishes an equilibrium price for land across the sectors and a link between commodity prices in the two sectors.

The model solution portrays market equilibrium over an extended time (up to 100 years), on a 5-year time step basis when running the combined agriculture-forest version of the model. Results yield a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic factors within these sectors.

The conceptual framework of the agricultural sector in FASOM is presented in Figure 3.6. Land, water, labor, natural resources, and other resources (e.g., fertilizer, capital) are used to produce raw primary commodities, including renewable fuels feedstocks. These primary commodities may move directly to markets or they may be used as inputs to processing activities generating secondary commodities (e.g., renewable fuels), as direct livestock feed, or in the production of blended livestock feeds. The primary and secondary commodities, renewable fuels, blended feeds, and imports go to meeting household demand, other domestic demand, livestock feeding, and exports.

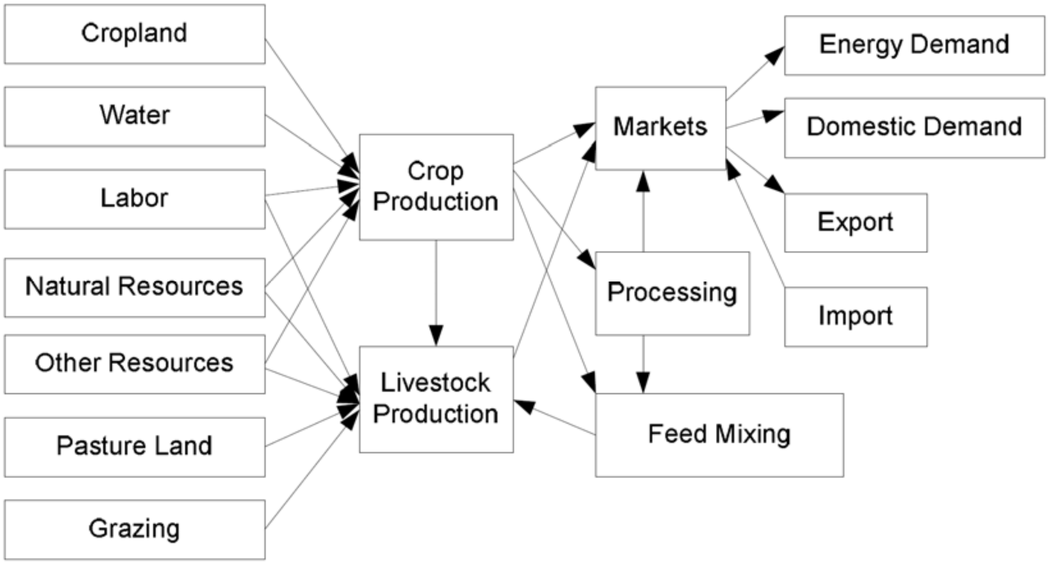

Figure 3.6. FASOM Agricultural Sector Modeling Structure.

FASOM divides the United States into 11 geographical market regions, as shown in Figure 3.7. International regions are generally defined more simplistically, with individual region-level supply and demand curves specified only for the commodities with the largest trade volumes, such as corn, wheat, soybeans, sorghum, and rice. In addition, only certain regions are defined for exporters and importers of a given commodity. In cases where commodities are traded in markets, then the regions that can supply and demand that commodity in the model can either export them to another explicit region or to the United States. Similarly, demand in a region can be met through imports from the United States or from other countries. The model solves for the spatial market equilibrium and trading patterns for these heavily traded commodities.

Figure 3.7. Map of FASOM Regions.

For many other commodities (e.g., cotton, oats, barley, beef, pork, poultry), trade is modeled as total excess import supply and export demand functions facing the United States rather than individual region supply and demand. In these cases, there are single curves representing the import supply and export demand facing the United States. In addition, there are many commodities without any explicit opportunities for international trade, such as hay, silage, citrus fruits, energy crops, and livestock, among others. Generally, trade is not explicitly modeled for commodities where international trade volumes for the United States are small or the commodity is not actively traded.

FASOM incorporates a number of assumptions regarding changes in yields, production costs, and demand over time. Assumed rates of technological progress that vary by commodity are included based on historical yield growth and projections of future yields. In addition, certain processing activities, particularly those that rely on relatively new technologies, are expected to experience increases in production efficiency and corresponding reductions in processing costs in the future. For these activities (e.g., cellulosic ethanol production), processing yields and production costs are assumed to change over time at rates that vary by process. Finally, domestic and export demand are assumed to change over time at growth rates that vary across commodities based on historical experience and USDA projections.

Simultaneous changes assumed for each of these variables over time are reflected in the baseline simulation. Changes in yield, production and processing costs, and demand over time will alter the relative returns to production of different commodities and will affect producer decisions. Other things being equal, for commodities where demand is growing faster than productivity, real prices will tend to increase over time. For commodities where demand growth is slower than productivity improvements, real prices will generally trend downward. These changes in relative returns will lead to shifts in land allocation and production practices until a new equilibrium is reached.

3.4.3 Key Drivers of Land Use Change Estimates in FASOM

Key drivers affecting land use change emissions in FASOM are how much land is converted to new uses and the type of land converted. Factors affecting the amount of land converted (normalized to biofuel volume) are:

- Crop yields on existing and new land
- Biofuel production yields
- Biofuel production plant co-product substitution for primary crops

A primary factor affecting the average emissions from land converted is the land cover type, i.e., how much carbon is stored above and below ground before and after conversion. In the following sections, we discuss the input data itemized above and summarize FASOM's land type definitions and substitution rules.

Key Input Data Affecting Amount of Land Converted

Assumed crop yields directly affect the amount of land converted. In the RFS modeling, FASOM was run for a Control case that included the RFS volumes of biofuels and also various Reference cases that simulated base cases with lower biofuel volumes for each type of biofuel. The difference in the two cases (Control and Reference) was the land use amounts attributed to each biofuel. Both cases – Control and Reference – were run with the same future crop yields. In addition, a higher crop yield scenario was also run for the Control and Reference cases, and these higher yield runs showed that crop yield assumptions do influence the amount of total domestic land converted.

FASOM does not include a price-yield effect, but landowners can switch from dryland to irrigated production, change tillage practices, or make other management decisions in response to price. FASOM also assumes that land converted from non-crop uses (from forest, or cropland pasture, or pasture) to crops had the same yield as the yields of existing crops. Yields estimated for various crops in the FASOM modeling are shown in Table 3.9 (Beach and McCarl, 2010). Biofuel plant yields also affect the amount of land converted. Selected biofuel plant yields assumed in the FASOM modeling are shown in Table 3.10. The biofuel plant yields shown in Table 3.10 are constant across all years.

Finally, biofuel plants produce co-products that can substitute for grains, and this also reduces the total amount of land converted. Distillers' grains and solubles (DGS) from corn ethanol plants, for example, replace corn and soybean meal in livestock feed. For the RFS, FASOM included major updates to the replacement rates that distillers grains from corn ethanol plants have on livestock rations. There are four primary co-products of the starch-to-ethanol process tracked within FASOM: DGS, gluten meal, gluten feed, and corn oil. FASOM includes feed substitution using DGS as a corn and soybean meal replacement possibility.

FASOM utilizes DGS substitution rates from research conducted by Argonne National Laboratory. FASOM assumes that replacement rates increase over time from a 1:1 replacement rate of DGS for corn and soybean meal initially to maximum technological replacement rate of 1:1.196 in 2017 for beef and dairy cattle (1 lb DGS substitutes for 1.196 lbs corn and soybean meal). FASOM uses a 1:1 replacement rate throughout the entire modeling timeframe for swine and poultry. FASOM also implements maximum DGS inclusion rates in livestock feed as a percentage of total feed based on the Argonne study. These limits vary by species and are assumed to increase between 2007 and 2017, reaching maximum levels of 50% for beef cattle, 30% for dairy cattle, and 25% for swine and poultry by 2017.

It is important to note that DGS produced as a byproduct of a dry mill ethanol production process with corn oil fractionation/extraction has different nutritional characteristics than traditional DGS, which contains higher levels of oil. Therefore, the proportion of soybean meal vs corn replaced by fractionated/extracted DGS is higher than for traditional DGS when used for swine or poultry feed, although the total replacement rate of DGS for a combination of corn and soybean meal remains at 1:1.

Table 3.9. FASOM National Average Yields for Major Commodities Used in the RFS.

Commodity	Units	2022 Yield (units/acre)	Annual Yield Growth (%)
Barley	bu	57.3	0.1
Corn	bu	186.3	1.62
Cotton	480 lb bale	1.7	0.43
Hay	ton	3.2	0.84
Hybrid Poplar	dry tons	4.6	0.75
Oats	bu	60.6	0.02
Rice	100 lb	79.2	1.33
Silage	tons	19.8	1.90
Sorghum	100 lb	63.5	0.09
Soybeans	bu	45.3	0.43
Switchgrass	dry ton	9.1	2.04
Sugarcane	tons	38.3	0.00
Willow	dry ton	4.2	0.75
Wheat, Durham	bu	34.9	1.11
Wheat, Hard Red Spring	bu	44.0	1.00
Wheat, Hard Red Winter	bu	73.1	1.31
Wheat, soft white	bu	78.3	1.11

Table 3.10. Feedstock Conversion Rates in FASOM.

Category	Crop	Biofuel Yield (all years)
Starch and Sugar-Based Ethanol Production	Barley	1.66 gal/bu
	Corn (dry mill)	2.71 gal/bu
	Corn (wet mill)	2.50 gal/bu
	Sorghum	4.25 gal/cwt
Biodiesel Production	Soybean Oil	0.13 gal/lb
	Corn Oil	1.02 gal/gal
Cellulosic Ethanol Production	Corn crop residue	92.3 gal/dry ton
	Sorghum crop residue	92.3 gal/dry ton
	Switchgrass	92.3 gal/dry ton

Because of the different effects on animal feed, FASOM applies different replacement rates for fractionated/extracted DGS and traditional DGS when used in swine and poultry feed. The production of co-products by feedstock used in the FASOM model are shown in Table 3.11.

We should note that the authors have previously attempted to validate these inputs in FASOM and to determine how much of an effect displacement ratios have on reducing land use change estimates. However, many of the RFS changes are hidden in special files in FASOM that cannot be viewed. Therefore, currently it is not possible to determine the size of these effects on land use changes, and to verify how these changes are implemented in the model.

Table 3.11. Co-products Produced by Feedstock.

Crop	Gluten Feed (lb/bu)	Gluten Meal (lb/bu)	Corn Oil (gal/bu)	DGS (lb/bu)
Barley	n/a	n/a	n/a	14.6
Corn – wet mill	13.5	2.5	0.2078	n/a
Corn – dry mill, no corn oil	n/a	n/a	n/a	17.0
Corn – dry mill, fractionation	n/a	n/a	0.1439	15.9
Corn – dry mill, extraction	n/a	n/a	0.1929	15.5
Oats	n/a	n/a	n/a	9.7
Rice	n/a	n/a	n/a	30.4
Sorghum	n/a	n/a	n/a	30.4
Wheat	n/a	n/a	n/a	18.2

Land Types and Substitution Rules

FASOM includes all cropland, pastureland, rangeland, and private timberland throughout the conterminous United States. Land categories included in the model are based on USDA Economic Research Service land use data.

Cropland is actively managed cropland, used for both traditional crops (e.g., corn and soybeans) and dedicated energy crops. Crop tillage systems in FASOM include conventional tillage, conservation tillage, and no-till. Cropland pasture is managed pastureland used for livestock production, but which can also be converted to cropland production. Forestland contains a number of sub-categories, tracking the number of acres both newly and continually harvested, the number of acres harvested and converted from other land uses, as well as the amount of forest acres on public land. Forest pasture is unmanaged pastureland with varying amounts of tree cover that can be used to raise livestock. A portion of this land may be used for timber harvest. Rangeland is unmanaged land that can be used for livestock grazing production. While the amount of rangeland idled or used for production may vary, rangeland may not be used for any other purpose other than animal grazing. For each of these categories, FASOM accounts for how much is actively used in production and how much is idled in a particular time period.

Also included in FASOM is Conservation Reserve Program (CRP) land and Developed land. CRP land is specified as land that is voluntarily taken out of crop production and enrolled in the USDA's Conservation Resource Program. Land can flow in and out of CRP in FASOM depending on relative economic returns. FASOM generally holds CRP land area fixed at initial levels, but for the EISA analysis, CRP land is permitted to convert back to cropland under the constraint that a minimum of 32 million acres of land remains in the CRP to be consistent with the 2008 Farm Bill and USDA assumptions.

Developed (urban) land is assumed to increase over time at an exogenous rate for each region based on projected changes in population and economic growth.

In other models such as GTAP, land transfers are in part controlled by a Continuous Elasticity of Transformation (CET) between land types. There is no CET function in FASOM; land transfers between uses are governed by relative economic returns.

In addition to the endogenous land allocation decision, land also moves out of agricultural and forestry uses into developed uses (e.g., shopping centers, housing, and other developed and infrastructural uses) at an exogenous rate. Thus, although land can move between forest, cropland, and pasture, the total land area devoted to agricultural and forestry production is trending downward over time as more land is developed.

3.5 FAPRI

The Food and Agricultural Policy Research Institute (FAPRI) was established in 1984 by a grant from U.S. Congress. The program is housed at Iowa State University and the University of Missouri-Columbia. At Iowa State University, the Center for Agricultural and Rural Development (CARD) is the affiliated research center for FAPRI. The Center for National Food and Agricultural Policy (CNFAP) manages FAPRI's research activities at the University of Missouri-Columbia. For legal purposes, the model is called the CARD Model when it is run by Iowa State University and the FAPRI Model when it is run jointly by Iowa State and Missouri. For this report, we refer to the model as the FAPRI Model.

3.5.1 History and Uses

Since its inception, the model has been used to evaluate the impacts of global agricultural policies including U.S. farm bills and World Trade Organization (WTO) talks (Elobeid et al., 2012). In recent years, the model was used to evaluate the Renewable Fuel Standard (RFS 2) from the EPA, the LCFS from the ARB, and the impact of removing distortions in the U.S. ethanol market (Elobeid and Tokgoz, 2008). The most cited use of the FAPRI model is certainly the *Science* article by Searchinger et al. (2008) which shows the influence of U.S. biofuel policy on land use change and greenhouse gas emissions. In addition to the aforementioned agencies, the USDA and several commodity groups are using the model as well (Elobeid et al., 2012).

Every year, the model projects a baseline over 10 to 15 years which includes all relevant policy provisions that are in place at the time of the baseline. This baseline represents the benchmark for all policy analysis. Once the baseline is established, the model can be shocked with different policies or different exogenous projections. For example, the baseline includes a particular evolution of the crude oil price. If the modelers are interested in a different evolution of the crude oil price, e.g., a high crude oil price, then the model assesses this scenario and provides the agricultural output under the new assumption. Based on the difference between the baseline and scenario, the impact of a high crude oil price can be assessed.

