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Global Agricultural Market and Land-Use Implications of Producing Sustainable Aviation Fuel from Second Crop Corn Ethanol in Brazil

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ABSTRACT

Ethanol can potentially serve as a feedstock for sustainable aviation fuel (SAF) production. This study evaluates the global land use and associated carbon implications of expanding Brazilian corn ethanol production using second crop corn. Using a global agricultural trade model, which explicitly represents second crop corn production in Brazil, this analysis examines scenarios regarding ethanol demand growth, corn supply elasticity, and trade constraints. Results show that increasing Brazilian ethanol production using second crop corn can moderately impact international prices, land-use, and greenhouse gas (GHG) emissions, especially when corn supply is highly elastic or double cropping intensifies. Under the limiting assumption of a perfectly elastic second-crop corn land response, our findings show minimal or even negative net land-use change. Focusing on land use, a life cycle analysis reveals that second crop corn ethanol can achieve lower or negative GHG emissions, primarily due to the use of feedstock grown on land already used in the same year (second crop), renewable process energy, and the substitution of soybean meal through corn co-products. These findings suggest that Brazilian second crop corn offers a low-carbon pathway for SAF production, contingent on preserving double-cropping systems and avoiding land-use change. The article highlights critical trade-offs and policy considerations for aligning climate goals with sustainable agricultural and energy systems.

JEL Classification: Q10, Q15, Q16, Q17

1 | Introduction

Global production of biofuels has increased significantly in recent decades to address climate change and the negative environmental impacts of fossil fuels. Depending on the origin and pathway, biofuels such as ethanol and bio-based diesel can result in lower greenhouse gas (GHG) emissions compared to fossil fuels (Reid et al. 2020).¹ An important determinant of the net GHG emissions of biofuels is the land use change associated with its production (see for example Timilsina et al. (2012); Hertel

et al. (2013); Carriquiry et al. (2020); Zhao et al. (2021); Austin et al. (2022)). Growing interest in producing sustainable aviation fuels (SAF) to reduce GHG emissions can continue to drive the demand for biofuels and agricultural feedstocks. However, this advantage of lower GHG emissions relative to fossil fuels depends on agricultural practices that limit land-use change (e.g., deforestation) and competition with food production, and/or adoption of climate-smart technologies such as no tillage or slow release fertilizers. In this analysis, we quantify the effects of using second crop corn from Brazil to potentially produce SAF to shed

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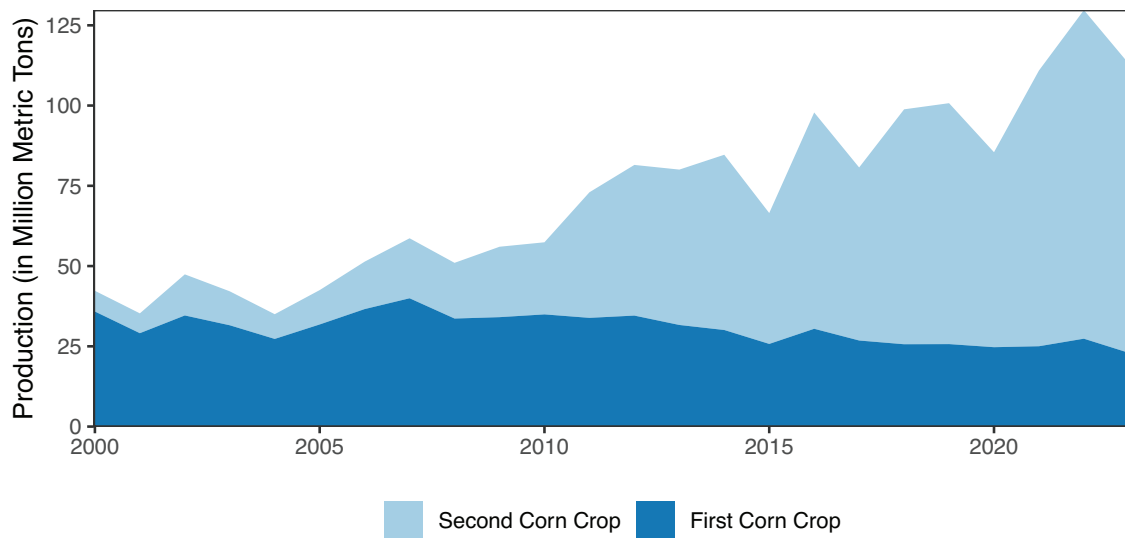


FIGURE 1 | Production of first and second crop corn in Brazil from 2001 to 2024. *Source:* Companhia Nacional de Abastecimento.

light on the effects on global agricultural markets and land-use, and associated GHG emissions.

SAF can be produced from a variety of renewable feedstocks including cooking oils and fats, food and yard waste, agricultural and forestry residues, algae, and dedicated energy crops like switchgrass. In addition, ethanol can also be converted to SAF, which is the pathway considered in this analysis. Due to government policies promoting renewable energy, Brazil is the second largest ethanol producer after the United States, with a share of almost 30% of the nearly 30 billion gallons of global production.² In 2024/25, ethanol, which is produced primarily from sugarcane, totaled over 9 billion gallons (7 billion gallons or 80% of domestic production from sugarcane). However, corn ethanol production is increasing rapidly in Brazil driven by the expansion of second crop corn production in the Center-West region (Colussi et al. 2023; Moreira et al. 2020; Gurgel et al. 2024) (Figure 1). While roughly 0.5 billion gallons of corn ethanol were produced in Brazil in 2019/2020, production is expected to reach 3 billion gallons in 2025/2026.³

1.1 | Brazilian SAF Policy

On October 8, 2024, the Brazilian National Congress approved Law No. 14,993/2024, creating the National Sustainable Aviation Fuel Program (ProBioQAV). This program is aimed at decarbonizing the domestic aviation sector, and is an integral part of the Fuel of the Future Law, which increases biofuel blending mandates and creates regulatory frameworks for SAF, green diesel, biomethane, as well as carbon capture and storage. ProBioQAV introduces progressive targets to reduce GHG emissions for domestic flight operators, beginning at 1% in 2027 and rising to 10% by 2037. The Brazilian approach prioritizes emissions-based mandates over volumetric ones, allowing for technological flexibility. These targets can be achieved by using SAF blended with conventional kerosene, improving flight efficiency, or through alternative methods to be specified in future regulations, such as using carbon credits and Lower Carbon Aviation Fuels (LCAF). ProBioQAV ensures alignment

with international commitments such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) by adopting international methodologies for measuring the life cycle (Câmara dos Deputados 2024; Ministério de Minas e Energia (MME) 2025; International Civil Aviation Organization (ICAO) 2025).

The implementation involves several agencies, including the National Agency of Petroleum, Natural Gas and Biofuels (ANP) (certification), the National Energy Policy Council (CNPE) (mandate adjustments), the Ministry of Mines and Energy (MME) (coordinating energy policy), and the National Civil Aviation Agency (ANAC) (regulating and overseeing targets). ANAC leads Conexão SAF and aims to coordinate the main public and private sector actors involved in the development of Sustainable Aviation Fuel (SAF) in Brazil. Conexão SAF's activities include collecting updated information on pilot projects, technological routes, and investments; mapping regulatory and infrastructure needs; and proposing solutions to accelerate the sector's maturation—including integrating Brazil with international standards and monitoring the interaction among ProBioQAV, certifications, and mechanisms such as Crédito de Descarbonização or carbonization credit (CBIO). Conexão SAF also aims to promote interministerial alignment and create a transparent environment in which companies, academia, and the government can anticipate trends and proactively overcome obstacles to scaling up the national SAF (Agência Nacional de Aviação Civil (ANAC) 2024).

In terms of financial incentives, a public call was launched by the Brazilian Development Bank (BNDES) and the Brazilian Innovation Agency (FINEP) in August 2024. R\$6 billion (Brazilian Reals) have been earmarked to support the projects, research, development, implementation, and operation of biorefineries dedicated to Sustainable Aviation Fuel (SAF). Several proposals specifically for SAF were received, totaling R\$120 billion. The proposals were required to include private investment (partial financing), competitive technical selection, and risk sharing between the public and private sectors. Additionally, Brazil is discussing tax relief, including exemption from the Tax on Industrialized Products (IPI) and the Tax on Operations Relating

to the Circulation of Goods (ICMS), as well as a special regime for importing equipment. There is also the possibility of integrating SAF into *RenovaBio*, which would create an additional incentive in the form of CBIOs.⁴ However, the methodological and regulatory requirements for broad integration are still under debate regarding both regulatory and technical aspects (Banco Nacional de Desenvolvimento Econômico e Social (BNDES) 2024; Ministério de Minas e Energia (MME) 2024; Dermirkol 2024).

1.2 | Brazil's Corn and Soybean Sectors and Potential to Meet SAF Demand

Corn and soybean production are central to Brazil's agricultural system. Over recent decades, soybean production expanded primarily through area growth, rising from 7 million hectares (has) in the 1970s to 47 million hectares in 2024/25, reflecting strong global demand. Corn area, on the other hand, grew by 10 million hectares (to 22 million hectares) over the last two decades. The dramatic increase in corn production came mainly through productivity gains from intensification and changes in cropping systems.

