

Induced Land Use Change (ILUC) in CORSA Eligible Fuels

Position Paper
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For:



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List of Abbreviations

AAF	Alternative Aviation Fuels
ANL	Argonne National Lab
ATJ	Alcohol-to-Jet
CARB	California Air Resources Board
CEF	CORSIA Eligible Fuels
CI	Carbon Intensity
CF	Carbon Footprint
CGE	Computable General Equilibrium (model)
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
dLUC	Direct Land Use Change
DOE	Department of Energy (USA)
DOT	Department of Transportation (USA)
GHG	Green House Gases
ECAC	European Civil Aviation Conference
EPA	Environmental Protection Agency
ETJ	Ethanol-to-Jet
GOC	Government of Canada
HEFA	Hydro-processed Esters and Fatty Acids
HVO	Hydrated Vegetable Oils
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
iLUC	Indirect Land Use Change
ILUC	Induced Land Use Change
IPCC	Intergovernmental Panel for Climate Change
IRA	Inflation Reduction Act
ITF	International Transport Forum
ISCC	International Sustainability and Carbon Certification
JRC	Joint Research Centre of the European Commission
LCA	Life Cycle Assessment
LCEF	Life Cycle Emissions Factors
LCFS	Low Carbon Fuel Standard
NAS	National Academies of Sciences
PE	Partial Equilibrium (model)
PJ	Petajoule
RED	Renewable Energy Directive
RFS	Renewable Fuel Standard
SAF	Sustainable Aviation Fuels
USDA	United States Department of Agriculture

Executive Summary

This position paper examines the inclusion of Land Use Change (LUC) emissions in carbon intensity (CI) calculations for CORSIA-eligible fuels, with a focus on U.S. corn ethanol pathways. Sustainable Aviation Fuels (SAF) are critical for reducing greenhouse gas (GHG) emissions in aviation, but monitoring the benefits of SAF and steering effective strategies for their utilization depends on accurate assessment of emissions, including those from Induced Land Use Change (ILUC).

ILUC quantification relies on economic models such as GTAP-BIO and GLOBIOM to estimate GHG emissions resulting from land-use changes induced by increased biofuel demand. While these models provide valuable insights to identify policy risks, they are subject to substantial uncertainties due to assumptions about economic, environmental, and agricultural dynamics.

The paper discusses the comparative analysis of the economic models used in the CORSIA framework to define the core LCA values and the Induced Land Use Change ILUC default values for U.S. corn-based alcohol-to-jet (ATJ) and ethanol-to-jet (ETJ) pathways for SAF production.

Key findings

The major findings relate to the uncertainties linked to ILUC modeling, the implications of ILUC approaches applied in different policy frameworks and the opportunities for improvement. These key findings can be summarized as follows:

- **Modeling Uncertainties**
 - *Baseline definition:* assumptions about baseline land use and agricultural productivity significantly influence ILUC outcomes. Fixed baselines may not account for technological advancements or dynamic land-use changes.
 - *Elasticities and conversion factors:* parameters such as supply-demand elasticity, yield elasticity, and land conversion coefficients vary widely across models and can have a significant impact on the results.
 - *Amortization period:* the choice of timeframes to distribute ILUC emissions (20 years for the EU Renewable Energy Directive (RED), 25 years for CORSIA, and 30 years for the California Low Carbon Fuel Standard (LCFS)) introduces variability and reflects political rather than purely scientific considerations.
 - *Spatial representation:* GTAP-BIO uses a broader economic lens, emphasizing economic-driven land-use transitions and changes, while GLOBIOM incorporates more granular spatial data, capturing ecological effects. These divergent approaches lead to different ILUC values for identical scenarios.
 - *ILUC emissions time shifting:* ILUC assessments focus on the implications of an additional, often substantial demand for biofuels (compared to current production levels), meaning that the calculated emissions, which are

reflected in the CI under CORSIA represent expectations of future emissions and not emissions that happened already.

- **Policy Implications**

- Differences in model assumptions create challenges in harmonizing ILUC calculations across frameworks like CORSIA, RED, and California LCFS. Policymakers should take these differences in due consideration when discussing model reliability against practical implementation constraints.
- The global scope of CORSIA introduces additional complexities, as ILUC models must capture diverse land-use dynamics, market responses, and regional policies.

- **Opportunities for Improvement**

- *Enhanced transparency:* Clear documentation of model assumptions and input data is crucial to build trust and improve stakeholder engagement.
- *Constant updating of models and underlying assumptions:* The recent release of the 45ZCF-GREET calculator highlights the significance of up-to-date data and modeling assumptions for ILUC assessment results and the subsequent evaluation of fuel pathways. Therefore, continuous model updates are essential. Additionally, the implications of the recent GTAP-Bio update under the 45ZCF release should be examined within the CORSIA framework.
- *Dynamic modeling:* Incorporating adaptive baselines that reflect evolving agricultural practices and market conditions could overcome the uncertainties related to static assumptions.
- *Integration of Low LUC practices and certification:* Incentivizing low-iLUC-risk feedstocks and farming practices through certification can mitigate land-use impacts and reduce uncertainties linked with the ILUC modeling.

Next steps and recommendations

This paper advocates for continued refinement of ILUC modeling methodologies to address uncertainties and improve the accuracy of SAF CI calculations. Regular updates to assumptions, integration of real data, the use of remote sensing and advanced monitoring and verification systems are essential to align models with actual land-use trends. As SAF production and use needs to accelerate, such enhancements will be critical to ensure that global policy frameworks achieve their GHG reduction goals while supporting sustainable SAF and biofuel production.

Introduction

Sustainable aviation fuels (SAF) are increasingly recognized as a promising solution for reducing greenhouse gas (GHG) emissions in the international aviation industry. Their appeal lies in their ability to serve as a "drop-in" fuel, meeting stringent international jet fuel standards while seamlessly integrating with existing aviation fuel infrastructure. This compatibility minimizes the need for significant modifications to current fuel distribution systems or aircraft engines. Additionally, SAF production from biomass is well-established, with these fuels already commercially available through two primary technological pathways: Hydro-processed Esters and Fatty Acids (HEFA) and Alcohol-to-Jet (ATJ).

The extent of GHG emissions reductions achieved by replacing conventional JET A-1 fuel with SAF depends on two critical factors: the carbon intensity (CI) of the fossil-based jet fuel and the CI of the SAF. The latter is determined by the specific characteristics of the biofuel's value chain. Carbon intensity can be measured and quantified using established methodologies such as product carbon foot printing and Life Cycle Assessment (LCA), which provide comprehensive insights into the environmental impact of SAF production and use. The International Energy Agency's (IEA) 2024 report provides a detailed analysis of the key factors and contributors to the CI of biofuel pathways. Emissions across the entire biofuel lifecycle — including the production of biogenic feedstock, its distribution, conversion to biofuels, and the subsequent distribution and use of the fuels— can be systematically measured and quantified. This comprehensive assessment encompasses both direct process emissions and upstream emissions associated with the production and use of inputs such as fertilizers, fuels, electricity, and process chemicals. To ensure accurate emission quantification, robust methodologies and verification schemes have been developed and implemented at both national and international levels. Notable examples include the California Low Carbon Fuel Standard (LCFS) and the U.S. Inflation Reduction Act (IRA) at the national level, as well as the European Renewable Energy Directive (RED) and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) at the international level.

In addition to the emissions associated with the life cycle of the biofuel or SAF, land conversion for feedstock cultivation can result in direct and indirect effects on GHG emissions, which may either increase or decrease the fuel's CI. International policy frameworks have adopted various measures to address both direct and indirect land use change effects resulting from the production and use of biofuels. In detail, the International Civil Aviation Organization (ICAO) defines that "*CORSA Eligible Fuel (CEF) production may require some additional land to be used and generate land use change GHG emissions. These could occur where the new CEF production is taking place (direct land use change) but also in other locations due to the displacement of crops (or animals) for which the land was previously used (indirect land use change)*". To account for GHG emissions from both direct and indirect land-use changes, the CORSA methodology includes Induced Land Use Change (ILUC).

GHG emissions from indirect land use change can neither be observed nor measured directly. Instead, the quantification of emissions from indirect land use change is based on economic models (e.g. GTAP-BIO and GLOBIOM) that estimate land use and land

cover changes driven by increased demand for a given biofuel type. These estimates are then combined with land-related emission factors and additional assumptions used to convert the estimated land use changes into GHG emissions.

ILUC events can lead to significant CO₂ releases, thereby reducing and potentially negating the GHG benefits of SAF use. Under the CORSIA framework, ILUC emissions are summed with the so-called core LCA values that express the GHG emissions associated with the life cycle of the SAF. ILUC emissions are therefore an important element determining the eligibility of specific feedstocks, regions and technologies for SAF production under CORSIA.

