Land Use Change Emissions Associated with Soybeans, Considerations for California's LCFS

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Life Cycle Associates

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TERMS AND ABBREVIATIONS

AEZ-EF	Agro-Ecological Zone Emission Factor Model
ARB	Air Resources Board
BGY	Billion Gallons per Year
Btu	British Thermal Unit
CA	California
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use and Land Management Change from Biofuels Production
CGE	Computable General Equilibrium
CH_4	Methane
CI	Carbon intensity
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	Carbon Dioxide
CO_{2e}	Carbon dioxide equivalent
DGS	Distillers' Grains
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ETA	Elasticity of Area Expansion
ETL	Elasticity of Land Transformation
FAPRI	Food and Agriculture Policy Research Institute
FASOM	Forest and Agriculture Sector Optimization Model
g CO_2e	Grams of carbon dioxide equivalent
GHG	Greenhouse Gas
GLOBIOM	Global Biosphere Management Model
GREET	The Greenhouse gas, Regulated Emissions, and Energy use in Transportation Model
GTAP	Global Trade Analysis Project
GWP	Global Warming Potential
ICAO	International Civil Aviation Organization
iLUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	International Standards Organization
LCA	Life Cycle Analysis or Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LUC	Land Use Change
mmBtu	million Btu
OBBBA	One Big Beautiful Bill Act
RINs	Renewable Identification Numbers
RFS	Renewable Fuel Standard

RFS2	Revised Federal Renewable Fuels Standard
SAF	Sustainable Aviation Fuel
SAM	Social Accounting Matrix
SOC	Soil Organic Carbon
WTW	Well-To-Wheel
YDEL	Yield Price Elasticity

EXECUTIVE SUMMARY

Land use change and how it is modeled across various regulatory frameworks has significant implications for soybean producers. To guide engagement the California Air Resources Board's deliberations on land use change, this analysis reviews the evolution of modeling approaches for soy-based fuels, evaluates the effects of the vegetable oil feedstock cap, and examines the role of sustainability and traceability requirements in shaping market access. The goal is to equip stakeholders with evidence-based insights and recommendations that strengthen the position of soybean feedstocks in California's LCFS and other low carbon fuel markets.

The following recommendations are based on the recent CARB workshop with justification and further detail found in the subsequent sections of the report.

Recommendations

- **Model Selection:** Due to improvements in GTAP, select the version implemented in CCLUB (GTAP 2017). Figure S.1 shows the evolution of iLUC values for soy biodiesel and renewable diesel for various regulatory schemes. It represents a long-run assessment of the global economy with many interactions between sectors and includes the following updates:
    - More refined land use categorizations (cropland/pasture/forest)
    - Improved nesting structures to distinguish intensification versus land use conversion
    - Yield/land intensification is distinguished in newer versions to account for yield growth, multi-cropping, and idle cropland to production
    - Better trade/substitution elasticities
    - Higher sector/region resolution from 57 to 65 sectors
    - Integration of AEZ-EF v54 with updated 2019 IPCC factors
    - For CARB, IPCC factor updates do not require a rulemaking

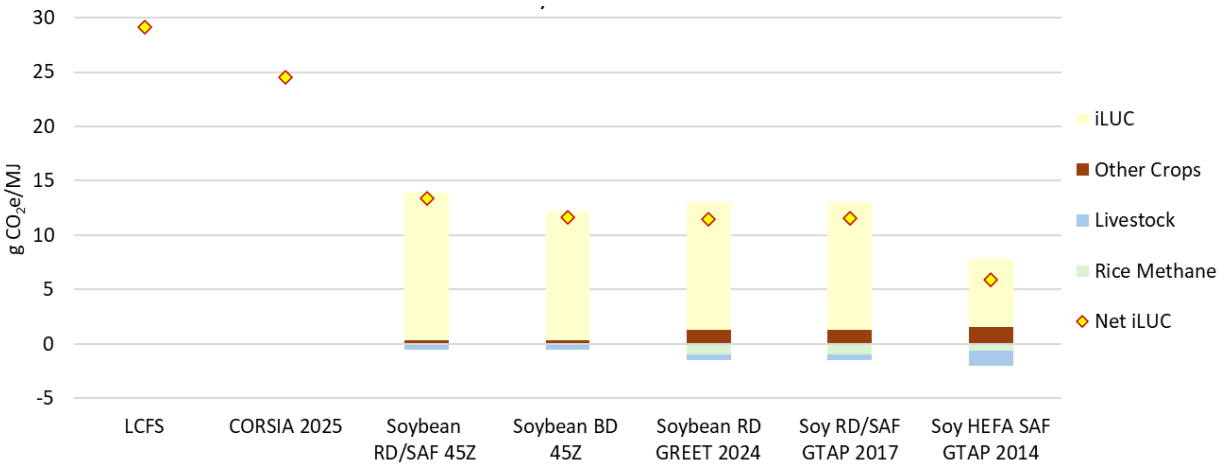

Figure S.1. Various iLUC modeling results for Soy Biodiesel and Renewable Diesel

- **Climate Smart Agricultural Practices:** CARB's comments on the regulation indicate that "staff is open to potentially amending the LCFS at a future date to recognize climate smart agricultural practices in the program…"[1]. Figure S.2 demonstrates the potential of feedstock carbon intensity reductions for soy across various CSA practices.
    - CARB can begin to take immediate steps to develop a framework for CSA practice inclusion in the LCFS through a stakeholder group consisting of organizations that are involved everyday with these practices.
    - The stakeholder group can work with CARB through points CARB raised around quantifying, reporting, and verifying these practices.
    - Oils and fat feedstocks are the largest category contributor to LCFS credits today for the production renewable diesel. This fuel category will be phased out of the LCFS by not including CSA practices and updating the GTAP model as previously described which eliminates an essential incentives for CSA.
    - Renewable Diesel is a success story of the LCFS where 2/3 of petroleum based diesel has been supplanted by lower CI, renewable diesel, exactly as the regulation intended.

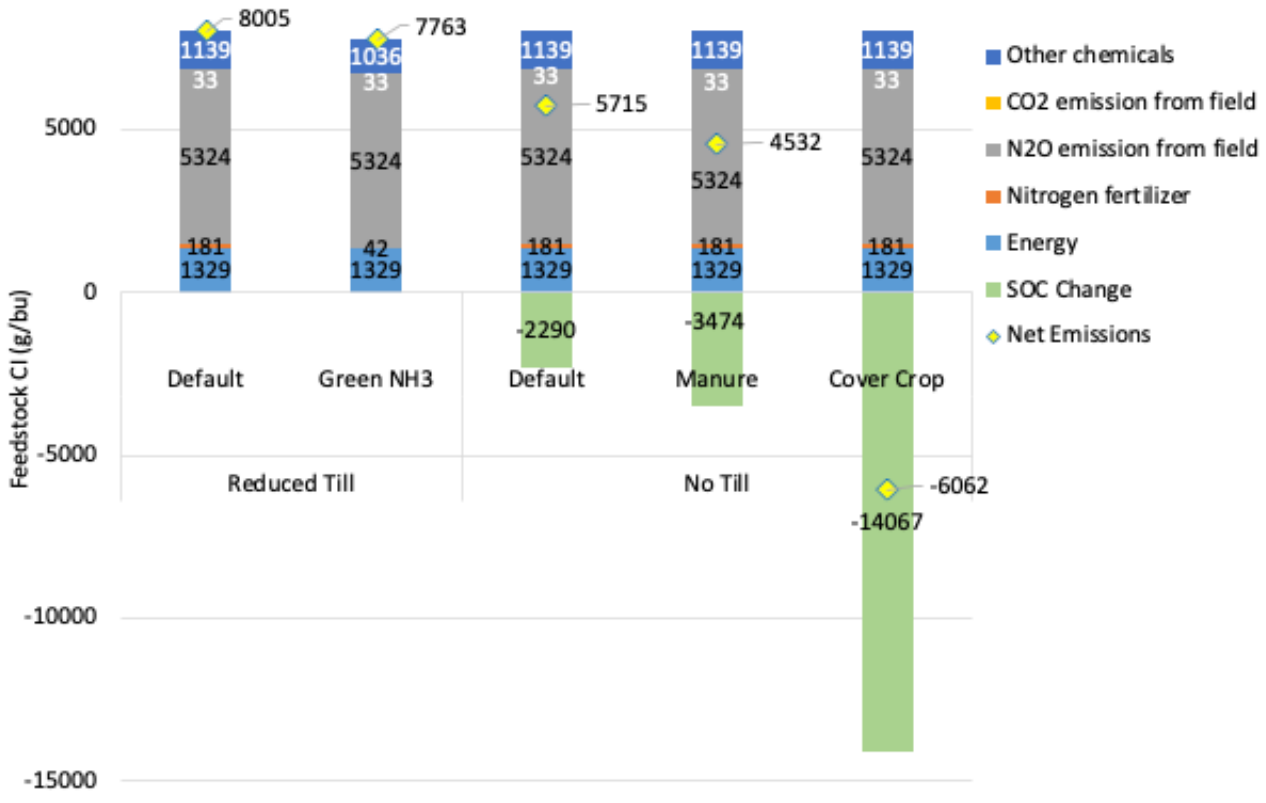

Figure S.2. Effect of CSA practices for soybeans in FD-CIC model[2].

[1] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2024/lcfs2024/fsor_appc.pdf?utm

[2] GREET1_2024, FD-CIC model, Champaign Illinois County.

- **Shock Size:** for iLUC modeling should be zero if a limit on crop-based fuels is implemented. Alternatively, the shock size should represent the incremental increase in soy oil biofuels that are induced by the regulation.

- **Dynamic Models:** have also been contemplated for iLUC modeling, such as in the RFS. Such models introduce new assumptions and uncertainties. Insights into the effect of California's fuel policy actions should be weighed against the uncertainties associated with long-term economic projections required for dynamic models.
    - GTAP gives you a prediction of a long run impact for biofuels, it is not a dynamic model but dynamic models do not help you make better decisions because they introduce uncertainty by requiring additional economic assumptions.

1. INTRODUCTION

Most biofuel policies around the world now require that eligible fuels achieve specific greenhouse gas (GHG) reductions compared to the fossil fuels they replace. These reductions are assessed using life cycle assessment (LCA), which accounts for all emissions from resource extraction through final fuel use. Results are expressed as carbon intensity (CI), in units of grams of CO_2-equivalent per megajoule (gCO_2e/MJ), enabling comparison across fuels on an energy-equivalent basis.

LCA results depend on numerous assumptions and inputs, which introduce uncertainty. One of the most debated sources of uncertainty is land use change (LUC). LUC occurs when land shifts from one use to another, such as forest or pasture converted to cropland, potentially releasing carbon depending on the land type and location. As biofuel demand grows to meet policy-driven targets, additional agricultural land may be required, either directly for biofuel feedstock production or indirectly through global market responses to changes in crop supply and demand. Price shifts in agricultural commodities may further incentivize indirect land conversions elsewhere.

Distinguishing direct from indirect LUC is not straightforward. Some biofuel pathways rely on feedstocks sourced from common commodity markets, while others depend on dedicated feedstock supply chains. Regardless, any expansion of arable land influences carbon fluxes both locally and globally. This report therefore uses "LUC" to refer to both direct and indirect effects. Concerns about the accuracy of LUC estimates persist, given the complexity of attributing land conversions to biofuel expansion and the uncertainties in modeling approaches.