Initially, the model was used to project commodity prices and to determine the impact of agricultural policies (e.g., subsidies, taxes, import restrictions, tariffs, etc.) on agricultural prices and output. However, the model has recently been utilized to evaluate land use change as a result of increased biofuel consumption in the United States as a consequence of the EPA's renewable fuel standard. This move towards the evaluation of land use change due to biofuel policies started in 2007 when Tokgoz et al. (2007) assessed the implications of increased U.S. ethanol production on prices, acreage, and livestock in the U.S. and globally. They assumed an increase in the crude oil price of $10 per barrel over the projection period and compared the resulting increase in ethanol production to their baseline scenario. The results of the model indicated that the additional production of 55.9 billion liters of corn ethanol would bring in an extra 10.8 million ha of cropland globally in 2016. This increase in ethanol production and the associated land use change was then used by Searchinger et al. (2008) to calculate the carbon emissions from land conversion of the additional cropland. The carbon loss due to this increase amounted to 3.8 billion tons of CO_2 equivalents. Those findings led to increased scrutiny concerning the effects of an increase in biofuel production on LUC and its associated emissions.

In the months and years following the Searchinger et al. (2008) article, a number of changes and extensions have been made to the FAPRI model to capture the interactions between agriculture, land use, and GHG emissions. Based on those additions, new baselines and scenarios were assessed to provide a sensitivity analysis of the Searchinger et al. (2008) results. The most important of these changes and additions are endogenous energy prices, endogenous yields, the Brazil Model and the Greenhouse Gases from Agriculture Simulation Model (GreenAgSiM).

Based on the research by Du and Hayes (2011), the FAPRI model incorporates endogenous gasoline prices. Specifically, an increase in the production of ethanol leads to a reduction in the price of gasoline from 0.73 to 1.69 per gallon for ethanol volumes and crude oil prices in 2011. This decrease in the price of gasoline makes the investment in ethanol plants and ethanol production less attractive. The second change that was incorporated was endogenous variable agricultural production costs. Direct energy such as fuel and indirect energy such as nitrogen are important inputs in the production of agricultural commodities. In Searchinger et al. (2008), the ethanol expansion was caused by high crude oil prices. With the production costs linked to the price of crude oil, the effect on land use change is going to be reduced because higher production cost make it less attractive to the landowner to increase production. Both changes were incorporated into the FAPRI Model with the 2008 agricultural baseline. In addition, the Energy Act of 2007 and the 2008 Farm Bill were taken into account, and a crude oil price of $75 per barrel was assumed.

Besides the 2008 baseline, a high energy price scenario was simulated which assumed an increase in crude oil prices by 40%, to $105 per barrel, and a 19% increase in natural gas prices (Hayes et al., 2009). This high energy price scenario is comparable to the fall 2007 high crude oil price scenario used by Searchinger et al. (2008) in the sense that both induce increased ethanol production through higher energy prices. However, these two scenarios are not exactly equivalent because the 2007 high crude oil price scenario was a “no bottleneck” scenario and the scenario used in Hayes et al. (2009) was a “bottleneck” scenario. “No bottleneck” in the adoption and distribution of ethanol leads to higher expansion in ethanol demand than in the “bottleneck” scenario. In the high energy price scenario, ethanol production increased by 29,859 million liters, which caused the conversion of 6.076 million ha to cropland. The endogenous energy prices have the effect that less land gets converted from native vegetation to cropland. If the price of crude oil increases, then the demand for the gasoline substitute ethanol increases. However, because the high crude oil price also influences the production/input cost of the farmer, less land gets converted. Despite the lower land conversion, the per gallon of ethanol cropland conversion did not change significantly from the Tokgoz et al. (2007) analysis to the (Hayes et al., 2009) meaning that the emissions per megajoule of ethanol remained almost unchanged (Dumortier et al., 2011).

Keeney and Hertel (2008) and Hertel et al. (2010) reject the hypothesis that a higher yield commodity price does not lead to higher yields in the long run. It is not clear what the exact mechanism is, but yields increase at a higher rate when commodity prices are higher. One explanation might be that seed companies invest more in research because farmers are willing to pay a higher price of high yielding commodities. It is also possible, that farmers use more precision farming when commodity prices are higher. Dumortier et al. (2011) incorporate the concept of endogenous yields ad-hoc and show that yield increases above the baseline have a significant effect on LUC in the sense that less land is used for the same amount of ethanol. Table 3.12 shows the yield elasticities with respect to output price used in the Dumortier et al. (2011) paper. In the later versions of the FAPRI Model, yield elasticities were explicitly incorporated in the model based on historical estimates.

Table 3.12. Yield Elasticities with Respect to Output Price.

Country/Crop	Barley	Corn	Sorghum	Soybeans	Wheat
Argentina	0.120	0.120	0.120	0.217	0.120
Australia	0.180	0.210	0.180	0.097	0.200
Brazil	0.110	0.110	0.110	0.218	0.110
Canada	0.150	0.150	0.150	0.070	0.180
China	0.110	0.110	0.110	0.071	0.110
European Union	0.150	0.150	0.150	0.170	0.090
Japan	0.200	0.000	0.200	0.200	0.200
Korea (South)	0.100	0.090	0.100	0.050	0.150
Mexico	0.180	0.160	0.180	0.018	0.140
United States	0.000	0.020	0.000	0.100	0.000
Rest of the World	0.120	0.120	0.120	0.010	0.120

The changes made to the FAPRI Model in terms of endogenous energy prices and yields are important to capture changing production technology and cost. Two important additions are the GHG model called GreenAgSiM and the Brazil Model. GreenAgSiM is a component of the FAPRI Model used to measure GHG emissions from agricultural production (livestock and crop management) and land use change based on the FAPRI Model output. The Brazil Model has been added because that country is important in all aspects of agricultural production and land use change. Most of the GHG emissions in Searchinger at al. (2008) were generated in Brazil. It is a major agricultural producer in terms of crop commodities as well as ethanol. In addition, the Brazilian cattle herd of almost 200 million head is twice as much as the herd in the United States. Brazil is also important because its agricultural production is situated very close to the frontier of the carbon-rich rain forest.

GreenAgSiM was first used in Dumortier et al. (2011) to re-evaluate the policies on emissions from corn ethanol. The key result was that emissions from land use change are highly sensitive to assumptions on yield increase. A slight change in yield leads to significant differences in emissions caused by land use change. Furthermore, their analysis did not find strong evidence of deforestation in the United States. Only grassland/CRP land comes out of production, which leads to a further decrease in emissions. The Brazil model was used for the first time by Dumortier et al. (2012) to model the effects of a U.S. cattle production tax on global livestock production. The Brazil model is special in the FAPRI Model because it models pasture explicitly; pasture area is an output of the model.

The FAPRI model was used together with the FASOM model to evaluate the RFS2 by the EPA. The workings of the FAPRI model described so far include the domestic as well as the international components of the model. The FASOM model by Bruce McCarl is more detailed at the U.S. level; it includes the forestry as well as wood processing sectors. It can also model carbon policies endogenously. Because of the FASOM model's level of detail, EPA used it to evaluate the domestic aspects of the RFS2, but used the FAPRI model to evaluate the international land use changes. The FASOM and FAPRI models do not connect at all, i.e., there is no communication between the models. Table 3.13 provides the results of the FAPRI modeling of international land use change in the RFS2 (EPA, 2010).

Table 3.13. Biofuel Shocks and FAPRI Estimated International LUC in RFS2 Analysis.

	Units	Corn Ethanol	Soybean Biodiesel	Switchgrass Ethanol
Change in Biofuel Volume Modeled	bgy	2.6	0.5	7.9
Cropland Change	million acres	1.949	1.675	3.355
Pasture Change	million acres	-1.102	-0.662	-1.433
Forest Change	million acres			
CRP Change	million acres			
LUC	kg CO_2e/mmBtu	31.79	42.54	15.07

EPA RIA Table 2.4-29

3.5.2 FAPRI Model Structure

The FAPRI model is a partial equilibrium model and includes three major agricultural sectors: cropland, livestock, and the biofuel industry. Each of those three sectors is further subdivided into separate modules. As noted in the previous sections, the FAPRI Model is constantly evolving and being extended to take significant policy developments into account. The biofuel component was developed for the EISA, and the Brazil Model was added because of the country's importance with respect to biofuel, land use change, pasture, and greenhouse gas emissions. Figure 3.8 represents a detailed graphical representation of the FAPRI model and its subcomponents.

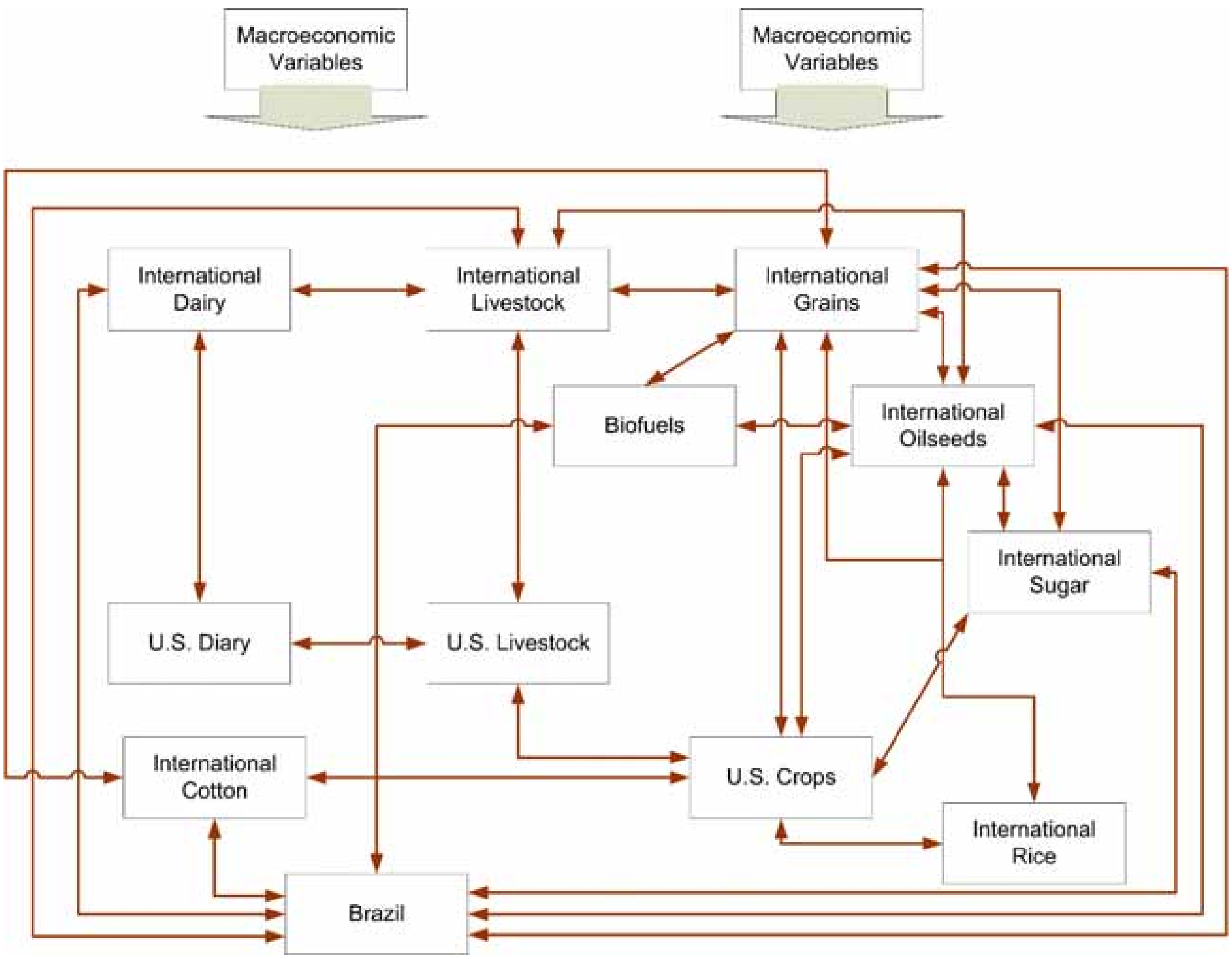

Figure 3.8. FAPRI Model Modules.

The crops covered are corn, wheat, sorghum, barley, soybeans, rapeseed, sunflower, sugar, rice, rapeseed, oats, and groundnuts. The livestock coverage includes cattle, poultry, and pork; beef is subdivided into categories such as beef cattle, dairy cows, and Kobe beef (Japan). The dairy sector covers milk, cheese, and butter. Note that major efforts are put on the main commodities, corn, soybeans, wheat, rice, and sugar as well as on biofuels (ethanol and biodiesel) and livestock. The exogenous variables (or inputs) to the model are population, Gross Domestic Product (GDP), GDP deflator, inflation, exchange rates, trade and agricultural policies for each country and each year over the projection period. The endogenous variables (output) are production, consumption, prices, trade flows.

The FAPRI model is solving for a set of world prices that make each market clear. Based on the optimization, the resulting price matrix that is fed into all the sub-models represented in Figure 3.8 equalizes supply and demand across all the sub-components. For example, the biofuel model communicates with the U.S. crop model as well as the international models. This interaction among the model components is represented by the red arrows in Figure 3.8. The FAPRI model checks whether the supply and demand for all markets is zero. If that is not the case, the model continues to search for a solution. The model is written in Microsoft Excel which uses a simplex solver to find the equilibrium in world commodity prices. This Excel feature enables the solution to linear programming systems through iteration. For the Brazil subcomponent, there is a price transmission system to the different states based on local transportation and production costs. From a computational perspective, solving for a world price and then adjusting prices in each country based on inflation, exchange rates, and production cost is also easier and less time consuming.

What makes the FAPRI Model a valuable tool for policy analysis is its global coverage: all major countries are modeled individually and smaller countries are grouped into regions, e.g., “Other Africa”, “Other Asia”, etc. In some older versions of the model, a category “Rest of the World” exists but the countries in that category were redistributed to the other categories including the “Other”. Note that the countries that are explicitly modeled also depend on the commodity. If a country is an important producer of one or two particular crops but not for other commodities, the country is in the category “Other” for all other crops. All commodities are also treated identically, i.e., corn is the same commodity no matter where it is grown.

The sub-models for the United States as well as Brazil are the sub-national level, i.e., the states in the United States and six regions in Brazil. Figure 3.9 depicts Brazil's six regions. The subdivision takes regional agricultural production practices into account. Some of the municipalities in the region of Mato Grosso (“Split”) are allocated to the Amazon biome to take the agricultural frontier into account.

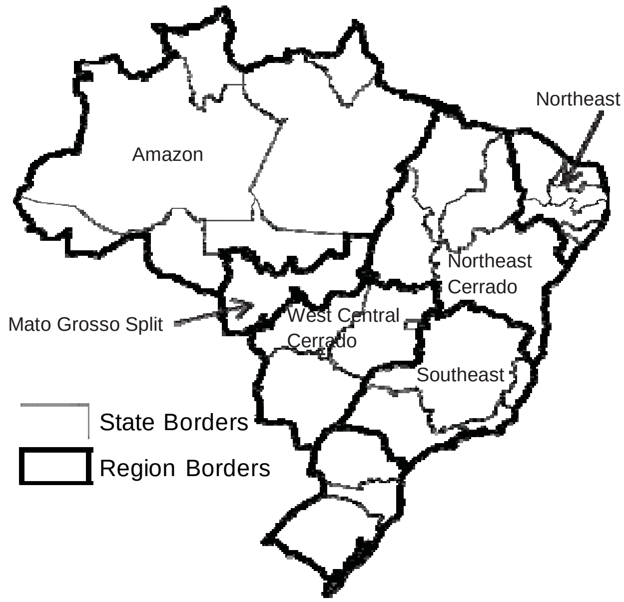

Figure 3.9. Regions in the FAPRI Brazil Model.