The adoption of such a complex modeling approach has raised some concerns about the potential uncertainties associated with ILUC quantification and the definition of ILUC values for SAF production pathways.

The objective of this position paper is to provide an analysis of the inclusion of ILUC values in life cycle emissions calculations under CORSIA. The focus is on the U.S. corn bioethanol production pathway, with a resulting comparative assessment of the ILUC value calculation in the GTAP-BIO and GLOBIOM models, as well as the GHG calculation tool GREET, as they are used in CORSIA. The aim is to highlight the strengths and weaknesses of each model in accurately representing the U.S. corn bioethanol pathway and its associated emissions at each life cycle stage.

The paper is structured as follows. Chapter 3 introduces the general concepts of indirect (iLUC), direct (dLUC) and induced (ILUC) land use change and discusses its relevance in the overall CI and eligibility of SAF. This is followed by a comparative analysis of the economic models used under CORSIA for iLUC quantification, along with a description of policy approaches and instruments for ILUC consideration (Chapter 4). The potential for the use of alternative approaches to address ILUC is discussed in Chapter 5. In conclusion, a thorough discussion of the main findings of the analysis is carried out in Chapter 7, where recommendations on ILUC modeling-related uncertainties are also provided.

The concept of ILUC and its relevance in policy frameworks for SAF

1.1 Introduction to the concepts of direct, indirect and induced land use change

If a feedstock for biofuel production is cultivated on land that has recently been converted to agricultural use, the conversion can impact the carbon stock stored in soil and vegetation. A decrease in carbon stocks due to land-use change is associated with emissions, which are typically factored into the CI of the produced biomass and, consequently, the resulting SAF. Conversely, if the land-use change leads to a net increase in carbon stocks within the soil and vegetation, this increase can also be attributed to the biomass produced on that land and reflected in the CI of the biofuel. Existing policy frameworks, such as the RED III, acknowledge the significance of LUC emissions and establish specific requirements for quantifying and verifying direct land use changes (dLUC) and the corresponding emissions associated with biofuel production.

While the conversion of land for the cultivation of biofuel feedstock can be observed in practice, the so-called indirect land use change effects cannot be observed or measured directly. iLUC refers to the phenomenon where the production of a specific commodity (often for biofuels) displaces existing agricultural or natural land uses, leading to land conversion elsewhere to meet the displaced demand. This concept is commonly associated with bioenergy and biofuel production, mainly due to the widespread promotion of biofuels in various global policy frameworks, which are accompanied by specific sustainability requirements aimed at avoiding direct land use change (Majer et al., 2018). This narrative is based on the hypothesis, that policy frameworks such as quotas for biofuels lead to an increasing demand for biofuel feedstock. Due to sustainability and CI reduction requirements for biofuel feedstocks, this additional demand cannot be met by an expansion of agricultural land. Instead, biofuel feedstock production may replace existing agricultural production for other markets. Since demand for the substituted product remains, and these other markets may lack land use change regulations, production could shift to another area, potentially leading to the conversion of natural land (compare Figure 1).

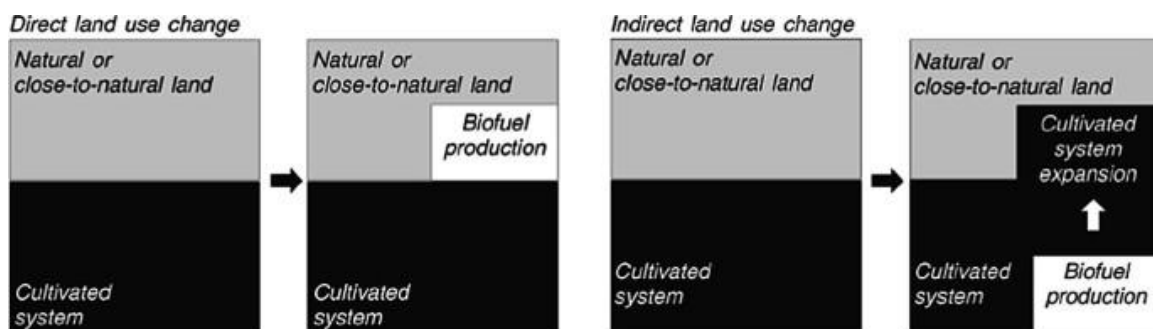


Figure 1 Direct and indirect land use change (Plassmann, 2018), Induced land use change refers to the sum of both

International policy frameworks such as CORSIA, the California LCFS or the RED have taken different measures to address direct and indirect land use change effects

from the production and use of biofuels. For example, the international framework for aviation, CORSIA has introduced a land use related component in its GHG reduction requirement for biofuels. This component, which addresses induced land use change (ILUC) is quantified via complex models and includes both emissions from area expansion and replacement effects to produce biofuel feedstocks. The concept of ILUC, as defined under CORSIA, accounts for the GHG emissions associated to both direct and indirect land use change. It is based on the definition provided by ICAO according to which “*CORSIA Eligible Fuel (CEF) production may require some additional land to be used and generate land use change GHG emissions. These could occur where the new CEF production is taking place (direct land use change) but also in other locations due to the displacement of crops (or animals) for which the land was previously used (indirect land use change)*”.

1.2 The current relevance of biofuels in the transport sector

Biofuel demand has steadily increased, reaching over 4% of global transport fuel consumption in 2024. According to the IEA’s main forecast, demand growth is expected to accelerate, reaching over 5% by 2030, with total consumption rising by 20% compared to 2023 levels. Growth in biofuel demand will primarily be driven by biodiesel and renewable diesel (hydrotreated vegetable oil, HVO), ethanol, and biojet fuel, contributing to 40% (biodiesel and HVO), 35% (ethanol), and 25% (biojet) of the growth, respectively (IEA, 2024).

Emerging economies such Brazil, Indonesia, and India are expected to lead the demand particularly through ethanol and biodiesel production. This will be supported by biofuel blending targets, rising transport fuel needs, and available domestic feedstocks. In contrast, growth in advanced economies is expected to be slower due to increasing electric vehicle adoption, improved vehicle efficiency, high biofuel costs, and technical challenges. In these regions, renewable diesel and biojet fuel are the key growth segments. Innovations like alcohol-to-jet fuel could further boost demand for ethanol as electrified vehicles reduce its traditional use in transportation. New technologies and practices could account for 15% of biofuel demand in accelerated deployment scenarios.

Corn-based ethanol production in the United States has increased significantly over the past few decades, with approximately 40% of the corn crop now used for ethanol production and related co-products (Ramsey et al., 2023). However, the USDA has noted that U.S. ethanol based demand for corn has plateaued in the last decade at approximately 5 billion bushels and 15 billion gallons annually (Ramsey, 2023; Ramsey et al., 2023). With the increased ethanol production, the U.S. is positioned to become a major producer of SAF through initiatives such as the IRA, which provides incentives for SAF production for fuels achieving a 50% or higher GHG reduction compared to conventional jet fuel (DOE, DOT & USDA, 2022). These incentives aim to increase SAF production from 16 million gallons to 3 billion gallons by 2030 (DOE, DOT & USDA, 2022; Swanson & Smith, 2024).

1.3 LUC emission levels and relevance from current biofuel production

The discussion on the consequences of potential land use change, driven by a growing demand for biofuel feedstock began with publications such as Searchinger et al. 2008 and Laborde 2011. These works sparked an intense debate around assessing the potential impacts of policy programs and targets for increasing biofuel use. Consequently, several publications have aimed to quantify the associated impacts related to such programs and targets, including the RED and various U.S. initiatives. However, most existing publications have focused on quantifying the consequences of projections for future demands, and not the impacts of current biofuel production.

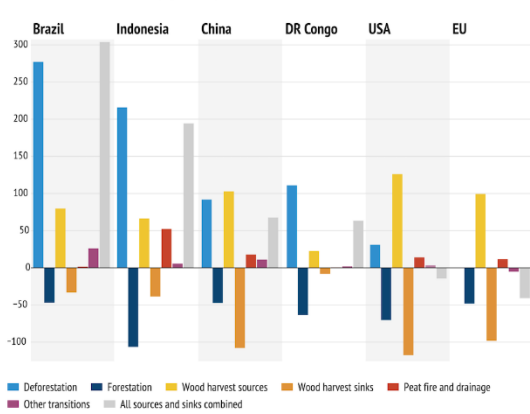
In this context, iLUC emissions included in the emission factors of biofuels partially reflect anticipated future emissions, which are integrated with actual, measurable emission data (e.g., from direct process emissions).

Considering current global land use change related emissions, the following contribute significantly more than the production of biofuels: the expansion of managed areas for food and feed production, fiber production, livestock farming, and the harvesting of fuelwood and timber. Biofuel production in its current state contributes approximately 6.6% to LUC-related emissions from agricultural land under continuous cultivation. Thus, current global LUC emissions from biofuel production are relatively low compared to the overall agricultural LUC emissions (Jeswani et al., 2020; Moreira, 2014; Tubiello & Conchedda, 2021; Václavík et al., 2013).