Yield growth has also been the main driver of increases in Brazilian crop production, especially for corn. In recent years, these gains have been supported by advances in genetics, fertilizer management, and no-till practices, along with the concentration of second-crop corn in high-productivity regions. As a result, total corn production more than doubled in the past decade, reaching about 141 million tons in 2024/25, while soybean production increased by roughly 80%, reaching more than 170 million tons.

Second crop corn (*safrinha*) has experienced significant growth since 2010. In the soybean-corn double-cropping system, corn is planted after soybean harvest on the same land. Second-crop corn, which was virtually nonexistent in the 1970s, now accounts for around 80% of total Brazilian corn production and occupies approximately 17 million hectares. Nearly all corn produced in the Midwest region of Brazil now comes from the second-crop system. This system, which has allowed Brazil to significantly increase corn production without proportional expansion of total cropland, has dramatically reshaped land-use allocation in Brazil.

Exports remain a critical component of both corn and soybean markets in Brazil, making it a top global exporter, with soybean exports consistently exceeding 100 million tons in recent years and projected to continue rising. Corn exports have also grown strongly, averaging over 40 million tons, despite increased domestic demand from ethanol production. Rapid production growth, driven by second-crop area expansion and yield gains, has allowed exports and domestic industrial use to increase simultaneously.

In terms of corn-based ethanol, its expansion has introduced an important source of domestic demand. Corn-based ethanol production has grown from a negligible level a decade ago to over one-quarter of Brazil's total ethanol output, with output projected to continue to rise. Despite this growth, ethanol currently absorbs only about 13% of total corn production, while exports and animal feed remain the dominant uses. Rather than directly competing with sugarcane ethanol, corn ethanol largely complements the

sector by supplying ethanol during the sugarcane off-season, stabilizing national ethanol supply and prices. The two sectors also benefit from shared infrastructure and institutional frameworks, facilitating the expansion of low-carbon fuel production.

More recently, between 2022 and 2024, Brazilian corn ethanol production increased from 1.2 to 2 billion gallons and is expected to reach 3.5 billion gallons in 2032, with industry sources expecting an even stronger expansion (EPE 2024). In the United States, the world's largest producer, corn is grown annually as a single crop, and ethanol is produced using natural gas. However, Brazilian corn is increasingly grown as a second crop with biomass (e.g., bagasse, eucalyptus chips, agro-industrial, and agricultural residues) as the ethanol energy source, thus reducing its carbon intensity (CI) score⁵ (Moreira et al. 2020). Given that Brazil is the second largest global producer of ethanol and a major exporter of corn (second only to the United States and narrowing the gap), the use of second crop corn to meet the increasing demand for ethanol could have significant implications for land-use change and food prices globally. The availability and possibility of using land already in cultivation for soybeans to grow corn as a second crop could allow for the expansion of the country's production with much lower (1) indirect land-use change encroaching on forests and pastures and (2) price effects relative to other biofuel feedstocks (Gurgel et al. 2024). Despite this, some authors (Colussi et al. 2025a) signal that the rapid expansion of corn ethanol (together with strong demand from the livestock sector) might be reducing corn exports.

Lower CI scores could also be achieved if induced land-use changes are limited by enforcing policies that reduce deforestation and/or promote double-cropping (Fiorini et al. 2023). While Brazil is offering incentives to encourage investments to reduce GHG emissions in the aviation sector, these regulations are still being developed. The SAF industry in Brazil is relatively new and is currently not available for commercial use. Thus, second crop corn ethanol produced in Brazil is likely to initially target more established markets for SAF such as those in the United States and the EU.⁶ Life cycle GHG emissions of corn ethanol in countries like the United States have been the subject of over 20 years of research but much less is known about the GHG emissions of the same fuel produced under Brazilian conditions, using second crop corn and renewable sources to process energy. This study analyzes the potential impact of expanding second crop corn production to meet increased domestic and export demand for corn ethanol in Brazil on local and global markets, and to estimate the indirect land-use changes and environmental implications associated with including ethanol produced from second crop corn. We consider different scenarios of ethanol demand with trade constraints and varying supply elasticities. For this purpose, an agricultural modeling system, modified to incorporate second crop corn, is used to implement scenarios of increasing corn ethanol production in Brazil. A land-use GHG model is used to assess the emissions from second crop corn ethanol production in Brazil.

2 | Methods

To analyze the effects of second crop corn on global agricultural markets and land-use change, we combine (1) the global

Long-Run Land-Use model (LRLU Model) to determine the economic effects and (2) an ad-hoc GHG model to calculate the life cycle emissions associated with land-use change. The GHG model is considered ad-hoc since there is no feedback effect on the economic model (e.g., due to carbon policies). This section briefly describes both models and we refer the reader to previous publications for more details. The LRLU Model as well as its predecessor have been used to evaluate the effects of biofuel policy on GHG emissions (Dumortier et al. 2011; Carriquiry et al. 2020; Fabiosa et al. 2010; Elobeid et al. 2012), climate change (Dumortier et al. 2021), cattle taxes (Dumortier et al. 2012), and trade conflicts (Elobeid et al. 2021).⁷

2.1 | LRLU Model

The LRLU Model is a deterministic partial equilibrium model used to quantify the impact of changes in market conditions and policies on global land allocation. The model solves for a set of commodity prices to equate global supply and demand for agricultural products. The model contains a single international market for trade, that is, there is no bilateral trade between individual countries and regions, but any domestic surplus (deficit) is exported (imported) to (from) the international market. The model is calibrated to 2023 for crops, livestock, dairy, and biofuels by country or region.⁸ Although the model can generate projections over 40 years, this study covers the 10-year period between 2024 and 2033. The model is recursively solved for ten successive annual equilibria.

The LRLU Model is composed of 22 countries/regions—selected according to their significance in the agricultural commodity marketplace—with all agricultural sectors/commodities contained within each country/region.⁹ Countries not modeled explicitly are aggregated as *Rest of World* to close the model. For this study, the crops considered and solved endogenously by the model are barley, corn, rice, sorghum, wheat, and soybeans. Livestock products (i.e., beef, pork, and poultry), soybean meal and oil, as well as ethanol and biodiesel are also included. The model has a dried distillers' grains with solubles (DDGS) sector (a coproduct of the ethanol production process), which competes with other forms of feed for livestock species.

Compared to previous versions, the LRLU Model is modified to explicitly include second crop corn in Brazil, that is, to represent the dynamics of the production of second crop of corn, double cropped with soybeans. The distinction between first crop and second crop is included only in production given our interest in land use change associated with the additional demand of corn for ethanol production. The demand side treats both first and second crop of corn as being the same product. Given the specific crop production system in which the second crop of corn is planted, on area already harvested with soybeans in the same growing season, the strategy followed was to model the area of this second crop as a proportion of the soybean area. The functional form used for that share is a constant supply elasticity function implemented in log form

$$s_t = \alpha_0 + \alpha_1 \ln(p_{c,t}) + \alpha_2 \ln(t),$$

which depends on the price of corn in year t ($p_{c,t}$) and a time trend t .

The area of the second crop of corn in year t is thus obtained by multiplying the share s_t by the area of soybeans planted the same year. Although the recent expansion path of the second crop of corn, together with soybean area availability, inputs and equipment available seem to indicate the response in terms of corn area should be elastic, there are no estimates of that elasticity in the literature. To shed light on the implications of this parameter, we run the base scenarios (Empresa de Pesquisa Energética or EPE and industry described in the Scenarios section) with a unitary elasticity and also a scenario with a perfectly elastic supply. Note that the elasticity on the time trend, while important for the baseline, does not affect the evaluation of the scenarios as the term will wash out when taking differences. Yields have evolved differently for first and second crops of corn, with the increase in productivity occurring more rapidly in the second crop of corn, thus improving its competitiveness vis-à-vis the first crop.² For this reason, the yield for each corn crop is projected separately. To our knowledge, few current models incorporate second crop corn production, which is necessary to accurately assess impacts on land-use change in Brazil and globally (Gurgel et al. 2024; Moreira et al. 2020).

Land allocation projections are determined by competition and driven by net returns. Within each country or region, the land use associated with each sector is placed within the hierarchical land-use structure.¹⁰ The first tier determines the total land allocated to agriculture and is driven by the net returns to agriculture. Thus, as agriculture becomes more profitable, land is taken away from the non-agricultural areas. In the second tier, productive forestry, pasture, and total crop area compete for shares of the total agricultural area. Thus, if crop production, overall, becomes more profitable, it is assumed that land will be taken out of pasture (or forestry) before new land is brought into agriculture. The third and final tier is competition between crops. If one crop becomes more profitable relative to other crops, it is assumed that land will be first taken away from the existing land devoted to crops before land is taken out of pasture or forestry. The proportion of the total crop area devoted to crops not modeled is held fixed.