Figure 3.10 shows the interaction between GreenAgSiM and the FAPRI Model (referred to as CARD Model in the figure). The figure includes the major components necessary for the GHG model. The output of the FAPRI model is in yearly time steps which makes the transition path to the equilibrium more explicit. Another major advantage of this approach is that policies that are put into effect (or phased out) in different countries in different years can be modeled, and the effect can be interpreted. For example if one country restricts commodity exports in 2016, and another country is planning to remove import restrictions on biofuels in 2019, then the FAPRI model can trace these effects year-by-year if the projection goes out to 2025. The calibration of the FAPRI model is based on historical data and estimation of the relevant parameters based on that data.

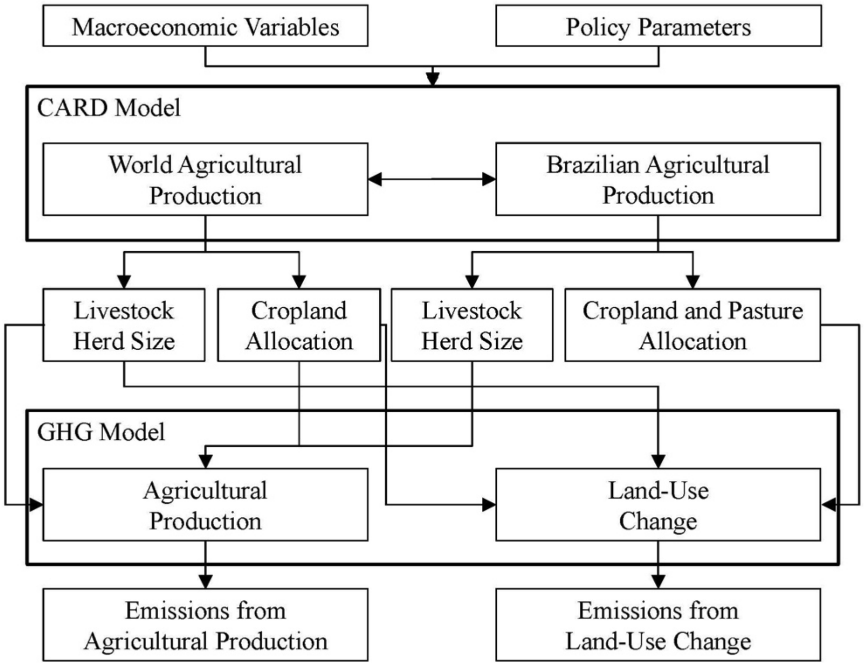

Figure 3.10. Interaction between FAPRI and GreenAgSiM.

3.5.3 Key Drivers of Land Use Change Estimates in FAPRI

As mentioned above, the FAPRI model includes neither a forestry sector model nor an endogenous carbon model. The LUC and GHG impacts were calculated ad hoc in the EPA analysis using coefficients from Winrock International. The FAPRI Model provides cropland as an output (among a multitude of other agricultural outputs) and the use of forestry is inferred from the cropland expansion. In addition, carbon policies cannot influence the agricultural sector. Efforts are underway to allow for more explicit carbon modeling. To calculate the impact of the forest carbon offset policies mentioned before, land was taken exogenously out of production based on calculations from the EPA (which in turn was using the FASOM model to calculate crop production impacts).

After the Searchinger et al. (2008) paper appeared, the need for an internal GHG model became apparent. The goal was to develop a model that predicts carbon stock changes from LUC as well as emissions from agricultural production. The result of those efforts was the Greenhouse Gases from Agricultural Simulation Model (GreenAgSiM). The model is completely based on the CARD Agricultural Outlook Model from which it receives all the necessary inputs. The interaction between FAPRI and GreenAgSiM is illustrated in Figure 3.10. Since GreenAgSiM is based on the CARD Model, it is global in scale. The model is composed of two modules: Agricultural Production and Land Use Change.

Land use change determines the emissions due to shifts in and out of cropland while tracking the status of idle cropland and native vegetation. Cropland is directly calculated as an output of the FAPRI Model and used as an input for GreenAgSiM. The model has evolved from its first use in Dumortier et al. (2011) to Dumortier et al. (2012). In the first version, only the land use change component was included. To capture spatial heterogeneity, large countries such as

Brazil, China, U.S., etc., are subdivided into their states. In total, 518 spatial units were defined in GreenAgSiM with their individual shares of bio-physical systems and crop production. The crop production at the state level is derived from the FAO Agro Mapping of Agricultural Production Systems (Agro MAPS) database. This leads to different carbon emissions from land use change depending on which crop is expanded/contracted. The model tracks of land use dynamics (especially movements in and out of idle cropland) and estimates the use of native vegetation.

LUC is seen to be the biggest problem and challenge in assessing GHG emissions from agriculture. The expansion of cropland into grassland and forests causes the release of carbon stored in soil and biomass. It is very difficult to measure LUC explicitly because the only way to measure it is through remote sensing, i.e., satellite imagery. The attribution of LUC to specific activities presents further challenges in validating LUC models. Consistent time-series data from remote sensing are not available on a global scale at this time. The calculation of LUC-related emissions is done in two steps. First, the land use dynamics are calculated based on output from the CARD (FAPRI) Model. In a second step, carbon emissions based on land dynamics and bio-physical conditions are computed. The two sources/sinks of carbon in GreenAgSiM are biomass and soil.

Each country in the FAPRI model is assumed to have a deterministic yield growth based on historic estimates. If land gets converted from native vegetation or set-aside land, this new land is assumed to have the same yield as all other land. In reality, this might be a restrictive assumption but insufficient data at the global scale requires this approach. Expansion onto new lands is referred to as the extensive margin as the land area represents an extension of existing land resources. Land changes due to yield improvements are referred to as the intensive margin as the intensity of land productivity is affected.

Key Assumptions Affecting How Much Land is Converted

The yield of biofuel in gallons per bushel is exogenous to the model. The crop yield per acre, crop to biofuel yield, and co-product yields are shown in Figures 3.14 to 3.16 respectively. FAPRI assumptions include a slight increase in crop yield over the projection period. The FAPRI model does not allow for ethanol plants to become more efficient if the price of the feedstock or other production inputs (crude oil) increases. This attribute differs from GTAP, where industry sectors respond to price.

Table 3.14. FAPRI Average Yields for Major Commodities Used in the RFS.

Commodity	Units	2022 Yield (units/acre)[a]	Annual Yield Growth (%)
Barley	bu	57.3	0.1
Corn	bu	186.3	1.62
Cotton	480 lb bales	1.7	0.43
Hay	tons	3.2	0.84
Hybrid Poplar	Dry tons	4.6	0.75
Oats	bu	60.6	0.02
Rice	100 lb	79.2	1.33
Silage	tons	19.8	1.90
Sorghum	100 lb	63.5	0.09
Soybeans	bu	45.3	0.43
Switchgrass	dry tons	9.1	2.04
Sugarcane	tons	38.3	0.00
Willow	dry tons	4.2	0.75
Wheat, Durham	bu	34.9	1.11
Wheat, Hard Red Spring	bu	44.0	1.00
Wheat, Hard Red Winter	bu	73.1	1.31
Wheat, soft white	bu	78.3	1.11

[a] Note the crop yields are the same as those shown for FASOM in Tables 3.9 to 3.11.

Table 3.15. Feedstock Conversion Rates in FAPRI.

Category	Crop	Biofuel Yield (2022)
Starch and Sugar-Based Ethanol Production	Barley	1.66 gal/bu
	Corn (dry mill)	2.71 gal/bu
	Corn (wet mill)	2.50 gal/bu
	Sorghum	4.25 gal/cwt
Biodiesel Production	Soybean Oil	0.13 gal/lb
	Corn Oil	1.02 gal/gal
Cellulosic Ethanol Production	Corn crop residue	92.3 gal/dry ton
	Sorghum crop residue	92.3 gal/dry ton
	Switchgrass	92.3 gal/dry ton

Table 3.16. Co-Products Produced by Feedstock.

Crop	Gluten Feed (lb/bu)	Gluten Meal (lb/bu)	Corn Oil (gal/bu)	DGS (lb/bu)
Barley	n/a	n/a	n/a	14.6
Corn – wet mill	13.5	2.5	0.2078	n/a
Corn – dry mill, no corn oil	n/a	n/a	n/a	17.0
Corn – dry mill, fractionation	n/a	n/a	0.1439	15.9
Corn – dry mill, extraction	n/a	n/a	0.1929	15.5
Oats	n/a	n/a	n/a	9.7
Rice	n/a	n/a	n/a	30.4
Sorghum	n/a	n/a	n/a	30.4
Wheat	n/a	n/a	n/a	18.2

The FAPRI model includes the effects of DGS, a co-product of dry mill ethanol production. The two important measures are the inclusion rate and the displacement rate. The inclusion rate represents how much DGS can be included in the ration of food for beef, pork, poultry, and dairy and the displacement rate. The displacement rate represents the equivalence of the DGS to corn and soybeans. Table 3.17 (reproduced from Elobeid et al. (2012)) summarizes the DGS inclusion and displacement rates.

Table 3.17. Co-Products Produced by Feedstock

Animal Being Fed	Maximum Inclusion	Displacement	
		Corn	Soybean meal
Beef	0.50	1.00	0.00
Pork	0.25	0.86	0.14
Poultry	0.25	0.74	0.26
Dairy	0.30	0.54	0.46

Key Assumptions Affecting Location and Type of Land Converted

In the Dumortier et al. (2011) version of GreenAgSiM, five categories of land are considered: forest, shrubland, grassland, set-aside, and cropland. Once the amount of agricultural land necessary per year and spatial unit are determined, land dynamics are calculated (Dumortier et al. (2011)). The most important feature of the model is the tracking of marginal agricultural land coming in and out of set-aside. It is fair to assume that agricultural land which comes out of production last in the case of a decrease in agricultural land is the first land which comes into production if more land is needed. It is important to keep track of the years and hence the amount of carbon sequestered in the set-aside land. The GreenAgSiM algorithm puts land which was last taken out of production first back into production. This land has been sequestering carbon for the least amount of years compared to the rest of the set-aside land. Only when all set-aside land is used do native vegetation systems such as forest and shrubland come into production. The base year in the current model is set to 1990. Hence, the model allows for accumulation of set-aside land for 19 years in the baseline.

The input data necessary for the land-dynamics model are the crop acres planted and the amount of set-aside. The CARD Model provides crop acres at the country or regional level and not at the state level. Because of spatial variation in the biomass and soil carbon stock, it is necessary to know where crop expansion takes place. For this purpose, the country crop area from the CARD Model is disaggregated with the help of the FAO Agro MAPS database which provides the information of the location by crop and by country of intra-country crop distribution. To determine the effect of agricultural expansion, it is assumed that regions which have a high proportion of agricultural activity are more likely to see a cropland expansion because the infrastructure is already in place. For example, suppose a country has two states, A and B. If the allocation of wheat area in that country is 80% in State A and 20% in State B, then an increase of 100 ha would be allocated as 80 ha in State A and 20 ha in State B. Hence, the proportion of cropland in a particular state within a country is fixed.

Note that the land conversion in GreenAgSiM follows a predetermined set of rules; prices and yield are not included in the decision process. This is one of the major shortcomings associated with the GHG accounting in the FAPRI model. Including global LUC decisions would require a significant amount of data which is not readily available for large parts of the world.

Biomass in forests is determined by the ecological zone, the type of native vegetation, and the continent. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories give the average above-ground biomass (in tons of dry mass per ha) and the shoot-to-root ratio. A default factor of 0.47 tons of carbon per ton of dry matter is used to calculate the biomass in CO_2-equivalent. This category also includes forgone carbon sequestration due to land use conversion. To determine the forgone carbon uptake, knowledge about the forest's age distribution is necessary. In most cases this information is not available and hence, a 50/50 distribution of trees younger and older than 20 years is assumed. Age distribution has a rather small impact on the forgone carbon uptake. Younger trees sequester at a higher rate per year but for a shorter period (until they are over 20 years) and older trees sequester at a lower rate for a longer period.

To determine which ecological zone is affected by a particular crop, the distribution of agricultural production was determined using the FAO Global Spatial Database of Agricultural Land-use Statistics (Agro-MAPS) on a first level administrative unit scale. For regions, data from the USDA Production, Supply & Distribution (PS&D) database were used to determine production coefficients. Then, a Geographic Information Systems (GIS) map of native vegetation was put together with the map of ecosystems (global ecological zones) to establish the type of native vegetation where an agricultural activity takes place. A map of native vegetation was used to evaluate if the undisturbed land in a particular region is forest, shrubland, or grassland. Together with the map of ecosystems, this helps to map the default values of the IPCC to match with the region of interest.

If land is converted to cropland, carbon stored in soils (soil organic carbon or SOC) is released into the atmosphere. The change in the amount of SOC depends on factors such as climate region, native soil type, management system after conversion, and input use. A global soil map (FAO Soil Map) was obtained, which subdivides soil into three large categories (20 t/ha, 40 t/ha, and 80 t/ha). As mentioned before, the conversion is assumed to be from forest, shrubland, grassland, set-aside to agricultural land (cropland and pasture). It is assumed that cropland is managed with medium input and full tillage. The top 30 cm of carbon is supposed to be lost after initial cultivation and, once taken out of cultivation, reaches the new equilibrium (initial stage) in 20 years.

A map of soil organic carbon from the FAO was used to determine the stock of carbon in the first 30 cm of soil. The IPCC provides default factors by which the reference carbon stock has to be multiplied depending on the climate region, land use, and management type. It should be noted, that carbon emissions are very sensitive to changes in assumptions about yield and land use change. This comes from the fact that the carbon content per ha is very high in the case of native vegetation.

3.6 MIRAGE-BioF

In 2009, the European Commission issued their Renewable Energy Directive (RED), establishing a 10 percent renewable energy mandate for the European transport sector by 2020. At the same time, the Commission revised their Fuel Quality Directive to include a 6 percent reduction in transport fuel lifecycle carbon intensity by 2020 and requested an analysis of LUC emissions resulting from European biofuel policy. Four separate analyses of LUC were launched; the analysis that has been referred to as the most "comprehensive" (Malins, 2012) was performed by the IFPRI utilizing the MIRAGE model. The initial study was published in 2010 (Al-Riffai, 2010), followed by a revised analysis in 2011 (Laborde, 2011). Because the MIRAGE model appears to be the main tool utilized to evaluate European LUC, we discuss it exclusively here, and refer the reader to a review done by the European Commission's Joint Research Centre (JRC, 2009) of other European models that have been utilized in the past to evaluate biofuel policy (Agricluture Link- COmmodity Simulation Model, AGLINK-COSIMO; European derivative of GTAP, LEITAP; International Model for Policy Analysis of Agricultural Commodities and Trade, IMPACT, and Common Agricultural Policy Regionalised Impact Modeling System, CAPRI).

3.6.1 History and Uses

The MIRAGE model was originally written in 2002 by Centre D'Etudes Prospectives et D'Informations Internationals (CEPII) researchers with significant contribution from researchers at IFPRI to analyze the impacts of international trade policy. It has been used extensively to evaluate the impacts of WTO negotiations as well as regional and bi-lateral trade agreements between Europe and African, Caribbean and Pacific countries. The IFPRI team has also trained economists in developing countries to use the model to evaluate trade agreements. In 2007, a consortium was formed to maintain the core model and ensure its consistency and transparency. There are nine organizations comprising the consortium including CEPII, IFPRI, the WTO, the European Commission, Trinity College, the United Nations (UN) Economic Commission for Africa, University of Molise, the International Trade Centre, and the Institut National de la Recherche Agronomique.