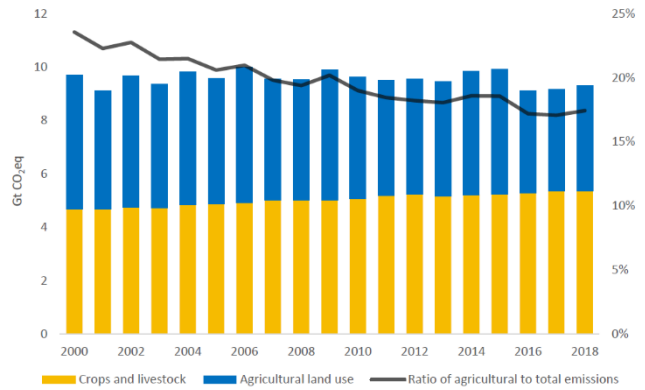
According to Tubiello & Conchedda (2021), in 2018 global LUC emissions from agriculture were 9.3 billion tonnes of CO₂ eq. with increasing contributions from crops and livestock production and a relative decrease in emissions from agricultural land use (compare Figure 2, (right)). Additionally, Schwingshackl et al., (2023) illustrate land use CO₂ fluxes and their main components for different countries and regions (Figure 2, left), highlighting the currently negative net land use CO₂ fluxes in the U.S. and Europe, and high emission levels some Asian and Latin American countries.

Components of land-use CO₂ fluxes

Mean land-use CO₂ flux (TgC/year)



Source: Dr Clemens Schwingshackl



Source: FAOSTAT 2020.

Figure 2 Land use CO₂ fluxes for different countries and regions according to Schwingshackl 2023 (left) and yearly emissions from crops and livestock, and related land use and share of agriculture in global GHG emissions from all sectors, 2000–2018 according to Tubiello & Conchedda, 2021 (right).

A study conducted by Lee, et al. (2021) on the implications for GHG emission reduction in the U.S. corn ethanol industry revealed a significant decrease in the CI of U.S. corn. Despite the expansion of the corn ethanol industry, the GHG intensity of corn ethanol has decreased due to enhanced farming techniques, increased yields and reduced energy use in biorefineries. This aligns with the trend of decreasing GHG emissions from agricultural land use discussed by Tubiello & Conchedda (2021). Figure 3 shows that although the production and yield of corn in the U.S. have increased over the past few decades, the area required for this production has remained constant. Moreover, the USDA (2024) projections indicate that corn production will continue to increase, with an increase in yield counterbalancing a decline in acreage. This efficiency in production can be attributed to a combination of factors, including the adoption of genetic engineering and the application of precision farming technologies (USDA, 2023, 2024).

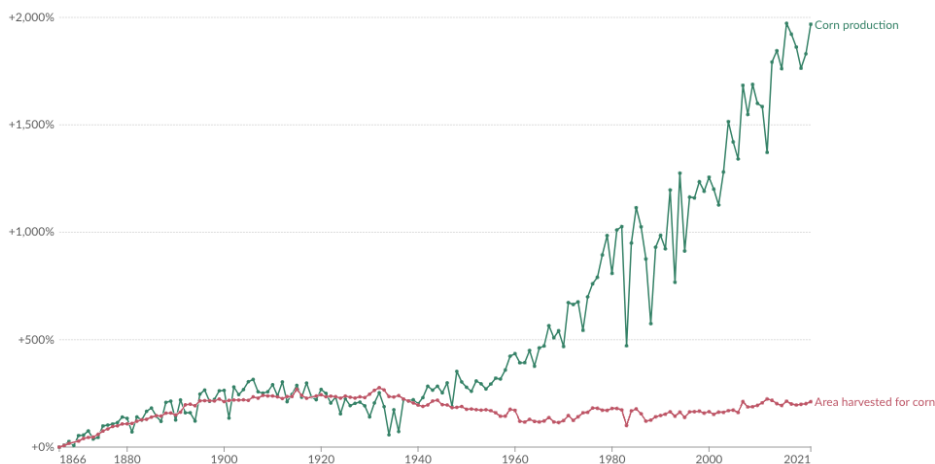


Figure 3 Change in land use and corn production in the United States from 1866 to 2021 (Calculated by Our World in Data (2024) based on U.S. Census Bureau and USDA)

Recent projections for the U.S. corn sector indicate a trend of increasing yields despite stable or slightly decreasing land use (Beckman et al., 2023; USDA, 2023, 2024). Moreover, Beckman et al., (2023) forecast a 3.1% increase in U.S. corn yields by 2036 (relative to 2016). This increase is supported by the historical data also reported by Ritchie & Roser (2024) and USDA (2024). However, it is important to note that the yield increases projected in the presented literature are subject to uncertainty, particularly due to factors such as climate change. For example, regions like Oklahoma, Kansas, and states north of Virginia are expected to experience declines in yield due to the increasing growing days caused by rising temperatures (Beckman et al., 2023).

The accuracy of ILUC modeling is contingent on the consideration of regional differences in yield, land-use efficiency, and technology adoption. A nuanced approach to these regional variations is essential for the effective prediction of environmental impacts and reduction of modeling uncertainty (Balugani et al., 2022; Paulson et al., 2024). Finally, the law of diminishing returns must be considered, which states that initial productivity gains from new technologies and practices will eventually slow down and plateau as the optimal capacity is achieved (Pichère, 2015).

1.4 Model-based quantification of induced and indirect LUC effects

Since the trade of agricultural products is mostly globalized, the actual location where a natural ecosystem is potentially converted into agricultural land can be distant from the site where the raw material for a biofuel is cultivated. This spatial disconnection makes it challenging to assign a specific ILUC factor to individual cultivation practices for biofuel feedstocks.

To address this challenge, two fundamentally different modeling approaches have emerged. On one hand, complex economic models, such as computable general equilibrium models and partial equilibrium models, have been developed. On the other hand, simpler models, often referred to as deterministic or causal-descriptive models, have also been created.

Economic Models

Economic models typically operate with marginal changes within a mathematically modeled economic system. These equilibrium models consist of equations that define the quantitative relationships between supply, demand, and price, supported by an extensive database (Di Lucia et al., 2012). They are generally complex and require large volumes of data. The fundamental assumption of these models is that the economy achieves equilibrium when demand matches supply. It is also assumed that markets operate under conditions of perfect competition.

For iLUC analysis, there are two main types of economic models:

- **CGE Models** (Computable General Equilibrium). These models analyze the entire global economy.

- **PE Models** (Partial Equilibrium): These focus on specific sectors, such as agriculture.

Both types rely on linear and nonlinear relationships between prices, demand, and production. These relationships are characterized by supply and demand elasticities, which are derived from statistical data and historical trends (Nassar et al., 2011).

Economic models like GTAP3 (CGE) and IMPACT4 (PE) were originally developed independently of the biofuel and iLUC debates. Over time, researchers from various disciplines have adapted these models to address new contexts. The first scientific paper on iLUC quantification using economic modeling was published by (Searchinger et al., 2008). It employed a PE model to calculate the iLUC effect of corn ethanol production in the United States. Since then, both PE models (e.g., IMPACT, FAPRI, AGLINK, and CAPRI) and CGE models (e.g., GTAP and LEITAP) have been utilized for iLUC quantification (Edwards et al., 2010). A key research institution in the field of iLUC quantification using economic modeling is the International Food Policy Research Institute (IFPRI), which published studies on this topic in 2009 and 2011. The 2009 study was the first to use CGE models to analyze the LUC effects of EU biofuel policies (Finkbeiner, 2013; Laborde, 2011).

CGE and PE models typically use a marginal change approach to analyze iLUC. First, a baseline scenario is calculated within the model. Next, a scenario with a marginally higher demand for a specific biofuel is introduced (Edwards et al., 2010). Modelers often refer to this step as “shocking the model” with a biofuel or policy shock. The result is a projection of the effects of increased biofuel demand from a specific country on global commodity markets and the additional need for agricultural land (Edwards et al., 2010).

Economic models do not distinguish between crops grown on “new” versus “existing” agricultural land (Edwards et al., 2010), instead their results reflect total LUC effects, encompassing both dLUC and iLUC (Edwards et al., 2010). In the next step, land-use changes are assigned to specific land types (e.g., grassland, forest) based on historical LUC patterns. Finally, biophysical models are used to estimate GHG emissions from these land-use changes (Nassar et al., 2011). By comparing the two scenarios—baseline and increased biofuel demand—it becomes possible to attribute a specific amount of GHG emissions to biofuel production. Since this value includes both iLUC- and dLUC-related emissions, directly assigning it to the carbon footprint (CF) of biofuels would result in double-counting dLUC effects (Delzeit et al., 2011). For this reason, modelers separate dLUC and iLUC in the qualitative interpretation of the model's results.