1.1 LUC

The concept of LUC and its potential impact on the CI of biofuels was brought to prominence by Searchinger et al. in 2008, who argued in their paper that land conversion could significantly increase biofuel emissions (Searchinger, 2008). While debate continues over modeling methods and results, academic research has shown significant reductions in estimated LUC values from since 2008. Accordingly, regulators have incorporated LUC into policy frameworks like the U.S. Renewable Fuel Standard (RFS2) and California's Low Carbon Fuel Standard (LCFS).

In agro-economic models designed for the agricultural sector, biofuel policy volume targets and other key inputs reflecting market and price dynamics are used to estimate the scale, location, and type of LUC. These model outputs are then combined with an emission factor database to calculate the resulting GHG emissions. Emission factor databases provide estimates of the carbon stored in vegetation and soils across different ecosystems and regions and quantify how much of that carbon is released when land is disturbed or converted.

Estimates of LUC from biofuel policies vary widely depending on the modeling approach and assumptions used. Agro-economic models typically generate these estimates by incorporating parameters such as crop yields, price elasticities, and land transformation coefficients. Some studies provide regional detail, while others group results under "rest of world," further highlighting the variability in outcomes.

These models not only estimate the scale and location of land conversion but also the types of land affected such as forest, pasture, or fallow. To calculate associated CI values, the outputs are paired with carbon stock datasets such as those from Winrock or the Woods Hole Research Center (WHRC). However, even when the same dataset is applied, differing assumptions can lead to widely divergent results, largely due to how land cover changes are represented in the models.

iLUC

Indirect land use change (iLUC) refers to shifts in land cover that occur when expanding biofuel production increases demand for biomass, such as clearing forests to grow corn for ethanol. These land conversions release carbon stored in soils and vegetation, contributing additional GHG emissions to a fuel's life cycle. Because iLUC emissions cannot be directly measured and occur through complex, global market interactions, these emissions must be estimated through agro-economic modeling.

To address this, both the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) developed methodologies that combine economic models of land use change with emission factors to calculate associated GHG releases. Since their initial adoption, CARB updated its iLUC methodology, in 2015, by applying a newer version of the GTAP model and introducing a revised set of emission factors. EPA, by contrast, has not formally revised its methodology but has published updated GHG values for some biofuels.

1.2 Role of GHG Calculations

GHG calculations are a central component of CARB's implementation of the LCFS. The iLUC analysis provides an additional assessment which aims to be consistent with the attributional LCA used for pathway calculations. As such, the iLUC analysis takes into account feedstock inputs, fuel yields, and co-product credits that are consistent with fuel pathway calculations for renewable diesel and biodiesel.

LCA'S quantify the emissions associated with each stage of a product's life cycle across various types of regulatory programs. Understanding the GHG implications within each framework is contingent upon an analysis of the modeling requirements and the treatment of credits and co-products. The CI calculation is influenced by how each model manages inputs, outputs, and the allocation of emissions. Credits may be issued for actions such as carbon sequestration or the use of renewable energy, while co-products can impact the overall GHG emissions profile if their production or utilization results in emission reductions elsewhere.

1.2.1 Regulatory Programs & Modelling Efforts

Numerous regulatory programs, primarily for low carbon fuels, have been implemented nationally and internationally. These programs establish unique methodologies for quantifying emissions throughout the product lifecycle, establish reduction targets over time, and offer various incentives to reduce emissions relative to a petroleum fuel baseline. To ensure these programs meet their emissions reductions requirements, they impose penalties for non-compliance. The following is a list of regulatory programs and the associated LCA modeling tool that greatly impact U.S. soybean feedstocks for biofuels:

- U.S. EPA Renewable Fuel Standard (RFS) Program/EPA Fuel Pathway Analyses
- California Low Carbon Fuel Standards (LCFS)/CARB Look Up Tables and Tier 1 Calculators
- The U.S. Inflation Reduction Act (IRA)/GREET
- One Big Beautiful Bill Act (OBBBA)/GREET
- Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

The RFS, expanded in 2007, sets annual volumetric requirements for renewable fuels with minimum lifecycle GHG reduction thresholds relative to petroleum baselines (EPA, 2025). The RFS aims to reduce greenhouse gas emissions, decrease dependence on imported oil, and support the development of advanced biofuels and renewable fuel infrastructure. The program uses a credit trading system where refiners and importers can buy and sell renewable identification numbers (RINs) to meet their blending obligations.

California's LCFS, adopted in 2009, requires reductions in the carbon intensity of transportation fuels over time (CARB, 2020). Compliance is based on lifecycle carbon intensity scores calculated using CA-GREET and iLUC values derived from GTAP-BIO and AEZ-EF modeling. CARB provides default lookup table values and calculator tools for Tier 1 pathways, while customized Tier 2 analyses allow producers to claim lower CI scores.

CORSIA is a global program under the International Civil Aviation Organization (ICAO) that requires airlines to offset emissions growth above 2020 levels (ICAO, 2025). Lifecycle analysis under CORSIA is standardized across countries, with approved methodologies, including GREET-based options, used to determine the carbon intensity of aviation fuels. These values determine eligibility for emissions units and credits in the international aviation sector.

The 2022 IRA provided tax credits for low-carbon fuels under Section 45Z and sustainable aviation fuel (SAF), with eligibility determined through lifecycle GHG analysis measured against a baseline "emission rate" requirement (Treasury, 2025). Under the IRA, the U.S. Departments of Treasury and Energy adopted tailored the GREET 45ZCF model to calculate carbon intensities of fuels. The IRA linked financial incentives directly to lifecycle emissions performance, making GREET a central tool in credit generation and compliance. The GREET 45ZCF model includes iLUC analysis based on the latest GTAP developments.

The 2025 OBBBA updates the IRA framework and adjusts incentive structures and qualification timelines for various renewable fuels (Congress, 2025). Like the IRA, GREET serves as the primary life cycle model to determine credit generation. The Act's alignment with GREET ensures continuity with existing policy while modifying credit structures and cost-sharing requirements for renewable fuel producers. The OBBBA has eliminated iLUC from the emission rate calculation.

1.3 Objectives

The objective of this study is to conduct analysis and provide recommendations for the CARB workshop on iLUC. In addition, the study provides further options for analysis and recommendations related to other low carbon fuel markets to maintain and grow the soybean feedstock market share, supporting soybean farmers.

1.4 Scope of Report

This study provides a comprehensive technical and policy analysis to inform engagement with CARB following the 2025 LCFS LUC workshop. The work reviews advances in iLUC modeling over the past decade and quantify how these improvements have led to lower emissions estimates for soy-based fuels through a comparative assessment of key models and identification of the main methodological drivers behind declining iLUC values. It also evaluates the regulatory cap on vegetable oil feedstocks and its impact on biodiesel and renewable diesel markets, including the implications for soybean utilization relative to other feedstocks under the LCFS. In addition, the analysis examines sustainability and traceability requirements, mapping regulatory criteria against production practices to identify verification and certification challenges.

2. LAND USE CHANGE MODELS

Land use change models are a critical component of life cycle assessment for biofuels. Their purpose is to estimate the GHG emissions that result when increased biofuel demand alters land-use patterns, specifically when new cropland is created by converting forests, grasslands, or other non-agricultural lands (IPCC, 2006). LUC models simulate complex economic, agronomic, and ecological responses across local and global systems, making them essential tools for evaluating the carbon intensity of biofuel. By capturing both direct and indirect pathways of land conversion, these models aim to ensure that fuel policy accurately reflects real-world environmental impacts.

Indirect Land Use Change accounts for the GHG emissions related to the conversion of land, such as forests or agricultural land, that occur indirectly as a result of biofuel production. It also considers the potential displacement of crops caused by the expansion of biofuel feedstock cultivation, which may lead to additional land being converted from non-agricultural use to compensate for the increased demand (CARB, 2015). As a result of the conversion, carbon stored in above-ground biomass and in the soil is released to the atmosphere, resulting in an increase in CO_2 emissions relative to business-as-usual. There is also a loss of on-going carbon sequestration in the vegetation that has been removed. This section of the report first presents background information on modeling of iLUC, which is followed by details of the iLUC models used in the LCA methodologies evaluated in this report.

The following is a list of LUC models associated with regulatory programs that greatly impact U.S. soy biodiesel and renewable diesel:

- Global Trade Analysis Project (GTAP)
- Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB)
- Global Biosphere Management Model (GLOBIOM)
- IRA Clean Fuels Production Credit (GREET 45ZCF)

2.1 iLUC Modeling Background

Estimating iLUC emissions requires many assumptions as compared to direct emissions and can differ widely between models and modeling systems. According to (Xin Zhao, 2021), “Induced land use change includes both direct and indirect land use change, as the two cannot be distinguished given the complexity of the market-mediated responses”.

Figure 2.1 summarizes the general approach to calculating the carbon intensity of iLUC (CARB, 2014). A biofuel “shock” through increased demand is modeled via agro-economic models to determine how much and what kind of land is converted as a result of the increased biofuel demand. Emission factors, above ground and below ground carbon, are applied to the converted land to determine the GHG impact of changing the land from, for example, native vegetation to

crop production. Emissions are then allocated over a certain time period, 30 years in U.S. policies like the RFS and LCFS, assumed to be consistent with the length of the fuel program.

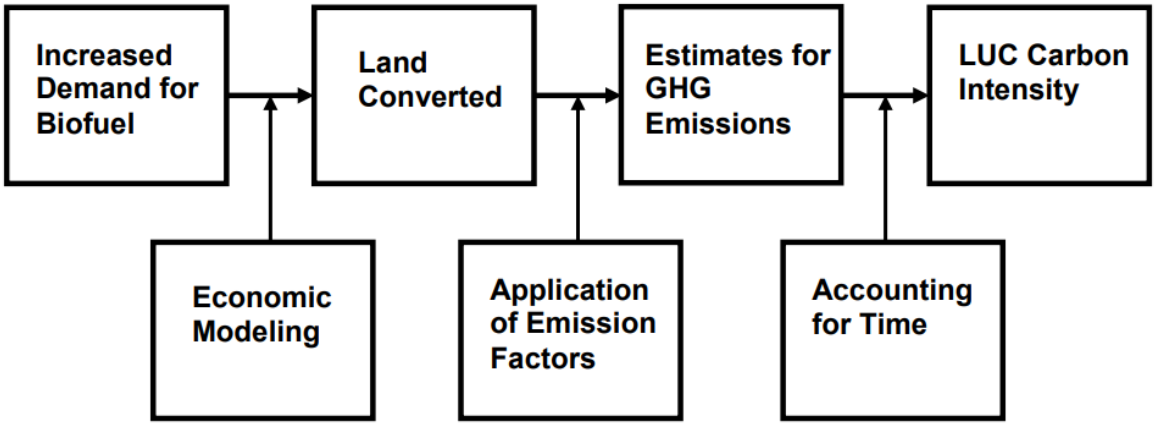

Figure 2.1. Simplified Block Flow Diagram of iLUC Modeling.

A typical land use change emissions profile is shown in Figure 2.2. Year 1 has the highest emissions as a result of land clearing and burning of the native vegetation. Most of the below-ground carbon, from roots and organic material, is released in years 1 to 5, with a slower release in years 6 to 20. Finally, foregone sequestration occurs during the entire project period, which as noted above, is assumed to be 30 years under U.S. policies.