In 2010, IFPRI adapted the core MIRAGE model to allow analysis of biofuel policy impacts on land use change, and named this version MIRAGE-BioF. This version of the model was utilized for the 2010 RED analysis mentioned above and was further refined for the 2011 revised analysis. The overall results of the revised analysis are provided in Table 3.18. The ethanol result is generally consistent with the updated GTAP result while the biodiesel LUC estimates are consistent with GTAP and FAPRI/FASOM estimates.

Table 3.18. Biofuel Shocks (2020) and MIRAGE Estimated LUC.

LUC Parameter[a]	Units	Total Biofuel	Ethanol	Biodiesel
2020 Biofuel Quantities	Mtoe	27.2	7.6	19.6
2020 Biofuel Quantities	bgy	10	4	6
Total Cropland Increase	1000 ha	2,708	1,547	3,694
Pasture Increase	1000 ha	-357	-199	-490
Managed Forest Increase	1000 ha	-127	-45	-187
Primary Forest Increase	1000 ha	-378	-329	-448
Savannah & Grassland Increase	1000 ha	-1,278	-696	-1,763
Other	1000 ha	-569	-279	-806
Peatlands	1000 ha	-33	2	-51
LUC[b]	g CO_2e/MJ	38	7-14	52-56

[a](Laborde & Valin, 2011) Scenario without trade liberalization
[b] Amortized over 20 years, values represent results for range of feedstocks.

3.6.2 MIRAGE Model Structure

The MIRAGE model is a dynamic CGE that utilizes the GTAP 7 (2004) database. The nesting structure was modified with the aim of analyzing biofuel LUC. The initial source of data for the model was the GTAP 7 database with global economic activity for 113 regions and 57 sectors. IFPRI modified the GTAP sectors to take into account multiple feedstocks and technology options. They developed 23 new sectors that replaced aggregate sectors in GTAP including corn (maize), rapeseed, soybeans, sunflower, palm fruit, and the related oils and co-products from ethanol production and oil seed crushing. New sectors were also developed for fertilizer production and fuel transport. The analysis also consisted of bottom-up representations of these sectors rather than relying on econometric data alone. Particular attention was given to consumption nesting to the substitution possibilities of similar products as illustrated in Figure 3.11.

Figure 3.11. Nesting Structure in MIRAGE.

The interaction of crops with land cover types was also modified in MIRAGE as illustrated in Figure 3.12. MIRAGE also includes a more detailed analysis of cropland and pasture. It addresses the competition between livestock production and cropland. In one configuration, pasture and forest land are considered as direct factors necessary for livestock and wood production where increases in production put pressure on available land which provides competition with cropland expansion.

MIRAGE uses a variety of elasticity factors to represent the substitution of products and effect of prices. The model is configured with additional agricultural detail such as elasticities of fertilizer use with respect to price change. Elasticity of other inputs is adjusted to match target values that are consistent with literature. The authors acknowledge uncertainties over projections of agricultural yield. The model inputs follow the recommendation of the ARB expert group on elasticities, and assumed an average magnitude of 0.2 for the elasticity of yield with respect to price (Babcock, 2011). The EU27 value is about 0.15, the U.S. value is 0.2, and the value for developing countries is 0.3, which takes into account these regions' larger intensification margins, as well as double-cropping possibilities.

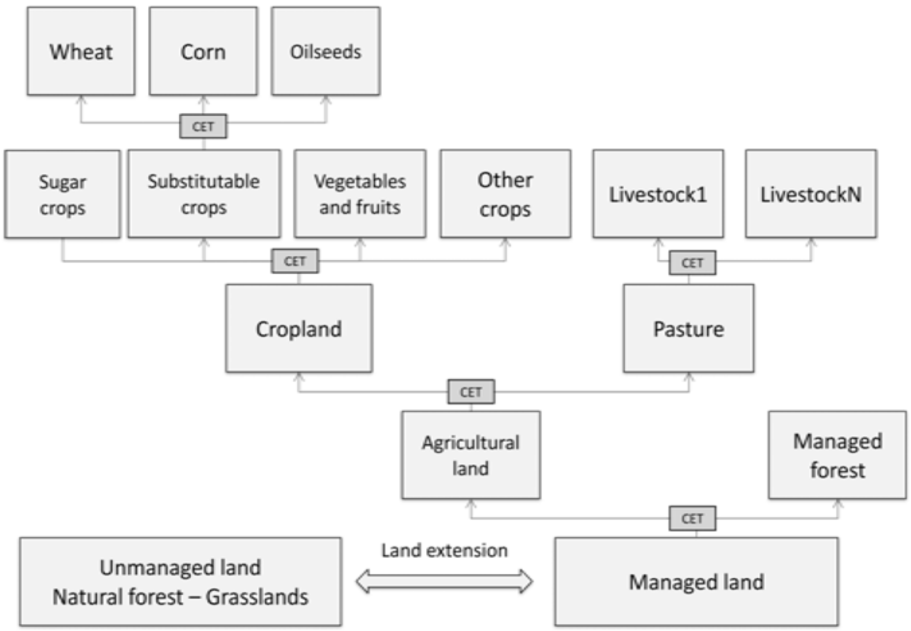

Figure 3.12. Interaction of Agricultural Sectors and Land Cover Types in MIRAGE BioF.

3.6.3 Key Drivers of Land Use Change Estimates in MIRAGE-BioF

The key drivers for MIRAGE are comparable to GTAP-BIO due to its CGE model configuration and use of the GTAP database. The MIRAGE authors cite a UC Berkeley study that identifies the key uncertainties in LUC analysis (Plevin 2010). The factors in the MIRAGE model that contribute to model variability include the following:

1. Elasticity of endogenous yield response
2. Elasticity of land substitution between highly substitutable crops
3. Elasticity of land substitution between other crops
4. Elasticity of land expansion into other land covers
5. Elasticity of Armington (between domestic production and imports and between imports)
6. Marginal yield return on cultivated land

3.7 Carbon Accounting

The focus of this study is on land use changes, including the location of those land use changes, the amount of land use changes, and the type of land converted, rather than disposition of above- and below-ground carbon as a result of the land use changes. Nevertheless, there are significant differences among the four economic models in their treatment of carbon accounting that will be covered briefly in this section.

3.7.1 Carbon Accounting in GTAP Studies

GTAP estimates both the location of land use changes (the country or group of countries), and the type of land converted (forest, pasture, cropland pasture). The model also contains the WHRC emission rates by country or region and land type that can be utilized with the land use changes to estimate emissions of land conversions. Alternatively, the user can output the land use changes by region and land type and use a separate set of emission rates that are outside of the model.

3.7.2 Carbon Accounting in FASOM

FASOM includes very detailed accounting methodology for estimating GHG emissions from above-ground and below-ground sources due to land use changes in the U.S. FASOM explicitly models changes in soil carbon due to change in crop production acres and in crop type. In addition, FASOM's forestry module models the change in above-ground and below-ground biomass carbon stock and soil carbon in the forestry sector due to land conversion. In addition to quantifying GHG emissions and sinks, FASOM distinguishes the unique time dynamics and accounting issues of carbon sequestration over time, the potential reversibility of carbon benefits, and the fate of carbon stored in products after forest harvest.

GHGs, generally in the form of carbon, can be sequestered in soils, standing trees, other vegetation, and wood products. Sequestration refers to storage of the GHGs for more than one year. As a consequence, the sequestration definition used in the model for standing vegetation is limited to carbon storage in trees, understory, and litter within both forests and plantations of woody biofuel feedstocks, but excludes carbon stored in annually cultivated crops. Carbon sequestration is also modeled in cropland soils, pastureland soils, soils in idled lands, timberland soils, and harvested wood products. In addition, changes in sequestration for lands that move out of forestry and agricultural production into some form of developed usage such as housing, shopping centers, and roads are tracked in the model.

Additional details on FASOM's carbon accounting are explained in Appendix A.

3.7.3 Carbon Accounting in FAPRI and MIRAGE

Similar to GTAP, FAPRI determines how much additional land is needed for crops and in what region, but cannot determine what kind of land is converted in each region. Therefore, carbon accounting is external to the model.

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4. LUC Modeling Drivers

Even though widely different LUC models are used to assess the impact of biofuel, the key drivers are comparable. This section focuses on drivers incorporated in each model to quantify land use change. It assesses how the models compare to each other in terms of size of land use change and implications for land use change emissions. Emissions are not necessarily proportional to the size of land use changes. Converting a relatively small amount of forest to cropland can produce equivalent or greater emissions than converting a relatively large amount of pasture to cropland, because of the much higher carbon storage on forest than pasture. Not only is the amount of land that is predicted to be converted important, but also significant is the type of land that is converted. In this section, we discuss four general categories of LUC modeling drivers:

- Model scope and structure (such as general versus partial equilibrium, U.S. vs. global, static versus dynamic)
- Predicted location of land use change
- Predicted amount of land use change
- Predicted type of land use change

The predicted location of land use changes are discussed prior to the amount of land use change because the location affects the amount, and not vice versa. In most cases, regions outside of the U.S., Canada, and Europe have lower crop yields. Thus, if the predicted land use change takes place mostly outside of these three regions, the land use change is greater than if the LUC occurs within these three regions.

The four models discussed in this study are economic models, and provide responses to biofuel "shocks", or the inputted increases in a particular biofuel or group of biofuels. Of course, the size of these shocks matter in the predicted land use change if the intended result is not normalized by volume of the shock, i.e., the larger the biofuel shock, the larger the land use change predicted by the model. So, the size of the shock is the most important "driver" of model-predicted land use changes. This driver, while important, is not discussed further in this section, because it is a modeling run input. We are assuming that the amounts modeled between the different models are the same, despite the fact that in actual practice they are often not the same.

4.1 Model Scope and Structure

The items we discuss in the section include the following:

- Global versus regional
- General versus partial equilibrium
- Static versus dynamic
- Land inventory

4.1.1 Global versus Regional

GTAP and FAPRI are global models as opposed to FASOM that models only the U.S. All things being equal, a global model is preferable because it is possible to model variations of trade between nations. For example, there can be elasticities of trade between nations that can be modified, and this can influence where the land use changes take place. GTAP uses so-called Armington trade elasticities, which mean that nations do not always seek the lowest price. Sometimes they continue to trade with certain nations even though the price of goods may be a little higher than elsewhere. FAPRI uses homogeneous trade assumptions, which assumes that nations always purchase from the low cost provider (including transportation costs).

While FASOM models only the U.S. for LUC, it is not strictly a U.S. model. It does account for exports and imports, but does not identify the source countries of those exports or imports. Thus, if it is modeling aggregated exports and imports properly, its evaluation of U.S. land use changes could be quite accurate and superior to global models. EPA recognized this fact when they evaluated the land use changes of the RFS by using FASOM for the U.S. and FAPRI for the rest of the world. FAPRI does have a U.S. land use component. FASOM includes a very detailed forestry model in addition to a complete carbon accounting for forest, pasture, and crops.

The strength of global models is their ability to account for leakage and unintended consequences. "Leakage" as used here is the conversion of land outside of the region where the biofuel shock is taking place. The important implications of leakage come into play when its effects are considered at the global level. If the harvest of a unit of land is used for biofuels instead of traditional sectors, prices in those sectors will increase, which makes it profitable for farmers to expand their acreage. Because land is a fixed resource, the supply of other commodities has to go down, which increases the price for those crops as well. By using the FAPRI model, Searchinger et al. (2008) has shown that this can lead to an increase in commodity prices and thus to an expansion of cropland around the world. The importance of the FAPRI, GTAP and other global models comes into play because they are able to evaluate those changes at a global scale.

The issue to be considered in this context is whether we can conclusively say that it is better to use a single, global model to evaluate world land use changes than to use multiple models, as in the EPA RFS2 case. The question becomes whether the type of model, e.g., global or regional, influences the results or not. FASOM cannot be used as a stand-alone model to evaluate land use change at the global level, but it is very precise at the U.S. level. Hence, FASOM must be supplemented with other models when modeling biofuel shocks in the United States. At this juncture, we cannot say whether model structure (global versus regional) drives land use changes to a significant degree. All we can say that a single model representing the entire world is at least internally consistent, and preferable on that basis, all other factors being equal.

4.1.2 General versus Partial Equilibrium

Partial equilibrium models concentrate on the analysis of decision makers in a particular market and assume that the other markets are held constant. The FAPRI model is an example of a partial equilibrium model because it focuses on the agricultural market and assumes the rest of the economy to be guided by demand and supply equations. The FAPRI model does not include a forestry sector. FASOM is similar to the FAPRI model but with three important differences: it models only the U.S.; it includes the U.S. forest and timber sector; and it also includes a complete U.S. carbon accounting model. GTAP is an example of a general equilibrium model that covers industries such as manufacturing and forestry in addition to the agricultural market.

The advantage of the general equilibrium approach is that decisions on how to use land are explicitly incorporated across different land categories. FAPRI only calculates total cropland and the allocation of land to different crops, but cannot evaluate whether land should be used for forest or pasture[3] instead. This has two consequences: First, taking land out of pasture or forestry might increase the price of those products and provide pressure on cropland, i.e., it becomes more expensive and thus unattractive to expand in forest and cropland. Second, assumptions need to be made from the FAPRI output on where cropland is taken from.

Overall, while general equilibrium models are preferable to partial equilibrium because of the greater number of sectors included, we do not think that partial equilibrium models, if properly designed, predict land use changes that are biased in any particular way.

4.1.3 Static versus Dynamic Modeling

The GTAP model estimates land use changes over a relatively short period of time of about five years, whereas FAPRI and FASOM estimate land use change over much longer period of time. The FASOM model, for example, estimates land use changes every five years, and can provide projections out to 100 years, although the accuracy of projections at 100 years should be considered quite uncertain because of the many items that can change over very long periods of time. More importantly, a static model generally uses a single calendar year database (in the case of GTAP, either 2004 or 2007), so that the "baseline" for a static model is the economic equilibrium in that particular year. The model is then shocked with the increase in biofuel, so it essentially is trying to answer the question of what the land use change would be in that year if the biofuels were increased all in that year.

A dynamic model achieves equilibrium simultaneously over several years in the projection period. The baseline is a series of land use values without a biofuel shock and then a series of land use values with the biofuel shock. The advantage of a dynamic projection is that it allows projections in food demand and crop yield trends as well as tracing out the transition paths which cannot be included in a static model.

If projected food demand increases at a lower rate than crop yields, then land needed to produce food declines over time and cropland becomes available for other uses such as biofuel. This

[3] An exception to this is the explicit modeling of pasture in the Brazil subcomponent of FAPRI.

eases the pressure put on forest and pasture, reducing land use emissions due to biofuels. However, if projected food demand increases at a higher rate than crop yield, then there is a need to convert land from other uses to cropland and land use emissions from biofuel use are higher. Dynamic land use modeling can be of better help in the evaluation of these projections. A study by GTAP for Argonne evaluated the potential adaptation of GTAP in a dynamic framework (Tyner, 2010) and a dynamic version of GTAP BIO is under development (Golub 2012).

There are other trends that also need to be evaluated. There has been a trend toward greater utilization of poultry and fish as sources of protein in the U.S. and other developed nations over the last 20 years. Poultry uses much less land per pound than beef. By some estimates, 20 million acres of land in the U.S. has become available in the last 20 years because of substitution of poultry for beef. This is one of the major reasons (in addition to crop yield increases) why there has not been widespread conversion of other land to cropland in the U.S. due to the expansion of U.S. biofuels. The impact of these types of trends is difficult to examine with a static model.