The assumptions made during the baseline definition have a critical influence on LUC results in both CGE and PE modeling. One key assumption involves elasticities, particularly the so-called constant elasticity of transformation, price-yield elasticity and the elasticity of land transformation. The latter describes how easily land can be converted to other uses when agricultural commodity prices change.

Deterministic Models

Unlike economic models, deterministic models do not model prices but rely on assumptions about how agricultural systems respond to increased biofuel production. They use cause-effect assumptions to describe system behavior (Bauen et al., 2010). The logic is that additional biofuel demand impacts the agricultural system, driving LUC and resulting in GHG emissions. Market response and LUC assumptions are typically based on historical data on trade, land use, and LUC patterns (Nassar et al., 2011)(Nassar et al., 2011). One example is the iLUC factor developed by the German Öko-Institut (Fritsche et al., 2010). This model uses statistical trade data and various assumptions, including that iLUC can be determined by analyzing exported products relevant to the bioenergy sector (e.g., soy and palm oil)

In a simplified approach, the key steps of the modeling in the example of Fritsche et al (2010) include:

- Calculating the land required for production by dividing traded commodity volumes by country-specific yields.
- Computing a “global mix” of land use for exports and assigning country-specific shares.
- Combining additional land needs with assumptions about dLUC in each country, then weighting results using IPCC conversion factors based on country contributions to the global mix.

The model assumes that one hectare of bioenergy production displaces one hectare of prior land use. However, displacement may be mitigated by increased yields and the use of fallow land. Assuming a 1% annual yield improvement until 2030, the maximum iLUC factor could drop to 75% of the theoretical value. The authors propose three efficiency scenarios—25%, 50%, and 75%—to account for potential productivity gains and the use of degraded land for expansion (Fritsche et al., 2010).

Lahl (2010) developed a simplified model to address criticisms that existing models fail to adequately account for the impact of governmental regulations on global agricultural markets especially through subsidies, tariffs, and trade restrictions (e.g., import/export bans). This approach emphasizes the significant role policy instruments play in shaping market dynamics and, consequently, land-use change.

1.5 General challenges regarding the interpretation of model-based quantification of ILUC emissions

The quantification of emissions from induced land use change (i.e., combining both, dLUC and iLUC), based on the previously described approaches is subject to various sources of uncertainty. Furthermore, a comparison of published ILUC values for various biofuels demonstrates significant variations over time. NAS (2022), highlights a number of potential variations regarding key parameters influencing the emissions from land use change across different studies and models. These include:

- **Differences in the nature of LUC:** Different model approaches show inherent differences regarding aspects such as price-yield elasticities, the

comprehensiveness of land use categories, changes in crop mixes, harvesting frequencies, etc. These variations might lead to different answers as to which lands would be used to meet a defined crop demand and what the impacts of these land use changes would be. Furthermore, the impacts of converting land from one use to another may depend on the details of historical uses which impact carbon stocks in the land in question.

- **Different assumptions for amortization time periods:** Frameworks such as CORSIA, the California LCFS, and the EU RED use a specific time period to amortize the overall quantified ILUC emissions. Often, this time period is defined based on an assumption about how long the respective biofuels policy is presumed to be in effect. Some studies have used 20 years for the amortization time horizon following the EU regulatory emissions guidelines, other authors used 30 years for the time horizon following U.S regulatory emissions guidelines. CORSIA, has applied a 25-year time horizon, a compromise between the U.S. and EU time horizons. NAS (2022) states that the choice of amortization time horizon directly affects ILUC values, but this decision may be influenced by political considerations and aligned with the time frames of policy goals. There is no single correct choice for the amortization period. However, (Schmidt et al. (2015) states that applying an amortization period introduces arbitrary assumptions, inconsistencies, and strange cause-effect relationships.
- **Variations due to model and parameter changes:** Over the last decade, various models have been used to assess land-use changes for biofuel pathways, with frequent modifications leading to evolving ILUC projections. While these changes increase variation, they may reduce uncertainties if improvements are based on verified observations. ILUC values remain inherently uncertain, but efforts to verify assumptions and examine factors like yield changes, land allocation, crop prices, land cover, and international trade over time could help limit uncertainty in ILUC evaluations.
- **Variations due to changes in the implemented emission accounting frameworks:** Projected ILUC values are subject to statistical and systemic uncertainties and are influenced by variations in feedstock, biofuel production technologies, and feedstock production location. Reducing uncertainty requires addressing key challenges, such as aligning land categories in models and emissions data, assigning accurate emission coefficients to various land types, accounting for changes in soil organic carbon and land management practices, and validating assumptions in emission datasets. To address uncertainty, ILUC quantification typically employs scenario-based assessments, detailed sensitivity analyses, and formal sensitivity tests.

1.6 Quantification of ILUC under CORSIA

The development of ILUC factors under CORSIA was undertaken by an expert subgroup, which focused on two specific models, namely the 'GTAP-BIO' and 'GLOBIOM' models. The ILUC factors derived from these modeling exercises form the foundation for the default values recommended under CORSIA. The basis for this analysis is fully detailed in a published lifecycle assessment report (ICAO, 2022).

The ILUC modeling pertinent to aviation necessitates the establishment of a baseline that delineates an equilibrium characterization of global land use in the absence of demand for Alternative Aviation Fuels (AAF), followed by the introduction of a quantifiable increment of AAF consumption. This permits the model to converge to a new equilibrium, which typically encompasses responses such as the expansion of land use, alterations in productivity, and a diminution in the consumption of biofuel feedstocks across other sectors. In this regard, the “shock size” (i.e. the quantifiable increment of AAF consumption) is a demand of approx. 104 PJ of ATJ from U.S. corn for the target year 2035.

A more detailed description of GTAP-BIO and GLOBIOM models is included in section 0.

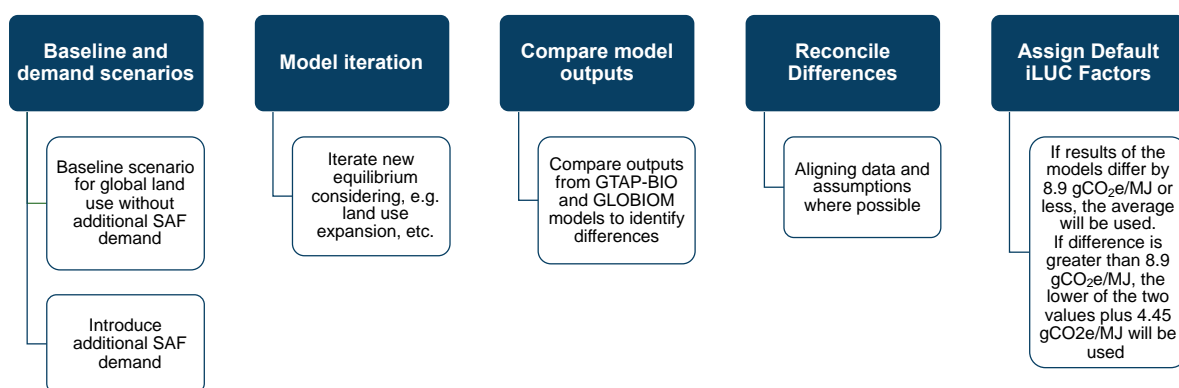


Figure 4 Process for the development of ILUC values under CORSIA

Results for U.S. Corn based SAF under the CORSIA framework

The CI of SAF pathways is an important element in frameworks promoting alternative aviation fuels. The CORSIA framework provides CI values for two SAF pathways based on U.S. corn. These values include core-LCA values (e.g., emissions associated with the value chain of the SAF production and distribution) and emissions from the induced land use change of these pathways.

Figure 5 shows the induced LUC (both iLUC and dLUC) emissions associated with the production and use of SAF derived from U.S. corn, calculated under the above-described process. The two respective pathways included under CORSIA are i) corn-grain-iso-butanol ATJ and ii) corn-grain-ethanol ATJ, with induced LUC emissions of 22.1 g CO₂-eq. per MJ of ATJ-Isobutanol and 25.1 CO₂-eq. per MJ of ATJ-Ethanol. Both values are averages, produced from the outcomes of the GTAP-BIO and GLOBIOM models. Additionally, the figure includes the ILUC value for ATJ-Ethanol from the GREET-40BSAF-Model, which has been normalized to a 25 yr amortization period (the same as under CORSIA) for comparison (ICAO, 2022).