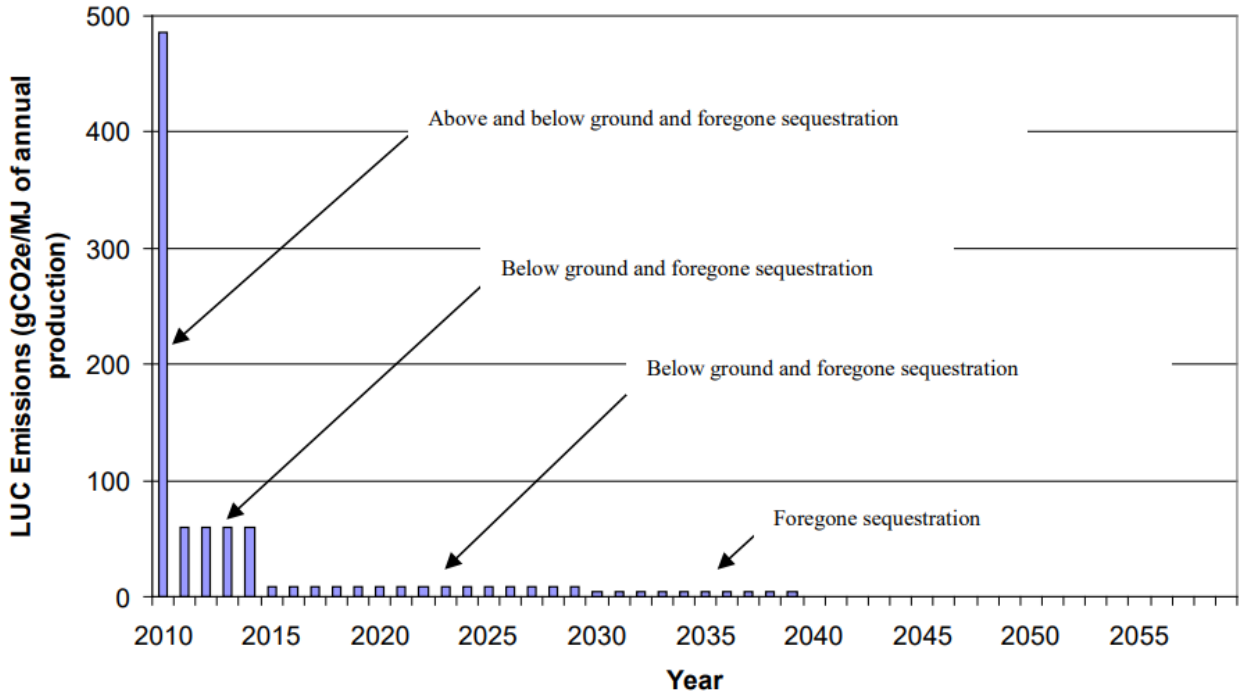

Figure 2.2. Emission Profile of ILUC (CARB, 2014)

Land use conversion is measured by assessing the carbon emissions associated with the transformation of one type of land use to another, such as converting forests or wetlands into agricultural land. The carbon released from soil and vegetation during land conversion is a key factor, as the carbon that was previously stored in biomass or soil organic matter is emitted as CO_2, contributing to Global Warming Potential (GWP).

Economic equilibrium models like GTAP form the backbone of many LUC analyses, including the LCFS, as shown in Figure 2.3 (CARB, 2014). GTAP-based approaches model the global agricultural economy to predict how biofuel-driven demand shocks redistribute land uses worldwide, considering trade, crop switching, yield responses, and land conversion costs. Emissions from these land conversions are then estimated using biophysical models and emission factors, such as the Agro-Ecological Zone Emission Factor (AEZ-EF) model that reflect carbon stocks in soils and vegetation, as well as foregone carbon sequestration.

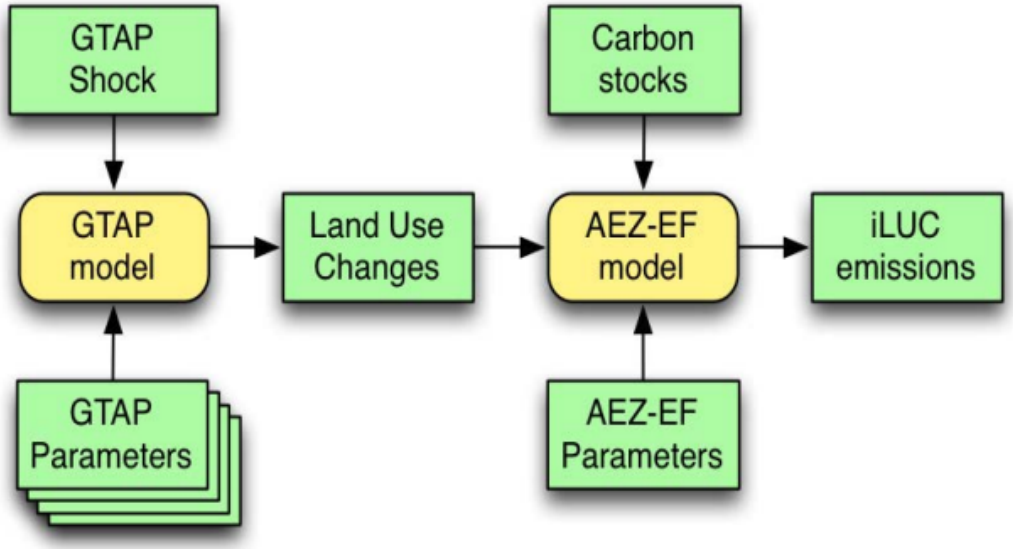

Figure 2.3. GTAP-BIO Model Integration with AEZ-EF Model for LCFS iLUC Calculation

Tools such as Argonne National Laboratory's CCLUB model also integrate GTAP outputs with detailed regional emission factors to generate refined carbon intensity values, capturing both international and domestic land use change effects (DOE, 2021). In the CCLUB model, land use change is quantified by calculating the direct and indirect carbon fluxes associated with land conversion. This includes emissions from the loss of carbon stored in vegetation and soils when land is cleared for agriculture or other uses. CCLUB employs detailed data on land cover types and the carbon sequestration potential of different land types to model these emissions.

Over the past decade, substantial advances have improved the quality of these models and their underlying data. Key improvements include refined land cover and land use databases, better representation of yield responses to price signals, enhanced regional differentiation in land transformation elasticities, and updated emission factors reflecting more granular soil and biomass carbon stocks.

2.1 Model Review

Indirect land use change modeling relies on integrated frameworks that link global economic dynamics with biophysical carbon accounting. The Global Trade Analysis Project (GTAP-BIO) is the primary tool used by CARB under the LCFS to simulate how biofuel demand reshapes agricultural production, trade, and land allocation worldwide, with land conversions translated into CO_2 emissions through the AEZ-EF model. CCLUB incorporates GTAP-BIO by applying detailed U.S. data on vegetation and soil carbon stocks to estimate emissions from specific land transitions.

2.1.1 GTAP

The Global Trade Analysis Project (GTAP) is the most widely applied model for estimating iLUC. It is a computable general equilibrium (CGE) model originally designed for global trade policy analysis, adapted in the late 2000s to evaluate biofuels. Its core mechanism is to impose a biofuel demand "shock" and trace how global markets rebalance across agriculture, land use, and trade. The resulting land conversion estimates are then coupled with emission factors to generate iLUC values. CGE models take into account how global economic systems react to economic changes include effects across a broad range of industries.

GTAP Modeling History

The GTAP model has evolved since its inception through various updates that impact iLUC values as shown in Table 2.1. The earliest applications (2008–2010) used GTAP-BIO with a 2001 social accounting matrix (SAM). Land was treated as a relatively homogeneous factor of production, with limited differentiation between cropland, pasture, and forest. Yield elasticities were set low (0.15–0.2), implying that most of the response to higher crop demand came from expanding cropland rather than intensifying production. These assumptions generated high iLUC values, often in the range of 60-75 gCO_2e/MJ for soy biodiesel.

Subsequent iterations addressed several shortcomings. Beginning in 2011, GTAP-BIO introduced agro-ecological zones (AEZs), which allowed land to be disaggregated by productivity class. This innovation recognized that not all land is equally suitable for crop production, reducing the model's reliance on high-carbon land, like tropical forest as a marginal supply source. Around the same time, cropland–pasture was introduced as a distinct land category. Empirical work by Taheripour and colleagues had demonstrated that much of U.S. cropland expansion occurred on existing cropland–pasture rather than pristine forest, and this refinement allowed the model to reflect those dynamics. As a result, deforestation estimates declined and iLUC penalties dropped in the range of 40 to 55 gCO_2e/MJ.

Table 2.1. Evolution of GTAP Model and Impact on iLUC

Timeframe	Model Evolution	iLUC Values
2008-10[a]	Biofuel sectors, limited co-products, 2001 SAM, reflecting high land expansion and low yield response	60-75 gCO_2e/MJ
2011-14[a]	AEZ's cropland pasture, elasticity refinements, 2004 SAM, reflecting improved land representation and substitution among vegetable oils	40-55 gCO_2e/MJ
2015 (CARB)[a]	GTAP-BIO 2014, AEZ-EF, conservative elasticities applied to LCFS	Soy biodiesel, 29.1 gCO_2e/MJ
2016-19[b]	2011/2014 SAMs, revised elasticities, improved land cover, econometric calibration	20-30 gCO_2e/MJ
2020-Present[c]	Higher resolution land data, remote sensing validation, endogenous intensification	12-20 gCO_2e/MJ

[a]LCFS Land Use Change Assessment (CARB, 2025)
[b] The GTAP Data Base: Version 10 (GTAP, GTAP Data Bases: GTAP 10 Data Base Documentation, 2019)
[c] The GTAP Data Base: Version 11 (GTAP, 2023)

By 2015, when CARB adopted GTAP-BIO for its LCFS update, the model incorporated AEZs and cropland–pasture but remained reliant on a 2004 SAM and conservative elasticity assumptions. Yield elasticities below 0.2 and limited trade responsiveness forced more land expansion than updated empirical evidence supported. The resulting estimate for soy biodiesel (29.1 gCO_2e/MJ) was higher than EPA's earlier RFS2 assessment (18.3 gCO_2e/MJ). Figure 2.4 shows the evolution of iLUC values for soy biodiesel and renewable diesel for various regulatory schemes.

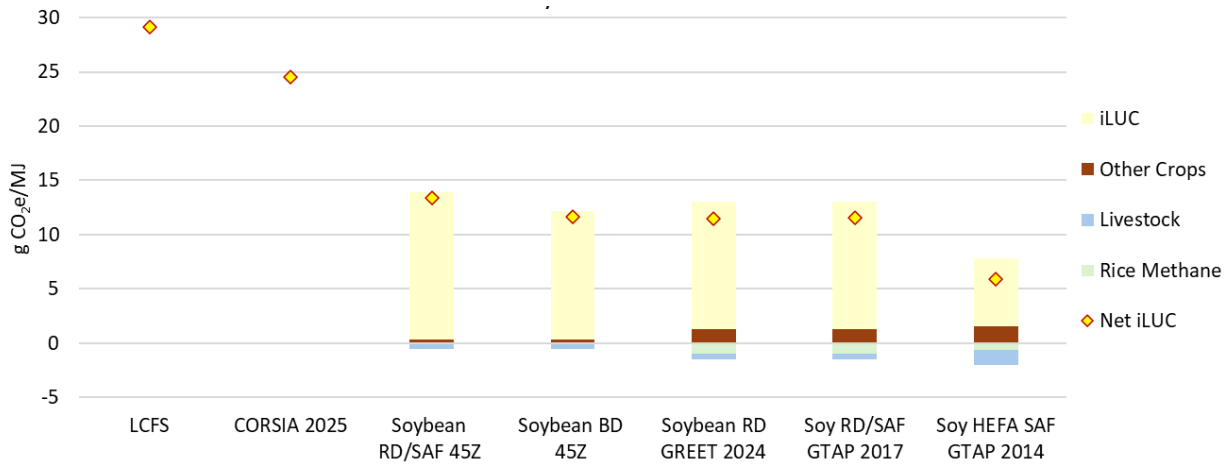

Figure 2.4. Various iLUC modeling results for Soy Biodiesel and Renewable Diesel

From 2016 onward, GTAP-BIO underwent major improvements. The database was updated to 2011 and 2014 SAMs, elasticities were recalibrated based on new econometric studies (Berry &

Schlenker, Rosas et al.), and land cover data were refined with FAO and IFPRI inputs. Yield elasticities were raised into the 0.25–0.35 range, reflecting stronger farmer responses to price incentives. Transition probabilities among land types were recalibrated against observed historical changes, reducing the likelihood of high-carbon land conversion. These updates produced iLUC values in the 20 to 30 gCO_2e/MJ range.