On the demand side, per capita demand for food increases with income but at a decreasing rate given the long-term nature of the model. That is, as consumers' per capita income increases and their food demands become increasingly satisfied, they devote smaller shares of the additional income to food products. While there is no cap on caloric or nutritional intake, these do not rise indefinitely as time passes and incomes increase.

Historical land-use data are derived from the United Nations Food and Agriculture Organization (FAO) crop and land resource databases as well as from the reports published by the Forest Resource Assessment (FRA) program of the FAO. Within this structure, we estimate the total land devoted to agriculture, as well as the areas for forest actively in production, pasture areas, and the areas for all of the major crops for which data is available from the USDA.

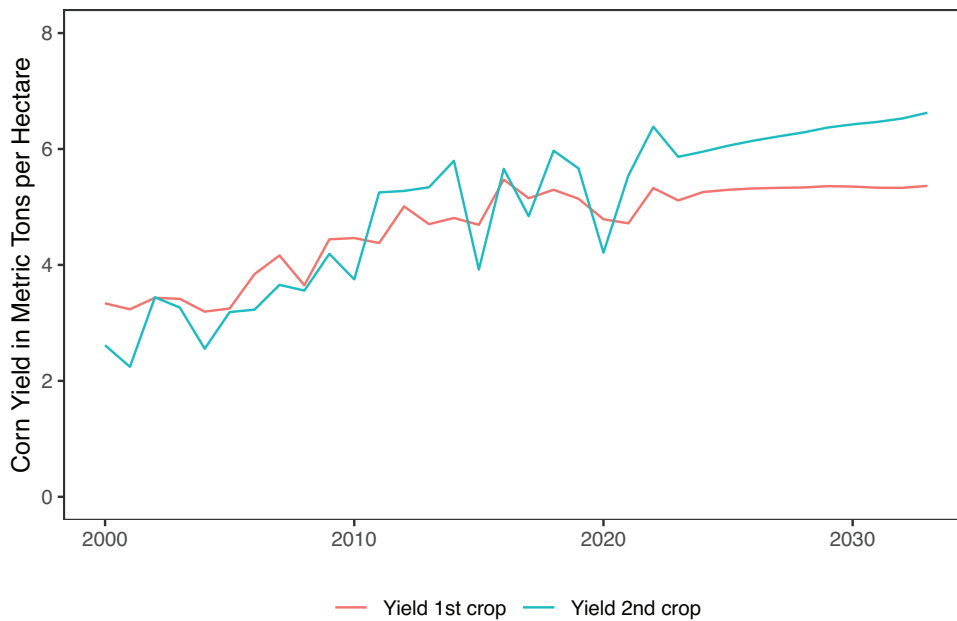


FIGURE 2 | Historic and projected yields for first and second corn crop.

2.2 | Land-Use GHG Model

The relationship between emissions from land-use change and biofuel policy has generated substantial discussion among researchers, policymakers, and stakeholders since the seminal paper by Searchinger et al. (2008). The range of emissions—measured in grams of carbon dioxide equivalent per megajoule ($\text{g CO}_2\text{-e MJ}^{-1}$)—for US corn ethanol is 9.7–107 $\text{g CO}_2\text{-e MJ}^{-1}$ (Searchinger et al. 2008; Dumortier et al. 2011; Carriquiry et al. 2020). To assess the emissions from producing ethanol from the second crop corn in Brazil, we use an ad-hoc land-use change and carbon model, based on output from the LRLU Model. The land-use GHG model has been used and described in previous publications such as Carriquiry et al. (2020) and Carriquiry et al. (2022).

The area harvested projected in the LRLU Model is the main driver for biomass and soil carbon emissions from land-use. In the subsequent calculations, we differentiate between area harvested and area used for agriculture. The production of second crop corn increases the area harvested but not the area used. There are no country- and crop-specific emission factors, but rather GIS raster data that are used for sub-national changes in the carbon pool. Specifically, the area used for the 22 regions covered in the LRLU Model is distributed at the sub-national country/region level based on the crop distribution maps by Monfreda et al. (2008). Biomass carbon is determined based on Global Ecological Zone and Global Land Cover 2000 data presented in Gibbs (2006). Soil carbon data is based on the Global Soil Organic Carbon (GSOC) map 1.5.0 by the Food and Agriculture Organization (FAO) of the United Nations. The detailed crosswalk between the various data sources can be found in the supplemental materials of Dumortier et al. (2022). We assume that each grid cell's share of total country area for a specific crop remains constant between the baseline and the scenarios. For example, a grid cell always contains 2% of a country's corn area, independent of the scenarios. However, the absolute value in terms of hectares changes if the corn area in the country increases. This change occurs proportionally at the

expense of non-cropland area in the grid cell (e.g., 30% forest and 70% grassland).

Given carbon coefficient uncertainty, we report minimum, mean, and maximum coefficients for biomass carbon (Gibbs 2006). To use biomass carbon coefficients besides the ones reported in Gibbs (2006), we include the carbon coefficients derived from potential vegetation (West et al. 2010). Those values are very similar to the maximum coefficients used in Gibbs (2006).

2.3 | Scenarios

The LRLU model is first run to establish a baseline, which includes 10-year projections for the corn used in ethanol production. In addition to the model baseline, projections of corn ethanol expansion are implemented to assess the market and land use effects of higher ethanol production from second crop corn. Two ethanol expansion pathways were used: (1) a scenario from Empresa de Pesquisa Energética (EPE)¹¹, which is a Brazilian policy research institution, and (2) industry projections that point to a higher level of ethanol expansion. EPE provides three ethanol growth scenarios (i.e., high, medium, and low) based on its competitiveness relative to gasoline, advancements in engine technology, and government policies (e.g., taxes). However, we only consider EPE's high growth scenario in this study (EPE), which remains less ambitious in comparison to the industry projections. We include three industry scenarios that, while identical in terms of gallons produced, include different assumptions on how the expansions affect global markets. The industry scenarios are comprised of (1) a base case called *IND*, (2) a case labeled *IND Fixed Exports* in which corn exports are fixed at the baseline level, and (3) a case in which the second crop corn area is perfectly (own-price) elastic (labeled *IND Perfect Elasticity*). The last industry scenario represents a limiting case of the ease of expanding second crop corn production.

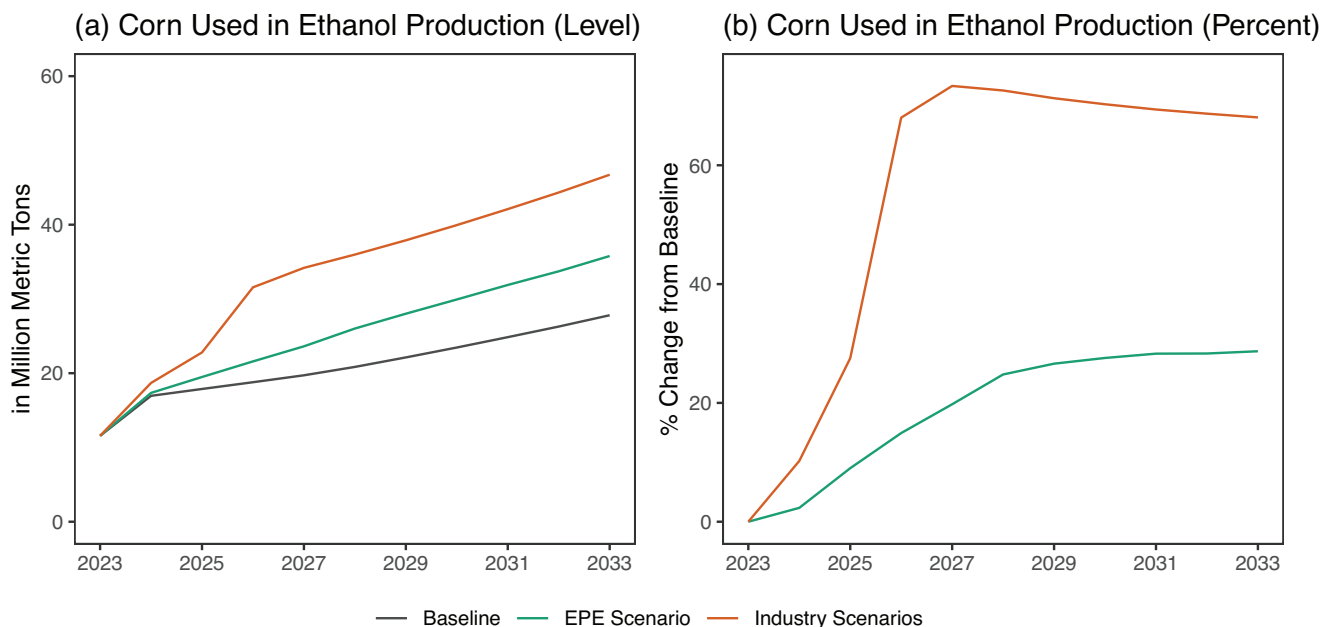


FIGURE 3 | (a) Corn used in ethanol expansion scenarios. (b) Corn used in ethanol expansion scenarios relative to the baseline. All industry cases, that is, *IND*, *IND Fixed Exports*, and *IND Perfect Elasticity* result in the same quantity of ethanol produced.