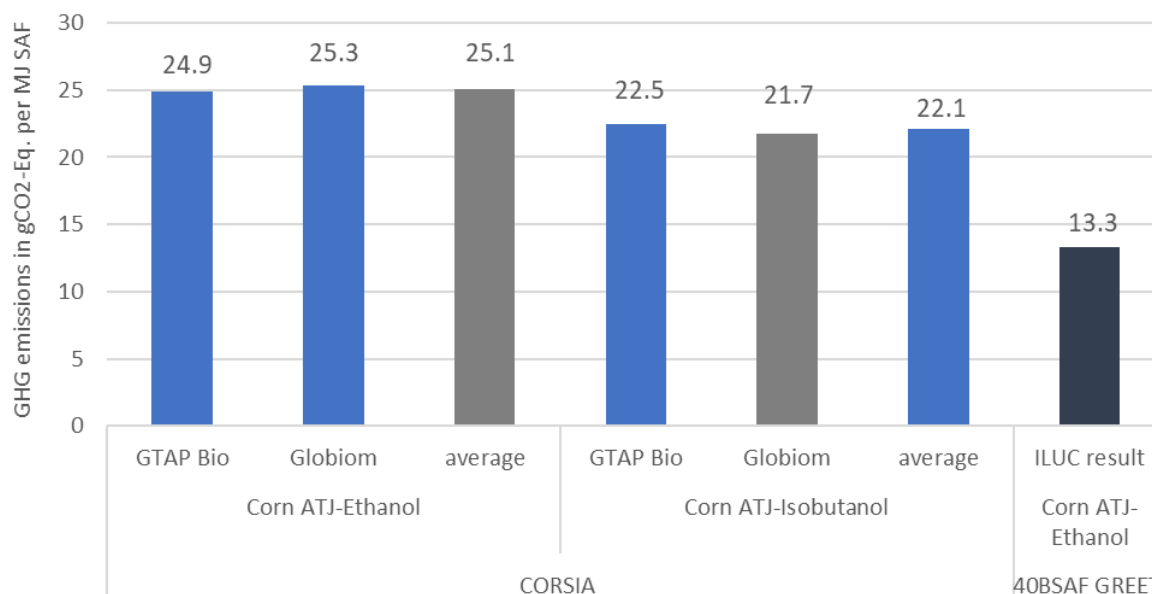


Figure 5 Emissions from induced land use change as included in CORSIA and the 40BSAF-GREET model (the latter was normalized to a 25-yr amortization period for greater comparability with the CORSIA values. The original value was 11.1 gCO₂eq. per MJ)

The ILUC emissions values for both pathways have been calculated for a 25-year timeframe, meaning that the calculated emissions from land use change have been annualized over the respective timeframe. Contrarily, the 40B SAF model uses a 30-year amortization period (note that the value in the figure has been normalized to a 25-year period for comparison with the CORSIA values). Even though the total emission intensity from the two models is close for both pathways, details of the assessment differ, especially with regard to market-mediated responses and the decomposition of land use change and emissions.

The calculated emissions represent the model response to an increasing demand (e.g., the “shock”) for the respective aviation fuel. For CORSIA, the induced shock was a production of 104 PJ ATJ-Ethanol SAF and 136 PJ of ATJ-Isobutanol respectively. Figure 6 compares the global land use change decomposition and emission decomposition between the two models for the U.S. corn ATJ-Isobutanol and ATJ-Ethanol pathways. The (net) total bar level in the land use change decomposition indicates the increase in feedstock harvested area, reflecting crop yield, technology conversion yield, meal coproduct substitution, and other market-mediated responses. Additionally, Table 1 summarizes the main characteristics and differences of the model assumptions for the ILUC values of the two CORSIA U.S. corn SAF pathways.

Table 1 Main characteristics and differences between model assumptions for CORSIA U.S. corn SAF pathways. Based on CORSIA 2022

	ATJ-Isobutanol		ATJ-Ethanol	
	GTAP-BIO	GLOBIOM	GTAP-BIO	GLOBIOM
Corn prod. incr. (Mt)	9.4 (91% USA)	8.9 (96% USA)	13.8 (91% USA)	11.6 (96% USA)
Corn area incr. (Mha)	1.04	0.74	1.53	1.14
Modelled land use area and management responses to produce additional corn demand (Mha)				

Crop switching	0.59	0.17	0.65	0.30
Cropland pasture	0.21	0.25	0.31	0.29
Multi-cropping & unused land	0.12	0.09	0.40	0.44
Abandoned land/other natural land	-	0.22	-	0.44
Forest & pasture	Minor	Minor	Minor	Minor
Emission and sources (MtCO₂)				
Natural vegetation	26	27	38	48
Soil organic carbon	22	35	32	44
Foregone sequestration	Lower	Higher	Lower	Higher
Agricultural biomass carbon sequestration	Smaller	Larger	Smaller	Larger
Total emissions	58	56	85	86
Key yield assumptions				
Baseline yield (t/ha)	8.95	9.01	8.95	9.01
Yield response	Moderate	Strong	Moderate	Strong
Key drivers of differences				
DDGS displacement (Feed crops)	More Displaced	Less Displaced	More Displaced	Less Displaced
Crop switching	Higher	Lower	Higher	Lower
Contribution of abandoned land	Lower	Higher	Lower	Higher

Although the results from both models appear similar, the underlying land use responses they model are very different. In fact, the differences between the models may be more pronounced than suggested by the reported ILUC factors alone (for a clearer comparison, figure 6 shows the land use change decomposition (left) and emission decomposition (right) for both U.S. corn pathways: ATJ-Ethanol (left) and ATJ-Isobutanol (right)).

Both models assume that the main share of the additional demand for corn will be met by U.S. production (91% GTAP-BIO vs. 96% GLOBIOM), with the remainder supplied by imports. GTAP-BIO predicts a 1.53 million hectare increase in global coarse grain area, driven by crop switching and use of cropland pasture. GLOBIOM projects a smaller increase of 1.14-million-hectares, utilizing crop switching, multi-cropping, and natural land.

GTAP-BIO tends to focus "cropland pasture", assuming easy conversion to crops with low carbon costs, and GLOBIOM emphasizes "other natural land," which includes unmanaged vegetation with lower carbon than forests for conversion into cropland. (ICAO, 2022)

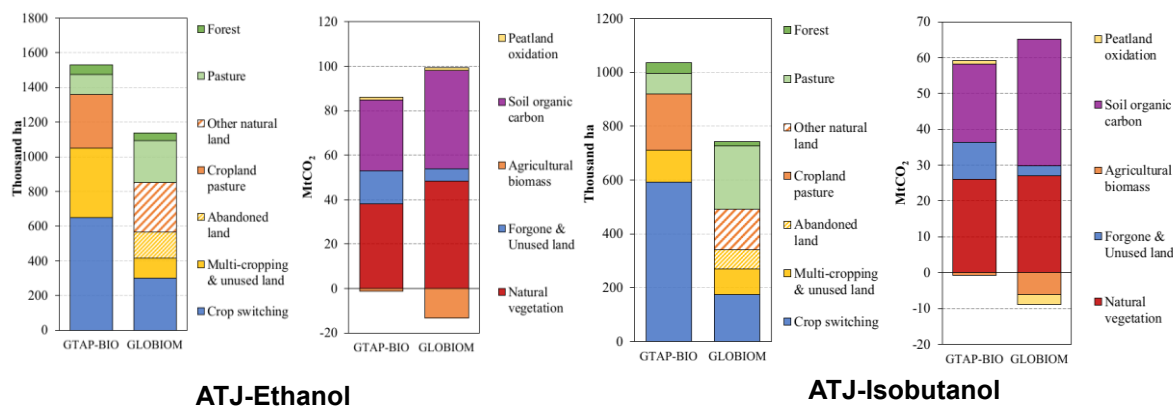


Figure 6 Land use change decomposition (left) and emission decomposition (right) for ATJ-ethanol (left) and ATJ-Isobutanol (right). CORSIA 2022

Additionally, the CORSIA framework features a second component for the CI of biofuels, the so-called core-LCA value. This value represents the emissions associated with the different process steps in the biofuel value chain. The background data and underlying assumptions for these calculations are sourced from two databases, the GREET model and the JRC database (ICAO, 2022). Amongst the various assumptions for process inputs and outputs, efficiencies and transports, the assumptions for crop yields and the efficiency for crop to fuel conversion are particularly relevant for the calculation of the iLUC emissions. Corn grain assumptions for the calculation of the core-LCA value range from 7.1 t per ha and year (JRC Database) to 10.4 t per ha and year (GREET). For the conversion efficiency assumptions range from 2.16 MJ of corn grain per MJ of fuel (GREET) to 2.38 MJ per MJ (JRC) for ATJ-Isobutanol and 0.13 kg corn grain per MJ of fuel (GREET) to 0.1 kg per MJ (JRC) for ATJ-Ethanol.