The most recent versions of GTAP include even more substantial revisions. Land cover maps and carbon stock data were improved with remote sensing and inventory-based estimates. Yield elasticities now fall in the 0.3 to 0.5 range, consistent with a growing body of evidence that intensification plays a major role in meeting new demand. Pasture-to-cropland conversions are assigned lower emission factors to reflect empirical SOC measurements. Regional disaggregation of key trade partners, Latin America, Africa, and Asia, provides more accurate representation of global market adjustments. Collectively, these advances have reduced iLUC estimates for U.S. soy biodiesel to 12 to 20 gCO_2e/MJ, significantly lower than CARB's 2015 value.

Model Inputs

Key inputs to GTAP include the baseline economic database, which specifies global production, consumption, and trade flows for a given year, and the biofuel production shock, which represents the increase in output being modeled. The model also requires parameters such as the yield price elasticity (YDEL), which defines how crop yields respond to changes in crop prices; the elasticity of area expansion (ETA), which sets the productivity of newly converted cropland relative to existing cropland; and the elasticity of land transformation (ETL), which governs the extent to which land shifts between cropland, pasture, and forest.

Additional inputs include demand and supply elasticities for energy and agricultural sectors, regional land transformation coefficients, and assumptions about co-product substitution effects such as distillers' grains replacing animal feed. Together, these inputs determine the amount and type of land converted when biofuel demand increases.

Model Structure

The GTAP-BIO model is structured as a global computable general equilibrium framework that links production, consumption, and trade across multiple regions and sectors. Land use is represented through a nested structure, where land can shift between forest, pasture, cropland, and cropland-pasture categories depending on economic signals. Within cropland, additional substitution occurs among different crop types, allowing the model to simulate how increased demand for one crop influences allocation of land to others.

The model also incorporates a land transformation tree that defines substitution possibilities and elasticities between land cover types and distinguishes between rain-fed and irrigated cropland as shown in Figure 2.5. Regional disaggregation is done by AEZs, which provide geographic specificity to land conversion processes. This structure enables the model to allocate biofuel-

driven demand shocks across regions, crops, and land types in a consistent equilibrium framework.

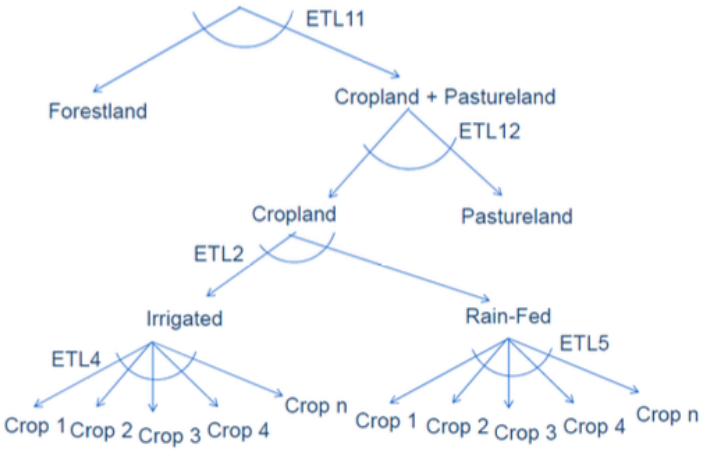

Figure 2.5. Modified Land Transformation Tree Structure, CARB 2014

2.1.2 Other Models

Several major policy frameworks incorporate land use change modeling to determine the greenhouse gas impacts of biofuels, but they differ in scope, structure, and units of measurement. The U.S. RFS applies a threshold-based approach, linking partial equilibrium models like FASOM and FAPRI to carbon stock data to estimate direct and indirect land use change. GLOBIOM, developed for European policy assessments, integrates global agriculture, forestry, and bioenergy markets in a partial equilibrium model to project land allocation shifts and associated carbon emissions. More recently, the OBBBA updated Section 45Z Clean Fuel Production Credit, which uses the 45ZCF-GREET model. This framework integrates GTAP-BIO land conversion results with CCLUB carbon stock estimates and expresses outcomes in kilograms of CO_2-equivalent per million Btu of fuel energy. Together, these approaches illustrate the evolving methodologies for quantifying land use change emissions in biofuel policy.

CCLUB

The Carbon Calculator for Land Use Change from Biofuels model, developed at Argonne National Laboratory, is not an economic model but a carbon accounting framework. Its purpose is to translate GTAP land allocation outputs into carbon intensity estimates. Over the last decade, CCLUB has steadily replaced older approaches such as AEZ-EF, by incorporating updated carbon stock data, better soil dynamics, and conservation practices. The model structure, data sources, and calculations are shown in Figure 2.6.

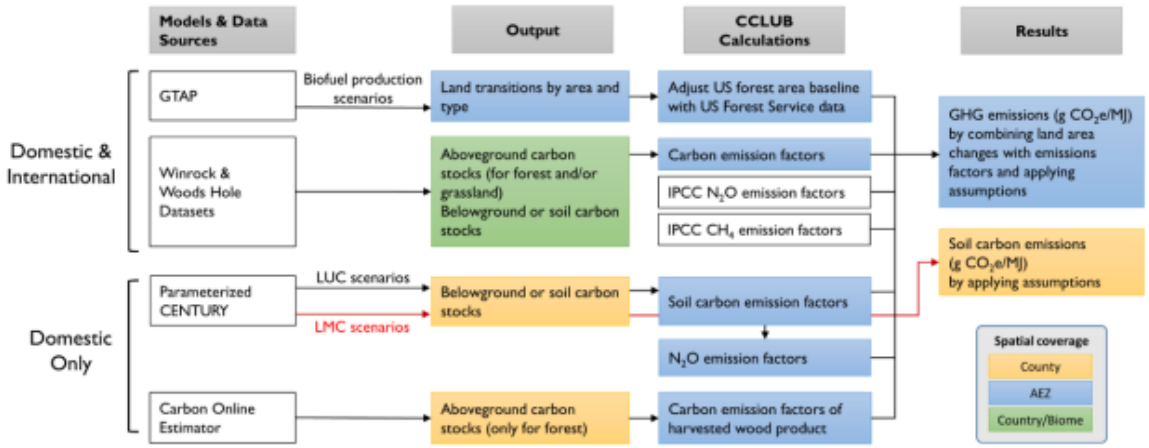

Figure 2.6. CCLUB Model Calculations and Data Sources Including GTAP Model Integration

The earliest version, 2010 to 2013, directly implemented AEZ-EF factors within GREET, using IPCC Tier 1 defaults for biomass and soil carbon. This approach assumed immediate, permanent loss of carbon stocks, which tended to overestimate emissions.

The model is organized into modules that track carbon fluxes from vegetation, soils, and foregone sequestration. Land conversion data are allocated across regions and land cover types, which are then linked to carbon stock databases. Aboveground carbon losses are modeled as immediate emissions from clearing, while belowground emissions are represented as gradual releases over time. Soil carbon fluxes are estimated separately and combined with biomass emissions. The model applies time accounting to integrate emissions over a standard horizon, producing carbon intensity values. Its structure emphasizes the linkage between land transition areas and region-specific carbon pools, ensuring that both direct emissions and lost sequestration potential are captured.

RFS

In the Renewable Fuel Standard, land use change is modeled using a combination of U.S. Department of Agriculture and university-based economic models. Domestic land use effects are estimated with the Forest and Agricultural Sector Optimization Model (FASOM), while international effects are captured with the Food and Agricultural Policy Research Institute (FAPRI) model. These agro-economic models simulate how increased biofuel demand alters crop production, prices, trade, and land allocation both in the U.S. and abroad.

The modeled land transitions, such as forest or pasture converted to cropland, are then paired with emission factors developed by Winrock International to estimate associated carbon releases from vegetation and soils. The resulting direct and indirect land use change emissions are integrated into the life cycle greenhouse gas assessments of biofuels under the RFS.

45ZCF-GREET

In the 45Z Clean Fuel Production Credit framework, lifecycle greenhouse gas emissions, including land use change, are modeled with the 45ZCF-GREET tool developed by Argonne National

Laboratory for the IRA. The model incorporates feedstock-specific data such as crop type, region of origin, and farming practices, while applying iLUC factors derived from GTAP-BIO and CCLUB modeling. Default iLUC values are built into the calculator for major feedstocks like corn ethanol, soy biodiesel, and sugarcane ethanol, though applicants can request updated values if supported by EPA- or CARB-approved modeling. The model assigns iLUC values that vary with a producer's fuel-conversion efficiency, and it calculates domestic iLUC emissions using DAYCENT outputs, which apply a more detailed IPCC Tier 3 approach to modeling carbon flux on U.S. soils.

GTAP-BIO provides estimates of land conversion triggered by biofuel demand, which are paired with regional soil and biomass carbon stock changes from CCLUB. Emissions from above- and below-ground carbon losses, along with forgone sequestration, are allocated over a 30-year horizon and averaged to yield an iLUC factor. This value is then integrated with other lifecycle components, farming, transport, conversion, and distribution, to generate the compliance-grade carbon intensity used for determining credit eligibility under Section 45Z.

2.2 Key Model Drivers

Several key model attributes strongly influence how iLUC is estimated, particularly in frameworks such as GTAP and CCLUB. Among the most important drivers are assumptions about future crop yields. In GTAP, yield projections and yield price elasticities determine whether additional biofuel demand is met through intensification on existing cropland or through the conversion of new land. Higher yield responses to price increases reduce the need for expansion, while lower responses result in greater land conversion and higher associated emissions. CCLUB incorporates these outcomes by linking the modeled land transitions to region-specific carbon stock changes in soils and biomass, which are highly sensitive to whether land is converted from forest, grassland, or marginal areas.

GTAP uses transformation elasticities to determine the likelihood of land moving between cropland, pasture, and forest. Low elasticities imply limited substitution, leading to higher commodity price responses, while higher elasticities allow land to shift more freely among categories. For example, the displacement of corn and soybean meal by distillers' grains (DGS) in livestock feed directly reduces cropland requirements, while substitution between beef and poultry consumption reflects shifts in land intensity across protein sources. These market responses directly affect the magnitude and type of land converted in the GTAP framework.

The consequences of these land allocation assumptions flow directly into CCLUB, where the emissions impact of converting high-carbon stock forest versus lower-carbon marginal land can differ by orders of magnitude. Together, the treatment of yield responses, feed substitution, and land transformation elasticities make GTAP and CCLUB sensitive to input choices, and these parameters explain much of the variability in published estimates of biofuel-induced iLUC.

2.2.1 Model Perspective (Static vs Dynamic)

Equilibrium models solve for the point where supply and demand functions intersect across sectors of the economy, ensuring that all resources and outputs are balanced. Because closed-form solutions are not available, these models iteratively converge on equilibrium values for prices and quantities. Static equilibrium models, such as GTAP, provide results for a single point in time using a fixed database. In comparative static analysis, the model is rerun with different exogenous inputs, such as changes in income, population, or fuel demand, to observe how outcomes vary. Dynamic models, such as FAPRI and FASOM, solve equilibria over multiple time intervals, capturing the transitions of agricultural and energy markets evolve over years or decades, rather than providing a single snapshot.