The *IND Fixed Exports* scenario allows for identifying the domestic modifications needed for Brazil to expand corn ethanol production by the volume indicated in the scenario, while not directly affecting the international corn markets. The fixed-exports scenario tests the sensitivity of the response of second crop corn production in the domestic market without a reduction in exports to the international market, that is, when all demand is met domestically. While this is an extremely strong assumption, it allows us to understand what type of land-use change (LUC) needs to occur with base-level supply elasticities if corn exports are not allowed to fall.

The *IND Perfect Elasticity* scenario explores the limits on the possibilities of second crop corn production in terms of land use expansions that can occur without the need to increase prices of corn or bring additional cropland into production through direct effects. This is critical as it directly mediates local and international price effects, relocation of production and consumption, trade, food security, land-use change, and associated GHG emissions. A justification for this exploration is based on the current rapid expansion of the second crop of corn in recent years as well as local conditions that might be contributing to this expansion. Salient among those conditions are the availability of land ready to be used as cropland, which is otherwise fallowed after soybeans—almost 17 million hectares suitable for second crop corn expansion (EPE 2024; Guilherme DePaula and Ary Fortes 2019; Colussi et al. 2024) as well as availability of machinery, capital, inputs, and infrastructure. Some research points to the limited effects on the relationship between local and international prices due to the corn ethanol expansion (Justus et al. 2024). As no reliable estimates of supply elasticities for the second crop corn exist, this article explores the implications of a range of plausible possibilities.

For all the scenarios, corn use for ethanol production increases over the projection period (Figure 3a) and is significantly higher

in all scenarios relative to the model baseline. However, given the slowdown in the increase in the industry scenarios, the relative difference between the *EPE* and industry scenarios remains fairly constant after 2027 (Figure 3b). By the end of the projection period (2034), the model projects corn used for ethanol production in Brazil to reach almost 28 million metric tons. Projections in the *EPE* and industry scenarios are about 8 and 19 million metric tons higher, respectively, compared to the model baseline. The *EPE* high growth scenario is, on average, about 20% higher than the model baseline whereas the industry scenarios are approximately 60% higher relative to the model baseline, on average, over the projection period (Figure 3b).

3 | Results

The results compare the *EPE* and industry scenarios reflecting the increase in Brazilian ethanol (and hence, corn) demand to the baseline. This additional domestic demand leads initially to lower exports and higher international prices in these industry scenarios. The model solves for international prices such that domestic prices are equal to the international price expressed in domestic currency. By 2033, the additional demand for corn results in a corn price increase of 0.6% and 1.4% relative to the baseline in the *EPE* and *IND* scenarios, respectively. The price response is mitigated by adjustments in production and consumption in Brazil and in the rest of the world. Additionally, while the increase in corn demand in Brazil represents a large domestic shock, this increase is proportionally smaller when aggregated at the world level, and hence, the small response in world prices.

For all scenarios except *IND Fixed Exports*, domestic prices and international prices change by the same percentage (Figure 4). When exports are fixed, or Brazilian supply is perfectly elastic, the international corn price varies little relative to the baseline.

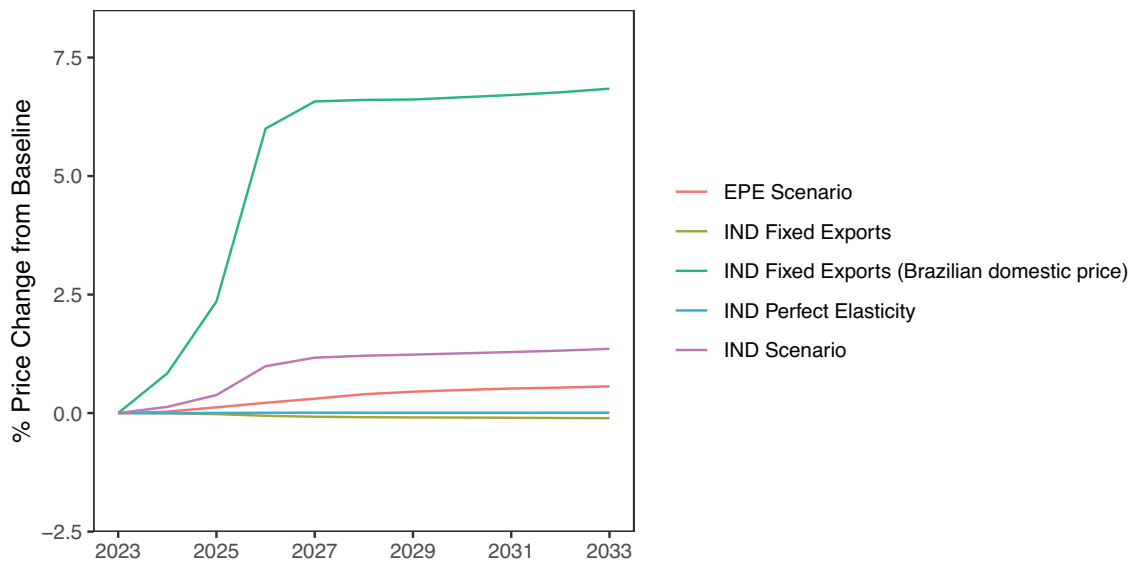


FIGURE 4 | International corn price percent change from baseline as well as domestic corn price change in Brazil.

At the end of the projection period, the corn price declines by 0.11% in the scenario *IND Fixed Exports* and does not change when supply is perfectly elastic. The decline in price in the *IND Fixed Exports* scenario is due to feed displaced by DDGS. As additional DDGS are supplied (and corn exports are fixed in the scenario), there is an excess supply of soybean meal globally that reduces the international demand for soybeans, thus easing the competition for land and partially replacing corn in feeds. Both effects tend to lower corn prices. Figure 4 also includes the change in Brazilian domestic corn price relative to the baseline for the *IND Fixed Exports* scenario. The international and domestic prices deviate in the *IND Fixed Exports* scenario as the domestic market for corn still needs to clear, in isolation of the global market of corn given the enforced fixed level of corn exports. In this scenario, to supply the additional corn needed to produce ethanol while keeping exports at the baseline level, the domestic price increases by almost 7%. In the *IND Perfect Elasticity* scenario, in which the domestic corn area is perfectly elastic, the price of corn does not need to change to encourage the supply of additional quantities.

Table 1 presents the change in the corn area for first and second crops, in terms of levels and percent change, relative to the baseline.¹² Both first crop and second crop corn areas increase in response to higher corn prices, with the area for second crop corn increasing by a much larger amount than the first crop. This implies a significant mitigation of induced land-use changes resulting from ethanol production. The price response is also dampened by lower corn consumption for other uses in Brazil and by adjustments in production and consumption in the rest of the world (as prices increase). Accounting for DDGS production and its usage by displacing corn and soybean meal in feeds also reduces both price and land-use changes. In any given scenario, second crop corn provides much higher quantities of the corn needed to expand ethanol production, relative to the first crop.

Changes are higher for the industry scenarios because those assume a larger corn ethanol production expansion than the *EPE* scenario. In the *IND Fixed Export* scenario, the domestic areas need to expand more than in previous scenarios to supply

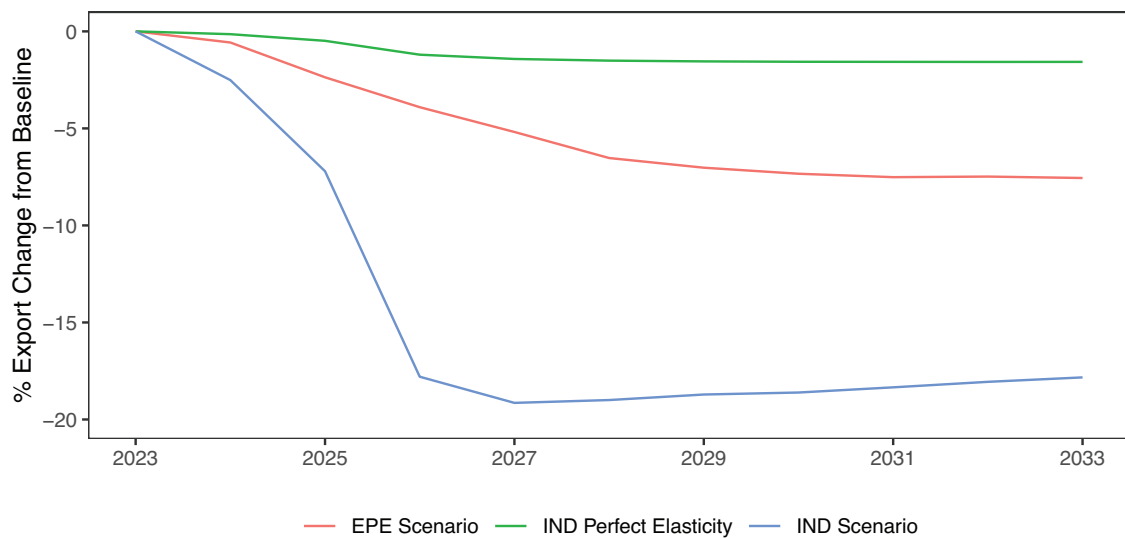
increasing quantities of corn ethanol while not reducing exports. In the *IND Perfect Elasticity* scenario, the area expansion is even higher than before (again, mainly in terms of the second crop), as the domestic price does not increase to reduce other sources of demand (domestic or exports). In the latter case, virtually all the increase in area is for second crop corn.