4.1.4 Land Inventories Used by the Models

All the economic models utilize a land inventory that includes different categories of land. Some include more land categories than others. For example, FASOM includes a number of different forest types for the U.S., whereas FAPRI and GTAP include only one category of forest. Our purpose here is not to describe all the different types of land included in the different models, but to illustrate how adding a new category of land to a model can have a significant effect on land use emissions.

Both FASOM and GTAP include CRP land. In its modeling for the RFS2, FASOM modelers estimate that in the baseline there were 37.1 million acres of CRP land, and with the biofuel shocks, this number was allowed to dip to as low as 32 million acres. FASOM's estimate of forest converted in the U.S. for corn ethanol was 52,000 acres. GTAP also includes CRP land, but the current model does not make use of this feature. The CRP inventory of land cannot be accessed when performing a model run without changing the program code. FASOM's estimate of forest converted is much lower per 1000 gal of ethanol than GTAP's. A good area of further study would be to enable access to CRP land (up to a point, like FASOM) and determine the effects on forest converted in the United States.

Also, recently cropland/pasture was added as a new land category in GTAP for both the U.S. and Brazil. Adding the new land type reduced the other types converted such as forest. Forests have by far the highest carbon pools; hence, reducing the conversion of forest to cropland also reduces the land use change emissions. The effect of adding cropland/pasture could be quantified with parametric GTAP runs. Therefore, it is critical for economic models to have as complete land use databases as possible for all major countries, especially where any crop expansion is taking place. A significant area of improvement would be to add cropland/pasture to GTAP for at least Europe and Canada. Thus, we conclude that expansion of land use types in the economic models is a high priority because it results in better estimates of the types of land converted in different regions.

4.2 Which Modeling Parameters Matter and Why?

There are three fundamental questions in estimating land use changes due to biofuels and the emission impacts of those changes:

- How much land is converted?
- Where is the land converted?
- What type of land is converted?

The amount of land converted does affect the total emissions. The location of the converted land affects emissions and is closely tied into the amount of land converted. Very significant variations in crop yields around the world exist; replacing one ha of high-yielding land in one location might require two ha of land somewhere else for the same amount of production. The type of land converted is critical because forests and, in certain regions of the world, peat contains significant amounts of carbon compared to other land types.

4.2.1 How Much Land is Converted?

This section is concerned with modeling parameters such as treatment of co-products, crop yields, or crop choices. In particular, we discuss the following parameters:

- Treatment of co-products from biofuels
- Crop price-yield elasticity
- Marginal crop yield relative to average yield
- Trends in crop yields
- Biofuel production plant yields[4]
- Crop choice assumptions

The list is by no means exhaustive but it was concluded by the study participants that those items have the most significant impact on land use conversion in response to biofuel expansion.

Treatment of co-products from biofuels
In GTAP, co-product treatment varies by feedstock. For corn ethanol, DGS is introduced as a co-product with approximately one-third of the weight of the corn used coming back as DGS. DGS can serve as a substitute for corn for animal feeding and can also be traded internationally. GTAP effectively uses a one-to-one substitution of DGS for corn because historical data has not shown a price impact of DGS on substitute feed products such as soybean meal. The early versions of GTAP did not include the effect of DGS on displacing other feed production. Incorporating a substitute value of DGS into the model reduced land use impacts of corn ethanol by one-third. Oilseeds (rapeseed, soybean, etc.) are crushed to produce oil and meal. The oil can be used to produce biodiesel or any of the conventional uses of vegetable oils. The meals go into the livestock sector as animal feed.

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[4] Changes in this parameter have only a small potential effect on land use for corn ethanol and soybean biodiesel, because the feedstock to fuel yields from these types of bio-refineries are approaching theoretical limits.

The FASOM documentation mainly discusses accounting for DGS from corn ethanol plants. The model assumes that 1 lb. of DGS replaces 1.196 lb. of corn and soybeans for cattle and dairy, and 1 lb. of DGS replaces 1 lb. of corn and soybeans for poultry and swine. The model also implements maximum inclusion rates in livestock feed of 50% for beef cattle, 30% for dairy, and 25% for both swine and poultry for 2017. These rates are all based on the 2008 study by Argonne. We do not know how much the DGS reduces total land use estimated by FASOM but suspect it is significantly more than one-third, because of the assumed substitution of DGS for not only corn but also soybeans. The model also accounts for fractionated/extracted (corn oil) DGS vs. traditional DGS, and also includes an export market for DGS.

The FAPRI model includes the effects of DGS. The two important measures are the inclusion rate, i.e., how much DGS can be included in the ration of food for beef, pork, poultry, and dairy and the displacement rate. The displacement rate measures the equivalence of the DGS to corn and soybeans. FAPRI uses the displacement ratios in the GREET model to determine the amount of corn and soybean meal that are substitutes for DGS.

The different treatment of co-products can affect LUC predictions because the substitute products require different levels of land for crop production. For example, corn yields are about 155 bu/acre compared with soybean yields of 40 bu/acre. Thus, the first-order approximation would be that substituting for soybean would result in a greater LUC credit than substituting for corn. Table 4.1 shows the implied (back-calculated) LUC results from three different LUC modeling systems. The LUC per kg of feedstock (represented as lower case iluc to indicate emissions per kg of material rather than per MJ of fuel) is determined by solving a system of equations based on the substitution ratios for feed used in the GREET model. This simple approximation allows for a comparison of the treatment of DGS as a co-product. Note that the LUC credit for DGS in the RFS modeling system is about twice that for the GTAP system, where DGS has the same LUC value as corn.

Table 4.1. Estimated LUC Impact per kg of Feedstock and Co-Product.

LUC Models Application	FASOM/ FAPRI RFS2	GTAP BIO LCFS	GTAP ADV Tyner 2011
LUC Variable			
M_{CORN} (kg corn/bu corn)	25.40	25.40	25.40
M_{EtOH} (kg EtOH/bu corn)	8.13	8.13	8.37
M_{DGS} (kg DGS/bu corn)	6.58	6.59	7.15
M_{SB} (kg SB/bu soybean)	27.22	27.22	
M_{BD} (kg biodiesel/bu soybean)	4.59	5.23	
M_{SBM} (kg soybean meal/bu SB)	22.44	21.77	
M_{SO} (kg soy oil/bu soybean)	4.77	5.44	
$iluc_{EtOH}$ (g CO_2e/kg EtOH)	709.2	808.5	390.8
$iluc_{BD}$ (g CO_2e/kg BD)	1,197	2,327	
$iluc_{SBM}$ (g CO_2e/kg SBM)	1,151	2,237	
$iluc_{CORN}$ (g CO_2e/kgcorn)	400.2	349.3	179.1
Back Calculate:			
$iluc_{DGS}$ (g CO_2e/kg DGS)	669.2	349.3	179.1
$iluc_{SB}$ (g CO_2e/kg SB)	1,151	2,237	
$iluc_{SO}$ (g CO_2e/kg SO)	1,151	2,237	

M = mass, iluc = indirect LUC per kg of material, EtOH = ethanol, SB = soy bean
SBM = soy bean meal, SO = soy oil, DGS distillers grains with solubles

Crop yield-price elasticity

In GTAP, the default value for crop yield-price elasticity is 0.25. That is, a 10% increase in price for any given commodity leads to a 2.5% increase in yield for that commodity. Lower values have been tested in an analysis done for ARB (Tyner, 2011). This elasticity affects yields on the intensive margin whereas ETA elasticity (productivity of new cropland compared to existing cropland) impacts yields on the extensive margin. The basis for the elasticity is work performed by Dr. Hertel of Purdue University and Dr. Keeny of North Carolina State University. The GTAP team is confident that this elasticity input is consistent with the best research available.

A review of elasticities from Dr. Berry of Yale University provides a contrasting view (Berry, 2011). Elasticity data are very difficult to determine empirically because these data should be obtained from events that do not correlate with each other. In most instances, prices respond to demand and demand responds to price, thereby many estimates of elasticity include auto-correlation effects.

The ARB expert working group recommended a range of elasticity values, with higher elasticities in developing countries (Babcock, 2011). This approach would reflect the higher degree of maturity of U.S. farming technology. However, determining a limit to innovation in farming is challenging, and farmers continue to have options to improve yields.

FASOM does not include a price-yield elasticity effect, nor does it assume that newly converted land (from forest or pasture) has a lower yield than the existing cropland; GTAP accomplishes this with the ETA parameter. These two assumptions might offset each other. If the costs of increasing productivity on existing land were lower than the value of increased production, then agricultural landowners would presumably have already adopted these productivity-enhancing actions. It is also possible that sufficient increases in commodity prices could induce farmers to adopt higher cost practices that increase productivity but are not profitable at lower prices. Landowners can also switch from dryland to irrigated production, change tillage practices, or make other management adjustments in response to the changes in price.

The effect of price is implicitly taken into account in the FAPRI model on a regional crop-by-crop basis. For example, the elasticity factors for U.S. and Brazilian corn ethanol are 0.02 and 0.21 respectively, which indicates the level to which U.S. corn production is optimized compared to production in other regions. The ratio of total revenue over variable cost determines the increase in yield. Net return, not just price increase, triggers a yield increase in the model. This aspect was handled differently in the Dumortier et al. (2011) paper which considered prices only.

Marginal Crop Yield Relative to Existing Average Crop Yield

As aforementioned, this result is driven by the ETA parameter in GTAP which differs by AEZ and region. GTAP ADV BIO uses a yield response with respect to land rent. FAPRI includes year-by-year yield projections.

In FASOM, newly converted land is assumed to have the same yield as existing cropland. Since FASOM only models the U.S, this is probably a safer assumption for the U.S. than for the rest of the world. To capture the fact that high productivity cropland is used first before low productivity cropland comes into use, the FAPRI model considered the average crop yield as a function of total area planted. For example, the elasticity of yield to cropland is -0.018 for Brazil representing the “yield drag” from expanding cropland (less productive land is brought into production). The calculation of yield drag for each individual country is difficult to implement because of data limitation (Elobeid et al., 2012).

Trends

Most GTAP biofuels analyses have been done with the comparative static version of the model. In that version, there are neither trends in yields nor demand growth. In one instance, the GTAP team adjusted the 2001 data base to 2006 by growing yields and consumption for every global region. However, that is not standard practice. Since GTAP is estimating the impacts of biofuel shocks, that is the only change made in the model for most simulations. Changes in the structure of livestock demand (fraction of different meats consumed) (Taheripour, Hurt, and Tyner, 2013) to this point have not been considered, although that is an item on the agenda for future research. With FASOM, crop yields are projected to increase significantly over time. The model provides outputs in 5-year increments: 2000, 2005, 2010, 2015, and so on. Corn yields are projected to increase by 1.62% per year, hay by 0.84%, sorghum by 0.09%, soybeans by 0.43%, switchgrass by 2.04%, and wheat by 1-1.3% (depending on type of wheat). Livestock is also included in the model, but it is not clear from the available documentation whether the model captures and extends the trends in livestock intensification (i.e., more animals per acre) and the ongoing transformation from beef to poultry.

In a recent publication, Elobeid et al. (2012) present time trend estimates for three different periods: 1960–1975, 1976–1991, and 1992–2008. They report that trend yields increased in important agricultural countries such as Brazil and Argentina during these three time periods. Technologically advanced countries/regions such as the United States and Brazil increased trend yields only by 15% and 23%, respectively. Intuitively this makes sense because countries that are far from the yield potential, or with a large gap between actual and potential yield, have more possibilities to close that gap according to the law of decreasing marginal productivity. The FAPRI model does not account for livestock intensification except for the Brazil subcomponent.

Biofuel Production Plant Yields

Biofuel production plant yield estimates are generally reported in gallons/bu of feedstock and do affect land use values. For biofuels that are commercially produced on a large scale such as corn ethanol or soybean biodiesel, those estimates are more accurate than for switchgrass or miscanthus. Across the models, the differences among the conversion parameters are very small and thus do not have a significant impact on the relative difference in land use impacts among the models. For example, one model may estimate corn ethanol conversion at 2.7 gal/bu, and another model may estimate it at 2.8 gal/bu. The difference in plant yields is only 3.5%, which does not translate to a large land use change difference.

The yield from feedstock to biofuel enters the LUC models through different means. The FASOM and FAPRI models contain explicit inputs defining the yield from feedstock to fuels (e.g., 2.7 gallons of anhydrous ethanol per bushel of corn). GTAP and MIRAGE represent the feedstock-to-fuel conversion in dollar amounts. The data on crop quantities and all other factors of production such as electric power, natural gas, and coal inputs are all derived from agro-economic statistics. Shocks to the GTAP model perturb the relative proportions of feedstock to fuel; however, these do not appear to drift to unusual ratios[5].

In the work performed for EPA on RFS2, FASOM had defined biofuel yields for the EPA projection year of 2022 for many different feedstocks. The yields for selected feedstocks are shown in the table below. The model also assumes some improvements to ethanol plant yields with time.

[5] The effect of GTAP parameters on feedstock to fuel yields should be examined in Task 3.

Table 4.2. FASOM Feedstock Conversion Rates.

Category	Crop	Biofuel Yield
Starch and Sugar-Based Ethanol	Barley	1.66 gal/bu
	Corn (dry mill)	2.71 gal/bu
	Corn (wet mill)	2.50 gal/bu
	Sorghum	4.25 gal/100 lb
Biodiesel	Soybean Oil	13 gal/100 lb soy oil
	Corn Oil	1.02 gal/gal
Cellulosic Ethanol	Corn crop residue	92.3 gal/dry ton
	Sorghum crop residue	92.3 gal/dry ton
	Switchgrass	92.3 gal/dry ton

The plant yields in FAPRI are identical to the rates used in the FASOM model, because EPA attempted to use consistent assumptions between the two models in modeling performed for the RFS2. GTAP's yields are included in the calculation of costs per unit of different biofuel products from the various feedstocks. Plant yields are also included in FASOM, with some allowance for improvement from current levels for cellulosic ethanol. For example, the model predicts that in 2022, ethanol yield from corn using the dry mill process is 2.71 gal/bu, from sorghum is 4.25 gallons per 100 lb., and from switchgrass is 92.3 gal/dry ton. The corn and sorghum ethanol yields are the same in 2022 as 2002, but the switchgrass yields are 28.4% higher in 2022 than in 2002. The biodiesel yield from soybean oil is 0.13 gallons/lb, and remains constant.

Crop Choice Assumptions

Crop decisions in GTAP are made in the nested land cover structure. There is pasture, forest, and cropland (and cropland/pasture in the U.S. and Brazil). Within the cropland nest, there are eight crop types. If an additional amount of a crop product is demanded, the model can get land from within the cropland nest by substitution among crops and/or get land from one of the other land categories. In addition, since the additional demand for the crop will lead to an increase in the crop price, there will also be a reduction in demand for the crop.

FASOM tracks many possible changes in the primary agricultural and forestry commodities produced and production practices employed on a given type of land as well as movements between the different types of land (cropland, pasture, CRP, cropland pasture, forest pasture and rangeland). Cropland can move freely between production of alternative crops (that are available for production within a region) with no conversion costs associated with moving between crops. The primary factor driving changes in production practices and land use in FASOM is the relative returns available, accounting for all relevant costs.