Partial equilibrium (PE) and computable general equilibrium (CGE) models differ structurally in how they distribute the effects of a biofuel demand shock, impacting iLUC estimate differences across frameworks. PE models confine adjustments to a narrow set of agricultural markets, typically crops, livestock, and sometimes forestry, while treating the rest of the economy as fixed. Because the shock cannot dissipate into non-modeled sectors, all adjustments must occur within agriculture through yield increases, land expansion, or conversion of pasture and forest. CGE models like GTAP endogenize all major sectors and factor markets, allowing the shock to be absorbed through a broader range of channels, including substitution among intermediate inputs, sectoral reallocation of capital and labor, adjustments in trade flows, and changes in macroeconomic variables such as wages and exchange rates. The availability of these additional adjustment pathways dilutes the pressure on land markets, because its architecture distributes the burden of adjustment across the full economy.

2.2.2 Land Conversion Emission Factors

Land use emission factors are applied to modeled land transitions into estimates of GHG emissions. While economic models like GTAP predict how much land shifts among crops, pasture, and forest in response to biofuel demand, they do not inherently quantify the carbon consequences of these shifts. This translation step requires linking land use changes to carbon stock data for vegetation and soils, and applying emission factors that represent the release of stored carbon or the foregone sequestration potential of land converted.

Comparisons of emission factor datasets including AEZ-EF, TEM, Winrock, and Woods Hole, show wide variation in estimated greenhouse gas emissions from land use conversions such as forest-to-cropland and pasture-to-cropland as shown in Figure 2.7 (Taharipour, 2024). While sources demonstrate that forest conversion releases more carbon than pasture conversion, the magnitude of emissions differs across regions due to variations in vegetation and soil characteristics. Even within a single region and land type, emission factors diverge among datasets, reflecting differences in assumptions, system boundaries, carbon stock data, and ecosystem classifications. These disparities are especially large for pasture conversions, where factors can differ by threefold or more, with TEM often producing higher estimates in Brazil and

Asia, and Woods Hole yielding higher values in China, India, Russia, and parts of Europe. Forest conversion estimates also vary across models, though the spread is narrower than for pasture.

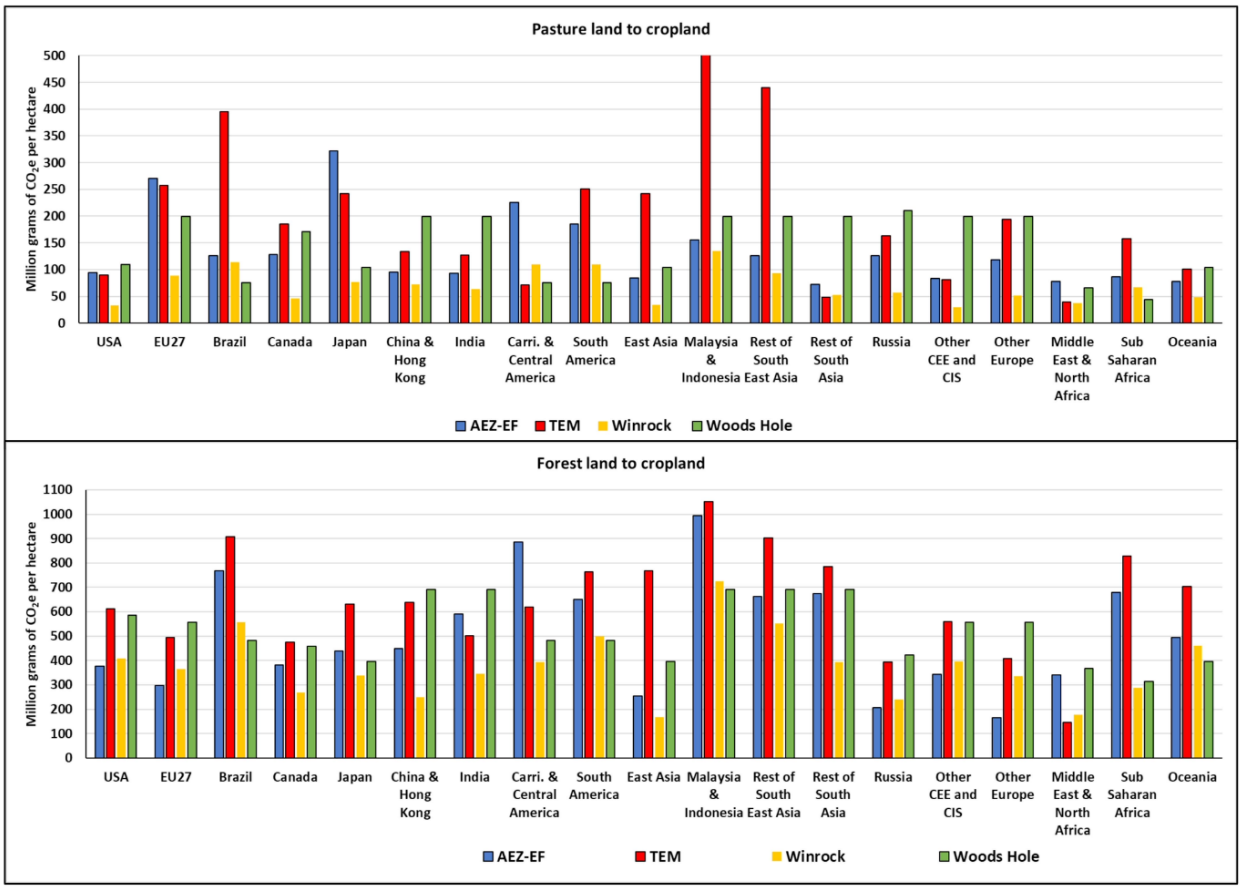

Figure 2.7. Emission factors for converting forest and pasture to cropland by region.

2.2.3 Shock Size

In LUC modeling, a "shock" refers to an exogenous change applied to the system, such as a rise in biofuel demand, a shift in trade policy, or an adjustment in crop productivity, that forces the model to recalculate global or regional equilibria. By design, these shocks are applied under ceteris paribus conditions, meaning that all other variables are held constant, so that the model isolates the impacts of the specified change. This approach is especially important for iLUC modeling, where the goal is to understand how a single policy action, like mandating additional soy biodiesel, translates into changes in agricultural markets, land allocation, and ultimately greenhouse gas emissions. Without this mechanism, the model would not be able to separate the effect of the policy from the myriad other changes occurring in the global economy.

In the GTAP framework, shocks are most commonly applied using the comparative static version of the model, which provides a snapshot of how the global economy and land use would adjust to a new equilibrium if only the specified shock occurred. For example, a biofuel shock might be

defined as an additional 0.812 billion gallons of soy biodiesel, which is then modeled as an exogenous increase in fuel demand. The model estimates how this additional demand raises crop prices, shifts trade flows, induces yield responses, and reallocates land between cropland, pasture, and forest. These land-use outputs are then linked to carbon stock changes via AEZ-EF or CCLUB to produce iLUC emissions. The independent shock sizes for each biofuel type used by CARB under its 2014 ILUC study are presented in Table 2.2.

Table 2.2. Biofuel Shocks from CARB 2014 iLUC Assessment

Shock	Shock Size (bgy)	Impact of Shock	LUC Impact
Corn Ethanol	11.59	Expands U.S. corn acreage; reduces soy/wheat; raises global corn price. DDGS offsets some feed demand.	Global forest & pasture conversion; moderate cropland-pasture shifts. Avg. iLUC = 19.8 gCO_2e/MJ.
Sugarcane Ethanol	3.0	Expands cane in Brazil, mainly displacing pasture; some forest loss.	Dominated by pasture conversion. Avg. iLUC = 11.8 gCO_2e/MJ.
Soy Biodiesel	0.812	Expands soy area; reduces other crops; vegetable oil market effects.	Moderate iLUC; sensitive to South American forest conversion. Avg. iLUC = 29.1 gCO_2e/MJ.
Canola Biodiesel	0.4	Shifts oilseed balance; imports of soy/palm adjust.	Modest land use changes. Avg. iLUC = 14.5 gCO_2e/MJ.
Sorghum Ethanol	0.4	Substitutes for corn; land response smaller; coproducts offset feed.	ILUC similar to corn but smaller scale. Avg. iLUC = 19.4 gCO_2e/MJ.
Palm Biodiesel	0.4	Expands plantations in Malaysia/Indonesia; replaces forest/peatland.	Highest iLUC; tropical forest and peat conversion dominate. Avg. iLUC = 71.4 gCO_2e/MJ.

CARB modeled iLUC by imposing an exogenous “volume shock”, an increase in production in billion gallons per year (BGY), for each pathway in the GTAP-BIO economic model, then converting the model’s land-transition outputs into GHG emissions with AEZ-EF spatial emission factors and averaging 30 scenario runs to get the pathway iLUC value. CARB’s 2015 update incorporated: a newer GTAP baseline (2004), explicit cropland-pasture in U.S./Brazil, revised elasticities, improved coproducts, and a more spatially detailed AEZ-EF set. These changes shifted land conversion away from forests toward cropland-pasture/pasture in many cases and lower overall iLUC relative to 2009 values.

Beyond GTAP, the concept of shocks is applied across other LUC models and contexts. In partial equilibrium models such as FAPRI or FASOM, shocks might include changes in feed demand, shifts

in protein consumption from beef to poultry, or productivity gains from technology adoption. In dynamic land-use models like GLOBIOM, shocks can represent both policy interventions and environmental stressors, such as weather extremes or changes in livestock stocking rates, which alter the availability of land for crops. Regardless of the framework, shocks connect external drivers to endogenous model behavior, providing a way to evaluate how policy or market changes ripple through agricultural systems and translate into land conversion and carbon emissions. This shock-response structure is intended to reflect the impact of the regulation on the requirements for new feedstock production.

Note that the shock size for soy biodiesel, is nearly double the current soy biomass based diesel in the LCFS (CARB, 2025). For 2024, the total volume for soy-based biodiesel and renewable diesel was 419 million gallons or 15.6% of total volume, as shown in Figure 2.8. The values for 2025 were estimated based on CARB data available through June 2025. The figure includes the shock sizes for each pathway from the 2014 iLUC analysis, compared to expected volumes for 2025, and far exceed both historic and current levels of use.