1.7 Quantification of ILUC under the 45ZCF-GREET Update

In addition to the previously mentioned tools, in January 2025, the U.S. Department of Energy released the 45ZCF-GREET model. This tool can be used for calculating carbon intensity scores and associated values for the §45Z Clean Fuels Production Credit. The release included the respective GREET calculator (U.S. Department of Energy, 2025a) as well as a manual (U.S. Department of Energy, 2025b) and supplementary material (ANL, 2025).

The calculator incorporates several updates and enhancements compared to previous versions of the GREET calculators. Some of the key differences are i) the specific focus on Clean Fuels Tax Credit, ii) updated background data, including an update of the background models used to calculate ILUC, iii) default values for testing.

A key difference to other GREET tools is the update of the background tools for the quantification of ILUC emissions from the pathways included. In this regard, the tool for the quantification of ILUC included GREET (Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB)) has been comprehensively updated. The updates cover aspects such as:

- **New global datasets:** The GTAP-BIO database has been updated to include new global datasets that represent the global economy in 2017. This is a shift from the previous version, which was based on data from 2014. The incorporation of more recent data allows for a more accurate assessment of land use and land management changes related to biofuels production.
- **Refinement of agricultural data:** The GTAP-BIO database has been further refined to align more closely with the Food and Agriculture Organization (FAO) production and price data for agricultural activities.
- **Updates on emission factors:** The report provides updated emission factors for induced land use changes used on the updated databases and models included in the CCLUB.

For U.S.-produced corn and its derivatives used as feedstock for fuel production, the update includes notable differences in emission intensities from calculated Induced Land Use Change effects. The 45ZCF-GREET calculator provides results for ethanol derived from corn and SAF produced from distillers' corn oil. The table below presents the calculated emission intensities per MJ of ethanol produced from corn.

Table 2 45ZCF-GREET ILUC results for US corn ethanol in gCO₂-eq. per MJ of fuel.

Pathway	Total	ILUC	Livestock	Other crops
Ethanol Fermentation U.S. corn starch	4.58	5.75	-1.58	0.41

In summary, the calculated emissions from ILUC and other indirect effects amount to 4.58 gCO₂-eq. per MJ of ethanol. Given that producing 1 MJ of SAF requires approximately 1.01 MJ of ethanol (see Table 4 in ANL, 2023), this translates to an estimated 4.6 gCO₂eq. per MJ of SAF. In case of a more conservative assumption for the conversion rate from ethanol to Jet in the range of 0.6 (e.g., as described in Geleynse et al., 2018), the corresponding ILUC value would be 7.6 gCO₂eq. per MJ of SAF. This represents potentially a notable reduction compared to the 11.1 gCO₂eq. per MJ value used in the 40BSAF-GREET calculator.

In summary, the release of 45ZCF-GREET and the updated CCLUB underscores the impact of database revisions on models like GTAP-BIO and GLOBIOM. It highlights the need for the continuous integration of updated economic and land-use data to better inform discussions on the indirect effects of biofuel and SAF production and use.

Comparative analysis of GTAP-BIO and GLOBIOM models and their application under CORSIA

GTAP-BIO and GLOBIOM are two modeling frameworks used to analyze induced land use change associated with biofuels, particularly in the context of CORSIA. Additionally, the 40B GREET calculator for SAF, relevant in U.S. markets, relies on GTAP-BIO for its calculations. However, it works with slightly different assumptions compared to CORSIA.

A general characterization of the computable general equilibrium model GTAB-BIO and the partial equilibrium model GLOBIOM is included in the following table.

Table 3 General characterization of the GTAP-Bio and GLOBIOM models

	GTAP-BIO	GLOBIOM
Model structure	Integrates all sectors and regions, focusing on the global economy.	Sector-specific, focusing on land use, agriculture, forestry, and bioenergy.
Focus and application	Economic analysis, global trade, and bioenergy policy impacts.	Detailed land use changes, environmental impacts, and sector-specific policy analysis.
	Applied for bioenergy mandates, subsidies, and global market effects.	Used for climate policy analysis, biodiversity, food security, and sustainable development.
Treatment of land use	Represents land use within a broader economic system.	Detailed, spatially explicit representation of land use and transitions.
	Operates at regional or country level with less spatial granularity.	Operates at finer spatial resolution, down to grid cells.
Environmental and ecological analysis	Focuses on economic implications, with environmental outcomes as secondary outputs.	Emphasizes environmental impacts, including GHG emissions, carbon sequestration, and biodiversity.
	Less detailed in ecological outcomes.	Provides detailed environmental and ecological outputs.
Sectoral integration	Integrates all economic sectors, including bioenergy.	Specializes in agriculture, forestry, and bioenergy sectors.
	Analyzes interactions between bioenergy and other sectors.	Focuses deeply on land-based sectors without encompassing the entire economy.

The quantification of induced land use change emissions under CORSIA combines insights from the two complementary frameworks, GTAP-BIO and GLOBIOM, each with distinct methodologies, productivity assumptions, and land-use change representations. GTAP-BIO is a general equilibrium model that captures the global economy with a focus on the biofuel industry. It uses dollar-denominated financial data and economic equations to analyze relationships between various factors, providing a static snapshot of results at a single point in time.

This model links higher prices to increased productivity while considering regional cropping practices and economic land-use changes. Its trade representation influences land-use patterns, though less significantly than other models.

In contrast, GLOBIOM offers a more detailed view of agriculture and forestry, modeling specific farming systems and broader land-use transitions. It considers both price-

driven productivity shifts and independent trends like yield improvements. GLOBIOM also captures indirect market effects and different carbon impacts of land conversion, leading to distinct land-use change patterns, particularly in regions like Southeast Asia.

Differences between CORSIA and 40B SAF-GREET

As discussed under section 1.6, the 40B GREET SAF calculator also includes ILUC values for U.S. corn based SAF (ATJ-Ethanol). This calculation, based on the GTAP-BIO model but with adapted assumptions, results in significantly lower ILUC GHG emissions (e.g., 11.1 gCO₂-Eq. per MJ vs. 24.9 gCO₂-Eq. per MJ from GTAP-BIO under CORSIA).

While the general shock size introduced to the model is comparable to the assumptions under CORSIA (e.g., a demand of 1 billion gallons of SAF), a substantial difference between the two frameworks is the timeframe for the amortization of the calculated land use change emissions. While CORSIA uses a timeframe of 25 years, the 40B SAF ILUC values are amortized over a period of 30 years, the same amortization period used in EPA's Renewable Fuel Standard and the California Low-Carbon Fuel Standard (ANL, 2023). As mentioned in chapter 1.5, the 25-year amortization period under CORSIA represents a compromise between the timeframes used under the California LCFS (30 yrs) and the EU RED (20 yrs). The timeframe for the amortization is highly relevant as the choice has a notable impact on the calculated CI value of a biofuel. At the same time, as stated by NAS, the choice of the amortization period is a political decision and there is no single correct choice for parameter. Furthermore, introducing an amortization period introduces arbitrary assumptions, inconsistencies and strange cause-effect relationships (Schmidt et al. (2015))

Additionally, the assumptions under the 40B SAF ILUC calculations lead to a significantly smaller amount of land being converted as a result of the introduced demand shock (i.e., Cropland/Pasture: 246,000 ha, Grassland: 68,000 ha and converted Forest: 20,000 ha, compare Table 3).

Description of Global Policy Options to Address ILUC Effects

1.8 Policy Frameworks and use of Instruments to address ILUC

To address the concerns surrounding ILUC, a range of policy instruments and regulations aimed at reducing the ILUC impact of bio-based products have been introduced by governing bodies in recent years. These policies typically rely on the feedstock categorization, CI calculations, and caps designed to mitigate ILUC-related emissions (Delzeit et al., 2017; Sumfleth et al., 2020). This section provides an overview of selected policies and instruments, highlighting how they are used to address ILUC in different regions.

ILUC has become a critical issue in renewable energy and biofuel policies within the EU. Key developments in ILUC-related policies can be traced through the EU's Renewable Energy Directives (RED I, RED II, and RED III) as well as the supplementary Regulation (EU) 2019/807.

The RED I (2009/28/EC), adopted in 2009, was the cornerstone for renewable energy policy in the EU. While RED I introduced sustainability requirements for biofuels, its focus was primarily on direct land use change. Although iLUC was not directly addressed, it was acknowledged as a potential concern. In 2018, RED II (Directive 2018/2001/EU) came into effect, directly addressing iLUC and implementing stringent measures to manage its impact.

RED II implemented a cap system as a means to limit the contribution of biofuels with a high ILUC risk. The measures implemented included setting limits on high iLUC-risk biofuels¹, halting their usage at 2019 levels for the period between 2021 and 2023, and mandating a gradual reduction with the objective of reaching zero by 2030. Moreover, the supplementing Delegated Regulation (EU) 2019/807 introduced a 10% threshold for high iLUC-risk feedstocks. RED II also has alternatives that are exempt from caps and can be certified through voluntary schemes recognized by the European commission.