The FAPRI model only chooses among the optimal allocation of crops on cropland. The model includes a component that specifies the area's elasticity with respect to net returns from crops which are a function of prices and production cost. For example, if net returns (revenue-variable production cost) increase by 1% and the area's elasticity is 0.3, then the area increases by 0.3%.

4.2.2 Location of Land that Changes

In GTAP, the model takes land from anywhere in the world based on land productivity, production cost, demand factors, etc. In other words, all supply and demand (including transport and trade) factors are drawn into the decision on where land will be taken. FASOM covers only the United States and thus, all crops are domestic. The land in the FAPRI model is modeled at the national level (recall that FAPRI models on a global basis). The difficulty in calculating GHG emissions was to allocate the expansion (or contraction) of cropland with carbon coefficients. This is done with map layers of current crop type location, soil carbon map, and a biomass carbon map. Note that FAPRI only models the U.S. and Brazil at the subnational level.

4.2.3 Land Cover Types

In GTAP, land can come from pasture, forest or other crops. Previously, the constant elasticity of transformation was -0.2 among pasture, forest, and cropland for all regions. In the new version (Taheripour and Tyner, 2013), the CET inputs are configured with parameters that represent recent experience in global land use change. For example, the land use change data shows that there has been very little cropland addition in the U.S. and the E.U., so those regions now have much lower elasticities. Other regions, e.g., Sub-Saharan Africa, have experienced very large cropland cover additions leading to larger parameters for those regions. In addition to the parameter changes, the new model structure has one nest for substitution between pasture and cropland; that nest can be used to substitute with forest. This change reflects the fact that it is easier and less expensive to convert pasture to cropland than forest to cropland. These changes mean that much less simulated land use change now occurs in regions like the U.S. and E.U. and much more in regions that have actually experienced significant land use change.

Again, the primary factor driving changes in production practices and land use in FASOM is the relative returns available, accounting for all relevant costs. As noted above, it is generally more expensive to convert forest to cropland than pasture to cropland because there is more site preparation work involved, although some forest conversion also generates revenue from timber. Costs are represented in each region by step functions to reflect increasing costs, as the percentage of land being converted increases. Land conversion costs are lower for the initial 10% of land converted, and higher for the next 50%, and even higher for the last 40%. Land-use emissions are driven primarily by forest conversions. The low land use emissions from FASOM for various biofuel increases in the U.S. are probably the result of very low estimated forest conversions predicted by this model as compared to other models such as GTAP.

The land use change model in FAPRI is an ad-hoc model, meaning that it calculates crop area and livestock as an output, and in a second step calculates land use change without any feedback effects on the agricultural production model. Four land cover types are distinguished: cropland, grassland, forest, barren/sparsely vegetated. Global livestock distribution and global crop densities are used to get the location of crop and livestock covered in the FAPRI model. Next, a map layer with carbon coefficients is merged with the data from the previous layers. This allows estimation of crop specific carbon coefficients for 57,222 grid cells globally (Dumortier et al., 2012). It turns out that the carbon estimates by Searchinger et al. (2008) and by Dumortier et al. (2011) are fairly consistent with each other despite changes in the carbon accounting method. However, it is important to keep in mind that the carbon stored per ha is significant, and that small changes in the assumptions, e.g., yield, can have significant effects on the emissions.

4.3 Modeling Methodology

Generally, when land use is modeled with any of the models, it involves an economic "shock", e.g., an increase in biofuel production. For example, for GTAP, if the base data year is 2004, and it is desired to model an increase in corn ethanol production, a future corn ethanol volume is selected, then compared to the corn ethanol volume in 2004. A percent increase in volume is estimated, and the model is shocked for that percent increase in corn ethanol. The model then finds a new equilibrium and determines the land use change.

Since FASOM and FAPRI are dynamic models, a baseline projection of land use is estimated in the future, without the shock. Then the model is shocked in the projection years for the increase in expected ethanol volumes, and the models find new equilibria in the projection years. Land use change is the difference in the baseline and increased ethanol volume runs. There is no "baseline" projection for GTAP; its baseline is simply the equilibrium in the base data year.

However, there are other aspects of how modeling studies are defined. There is the issue of single versus multiple biofuel shocks. Nearly all of the modeling done by the regulatory agencies has used single biofuel shocks, e.g., corn ethanol or soybean biodiesel. Also, the modeling can be constrained in certain ways. For example, the use of CRP land in the models can be constrained in the modeling run, if necessary, to reflect a given policy. Finally, the models are sometimes utilized to estimate land use changes assuming no reduction in food demand. This not a complete list of variations in which the modeling can be defined, but these serve as some examples, which are discussed further below.

<u>Single and multiple biofuel shocks</u> – Nearly all of the biofuel modeling done by both ARB and EPA to date has used single biofuel shocks. The reason for modeling only one biofuel at a time is so the model will produce a land use change that presumably can be associated with the particular biofuel. If a number of different biofuels are modeled simultaneously, it can be difficult to determine the land use change due to each biofuel change. The underlying assumption is that the land use change would not be any different if a number of biofuels were increased simultaneously. This latter situation, however, is closer to reality.

In a very interesting analysis, EPA performed multiple biofuel modeling when modeling the entire RFS.[6] Results are shown in the table below, which separates the domestic (FASOM) and international (FAPRI) results. These results are for corn ethanol, sugarcane ethanol, and soybean biodiesel. In this table, the single feedstock land use changes are summed and compared to the modeling of the RFS combined. Results show that for FASOM, the combined land use changes are similar to the sum of the individual feedstock modeling. But for FAPRI, the sum of the individual biofuels is much greater than the multiple biofuel modeling. Since all of the positive land use change impacts estimated by EPA for the biofuels came from the international (FAPRI) modeling, this appears to be a serious concern.

[6] 40 CFR Part 80, Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule, March 26, 2010.

Table 4.3. Comparison of Summed and Control LUC (1000s of ha).

Region	Total of Single Feedstock Scenarios	All Fuel Volumes Combined
Domestic (FASOM)	276.5	306.8
Foreign (FAPRI)	1863.1	794.4
World	2139.6	1101.3

Use of CRP Land – GTAP, FASOM and FAPRI all include inventories of CRP land. These are lands that were once farmed but are currently receiving government payment under the CRP program to remain unfarmed, for a variety of reasons that are beyond the scope of discussion in this study. In the RFS analysis, FASOM maintained CRP land at a minimum of 32 million acres in the future. During the 2008-09 timeframe when the modeling was performed, CRP land was 37 million acres, so approximately 5 million acres were available in FASOM for conversion to crops. This may have been a key reason why the domestic land use emissions for corn ethanol were estimated to be less than zero. GTAP also includes CRP land in its inventory, but this land has never been accessed in GTAP modeling performed for the regulatory agencies for land use changes. A switch is available in the GTAP model to turn on and off the use of the CRP land. The default GTAP model does not access CRP land.

Modeling of food demand impacts – When crop prices increase due to biofuel modeling, demand for food products decline (these are so-called "market-mediated impacts"). The decline in food demand leads to lower land use change for a given biofuel shock than if these market-mediated impacts were not taken into account. Some modeling has been performed to estimate the total land use changes that would have taken place had the model not reduced land use due to the food demand reduction.

4.4 Contribution of Modeling Parameters

Several modeling parameters drive LUC. The parameters are treated slightly differently in each model, but the effect of each parameter is similar. Figure 4.1 shows the author's estimate (Unnasch) of the effect of modeling parameters on the LUC for corn ethanol. The chart illustrates the LUC required per liter of ethanol starting with the direct land use for corn farm land and progressing to the final estimate of LUC from the GTAP ADV BIO model. The calculation of LUC takes into account co-product DGS. The GTAP ADV BIO model treats DGS as a substitute for corn because economic data has not shown a price response of other feed materials like soy bean meal to an increase in DGS production.

The chart shows the approximate contribution of factors affecting land productivity. GTAP projects yield improvement as a function of land rents. A comparable yield projection is included in FAPRI, where corn yields are projected to improve over time. Price-induced yield reflects the improvement in farming practices and reallocation of land to reflect higher crop prices. GTAP uses an elasticity factor of 0.25 where FAPRI uses a factor of 0.02 for U.S. corn and 0.21 for Brazilian corn. Market-mediated demand reduces the overall demand for grain crops, as higher prices induce a shift from cattle to other food products. Finally, shift in crop types can reduce the overall requirement for land. The shift in crop types may be one of the most important LUC effects predicted by agro-economic models. Corn ethanol is an example; the DGS co-product represents about one-third of the mass of the corn crop. The mass of DGS exceeds that for soy meal production on the same acreage, which represents an often cited situation where an expansion in corn ethanol results in no net change in calorific feed supply. Other agro-economic impacts of moving from corn-corn-soy rotations to continuous corn are not examined in economic models. Soy farming adds nitrogen to the soil, but this nitrogen can be made up with fertilizers. Rotating crops could also reduce the potential for crop diseases. Finally, the overall acreage required for crop production is reduced through demand mitigation. Higher commodity prices lead to a shift in feed prices, and consumers switch from beef to less feed-intensive food sources.

The chart shows how economic parameters affect the estimation of LUC with only land cover change and without the effect of carbon stock. Conversion of pasture and grassland results in lower GHG emissions than the conversion of forest. The chart also shows the relative contribution of grassland and forest. The initial direct land use corresponds to 158 bushels per acre and 2.8 gallons of ethanol per bushel. Converting the units gives 2.42 m^2/L of ethanol. The effect of DGS with a 1:1 corn substitution ratio corresponds to 2,389 lbs. of DGS per acre with 5.4 lbs. DGS/gallon of ethanol. Of the 8,848 lbs. of corn produced per acre, 27% is sold as DGS feed, so the LUC drops by 27%. Estimating the effect of other variables is not so straightforward since the effects are interrelated. For example, varying the YDEL (price/ yield elasticity) parameter in GTAP BIO from 0.25 to 0.15 increases the land cover required for 13.5 billion gallons of ethanol from 491,142 to 581,806 ha. Not all of this LUC is associated with the response of yield to price. For example, crops are also shifting in response to the demand for ethanol, and demand for all commodities is mediated by price changes.

The magnitude of yield effects is an approximation. The relative contribution of model parameters could be determined from a series of GTAP runs, where each variable is modified to enable a calculation of the relative contribution of each input. The GHG emissions for the existing GTAP models for corn ethanol, soy biodiesel, and Brazil sugarcane could each be examined to determine the relative contribution of each parameter. GTAP is configured with a decomposition feature that may also enable the presentation of the relative contribution of key parameters to the result.

The relative contribution analysis could also be estimated for FAPRI based on the raw inputs and comparisons of prior FAPRI runs. Similarly, raw yield inputs for FASOM could provide the basis to estimate the contribution of yield inputs. This analysis would answer the question of how important yield improvements are compared to shifts in crop activity.

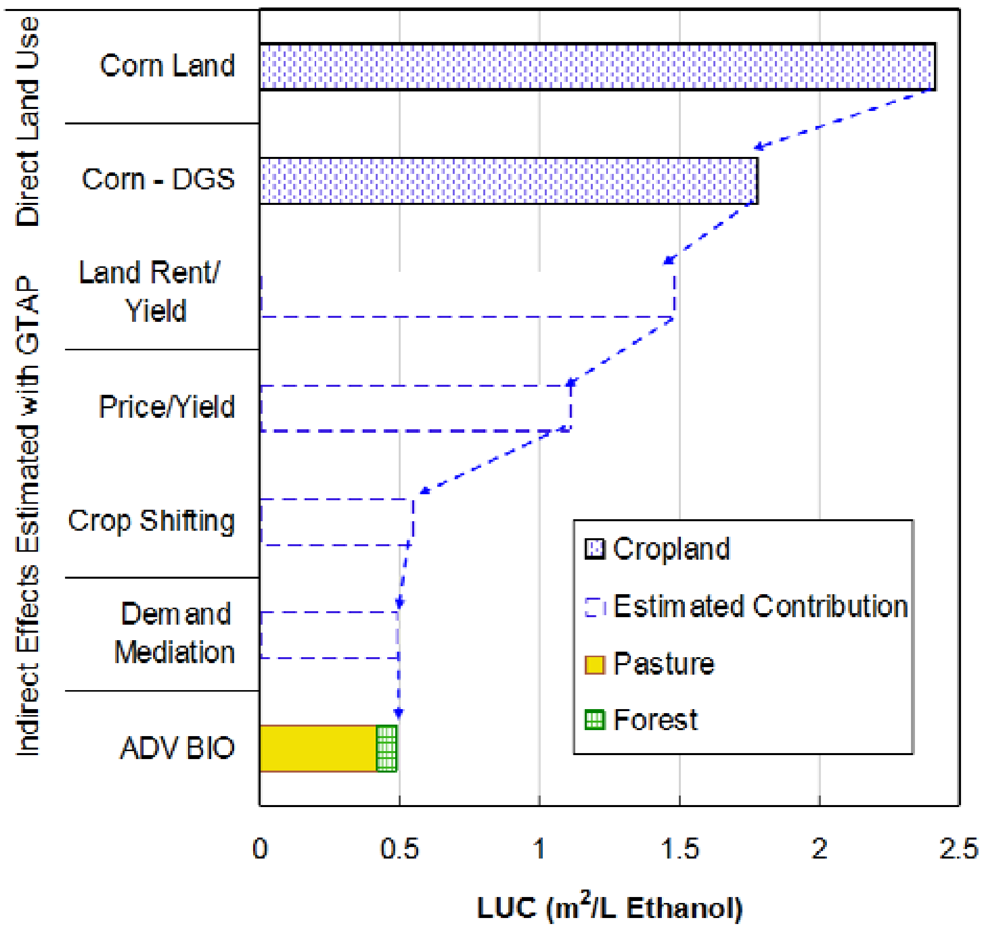

Figure 4.1. Contribution of Modeling Inputs for Corn Ethanol (Rough approximation).

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5. Recommendations

This study identifies the key inputs to agro-economic modeling of LUC for biofuels. Key drivers for the estimation of LUC are modeling factors that affect crop yield (price induced yield and yield vs land rent or time projections). Land cover type is also important because forests store more carbon than grassland or cropland. The LUC models also predict changes in land cover due to crop shifting as well as demand mitigation. Finally, the cumulative effect of biofuels, petroleum prices (via additional biofuel demand), and global growth also affects the overall demand for agricultural commodities.

The following recommendations would further elucidate the contribution of modeling parameters to LUC predictions as well as improve the transparency and accuracy of LUC models.

- Perform modeling runs to isolate key variables.
    - Estimate effect of multiple shocks.
    - Isolate inputs, including:
        - Elasticity
        - Exogenous yield
        - Armington trade
        - Petroleum prices
    - Determine effect of each key variable towards LUC
    - The effect of elasticities is uncertain. Model outputs should include explicit representations of yield for both feedstocks such as corn and crops indirectly affected by feedstock use. The net change in demand for agricultural commodities should also be explicitly reported. For example reductions in corn consumption due to a shift from beef to poultry should also be a model output.
    - Perform GTAP runs with multiple biofuel shocks in order to assess the effect of cumulative biofuel policies both in the U.S. and Europe.

- Find a mechanism to add cropland pasture for areas other than U.S. and Brazil to GTAP
    - Cropland/pasture was recently added to GTAP for the U.S. and Brazil. This caused a significant reduction in LUC, because it had the effect of reducing the forest converted to crops in these countries. The change in cropland with biofuel feedstocks such as soybeans should be compared to changes in pasture land to back test the model. In addition, there are significant amounts of cropland/pasture in Canada, Europe, and many other parts of the world. Data on cropland/pasture should be developed for other regions of the world and added to the model.