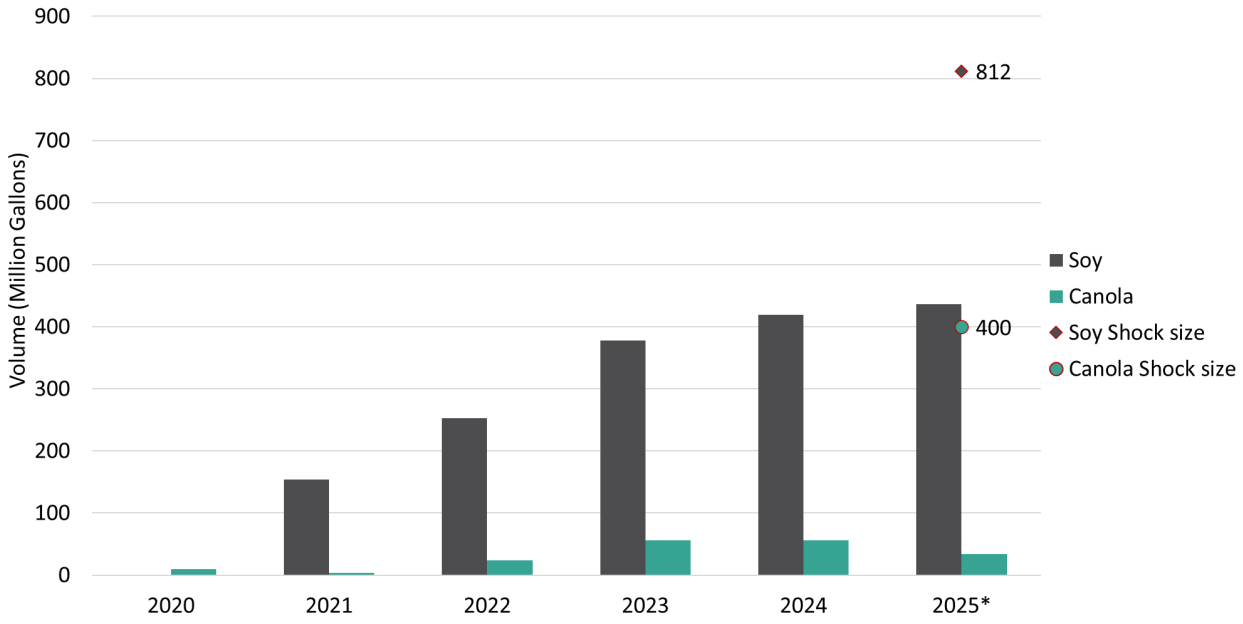

Figure 2.8. Crop-based Oils Used in LCFS Biomass Based Diesel Production Compared to CARB iLUC Analysis Shock Size, *LCA estimates

Feedstock Limits

The amended LCFS regulation that took effect July 1, 2025 introduced a 20 percent combined cap on the use of virgin soybean oil, canola oil, and sunflower oil in biodiesel and renewable diesel pathways (CARB, 2025). The cap applies to each company's total annual biomass-based diesel volume, covering fuel produced in California, fuel produced for import, and fuel imported into the state. Any volume of these seed oils that exceeds the 20 percent limit is assigned a carbon

intensity equal to the annual benchmark CI or the pathway's certified CI, whichever is higher, which prevents the excess volume from generating LCFS credits.

- Effectively risk based limit – the cap is expressed as a percentage limit per company on the use of these seed oils and it operates effectively as a risk-based control mechanism. Instead of relying on lifecycle modeling or iLUC factors for every feedstock, a control mechanism is introduced.
- Cap would potentially limit the use of feedstocks – by imposing the cap, the regulation potentially limits the use of crop based soy and canola oil feedstocks in eligible credit-generating volumes, constraining feedstock sourcing decisions for companies seeking LCFS credits.
- With such a cap, the shock would be zero with a corresponding iLUC of 0 g CO_2e/MJ – as the regulation disincentivizes additional use of those oils for credit-earning fuel.

2.2.4 Elasticity Factors

Elasticities are influential parameters in iLUC modeling and describe how markets respond to changes in prices and returns. Elasticity measures the percentage change in one variable resulting from a one percent change in another, expressed as a unit-free ratio. In iLUC modeling, elasticity functions are used to capture interactions in trade, production, and land allocation. The Constant Elasticity of Substitution (CES) governs how easily different inputs can be exchanged in production processes, such as substituting one feed component for another. The Armington elasticity, widely applied in global trade modeling, distinguishes goods by country of origin to reflect the persistence of trade relationships even when price differences exist where higher Armington values imply stronger substitution across borders and more dispersed land use change, and lower values concentrate land conversion within the biofuel-producing country.

Land allocation elasticities are important for estimating the extent and type of land conversion. Many computable general equilibrium models use a Constant Elasticity of Transformation (CET) function to govern shifts among land categories. In GTAP-BIO, this is represented as a nested structure: land is first allocated among broad categories such as cropland, pasture, and forest, and then cropland is further divided among competing crops as shown earlier in Figure 2.5. The CET elasticity determines how much land in one category expands in response to changes in land rents, directly influencing both the magnitude and distribution of predicted land conversion. The CET function models how land is allocated across competing uses, such as cropland, pasture, or forest, based on the relative returns of each use. Higher prices for one land-intensive activity incentivize land shifts toward that use.

GTAP BIO ADV includes major changes to the CET to improve the representation of land use and land use changes. The 2011 analysis used single-level CET structure for land allocation, but subsequent updates include empirically grounded formulations to more accurately model policy impacts. An advanced version of the model, GTAP-BIO-ADV, includes a multi-level CET, into one version.

Emission Factors by AEZ

The AEZ-EF model pairs GTAP outputs with carbon stock values differentiated by region and land cover type. AEZ-EF draws from global soil and biomass datasets to assign CO_2-equivalent emissions to transitions such as forest-to-cropland or pasture-to-cropland. CARB justifies the use of AEZ-EF as providing transparent, region-specific emission factors consistent with IPCC guidelines, while also allowing uncertainty analysis by varying the key parameters. The resulting iLUC factors are averaged across scenarios and incorporated into LCFS carbon intensity values.

The GTAP simulation results from the 2014 iLUC analysis are in the form of estimated land area types and amount changes as a result of the specified biofuel shocks. The result is a set of emissions profiles that are averaged over a 30-year accounting period and normalized by fuel energy, producing compliance-grade iLUC values expressed in gCO_2e/MJ under the LCFS. CARB justifies AEZ-EF on its alignment with GTAP's AEZ structure, its reliance on IPCC-based carbon stock data, and its ability to capture uncertainty by running multiple parameter scenarios.

SOC Impacts

SOC impacts arise from two distinct but sequential components of the modeling system. In the LCFS, substitution and transformation elasticities inside GTAP determine how much cropland expands and which land types are displaced when biofuel demand increases. These elasticities influence the pattern and scale of land conversion but do not quantify carbon. Instead, they shape the likelihood that high SOC land such as pasture or forest is brought into production.

CCLUB assigns SOC emission factors based on regional baseline stocks, depth-specific values, depletion rates for each land transition, and the presence of conservation practices. CCLUB calculates the actual carbon loss, amortizes it over thirty years consistent with IPCC guidance, and incorporates additional soil emissions such as N_2O from mineralization. LCFS elasticities determine the land-use response that exposes SOC pools to disturbance, while CCLUB determines the magnitude of SOC emissions once those pools are disturbed.

2.2.5 Improved Agriculture

Climate-smart agricultural (CSA) practices such as no-till, manure application, and cover cropping have the potential to materially alter the iLUC values assigned to soy biodiesel under the LCFS, but these practices are not currently incorporated into the program's modeling framework. In the LCFS system, iLUC is estimated using GTAP-BIO to simulate land use responses and the AEZ-EF model to assign carbon stock changes. These models assume average management practices across large regions and do not differentiate between conventional and conservation-oriented farming. As a result, the additional soil carbon storage and emission reductions achieved through improved practices are not captured in the regulatory values, leading to a more generalized and potentially conservative estimate of iLUC.

Technically, adoption of climate-smart practices would shift both the carbon accounting and the economic parameters underlying iLUC. On the carbon side, no-till and cover crops increase soil

organic carbon, reduce decomposition rates, and enhance belowground biomass inputs, while manure provides additional organic matter and reduces synthetic fertilizer use. These effects raise the carbon carrying capacity of cropland and reduce the emissions intensity of converting land into soy production. On the economic side, practices that stabilize or enhance yields under stress effectively increase the yield response to prices, which in GTAP terms raises the yield-price elasticity. A higher elasticity channels more of the adjustment to increased biofuel demand into yield gains rather than land expansion, thereby reducing the modeled scale of land conversion.

Figure 2.9 demonstrates the various impacts of CSA practices on feedstock carbon intensity, with particular reductions attributed to cover crop and no till practices for soybeans. The figure highlights the major impact that CSA practices have in reducing the CI of feedstocks and therefore final form renewable fuels. CSA considerations in LUC modeling are based on an implied price-induced yield. In practice, polices such as the national 45Z under the IRA, may incent CSA further with the opportunity to support additional GHG savings.

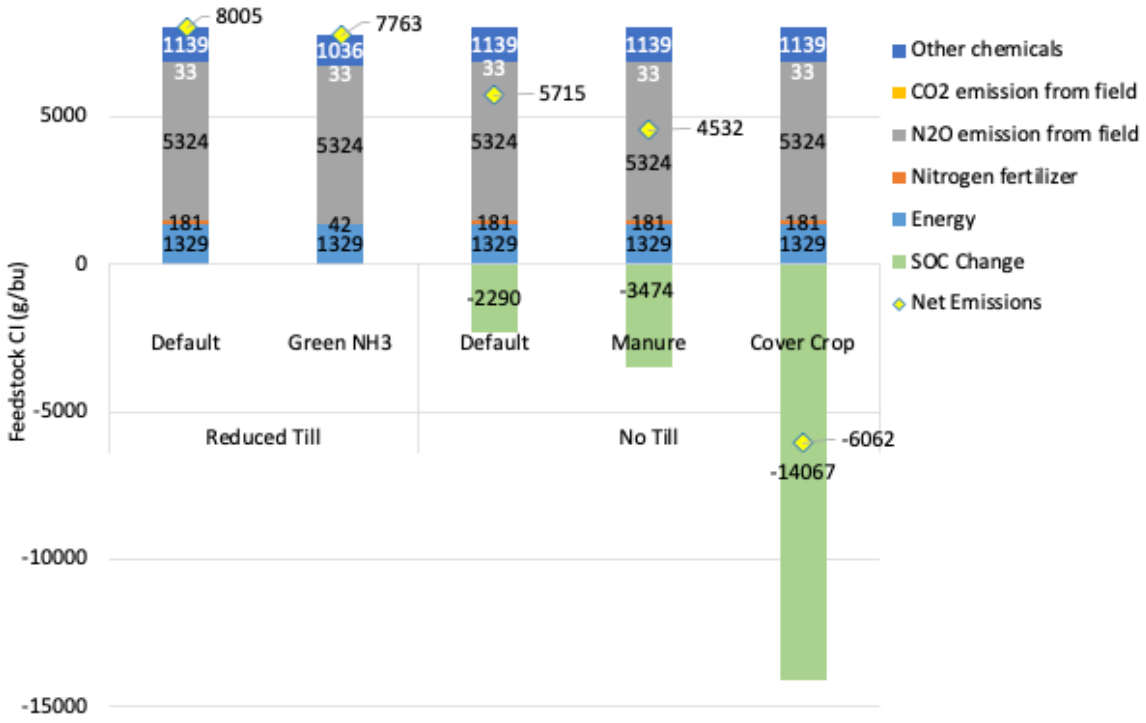

Figure 2.9. Effect of CSA practices for soybeans in FD-CIC model[3].

2.3 Comparison of Land Use Change Model Outputs

This section presents the findings from the review of the 2014 assessment of iLUC by CARB for the California LCFS program. The detailed analysis from the CARB 2014 assessment has been published by CARB (CARB, 2014). The CARB report explicitly states that the only indirect effect

[3] GREET1_2024, FD-CIC model, Champaign Illinois County.

identified by CARB to be significant was iLUC, resulting from potential changes in land use due to increased biofuel production following the re-adoption of the LCFS.

2.3.1 Inclusion of iLUC in LCFS

The California LCFS GREET model, is tailored specifically to meet the requirements and objectives of California's LCFS program (CARB, 2024). Implemented by CARB, the LCFS aims to reduce the carbon intensity of transportation fuels used in the state, thereby decreasing greenhouse gas emissions from the sector. The California LCFS GREET model adopts a well-to-wheels (WTW) framework, like the original GREET model, but with enhancements and adjustments specific to California's conditions and policies. The model includes detailed pathways for conventional and alternative fuels, including gasoline, diesel, natural gas, electricity, hydrogen, and a variety of biofuels like ethanol and biodiesel. The model incorporates California-specific data on electricity generation, fuel production, and transportation infrastructure, ensuring that the assessments accurately reflect the state's unique energy landscape of renewable energy sources.