The latest revision, RED III (Directive 2023/2413/EU), introduced in 2023, builds on RED II's policies by further emphasizing the promotion of advanced biofuels that do not compete with food crops and phasing out high iLUC-risk feedstocks.

The RED framework acknowledges the potential risks of land-use change associated with biofuels but avoids directly calculating ILUC effects for individual producers. Instead, it adopts a flexible, risk-based approach by adjusting targets for different biofuel pathways.

The inclusion of ILUC in U.S. policy is summarized in the Renewable Fuel Standard (RFS2) and state-level initiatives such as California's Low Carbon Fuel Standard (LCFS), which are the two main policies that aim to reduce GHG emissions from transportation fuels.

¹ High ILUC-risk biofuels are defined as those produced from feedstocks that have led to significant expansion into areas with high carbon stock, such as forests, wetlands, and peatlands.

Low ILUC-risk biofuels are defined as those whose feedstock production avoids displacement of other land uses, particularly food and feed crops

The incorporation of ILUC into the RFS2 was finalized by the U.S. Environmental Protection Agency (EPA) in 2010. This regulation expanded on the original Renewable Fuel Standard (RFS1) by integrating LCA to include GHG emissions from iLUC. Under RFS2, renewable fuels produced in facilities built before December 2007 are exempt from the 20% GHG reduction threshold² (ICCT, 2010). Similarly, CARB included iLUC impacts when establishing the market-based California LCFS in the 2009, which aims to reduce the carbon intensity (CI) of fuels in California (CARB, 2009). The California LCFS incorporates iLUC emissions by assigning CI values that are benchmarked against conventional fuels. It indirectly employs a cap through CI reduction targets, which limits the use of fuels with high iLUC impacts (CARB, 2009).

The International Civil Aviation Organization (ICAO) developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016 as a global market-based method for achieving carbon neutrality in the aviation sector (ICAO CORSIA, 2016). The CORSIA framework addresses the induced land use change associated with growing demand for alternative aviation fuels. CORSIA includes ILUC values in its default life cycle emissions calculations for eligible fuels, combining these values with Core-LCA values to determine the total Life Cycle Emissions Factors (LCEF). This allows feedstocks to be classified into either sustainable or unsustainable categories. While CORSIA effectively acts as a “de facto” cap by excluding unsustainable feedstocks and incentivizing low-emission fuels, it does not formally define this mechanism as a “cap.”

The international frameworks mentioned in this section use different methods to account for land use change related emissions. Caps on unsustainable feedstocks, the use of default values, as well as certification schemes are the main instruments used. Table 4 provides an overview of different aspects and approaches, where the use of default ILUC values for policies and frameworks such as CORSIA, RED II/III, and California LCFS are central to their implementation and effectiveness. These frameworks can use modeling systems to estimate ILUC impacts, which include both default values and individualized assessments based on specific supply chain data. The variations from models, assumptions, and the treatment of ILUC within these frameworks all lead to differences in how ILUC is quantified and managed, ultimately influencing their implementation as well as their effectiveness.

Table 4 Overview of ILUC methodological features in different policy frameworks

	ICAO CORSIA	EU RED II / III	California LCFS
Model for calculating ILUC	Combination of GTAP-BIO and GLOBIOM	iLUC is calculated to assess policy impacts, not on the producer level MIRAGE-BioF, GLOBIOM	GTAP-BIO and AEZ-EF
LCA approach	Attributional & consequential (LUC)	Consequential	Attributional & consequential (LUC)

² RFS2 GHG reduction threshold: at least a 20% reduction for conventional biofuels compared to gasoline, based on a 2005 baseline

Main emission factors database	GREET and JRC (among others)	Biograce and JRC database	CA-GREET
Allocation	Quantitative: Specific numerical values for ILUC	Qualitative: Risk-based categorization system	Quantitative: Specific numerical values for ILUC
Model for calculating default and individual core values	ICAO-GREET model and other tools	Default values for multiple pathways and methodology for individual calculations	GREET model
References: IEA 2024; ICAO 2024; Directive 2023/2413/EU			

The strategies to incorporating ILUC in biofuel policies varies considerably across different regions, reflecting the adoption of diverse approaches and different priorities. Table 4 summarizes these differences. The EU's RED explicitly incorporates iLUC, restricting high-iLUC-risk feedstocks and promoting low-iLUC-risk alternatives. CORSIA incorporates ILUC into climate impact calculations by adding default ILUC values to life cycle emissions. In the U.S., the RFS program and California LCFS include ILUC in their life-cycle GHG assessments and carbon intensity calculations, respectively (CARB, 2009; ICAO, 2022; IEA, 2024). Conversely, Brazil's RenovaBio and Japan's METI biofuel policies exclude ILUC, focusing solely on direct emissions (IEA, 2024; Sasatani, 2022). Nevertheless, certain frameworks, including Canada's CFS, which presently excludes ILUC, do recognize its significance and suggest potential future integration (GOC, 2022).

Table 5 Overview of the inclusion of ILUC in different policy frameworks

Framework (Region)	ILUC Inclusion	Details
RED (EU)	Included	Incorporates iLUC considerations in RED II, includes iLUC risk approach, limits high ILUC risk feedstocks, considers low-iLUC-risk feedstocks
RFS (USA)	Included	RFS program includes lifecycle GHG assessments that factor in some land use change considerations
CORSIA (international)	Included	Includes considerations for low-iLUC-risk feedstocks
CFS (Canada)	Excluded	The CFS does not include ILUC in their carbon intensity calculations. However, the regulations do acknowledge the potential impact of ILUC and have provisions for future consideration of this factor.
RenovaBio (Brazil)	Excluded	RenovaBio focuses on direct emissions, does not explicitly include ILUC factors
METI (Japan)	N/A	Japan's biofuels policy does not explicitly include ILUC in its carbon intensity calculations

These variations illustrate the complexity of aligning global biofuel policies and the challenges of addressing ILUC. The ongoing divergence complicates efforts to create consistent, sustainable biofuel production standards.

1.9 Comparison between risk-based approaches versus direct quantification methods for addressing ILUC

Risk-based approaches and direct quantification methods are the two primary approaches used by biofuel policies to address ILUC (Sumfleth et al., 2020; Woltjer et al., 2017). Direct quantification methods, employed by CORSIA, RFS 2 and the California LCFS, calculate specific ILUC values through complex economic models. On the other hand, the risk-based approach, used by RED III, aims to minimize the likelihood of iLUC impacts by identifying and excluding high-risk biofuel feedstock while certifying those with low iLUC impact risk.

The two approaches have distinct yet complementary roles in addressing ILUC. Table 4 provides a comparative analysis of the main aspects of the two approaches, highlighting the differences between them. While risk-based approaches rely on the proper enforcement of sustainability standards, quantification methods use a more effective and robust method for the identification of ILUC through models (Finkbeiner, 2013; Sumfleth et al., 2020). However, this reliance on modeling inputs that are often uncertain can limit practical applicability in real-world cases (Finkbeiner, 2013; Sumfleth et al., 2020). Risk-based approaches have an advantage in terms of application since they require less detailed data and fewer computational resources, which makes them more practical for policy application compared to quantification methods.

Table 6 Comparison of the different aspects of risk-based approaches and quantification methods used to address ILUC.

Aspect	Risk-Based Approaches	Quantification Approaches
Focus	Minimize ILUC risk by promoting sustainable practices.	Measure ILUC emissions directly using models.
Method	Categorize feedstocks as high or low iLUC risk	Use economic models to estimate ILUC emissions
Implementation	Easier to implement in policy frameworks	More complex to implement, require extensive modeling
Precision	May oversimplify complex iLUC dynamics	Provide numerical estimates of iLUC emissions
Uncertainty	Lower uncertainty in classification	High uncertainty in model outputs
Policy Integration	Easier to integrate into existing sustainability certification schemes	More challenging to integrate into policies
Data Requirements	Require less detailed data	Require extensive data inputs
Effectiveness in Reducing ILUC	Dependent on proper enforcement of sustainability standards.	Potentially more effective if accurate but subject to model limitations.

Flexibility	Allow for recognition of improved agricultural practices	Less flexible in recognizing specific practices
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Risk-based approaches offer more flexibility and recognize improved agricultural practices along with other progressions, which makes them adaptable for various policy contexts. However, this flexibility comes with potential shortcomings, as the broad criteria and general classifications often used in risk-based approaches may oversimplify the complexities of ILUC dynamics. This reliance on general classifications may limit the effectiveness of this approach.