In terms of percentage change from the baseline for the second crop corn, the largest increases in area are seen when exports are fixed or when area is perfectly elastic (6.9% and 9.1% higher relative to the baseline, respectively, in the last year of the projection period). Again, the relative area increase is higher in the *IND Perfect Elasticity* scenario than for the *IND Fixed Exports* scenario where the higher domestic price reduces other sources of corn demand. In terms of the response of only first crop corn to the shock of corn ethanol, the increase is much smaller than for the second crop. This is to be expected given the market dynamics and evolution of the areas of first and second crops in recent years, which show a much higher dynamism and competitiveness of the second crop relative to the first. Other uses also respond. The area of first crop corn increases in the *IND Perfect Elasticity* scenario even though the price of corn does not change. This is because soybeans become less competitive (given the availability of DDGS), and the area shifts from soybeans to the first crop corn.

The additional domestic demand for corn ethanol production in Brazil is partly satisfied by increasing domestic production, partly by reducing other forms of consumption, and partly by reducing exports (Figure 5). The impact is greatest in the *IND* scenario, where net exports of corn decrease by about 18% (by approximately 8% in the *EPE* scenario and 1.6% in the *IND Perfect Elasticity* scenario) compared to the baseline by the end of the projection period. This leads to changes in land use in other countries as those respond to the created excess demand. The international impacts can be lowered if domestic production is highly elastic or if there exist other local constraints that limit the change in exports. Note that in the *EPE* and *IND* scenarios, the lower exports result mostly from higher domestic demand. The

TABLE 1 | Changes from baseline of first crop and second crop corn area in Brazil.

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
<i>First Crop Corn Change from Baseline (1,000 hectares)</i>										
EPE	0.5	2.1	4.0	6.0	8.3	10.0	11.4	12.6	13.5	14.2
IND	2.2	6.5	17.4	22.9	26.6	28.9	30.6	32.0	33.1	34.0
IND Fixed Exports	8.6	26.3	69.9	93.9	108.0	115.6	120.8	124.7	127.3	127.9
IND Perfect Elasticity	1.2	3.4	9.4	12.2	14.8	16.8	18.2	19.2	20.2	21.1
<i>First Crop Corn Change from Baseline (%)</i>										
EPE	0.0%	0.0%	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%	0.3%	0.3%
IND	0.0%	0.1%	0.3%	0.5%	0.5%	0.6%	0.6%	0.6%	0.7%	0.7%
IND Fixed Exports	0.2%	0.5%	1.4%	1.9%	2.1%	2.3%	2.4%	2.5%	2.5%	2.5%
IND Perfect Elasticity	0.0%	0.1%	0.2%	0.2%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%
<i>Second Crop Corn Change from Baseline (1,000 hectares)</i>										
EPE	5.5	22.1	39.2	55.1	73.5	84.2	92.8	101.2	107.3	115.1
IND	24.1	68.8	180.2	210.3	220.4	228.0	238.6	250.5	262.6	275.9
IND Fixed Exports	150.3	418.8	1080.3	1194.5	1219.6	1240.7	1280.1	1326.9	1372.7	1418.5
IND Perfect Elasticity	193.9	537.0	1374.8	1531.7	1576.3	1613.7	1671.0	1734.8	1796.7	1855.4
<i>Second Crop Corn Change from Baseline (%)</i>										
EPE	0.0%	0.1%	0.2%	0.3%	0.4%	0.5%	0.5%	0.5%	0.5%	0.6%
IND	0.1%	0.4%	1.0%	1.2%	1.2%	1.2%	1.3%	1.3%	1.3%	1.3%
IND Fixed Exports	0.9%	2.5%	6.3%	6.8%	6.8%	6.8%	6.8%	6.8%	6.9%	6.9%
IND Perfect Elasticity	1.1%	3.2%	8.0%	8.7%	8.8%	8.8%	8.9%	8.9%	9.0%	9.1%

**FIGURE 5** | Percent change compared to the baseline of net corn exports from Brazil.

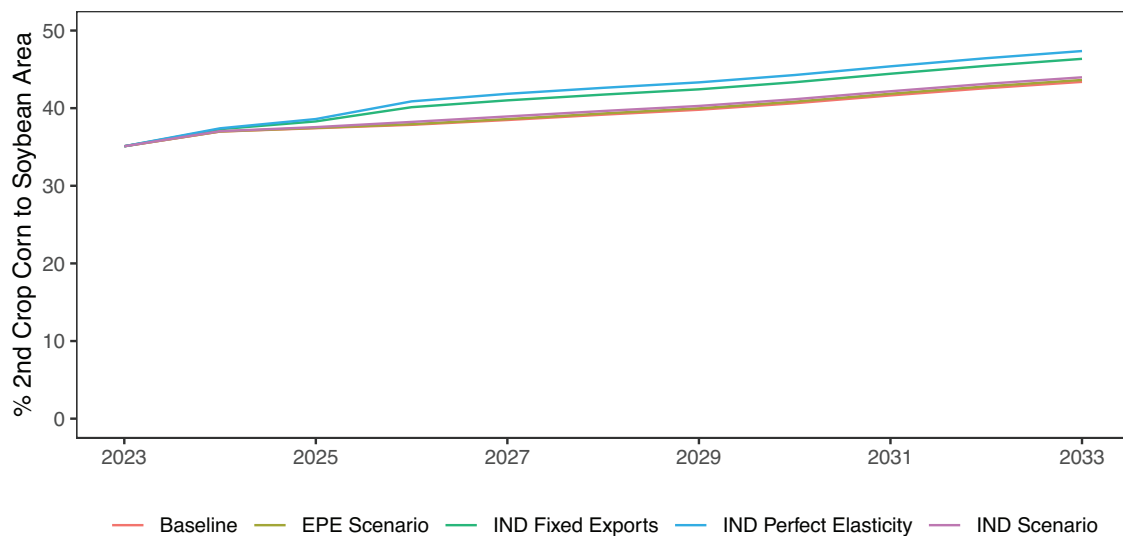
reduction in exports in the *IND Perfect Elasticity* is due mostly to lower international demand for Brazilian corn.

The percent changes in corn area relative to the baseline for 2033 by country/region are presented in Table 2. The “All Other Countries” category comprises all countries and regions not listed (including the aggregate of all non-modeled countries/regions). Regarding country responses, Brazil experiences the highest

relative change in corn cultivation area across all scenarios, primarily due to the high price elasticity associated with the second crop of corn (Table 2). The differences are greatest when all the additional supply comes from Brazil (*IND Fixed Exports*) or when perfect elasticity of the second crop corn area is assumed. Most of the effects of land use for corn are observed in Brazil in these two scenarios. Note also that in the *IND Fixed Exports* and *IND Perfect Elasticity*, the changes in areas of “All Other

TABLE 2 | Change in corn area by country/region (percent change from baseline in 2033/34).

	Argentina	Brazil	China	EU	USA	All Other Countries	World
EPE	0.24%	0.51%	0.11%	0.10%	0.21%	0.14%	0.19%
IND	0.58%	1.21%	0.28%	0.23%	0.51%	0.33%	0.46%
IND Fixed Exports	0.11%	6.06%	-0.01%	-0.02%	0.03%	-0.03%	0.73%
IND Perfect Elasticity	0.11%	7.35%	0.01%	0.00%	0.05%	0.00%	0.91%

**FIGURE 6** | Ratio of second crop corn area to soybean area in Brazil.

Countries” are negative. Again, this is the effect of the higher supply of coproducts, which lowers soybean and soybean meal demand internationally.

The proportion of the soybean area double-cropped with corn is projected to increase in the baseline and all other scenarios (Figure 6). The increase is higher when a larger amount of corn for ethanol production is obtained domestically (*IND Fixed Exports* and *IND Perfect Elasticity*). In those cases, less land-use change is exported. It is important to note that even in the cases in which most of the reaction in terms of area of corn occurs domestically, there is still significant room for second crop corn expansion as more than half of the area is not double cropped by the end of the projection period. The availability of this expansion potential has already been discussed by Colussi et al. (2025b); EPE (2024).