The California LCFS program imposes CI targets on transportation fuels that are expected to be met through the substitution of lower CI renewable fuels for higher CI conventional fuels and by technology substitution such as battery electric vehicles displacing internal combustion engine vehicles. LCA analysis is performed using CA-GREET and the Tier 1 Calculators. The LCI data in CA-GREET and the Tier 1 Calculators are derived from GREET with LUC values developed by CARB in 2015 based on the GTAP model (CARB, 2015). An update to the model, CA-GREET4.0, was released in December 2023 (CARB, 2023) . Soybean pathways include biodiesel and renewable diesel production. The simplified calculators contain built-in assumption factors around farming, meaning that soy farming data is fixed, as well as energy, fertilizer inputs, and yields of biofuel and co-products for each production pathway. The simplified calculators were updated along with the finalized CA-GREET4.0 model (CARB, 2024).

2.3.2 Model Results

The following section presents the results from multiple GTAP modeling vintages to show how global land-use change and associated carbon emissions for soy-based biofuels have evolved over time. The analysis compares both land-use change intensity and absolute land conversion outcomes, highlighting how updates to GTAP economic parameters, yield assumptions, land transformation elasticities, and carbon-stock data drive differences in modeled responses.

Figure 2.10 shows global land use change per billion gallons soy feedstocks for biodiesel, HEFA, and renewable diesel across several GTAP vintages. The chart shows modeled global land-use transitions associated with soy-based biofuels in hectares per billion gallons of fuel, disaggregated into cropland minus cropland-pasture, cropland-pasture, grassland, and forestry. Early GTAP 2004 scenarios, including CARB case 8, the CARB average proxy, and the baseline soy biodiesel run, produce the largest total land-use change signals, driven primarily by substantial conversion of cropland-pasture and additional contributions from grassland and forestry. These negative land category shifts are offset by large positive increases in cropland minus cropland-

pasture, indicating the expansion of active cropland needed to supply higher soybean oil demand.

More recent GTAP vintages show progressively smaller land-use change responses due to updated economic parameters, revised baseline yields, and refined land transformation functions. GTAP 2011 and 2017 generate moderate cropland expansion with proportionally smaller withdrawals from other land categories, while GTAP 2014 produces the lowest overall signal across all pathways. Collectively, the chart demonstrates that structural updates to the GTAP framework significantly influence both the magnitude and distribution of modeled global land-use change for soy feedstocks, with newer models indicating lower land conversion requirements per unit of fuel. Note the larger land conversion per unit of fuel for larger biofuel shocks. As mentioned previously, the CARB shock size far exceeds the use of soybean oil in California as well as the incremental use of soybean oil due to the regulation.

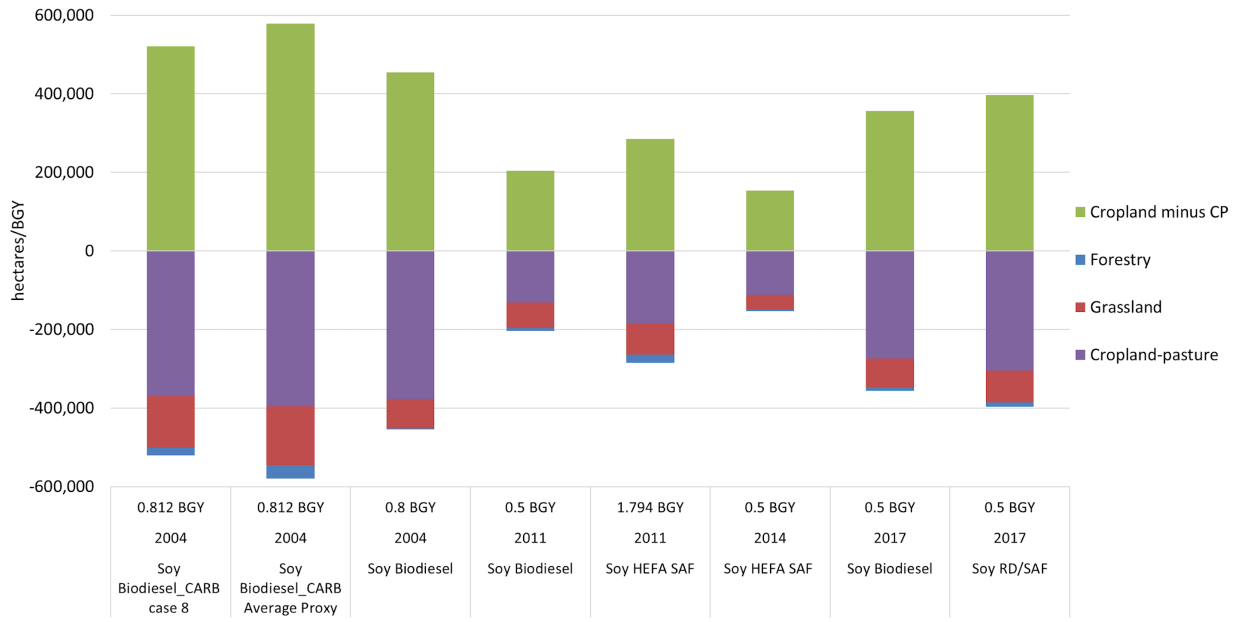

Figure 2.10. Global Land Use Change for Soy Feedstock Across GTAP Models

Figure 2.11 presents the breakdown of the land use change emissions in Mg C/BGY of soy for GTAP 2004 (CARB average), GTAP 2011 and the GTAP 2017 model (Wang, 2025). The chart includes CARB's iLUC CI from its 2014 analysis and differentiates results by AEZ-EF and shock size, 0.812 BPY for both 2004 charts and 0.5 BGY for 2011 and 2017. The chart shows how soybean biodiesel indirect land use change emissions, measured in megagrams of carbon per billion gallons of fuel (Mg C/BGY), have varied across successive versions of the GTAP model.

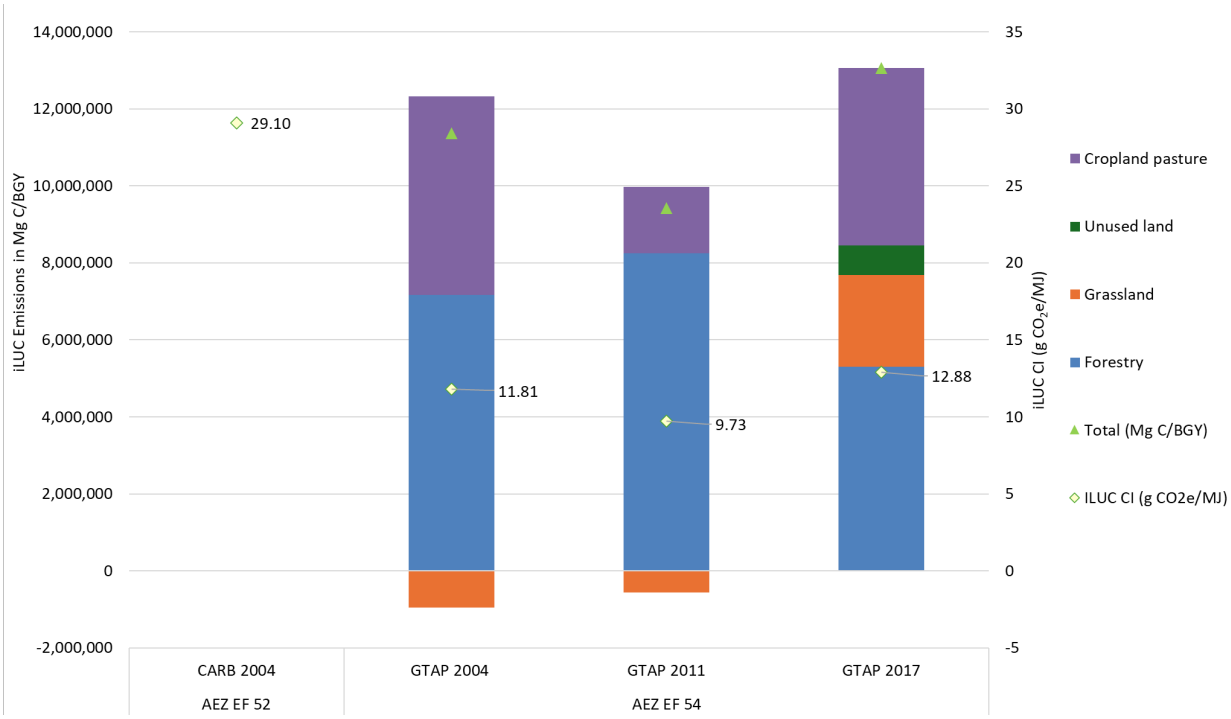

Figure 2.11. Land Use Change Emissions of Soy Across GTAP Models

Under GTAP 2004, total iLUC emissions were nearly 12 million Mg C/BGY. Most of these emissions came from the conversion of cropland pasture and unused land, with smaller contributions from grassland and forestry. This reflects the early model's limited regional detail and conservative yield elasticities, which tended to overpredict new land expansion. The iLUC CI values for GTAP 2004 and CARB are significant, 11.81 g CO_2e/MJ compared to CARB's 29.1.

By GTAP 2011, total iLUC emissions dropped to roughly 10 million Mg C/BGY, showing major reductions in cropland pasture conversion and a smaller overall land footprint. This version incorporated refined land-use elasticities, updated land-cover data, and improved co-product treatment, resulting in a more constrained land response to biofuel demand.

The GTAP 2017 results show a modest rebound in total land-use carbon at around 13 million Mg C/BGY, but with a more diversified composition that includes smaller cropland pasture effects, measurable forest and grassland transitions, and better representation of intensification. The results reflect a change in land use categories in GTAP, like unused land that were added with the model update.

The following figures illustrate the modeled shift across various GTAP vintages. Figure 2.12 shows modeled global land use changes from soybean biodiesel expansion using the 2004 version of the GTAP model, expressed in hectares. The results indicate extensive land conversion in the United States, where cropland increases by roughly 250,000 hectares, offset by about a 300,000-hectare reduction in cropland pasture. Smaller changes appear in Brazil, Argentina, and the European Union, which show moderate cropland gains largely drawn from grassland and pasture. Forest changes remain minimal in all regions. Overall, the GTAP 2004 results reflect an early

modeling framework that assumed limited yield growth and less refined land categorization, resulting in greater dependence on land conversion from existing agricultural areas to meet soybean biodiesel demand compared with newer GTAP versions.