- Fallow land should be more readily accessed in GTAP
    - Fallow or idle land is part of cropland or cropland/pasture in GTAP, but the model has no way of accessing this land directly in estimating the LUC of biofuels. It is the first land converted back into production, and this conversion occurs without a carbon release. There are millions of acres of fallow land in the U.S., Canada, and Europe. The model should be revised to use fallow land more readily before converting cropland/pasture, pasture, and forest to crops.

- Enhance GTAP for flexibility and dynamic modeling.
  - GTAP is a static model. FAPRI and FASOM are dynamic models. Converting GTAP to a dynamic model would allow researchers to evaluate more "trend" data, such as trends in demand, trends in crop yields, and trends in protein use (e.g., substitution of poultry for beef).
  - Alternatively, GTAP could be modified to allow for trend data to be introduced via existing modeling parameters.
  - Develop mechanisms to report crop yields, feed substitution, and the effects of key inputs.
  - Develop mechanisms for users to perform multi-fuel shocks.

- Improve modeling of co-products on LUC.
  - There is still a debate on the size of this effect. FAPRI and FASOM use substitution ratios that are consistent with GREET. GTAP analyzes the historical effects of co-products on corn and soybean prices. The nesting structure in GTAP models DGS as primarily a substitute for corn. But FAPRI and FASOM use the Argonne research that indicates DGS is also replacing soybean meal, because DGS contains a higher protein content than corn. Soybeans have a lower yield per acre than corn, so any substitution of DGS for soybeans would affect the calculation of net LUC.
  - FAPRI and FASOM should be run with and without co-products enabled to determine what LUC reduction these models are providing to corn. It could be as high as 50-55%. Their response to DGS should be compared to GTAP.
  - Develop calculation methods to evaluate LUC from different co-product substitution ratios based on animal nutrition requirements and scenarios for feed demand.

- Develop mechanisms to report LUC impacts for feedstocks, not just fuel scenarios.
  - LUC results are reported for biofuel scenarios while the impacts depends almost entirely on the amount of feedstock consumed and co-product feed produced per gallon of fuel.
  - Reporting of LUC on a feedstock basis would allow for the development of more biofuel scenarios and also provide a closer link to comparing changes in crop use to historical LUC.

- Evaluate protein trends in developed nations
  - There has been a trend toward use of more poultry and less beef in the U.S. and other developed nations. Poultry is much more efficient with respect to land use than beef. This trend has resulted in millions of acres of pasture becoming available for crops in the U.S. and elsewhere in the last 20 years. The models should be evaluated for how they handle these trends.

- Examine U.S. historical data
  - FASOM, FAPRI and GTAP all make predictions of land use changes for the U.S. They should be supplied with the same U.S. "shock". Their results for crop price

changes, changes in exports, and land use changes in the U.S. should be compared in detail, with an eye toward determining which model best represents the U.S. If biofuel shocks in the U.S. are not well-modeled, then the international modeling results cannot be trusted.

- Validate model predictions
  - Biofuel use has grown substantially in the past decade. Additional modeling should attempt to validate predictions. The analysis should strive to adjust for changes in co-product use, shifts in income, animal feed patterns, fuel prices, and other factors that affect LUC.

- Develop approach for land cover selection in FAPRI.
  - EPA's implementation of FAPRI has no way to determine what type of land is converted in different regions of the world. Ostensibly, it can tell how much land is converted and in what regions, but it does not know which type is converted. Thus, EPA relied on satellite data of historical trends (due to multiple causes, not just a biofuel shock) in conversion. This means that the conversion cannot be definitely associated to the biofuel shock. (Another problem is that EPA makes the assumption that the trend stays the same in the future.) FAPRI researchers should develop economic criteria for international land use changes similar to FASOM.

Appendix A. Carbon Accounting in FASOM

This section summarizes carbon accounting in FASOM. Most of the discussion below was taken directly from the report written by Dr. Bruce McCarl and Robert Beach for the EPA's use in the RFS2 (Beach, 2010)[7].

Forest carbon accounting in FASOM follows the FORCARB model developed by the U.S. Forest Service and used in the periodic aggregate assessments of forest carbon sequestration. Tree carbon is the largest forest carbon pool and is modeled as a function of three factors: (1) merchantable volume, (2) the ratio of growing stock volume to merchantable volume, and (3) parameters of a forest volume-to-biomass model developed by U.S. Forest Service researchers (Smith, 2003). Harvest age is allowed to vary; thus, the growth of existing and regenerated/afforested stands must be modeled. Timber growth and yield data are included for existing stands, reforested stands, and afforested lands. These data, in turn, are used in computing forest carbon sequestration. These data indicate the wood volume per acre in unharvested timber stands for each timber stand strata (e.g., a stand giving location, forest type, management intensity class) by age cohort. The data used are derived largely from the U.S. Forest Service RPA modeling system (Haynes, 2003). Merchantable volume, by age, on each representative stand is obtained from the timber growth and yield tables included in FASOM. The volume factors and biomass model parameters vary by species and region and are obtained from (Birdsey, 1996a, 1996b) and Smith et al. (2003).

Carbon in live and standing dead trees is calculated using the parameters of the forest volume-to-biomass model equations for live and dead tree mass densities (above- and below-ground) in Smith et al., (2003) weighted for the FASOM region/forest type designations. Forestland area data reported by the RPA assessment are used to calculate the appropriate weights. Birdsey's assumption that the mass of wood is approximately 50% carbon is used to derive the associated levels of carbon (Birdsey, 1992).

Soil carbon is the second-largest carbon pool of carbon. Treatment of soil carbon follows Birdsey (1996a, 1996b) and recent work by Heath, Birdsey, and Williams (Heath, 2002). FASOM computes soil carbon profiles using soil carbon data over time from Birdsey (Birdsey 1996a, 1996b). As Heath, Birdsey, and Williams (Heath et al., 2002) noted, little change in soil carbon occurs if forests are regenerated immediately after harvest. As a result, FASOM assumes soil carbon on a reforested stand remains at a steady-state value. Currently, the age at which this value is reached is assumed to be the minimum harvest age for FASOM region/forest type.

This assumption is generally consistent with the ages at which steady-state levels of soil carbon are achieved in Birdsey (1996a, 1996b). Afforested land coming from crop or pasture use start with the initial soil carbon value for that land/region combination reported by the Century Model, which was developed by Colorado State University.[8] The land then accumulates carbon

[7] The Authors thank Robert Beach for permission to use material from the study for EPA.

[8] The current version of the CENTURY agro-ecosystem model simulates carbon, nitrogen, phosphorus, and sulfur dynamics through an annual cycle over time scales and centuries and millennia. CENTURY is capable of modeling

until reaching the steady-state value for forests of the type planted in the region afforestation takes place (where steady state is assumed to be reached at the minimum harvest age in FASOM for that region/forest type).

Forest floor carbon constitutes the third largest carbon storage pool, but is much smaller than tree or soil carbon pools. Smith and Heath's model (2002) estimating forest floor carbon mass forms the basis for forest floor carbon estimates in FASOM. The model's definition of forest floor excludes coarse woody debris materials; e.g., pieces of down dead wood with a diameter of at least 7.5 cm that are not attached to trees (Smith 2004). In order to account for this material, coarse woody debris is assumed to be a fixed fraction of live tree carbon based on ratios of coarse woody debris carbon to live tree carbon (EPA, 2003). This value is then added to the forest floor carbon values generated by Smith and Heath's forest floor model. The model for net accumulation of forest floor carbon is a continuous and increasing function of age, although the rate of accumulation eventually approaches zero (i.e., forest floor carbon reaches a steady state).

Understory vegetation comprises the smallest component of total carbon stock and includes all live vegetation except trees larger than seedlings. FASOM assumes that understory carbon is a fixed fraction of live tree carbon and uses published ratios reported in U.S. EPA (2003) as the basis for these calculations.

When timber is harvested, FASOM tracks the fate of the carbon that had been sequestered on the harvested land. Figure A.1 summarizes the disposition of carbon following harvest. To calculate carbon in harvested logs, cubic feet of roundwood (the units in which timber is quantified in the model) are converted into metric tons of carbon using factors reported in Skog and Nicholson (Skog, 2000). These factors vary by region and are reported for logs coming from an aggregate softwood and hardwood stand. They exclude carbon in logging residue left onsite. Logging residue is tracked separately in the forest floor carbon pool described above. Table A.1 presents an example of carbon disposition over time based on FASOM accounting procedures (Depro, 2008).

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a wide range of cropping system rotations and tillage practices for analysis of the effects of management and climate on agro-ecosystem productivity and sustainability. The model has undergone numerous enhancements since the original version developed in Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51:1173-1179.

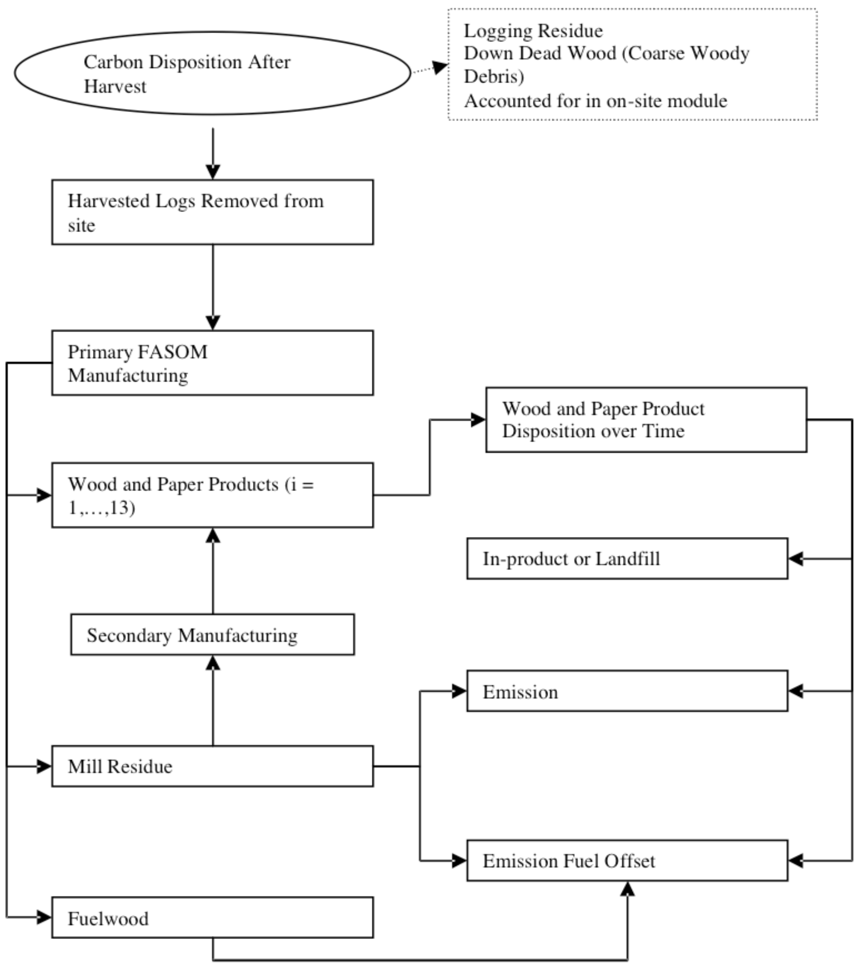

Figure A.1. Carbon Disposition after Timber Harvest.

Source: Adams et al., 2005.

Table A.1. Example of Disposition Patterns of Harvested Wood by Region and Harvest Type, 100 Year Period: Southeast.

Region	Type	Product	Disposi-tion	Years after Harvest										
				0	10	20	30	40	50	60	70	80	90	100
Southeast	Softwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Southeast	Softwood	Pulpwood	Landfills	0.00	0.16	0.16	0.16	0.10	0.14	0.14	0.13	0.12	0.11	0.11
Southeast	Softwood	Pulpwood	Energy	0.44	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Southeast	Softwood	Pulpwood	Emissions	0.26	0.32	0.34	0.35	0.41	0.37	0.38	0.39	0.40	0.41	0.41
Southeast	Softwood	Sawtimber	Products	0.47	0.28	0.24	0.21	0.18	0.17	0.15	0.14	0.13	0.13	0.12
Southeast	Softwood	Sawtimber	Landfills	0.00	0.13	0.16	0.17	0.18	0.19	0.19	0.19	0.18	0.18	0.18
Southeast	Softwood	Sawtimber	Energy	0.38	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41
Southeast	Softwood	Sawtimber	Emissions	0.15	0.19	0.20	0.22	0.24	0.24	0.25	0.26	0.28	0.28	0.29
Southeast	Hardwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Southeast	Hardwood	Pulpwood	Landfills	0.00	0.16	0.16	0.15	0.15	0.14	0.13	0.12	0.12	0.11	0.10
Southeast	Hardwood	Pulpwood	Energy	0.39	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Southeast	Hardwood	Pulpwood	Emissions	0.31	0.37	0.38	0.40	0.40	0.42	0.43	0.44	0.44	0.45	0.46
Southeast	Hardwood	Sawtimber	Products	0.27	0.12	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.04
Southeast	Hardwood	Sawtimber	Landfills	0.00	0.11	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12
Southeast	Hardwood	Sawtimber	Energy	0.42	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Southeast	Hardwood	Sawtimber	Emissions	0.31	0.34	0.36	0.35	0.36	0.37	0.38	0.39	0.39	0.39	0.40

Note: These are proportions of the harvested stock allocated to each pool in the years following harvest. Column totals may not sum to one due to independent rounding.

Source: Depro et al, 2008.

Harvested logs removed from site are converted into three types of outputs through primary manufacturing processes: FASOM wood and paper products, mill residues, and fuel wood. The fate of each of these outputs is discussed in turn below.

FASOM contains the following 13 wood and paper products:

- softwood sawlogs for export
- hardwood sawlogs for export
- softwood lumber
- softwood plywood
- oriented strandboard
- hardwood lumber

- hardwood plywood
- softwood miscellaneous products
- hardwood miscellaneous products
- softwood used in non-oriented strand board reconstituted panel
- hardwood used in non-OSB reconstituted panel
- softwood pulpwood
- hardwood pulpwood

The distribution of product carbon changes over time and FASOM tracks the fate of product carbon for each end-use using two pools: carbon remaining in-product and carbon leaving the product (Figure A.2). Carbon that leaves the product ultimately makes its way to emissions or is permanently sequestered in landfills.

The fraction remaining in the product, shown in Table A.2, is based on a model specifying half-life values for a set of end-use categories (Skog, 2000). The half-life represents the time it takes for approximately half of the product to decompose. For instance, carbon that is stored in paper products is assumed to have a relatively short half-life, with 50% of carbon decomposing within two years, whereas carbon stored in wood used for single-family homes has a half-life of 100 years. These values from Skog and Nicholson (2000) were mapped to FASOM wood and paper products categories, weighting by wood and paper product use in various end uses.