3.1 | Changes in Crop Area Over Time for the Different Scenarios

Table 3 shows the changes in land use over time, which illustrates the growth of corn ethanol production across the different projection years for each scenario. The *IND* scenario involves a more rapid and stronger corn ethanol production expansion than the *EPE* scenario, simply reflecting a larger corn ethanol expansion. However, in *IND*, the expansion rate stabilizes after a few years. In the last year of the projection period, corn area increases by 54.9 thousand hectares relative to the baseline. When

Brazilian net corn exports are fixed at the baseline levels (but corn ethanol production expands in the same way as in the *IND*), the evolution of cropland expansion is very different. Brazilian land use expands by 228 thousand hectares in 2033, more than in the other scenarios. For all other countries modeled, the area declines by 212 thousand hectares in the same year as the expansion of coproduct availability (DDGS) displaces soybean meal and results in additional feed exports. Corn area decreases in the *IND Perfect Elasticity* scenario by 2.4 thousand hectares relative to the baseline in 2033.

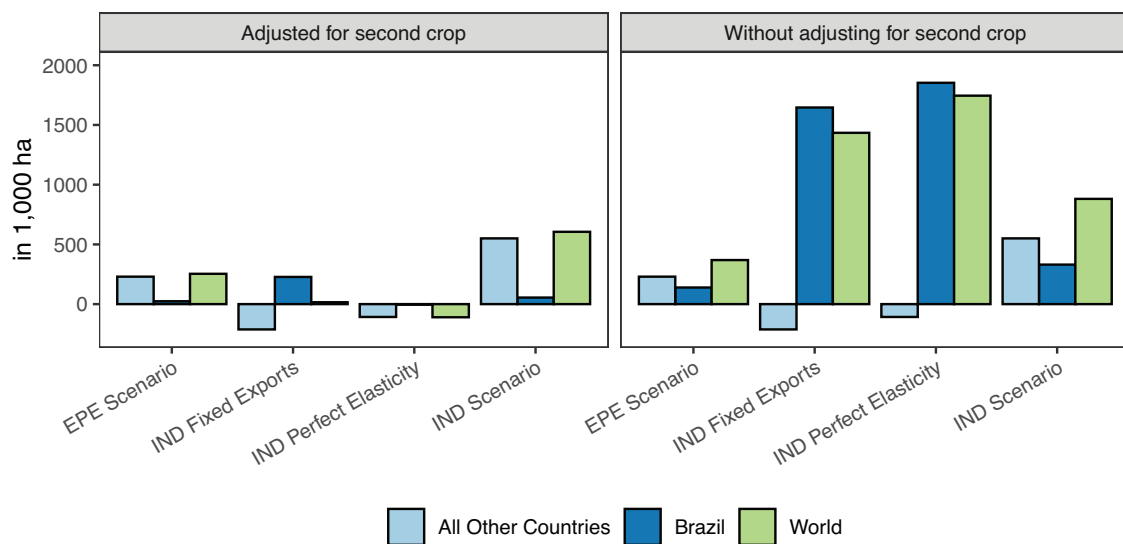
In the *IND Perfect Elasticity* scenario, Brazilian and the “All Other Countries” crop areas decline by about 2 thousand hectares and 108 thousand hectares, respectively, relative to the baseline. Most of the additional corn production comes from the second crop of corn in Brazil (no net increase in cropland). Additionally, there is a reduction in soybean acreage, as soybeans become relatively less competitive. This is largely due to the increased availability of substitutes for soybean meal (such as DDGS), which leads to a decrease in its price.

3.2 | Changes in Crop Area and Induced Land-Use Change

The crop area impacts from corn production expansion for ethanol use for the different scenarios are presented in Figure 7 for the last projection year (2033). These impacts are expressed in thousand hectares and presented for Brazil, “All Other

TABLE 3 | Changes from baseline of corn area for all scenarios in Brazil (1000 hectares).

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
<i>EPE</i>										
Brazil	2.2	8.2	12.7	16.2	20.6	21.6	22.6	23.4	23.5	24.0
All Other Countries	11.1	46.4	84.4	119.4	157.6	179.8	196.2	211.4	220.5	229.9
World	13.2	54.5	97.1	135.6	178.1	201.4	218.8	234.8	244.0	253.9
<i>IND</i>										
Brazil	9.4	23.9	61.1	55.3	55.2	55.2	55.8	55.8	55.3	54.9
All Other Countries	48.4	146.8	382.1	466.9	488.7	495.8	508.8	525.3	539.2	550.4
World	57.9	170.7	443.2	522.2	543.9	551.0	564.6	581.1	594.5	605.3
<i>IND Fixed Exports</i>										
Brazil	36.0	95.8	238.8	247.3	244.0	237.9	236.7	236.6	233.7	227.6
All Other Countries	-21.3	-61.8	-155.3	-190.1	-199.4	-201.7	-202.9	-206.1	-210.1	-211.9
World	14.7	34.0	83.5	57.2	44.6	36.2	33.8	30.4	23.6	15.7
<i>IND Perfect Elasticity</i>										
Brazil	3.4	6.6	16.9	1.5	-0.7	-0.6	-0.6	-1.4	-2.3	-2.3
All Other Countries	-9.8	-27.8	-70.8	-85.8	-91.7	-95.7	-98.1	-101.0	-104.3	-107.6
World	-6.4	-21.2	-53.9	-84.3	-92.4	-96.3	-98.7	-102.4	-106.6	-110.0

**FIGURE 7** | Crop area change (from the baseline) for different scenarios in 2033 with and without adjusting for the second crop (1000 hectares).

Countries,” and the World relative to the baseline. The results are presented in terms of adjusting for second crop and without adjusting for second crop, which assumes additional corn production for ethanol requires new, separate land.

Figure 7 illustrates the role of second-crop expansion by comparing the results from the model that includes double cropping to results from the model where additional corn production comes from new land rather than double cropping. The latter results highlight how the availability of double cropping alters the land-use implications of increased ethanol demand. When second-crop expansion occurs on existing soybean land, production can respond to higher demand primarily through intensification

rather than cropland expansion, thereby alleviating pressure on land-use change. Second crop corn has expanded rapidly over the past two decades and now accounts for approximately 80% of total Brazilian corn production, while first-crop corn area has declined as soybeans have become more profitable during the primary growing season.¹³ Much of this second-crop corn expansion has occurred through double cropping on land already used for soybeans, meaning that the fixed costs of land conversion were incurred previously (Companhia Nacional de Abastecimento (CONAB) 2025). As a result, positive market signals can trigger relatively rapid increases in second-crop acreage by extending production within existing agricultural areas. Consistent with this historical trajectory, the model results suggest that a large

TABLE 4 | Crop Area Change Per Unit of Ethanol Produced for Different Scenarios in 2033.

	EPE	IND	IND Fixed Exports	IND Perfect Elasticity
<i>Not adjusted for second crop (in 1,000 hectares per billion liters)</i>				
Brazil	39.6	39.7	197.7	222.5
All Other Countries	65.5	66.1	-25.4	-12.9
<i>Adjusted for second crop (in 1,000 hectares per billion liters)</i>				
Brazil	6.8	6.6	27.3	-0.3
All Other Countries	65.5	66.1	-25.4	-12.9

share of production responses to increased demand may occur through second-crop expansion. However, uncertainty remains regarding the magnitude of the supply elasticity for second crop corn, which motivates exploring a range of elasticity assumptions, from unitary to perfectly elastic, in order to assess potential land-use outcomes.

Brazil's area increases in all four scenarios when not adjusting for second crop, with larger changes in the *IND Fixed Exports* and *IND Perfect Elasticity* scenarios relative to the *EPE* and *IND* scenarios. When adjusting for second crop, the area increases in Brazil are much smaller in the *EPE* and *IND* scenarios, and actually decline in the *IND Fixed Exports* and *IND Perfect Elasticity* scenarios. For "All Other Countries", area expands in the *EPE* and *IND* scenarios, and decreases in the other two scenarios. The world area changes are the sum of the changes in Brazil and "All Other Countries".

Table 4 shows the changes in crop area normalized per unit of corn ethanol produced under different scenarios of corn expansion for ethanol production. Normalization determines how much land is needed to produce a fixed amount of ethanol and makes it easier to compare results across scenarios. As in Figure 7, the changes are presented in terms of adjusting for second crop and without adjusting for second crop. When adjusting for second crop, Brazil shows much lower land-use change per unit of ethanol in the *EPE* and *IND* scenarios (about 7 million hectares per billion liters) relative to the changes when double cropping is not considered (nearly 40 million hectares per billion liters).

In the *IND Fixed Exports* scenario, adjusting for second crop, the land requirement increases by 27 thousand hectares per billion liters, while in the *IND Perfect Elasticity* scenario, Brazilian area declines slightly with double cropping, indicating that increased ethanol demand is met by higher second crop adoption. When not adjusting for second crop, Brazil's area increases significantly by 222.5 thousand hectares per billion liters relative to the baseline in the *IND Perfect Elasticity* scenario. "All Other Countries" show much higher land use in the *EPE* and *IND* scenarios when compared to Brazil, and negative values in the *IND Fixed Exports* and *IND Perfect Elasticity* scenarios.¹⁴ Overall, second crop corn in Brazil substantially reduces land expansion pressure. Without second cropping, Brazil must expand cropland significantly to meet ethanol demand especially in the *IND Fixed Exports* and *IND Perfect Elasticity* scenarios. These results highlight the need to explicitly consider and model the Brazilian capacity to intensify production by double

cropping. We discuss the environmental implications in the next section.