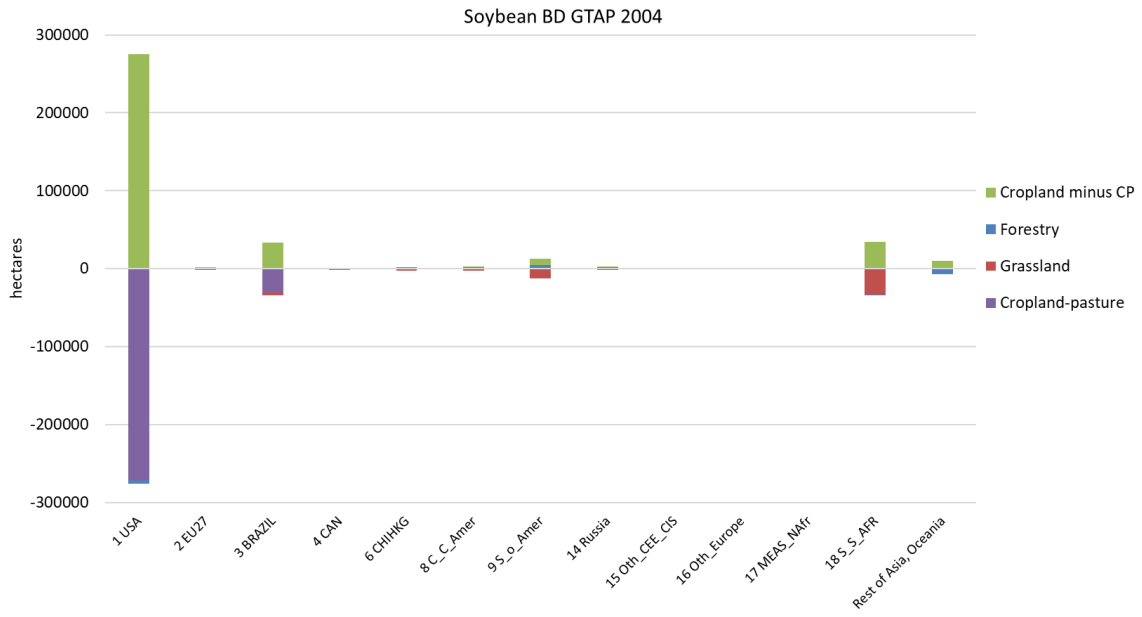

Figure 2.12. Soy Biodiesel Land use Conversion for GTAP 2004

Figure 2.13 illustrates the modeled shifts in land cover globally in response to a soy biodiesel demand shock, showing the land-use change intensity of soy biodiesel by measuring how many hectares are converted globally for each additional billion gallons of annual production. The results indicate that the largest land conversions occur in the United States and Brazil, where significant areas shift from forest, grassland, and cropland-pasture into cropland to meet the additional demand for soy production. In the United States, cropland expansion is largely offset by reductions in cropland-pasture and, to a lesser extent, forested land. In Brazil, the conversion of forested areas represents the dominant component of total land-use change, highlighting the higher carbon intensity of expansion in that region. Other regions such as China, India, and the European Union show minimal land-use shifts, suggesting that soy biodiesel demand has relatively localized impacts outside the main producing regions.

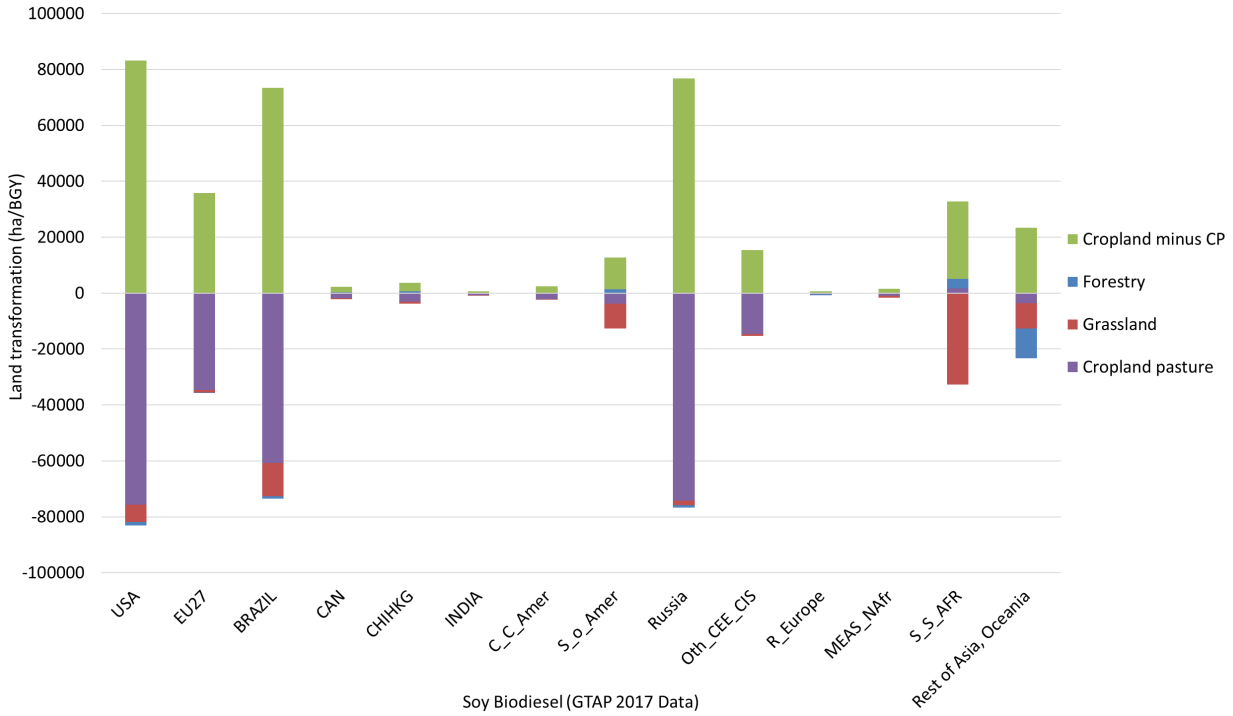

Figure 2.13. Global Land Use Change Intensity for 2017 GTAP Model for Soy Biodiesel

In contrast, smaller but noticeable transitions occur in parts of Asia and Sub-Saharan Africa, where modest cropland expansion is balanced by reductions in grassland and forest areas. Overall, the global total shows a net increase in cropland area, primarily offset by losses from forest and cropland-pasture, indicating that soy biodiesel expansion under the 2017 GTAP framework is driven largely by land conversions with high associated carbon emissions.

Figure 2.14 shows the total hectares converted across land categories with soy biodiesel under GTAP 2017, reflecting the full absolute land-use change outcome of the modeled biodiesel shock. In the United States, cropland increases by about 30,000 hectares, largely offset by a 40,000-hectare reduction in cropland-pasture and smaller declines in grassland. Brazil shows roughly 25,000 hectares of new cropland, mostly drawn from pasture and grassland, while the European Union adds around 10,000 hectares of cropland with minimal forest change. Across all regions, forest conversion remains limited, generally below 5,000 hectares. Overall, the GTAP 2017 results indicate that most new soybean area for biodiesel production comes from reallocation of existing agricultural land rather than deforestation, reflecting improved yield assumptions, higher cropping intensity, and more efficient global land use relative to earlier model versions.

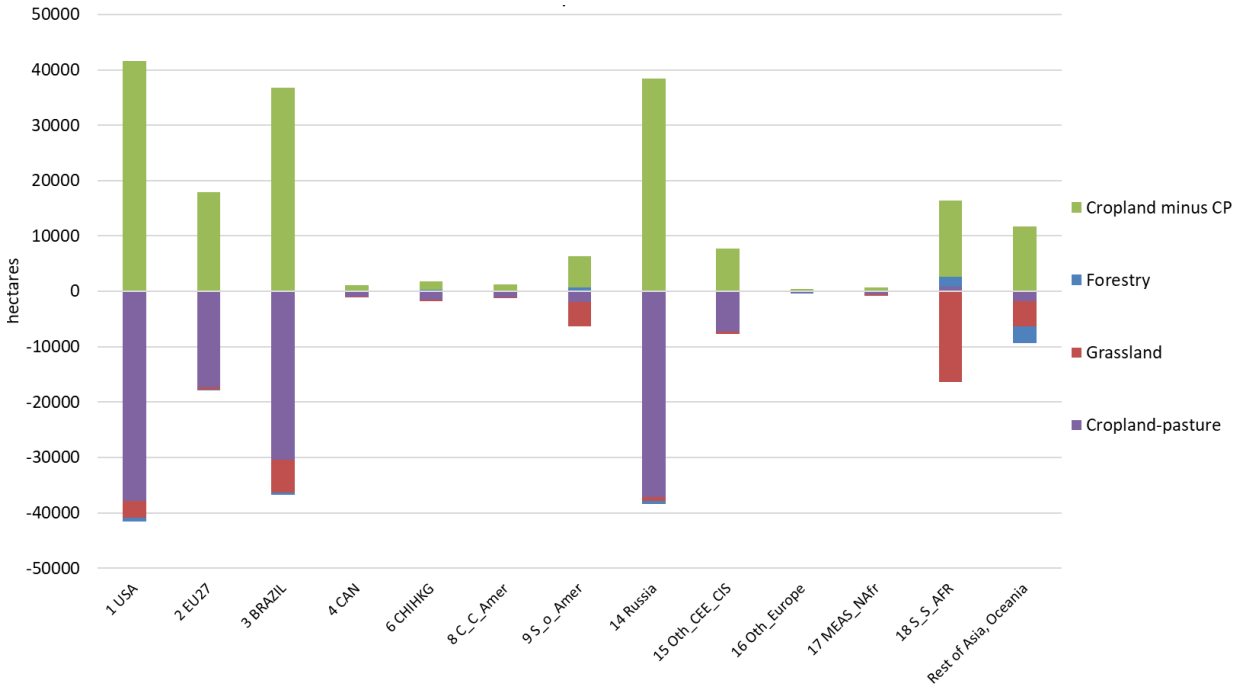

Figure 2.14. Soy Biodiesel Land use Conversion for GTAP 2017

3. CARB Land Use Change Recommendations

Land use change modeling plays a critical role in shaping how soy-based renewable fuels are treated under low carbon fuel regulations, with significant consequences for soybean farmers and renewable fuel producers. This analysis provides the following recommendations for CARB, following the recent workshop on land use change:

Recommendations

- **Model Selection:** Due to improvements in GTAP, select the version implemented in CCLUB (GTAP 2017). It represents a long-run assessment of the global economy with many interactions between sectors and includes the following updates:
    - More refined land use categorizations (cropland/pasture/forest)
    - Improved nesting structures to distinguish intensification versus land use conversion
    - Yield/land intensification is distinguished in newer versions to account for yield growth, multi-cropping, and idle cropland to production
    - Better trade/substitution elasticities
    - Higher sector/region resolution from 57 to 65 sectors
    - Integration of AEZ-EF v54 with updated 2019 IPCC factors
    - For CARB, IPCC factor updates do not require a rulemaking

- **Climate Smart Agricultural Practices:** CARB's comments on the regulation indicate that "staff is open to potentially amending the LCFS at a future date to recognize climate smart agricultural practices in the program…"[4].
    - CARB can begin to take immediate steps to develop a framework for CSA practice inclusion in the LCFS through a stakeholder group consisting of organizations that are involved everyday with these practices.
    - The stakeholder group can work with CARB through points CARB raised around quantifying, reporting, and verifying these practices.
    - Oils and fat feedstocks are the largest category contributor to LCFS credits today for the production renewable diesel. This fuel category will be phased out of the LCFS by not including CSA practices and updating the GTAP model as previously described which eliminates an essential incentives for CSA.
    - Renewable Diesel is a success story of the LCFS where 2/3 of petroleum based diesel has been supplanted by lower CI, renewable diesel, exactly as the regulation intended.

- **Shock Size:** for iLUC modeling should be zero if a limit on crop-based fuels is implemented. Alternatively, the shock size should represent the incremental increase in soy oil biofuels that are induced by the regulation.

[4] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2024/lcfs2024/fsor_appc.pdf?utm

- **Dynamic Models:** have also been contemplated for iLUC modeling, such as in the RFS. Such models introduce new assumptions and uncertainties. Insights into the effect of California's fuel policy actions should be weighed against the uncertainties associated with long-term economic projections required for dynamic models.
    - GTAP gives you a prediction of a long run impact for biofuels, it is not a dynamic model but dynamic models do not help you make better decisions because they introduce uncertainty by requiring additional economic assumptions.

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