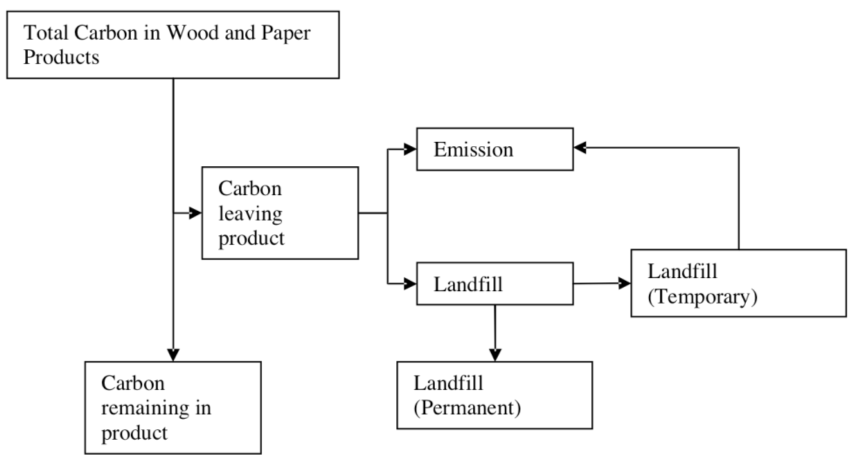

Figure A.2. Wood and Paper Product Carbon Disposition.

Source: Adams et al., 2005.

As shown in Figure A.2, carbon leaving the product pool moves to either the emissions or landfill pools.[9] Skog and Nicholson (2000) assumed that 67% of carbon leaving the wood

[9] There are two landfill pools that are tracked: permanent and temporary. Carbon in permanent landfills is sequestered forever, but carbon in temporary landfills decays and is eventually released as emissions. The model assumes that approximately 77% of wood products and 44% of paper products going into landfills remain permanently sequestered. The rest is eventually released to the atmosphere as emissions based on an assumed half-life of 14 years.

product pool and 34% of carbon leaving the paper product pool goes to landfills. The remainder of the carbon leaving the wood and paper product pools goes into CO_2 and CH_4 emissions to the atmosphere.

In addition, FASOM tracks the fate of mill residue using two different pools. The first is for mill residue that is used as an intermediate input in the production of wood and paper products. This carbon is tracked using the appropriate product category as described above. The second pool is for carbon in mill residue that is burned for fuel, with the fraction burned in each region based on Smith et al. (2001). It was assumed that one-third of mill residue burned is used to offset fossil fuels.

Harvested fuel logs and their associated carbon are used as to produce energy at mills. For fuel wood, FASOM assumes that 100% of fuel wood burned in the sawtimber and pulpwood production process is used to offset fossil fuels.

Table A.2. Half-life for Forest Products in End Uses.

End Use or Product	Half-Life in Years
Paper	2
New residential construction	
Single family	100
Multifamily	70
Mobile homes	12
Residential upkeep & improvement	30
New nonresidential construction	
All ex. railroads	67
Railroad ties	12
Railcar repair	12
Manufacturing	
Household furniture	30
Commercial furniture	30
Other products	12
Shipping	
Wooden containers	6
Pallets	6
Dunnage etc.	6
Other uses for lumber and panels	12
Uses for other industrial timber products	12
Exports	12

Source: Adams et al., 2005.

Effects of Changes in Forest Area on Carbon Storage

In FASOM, land used in forestry can move to agriculture or developed use, resulting in a dynamic change in carbon storage levels on the previously forested land. When land moves from forestry to one of these other uses, two carbon pools associated with the land are tracked as residual forest floor carbon and soil carbon (in agricultural or in developed use) shown in Figure A.3.

For agriculture and developed land uses, the path of residual forest floor carbon stock is assumed to be the same as for the forest floor carbon profile after a harvest, which is described above. This model of decay is based on the average forest floor of mature forests and regional averages for decay rates, as described in Smith and Heath (2002).

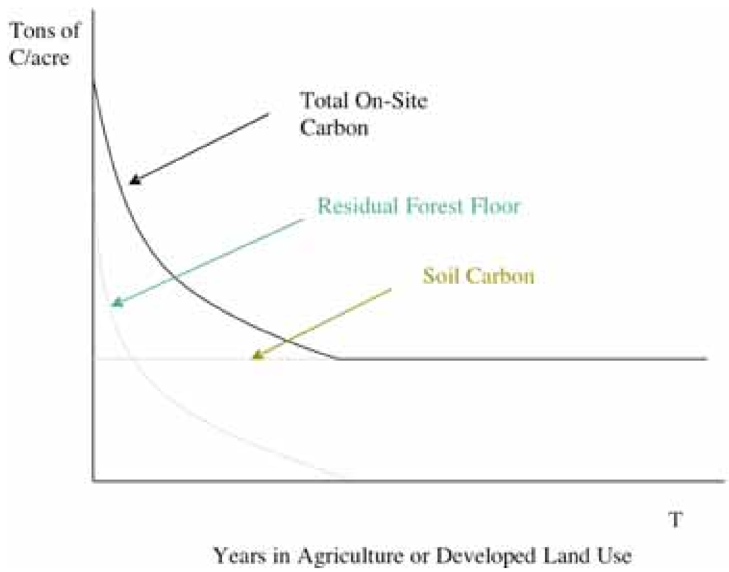

Figure A.3. Disposition of On-Site Carbon after Deforestation.

The approaches used in FASOM to account for transition paths of soil carbon following deforestation are defined as follows. When forested land switches to agriculture, soil carbon levels are assumed to be consistent with Century Model data on agricultural soil carbon for the appropriate category of agricultural land and do not vary over time. In the case of timberland switching to developed land uses, the soil carbon levels are assumed to be consistent with the steady-state value of the minimum harvest age. As for land moving to agriculture, the soil carbon level does not vary over time.

In addition, the carbon stored in the forest products produced from the harvest that cleared the land is tracked over time as described in the previous section. The change in forest sequestration associated with a policy change is calculated as the difference in carbon sequestration in each of the carbon pools tracked between the model simulation with the policy in place and the baseline model simulation. Thus, any potential foregone sequestration that may be associated with reallocation of forestland to agricultural land in response to a change in policy would be captured in the calculation of the difference between the forest carbon sequestration values under baseline and policy conditions.

Soil Carbon Sequestration

Agricultural soil carbon sequestration depends on management activities that influence carbon storage per acre. Key factors that affect soil carbon sequestration include the following:

> **Intensity of agricultural tillage**. Agricultural soils have traditionally been tilled to create a suitable seedbed, reduce weed competition, and remove restrictions to crop root growth. However, by loosening the soil, tillage breaks up soil aggregates and increases the exposure of soil organic matter to oxygen, which speeds oxidation and results in reduced soil carbon with an associated release of CO_2 into the atmosphere. The use of tillage alternatives that reduce soil disturbance and therefore reduce oxidation of soil organic matter will increase soil carbon sequestration. Reduced tillage practices also leave crop residues on the soil, thereby potentially increasing carbon inputs. Typically, reduced tillage involves movement from intensive tillage practices such as moldboard plowing to conservation or zero tillage practices.[10]
>
> **Irrigation status**. Based on data from the Century model, there are differences in soil carbon sequestration per acre for a given region between irrigated and dryland cropland systems.[11] For sites receiving irrigation, the increased yields are expected to increase biological activity and hence soil carbon sequestration throughout the year. FASOM incorporates these differences in soil carbon storage within tables of soil carbon storage that vary by irrigation status.
>
> **Relative abundance of grasslands**. Normally, pasturelands and land in the CRP experience less soil disturbance than actively tilled croplands and tend to store more carbon per acre. Thus, changes in the distribution of land between pastureland, cropland, and land in the CRP will affect agricultural soil carbon sequestration.
>
> **Mix of annuals versus perennials**. Because perennial crops would not be tilled on an annual basis, there will typically be a reduction in soil disturbance relative to actively tilled annual crops. By definition in FASOM, perennial crops such as switchgrass, hybrid poplar, and willow are produced under zero tillage. Similarly, as described in the previous section on forest carbon sequestration, forest soils have higher rates of carbon sequestration per acre.

Baseline carbon storage is estimated from the baseline distribution of land across tillage practices, irrigation status, land use, and cropping patterns, assuming carbon sequestration rates are equal to those at equilibrium. Soil carbon accounting for changes in tillage practices is done as if land remained in the initial tillage forever.

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[10] In addition to changes in soil carbon, there are additional changes in emissions associated with tillage changes that are tracked in FASOM. Less-intensive tillage typically reduces emissions from fossil fuel use by tractors, but may result in increases in the use of pesticides and changes in the rate of fertilization, which can increase emissions associated with agricultural chemical production and use. FASOM tracks these indirect effects on GHG emissions.

[11] All pastureland and CRP land in FASOM are assumed to be produced in dryland systems.

Changes in soil carbon due to changes in tillage, irrigation status, or land use are generally assumed to take place over a number of years as the soil carbon levels adjust to a new equilibrium. In FASOM, soil carbon levels are assumed to reach a new equilibrium after 25 years, although almost 94% of the adjustment takes place within 15 years (see Figure A.4).[12]

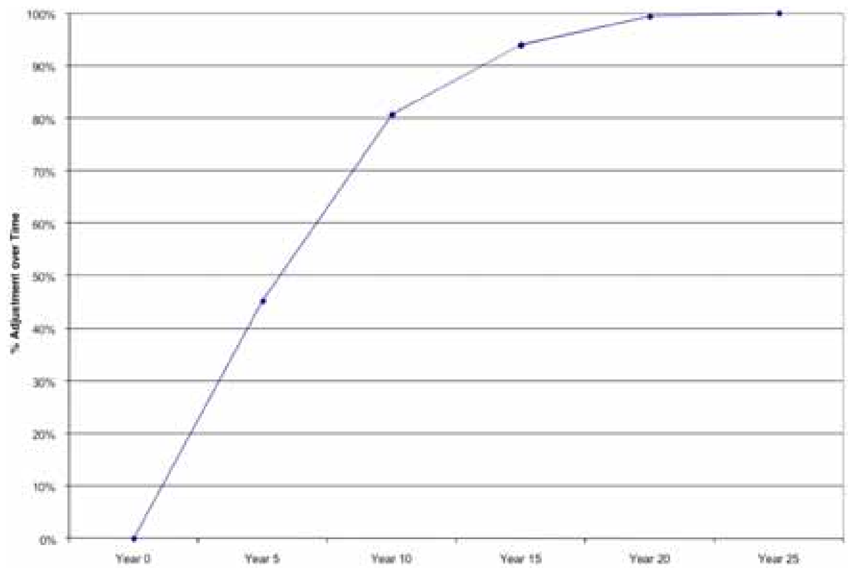

Figure A.4. Percentage Adjustment over Time to New Soil Carbon Equilibrium Following Change in Land Use or Management.

Because movement of soil carbon sequestration towards equilibrium levels is not constant over time, FASOM yields non-uniform changes in soil carbon consistent with the generally accepted scientific finding that carbon sequestered in an ecosystem approaches steady-state equilibrium under any management alternative. As shown above, the rate of change in carbon storage decreases over time and eventually reaches zero at the new equilibrium (saturation) (West and Post, 2003). Soil carbon per acre may increase or decrease depending on the land use change or change in land management taking place. For instance, Figure A.5 presents examples of changes in soil carbon for the Northern California region in FASOM. In the cases shown, soil carbon initially decreases when moving from the initial equilibrium state to a new state, but then it increases per acre over time until reaching a new equilibrium at a higher level of carbon storage per acre.

To reflect the timing of changes in soil carbon, FASOM output on GHG emissions associated with increases or decreases in agricultural soil carbon represents changes in cumulative soil carbon relative to the baseline. Values reported reflect all changes in soil carbon that are taking place in a given period, including those changes associated with land use change or alterations in management practices that occurred in earlier periods, but where soil carbon levels continue to adjust to their new equilibrium values. For instance, emissions from changes in soil carbon

[12] There is an immediate jump in carbon storage in year 0 due to changing tillage, irrigation, and/or land use that depends on the initial state and the new state.

sequestration reported for 2022 would reflect the appropriate portion of emissions related to all changes in tillage, irrigation status, land use change, and cropping patterns that have taken place at all points between the baseline and 2022 based on the assumed rate of saturation over time. For analogous reasons, changes in land use in 2022 would continue to affect soil carbon emissions calculated in the model for the next 25 years.

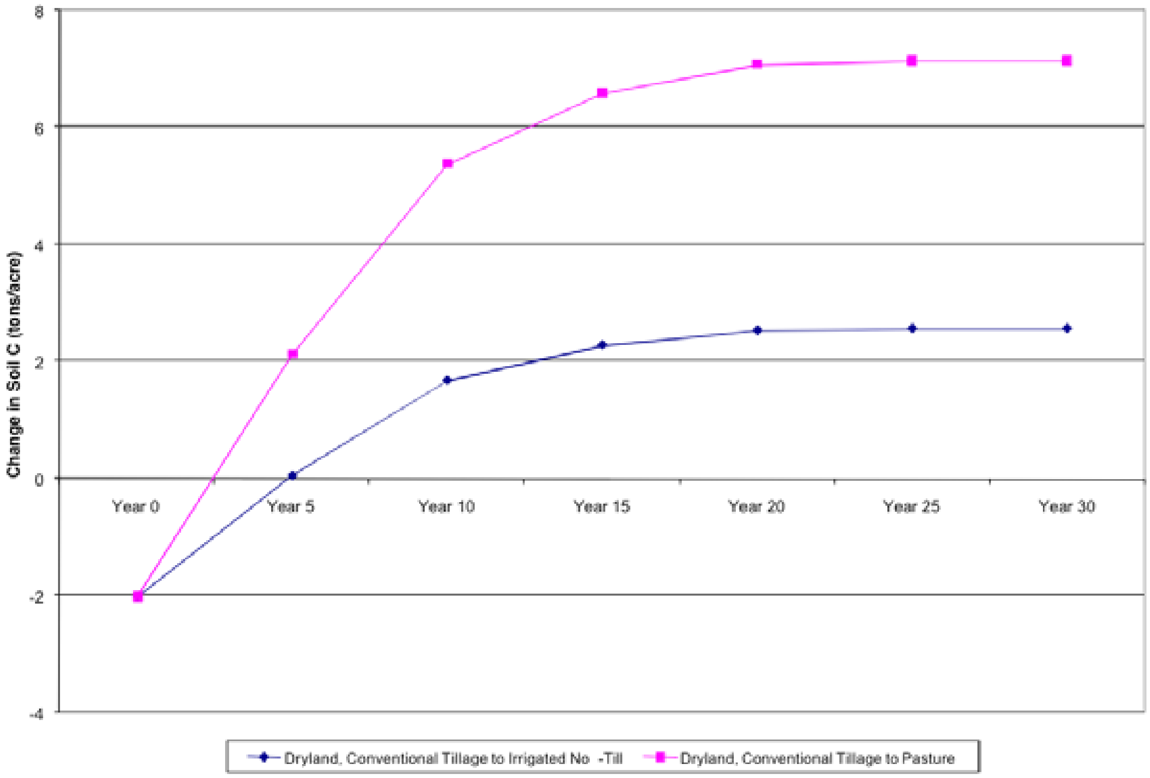

Figure A.5. Change in Soil Carbon for FASOM Northern California Region for Selected Changes in Land Use and Management.

For the analysis of the RFS2 renewable fuels volumes, the control case reduces net soil carbon sequestration and increases CO_2 emissions. There are increases in cropland soil carbon relative to the reference case, reflecting the reduced conversion of cropland to pasture over time relative to the baseline simulation when demand for agricultural commodities is increased by the policy. However, reductions in pastureland soil carbon more than outweigh the increases in cropland soil carbon, resulting in net reductions in soil carbon sequestration under the control case.

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