3.3 | Land-Use Carbon and Life Cycle Emissions

The equilibrium for which the GHG calculation results are presented corresponds to 2033 as the last year of the projections. Additionally, in this section, we only discuss the *IND* scenario and the *IND Perfect Elasticity* scenario. There are substantial differences in land use and emissions as well as the resulting life cycle analysis (LCA) between the *IND* and *IND Perfect Elasticity* scenarios. As indicated in Figure 4, although both scenarios simulate double cropping of area in Brazil, the *IND Perfect Elasticity* scenario results in no corn price change after an increase in domestic corn demand. If the supply is perfectly elastic, the pressure on domestic prices will rapidly create a commensurate increase in domestic production, and thus exports will not be reduced. Land-use changes are caused by indirect effects due to the availability of coproducts (DDGSs) that displace feed and affect feed markets (e.g., soybean meal and soybeans). The difference between the baseline and the two scenarios for barley, corn, rice, sorghum, soybeans and wheat only includes the first crop corn since the second crop corn is harvested in an area previously harvested for soybeans in the same year (Figure 8).

Figure 9 focuses only on changes from the baseline of corn area for the *IND* and *IND Perfect Elasticity* scenarios for the last year of the projection period. As indicated earlier, the rest of the world represents an aggregation of all other countries included in the LRLU model. Table 3 shows that, in the *IND* scenario, global area used increases by 605.3 thousand hectares in year 2033, whereas, in the *IND Perfect Elasticity* scenario, the total area decreases by 110 thousand hectares in the same year. Due to the corn price increase at the global level in the *IND* scenario, the crop area increases in all countries (Figure 9). This is not the case for the *IND Perfect Elasticity* scenario in which crop area declines across the board.

Those changes in crop area at the global level have substantial impacts on GHG emissions from land-use change (Figure 10). For the *IND* scenario, the land-use change emissions range from 46.5 to 95.6 million metric tons of CO₂-e. A range of -8.0 to -13.4 million metric tons of CO₂-e is obtained for the *IND Perfect Elasticity* scenario. Using mean carbon coefficients, the changes to the global carbon pool are 61.7 and -9.8 million metric tons of CO₂-e for the *IND* and *IND Perfect Elasticity* scenarios, respectively. Because the global corn price is higher in the *IND* scenario,

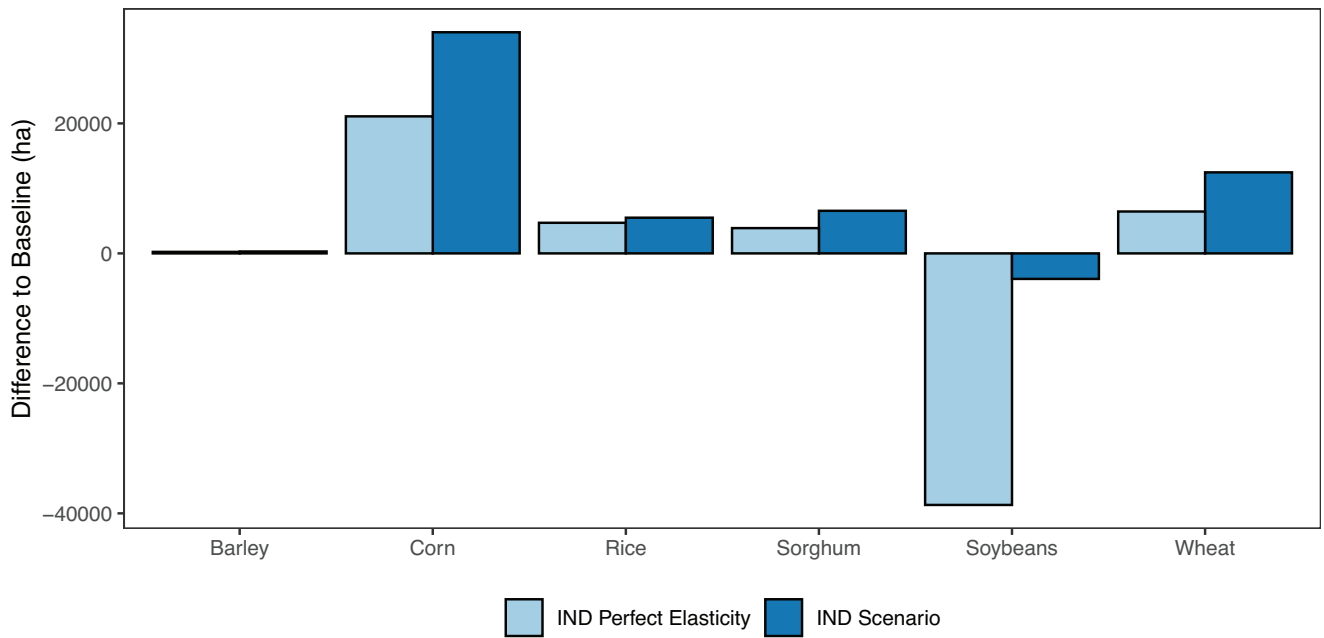


FIGURE 8 | Change in area harvested between the baseline and the scenarios for crops in Brazil in 2033/2034.

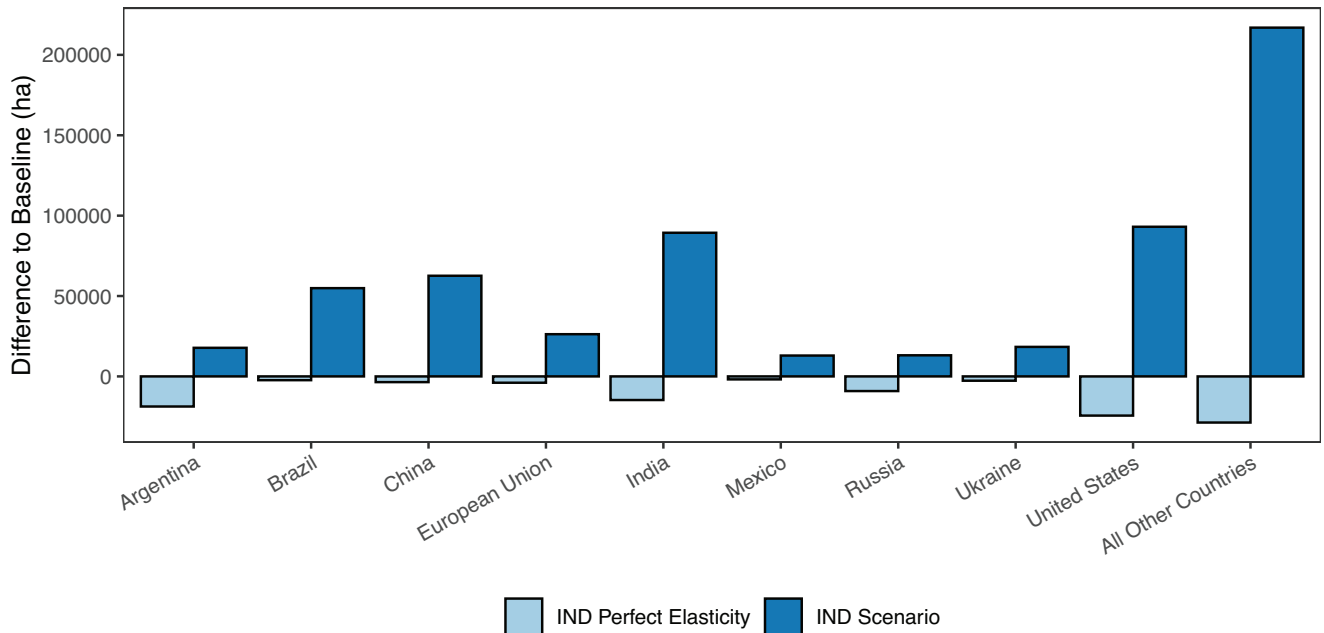


FIGURE 9 | Difference in area used between the baseline and the scenarios for modeled countries

the corn area increases depending on the country between 0.2% (European Union) and 0.7% (Brazil). The increase in “All Other Countries” is 0.3%. This amounts to an area of 34.4 thousand hectares from corn alone in areas high in biomass and soil carbon such as Western and Central Africa.