Discussion and considerations for potential ways forwards

Different policy frameworks support the use and scale up of sustainable aviation fuels on an international scale. However, an increasing demand for SAF and consequently for biogenic feedstock might also induce an additional demand for land to grow biofuel feedstocks. This could potentially lead to conflicts with food production and emissions from direct and indirect land use change. Policy frameworks for SAF, such as the California LCFS, CORSIA or the RED have defined different approaches to limit GHG emissions from land use change and to ensure sustainability in bioenergy production (Kupczyk et al., 2019) (Yeh & Sperling, 2010) (Gilbert et al., 2017).

Since emissions from indirect land use change cannot be measured directly, frameworks such as CORSIA and the California LCFS use modeling approaches to simulate market and land use responses to demand increases and to calculate the corresponding emissions. The modeled iLUC emissions are then incorporated into the overall GHG emissions calculation for SAF and benchmarked against a defined reference value to determine the general eligibility of the SAF. The modeling of ILUC impacts is subject to significant uncertainties due to the assumptions and modeling steps involved. The scientific consensus is that iLUC factors are highly uncertain, with terms like ‘substantial’ (Laborde et al. 2011) and ‘immense’ (Edwards et al. 2010) used to describe the extent of this uncertainty. Publications by Daioglou et al. (2020) and Delzeit et al. (2017) emphasize that recent improvements in ILUC assessment methods have not significantly reduced uncertainty or increased confidence in ILUC factors.

While these models can help identify policy risks, they do not offer simple cause-and-effect relationships for individual producers. Furthermore, ILUC assessments focus on the implications of an additional, often substantial demand for biofuels (compared to current production levels), meaning that the calculated emissions, which are reflected in the CI under CORSIA represent expectations of future emissions and not emissions that previously occurred. In these future projections, models tend to assume fixed land-use categories and fail to account for improvements in agricultural practices, degraded land recovery, or other dynamic land-use responses. Furthermore, the choice of a baseline for land use (e.g., assuming current agricultural productivity levels) can significantly influence iLUC estimates and may not reflect real-world trends or technological advancements (Kløverpris & Mueller, 2012). Contrary to the CORSIA or the California LCFS approaches, the EU RED framework does not include a calculation of iLUC emissions in biofuels CIs. Instead, the EU RED seeks to limit indirect land use change emissions through the classification of different biofuel feedstocks into low and high ILUC-risk categories (Gilbert et al., 2017) (Yeh & Sperling, 2010) and limits the amount of fuel pathways with high iLUC risks in the overall system. The certification of low iLUC risk fuels also gives feedstocks and fuel producers the opportunity to demonstrate that their production does not lead to significant indirect land use change effects.

Table 5 summarizes the policy approaches under CORSIA, the California LCFS and the EU RED according to a range of challenges caused by a variety of factors, including uncertainty and implementation aspects. It is evident that all the frameworks under consideration share the objective of reducing uncertainty related to key ambiguities in lifecycle emissions, carbon accounting, and the sustainability of

feedstock, particularly in the context of ILUC. However, their differing methodologies and scopes mean that they face different challenges. While RED uses clear targets, certification processes, and builds on established EU policies to reduce uncertainty in estimating ILUC impacts, CORSIA faces more significant challenges due to a rigorous quantification approach which has a global-scale focus and reliance on complex economic modeling.

In terms of implementation, the RED, the California LCFS and CORSIA differ due to their scope and methodologies. Although the California LCFS employs a complex quantification methodology and has demonstrated adaptability through several amendments incorporating technological advancements in recent years, it has not updated its iLUC values in recent years (CARB, 2009, 2014, 2024). Additionally, the California LCFS's local focus facilitates easier implementation within regional policy frameworks. CORSIA emphasizes the detailed quantification of ILUC emissions on a global scale, taking into account various agricultural practices and land use patterns (ICAO, 2022). This comprehensive approach improves the accuracy of emissions accounting but introduces complexity in implementation compared to the RED and the California LCFS, which are regionally focused frameworks. However, to accurately measure and mitigate the environmental impact of aviation fuels on a global scale, this careful quantification is essential.

Despite the challenges currently being faced by the frameworks, including data quality issues, model uncertainties, implementation complexity, and the difficulty of quantifying ILUC, there are several ongoing efforts to improve the effectiveness of the frameworks in addressing ILUC.

Table 7 Comparative analysis of various aspects and challenges of RED, CORSIA and California LCFS frameworks.

Aspect	RED III	CORSIA	California LCFS
Sustainability criteria	Strict criteria for biofuels	Eligible Emissions Units must meet specific criteria	Life cycle analysis of fuel carbon intensity
Feedstock considerations	Limits on high iLUC-risk feedstocks	Includes iLUC in emissions calculations	Caps on crop-based feedstocks from 2028 to limit iLUC impacts
Reduction of uncertainty	Moderate; uncertainty reduction through clear targets and guidance	Moderate; uncertainty greater due to global scale and reliance on complex economic modeling	High; due to continuous updates to data and calculation methods, and local focus
Implementation feasibility	High implementation feasibility, due to established framework & tailored to the EU	Challenging due to global scale considerations, model uncertainties and data quality	High, due to regional focus

Mitigation of negative land use change impacts as well as the protection of natural land must be addressed by regional policy approaches. While some regions have implemented strategies to reduce iLUC effects (e.g., promoting the use of marginal lands), these policies are often not fully captured in modeling systems. The following

paragraph discusses key considerations for incorporating ILUC risks into future policy frameworks.

While it is essential for policy frameworks and initiatives promoting the use of SAF to address potential risks and implement effective mitigation measures, it is equally important to thoughtfully evaluate and weigh the approaches used to achieve these goals. As previously discussed, current methods for quantifying iLUC impacts of specific SAF and biofuel pathways are subject to significant uncertainties (see Chapter 3.4). Moreover, The present methodologies and frameworks do not adequately capture the complex interactions and displacement effects associated with the utilisation of residues and waste materials (Finkbeiner, 2013; Pavlenko & Searle, 2021). This situation could be regarded as disadvantageous to agricultural commodities due to this inadequacy in current ILUC calculations. This further emphasises the complexity and potential shortcomings of current methodologies for assessing the true impact of both residues and wastes, as well as agricultural commodities.

Nevertheless, these assessments play a critical role in calculating carbon intensity under frameworks like CORSIA and the California LCFS, which ultimately determine the eligibility of specific feedstocks or fuel pathways.

It is crucial to regularly update the technical assumptions and background data used in the models and calculators to ensure they accurately reflect characteristics such as yields, conversion efficiencies, and assumptions related to energy sources and by-product utilization. The respective data should be transparently communicated, allowing market stakeholders to submit evidence of improvements and increased efficiencies when necessary. Additionally, uncertainties arising from the assumptions and structures of the CGE models should be acknowledged and openly addressed. Efforts to identify opportunities to improve these models should be prioritized to enhance the accuracy of iLUC quantification. The recently released 45ZCF-GREET calculator underscores the importance of these aspects, by showing significant changes in ILUC emission levels compared to previous GREET calculators. These changes result from various updates to the underlying ILUC models.

To effectively mitigate negative ILUC impacts, frameworks should, whenever possible, incorporate best practices in feedstock production and conversion while incentivizing continuous improvements. Low LUC certification options³ include a few approaches – the so-called low LUC risk practices - designed to increase land area and feedstock efficiencies during the agricultural production phase, and to produce fuels with low risks of indirect/induced land use change. Respective approaches are implemented under certification schemes like the International Sustainability and Carbon Certification (ISCC) or the Roundtable on Sustainable Biomaterials (RSB) and could be integrated in global policy frameworks such as the California LCFS or initiatives, like CORSIA where the option is already available. Under CORSIA, feedstocks produced on unused land (e.g. marginal lands or degraded pastures) or through land management practices that increase yield on existing land can qualify for an ILUC

³ The EU RED framework offers the option of Low ILUC risk feedstock for biofuels, while under CORSIA a similar option is covered by the Low LUC risk feedstock production for CEF.

value of zero. Such low LUC risk practices help avoid market mediated land use changes, ensuring that additional CEF feedstock is available relative to a baseline, without increasing land requirements.

Finally, in recent years, remote sensing tools and auditing practices have advanced and are highly effective tools for monitoring protected areas such as natural forests or highly biodiverse land. These tools and approaches should continue to be developed and integrated into monitoring systems supporting the practical implementation of national and international land use policies.

To summarize, the position of this paper is that while it is crucial to consider ILUC effects associated with SAF production, significant uncertainties in modeling assumptions and data variability can have an impact on the assessment of feedstock eligibility under frameworks such as CORSIA. These uncertainties could potentially penalize viable and sustainable feedstocks, hindering the advancement of SAF and aviation decarbonization efforts. Therefore, it is recommended to address these uncertainties through improvements in modeling and risk-based approaches to ensure an accurate and equitable evaluation process."

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