To determine the life cycle emissions from ethanol production using double cropping in Brazil, we proceed using the same steps as in Carriquiry et al. (2020), who also compare to the LCA of US corn ethanol. Carriquiry et al. (2020) model an increase in US ethanol production by 15%. This increase leads to changes in the corn price and allows for

market effects in the livestock sector because of increases in the feed prices. An important aspect of land-use change emission calculations is the effect on crop yields. Higher commodity prices due to, say, an increase in ethanol demand, may lead farmers to intensify their crop management, leading to an increase in crop yields. Besides the market effects associated with the adjustment of all commodities considered (including the livestock sector), the analysis by Carriquiry et al. (2020) also includes the price-induced yield effects. These scenarios are referred to in what follows as the *Market Mediation and Yield* and *Market Mediation* scenarios, respectively.

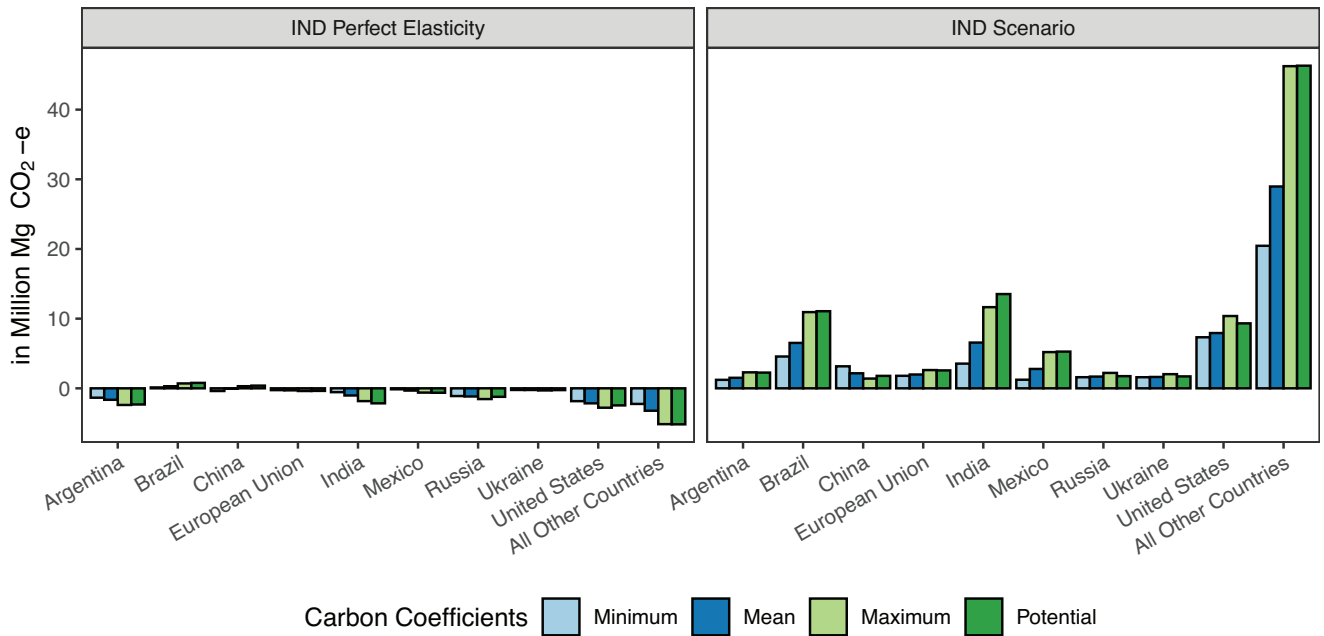


FIGURE 10 | Changes in CO₂ emissions from land-use for barley, corn, rice, sorghum, soybeans, and wheat.

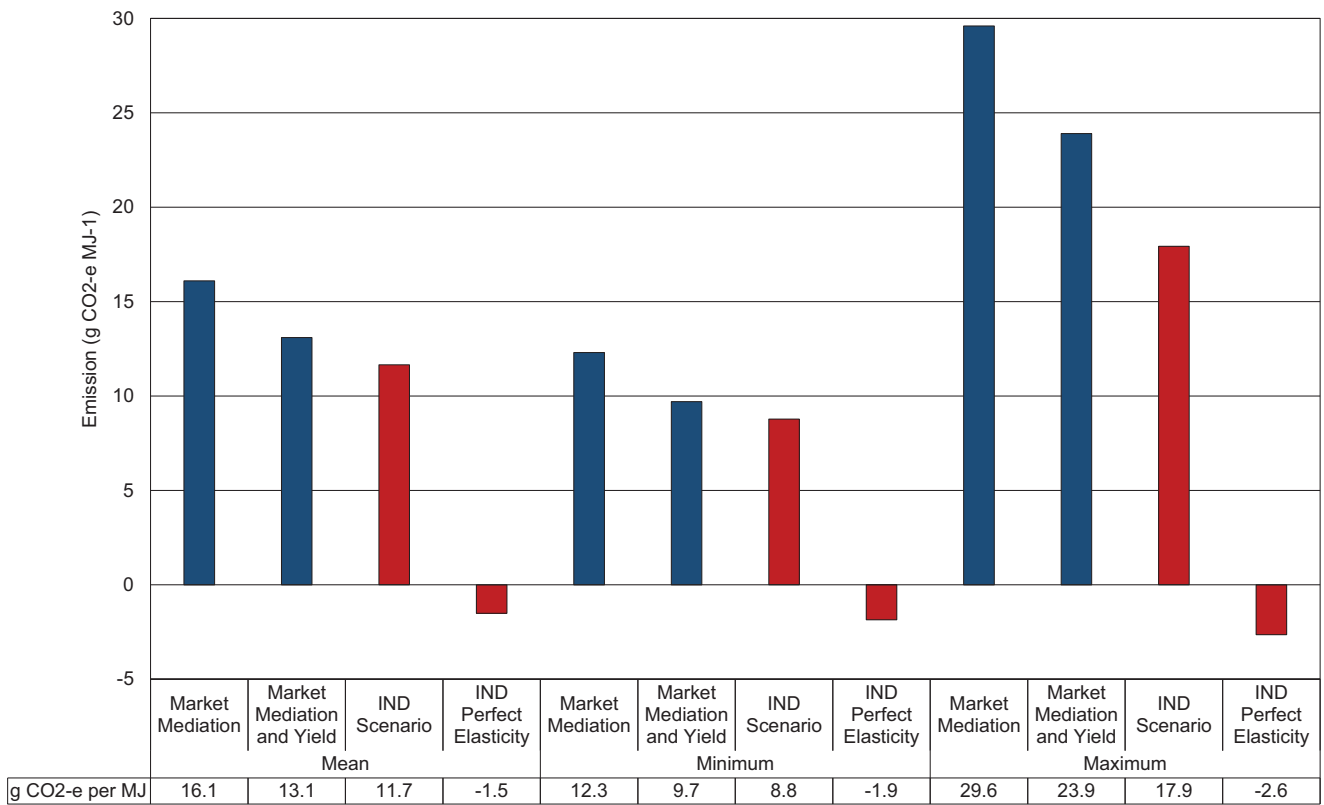


FIGURE 11 | Comparison of life cycle emissions from US biofuels between the IND and IND perfect elasticity scenarios (red bars) and the market mediation and market mediation and yield scenarios (blue bars) in Carriquiry et al. (2020).

The LCA results for the *IND* scenario suggest emissions of 11.7 g CO₂-e MJ⁻¹ using mean carbon coefficients. This is slightly lower compared to the LCA numbers for US corn ethanol reported in Carriquiry et al. (2020) that amount to 13.1 and 16.1 g CO₂-e

MJ⁻¹ for the *Market Mediation* and *Yield and Market Mediation* scenarios, respectively (Figure 11). Note that the double cropping scenario still leads to an increase in global land area and hence, positive GHG emissions associated with an increase in ethanol

demand. However, given that the total area change is negative in the *IND Perfect Elasticity* scenario, the LCA results lead to negative emissions per MJ of energy produced. This negative LUC emissions result is aligned with previous literature. Moreira et al. (2020) estimated values between $-2.6 \text{ g CO}_2\text{-e MJ}^{-1}$ and $-7.4 \text{ g CO}_2\text{-e MJ}^{-1}$, considering different levels of DDGS efficiency. Fiorini et al. (2023) for regular and zero deforestation estimated LUC emissions between $-298 \text{ g CO}_2\text{-e MJ}^{-1}$ and $-37.4 \text{ g CO}_2\text{-e MJ}^{-1}$ for different bio-SAF blends of corn in Brazil. The intuition behind this result is that higher corn ethanol production (and resulting coproducts) displaces other feed commodities in Brazil (i.e., soybean meal), leading to a reduction in domestic demand and increased exports. This results in lower domestic as well as global commodity prices.

4 | Conclusion

Since the start of using crops for energy production to reduce fossil fuel consumption and GHG emissions, concerns about the implications for land-use change and food security have been raised. Given Brazil's important role in biofuel and agricultural markets, the country's efforts to decarbonize the energy sector, and the implications on climate change and global food prices are critical due to the vast amounts of Brazilian agricultural land. The expansion of cropland in Brazil into native vegetation can have substantial negative consequences, including large GHG emissions and biodiversity losses (Dumortier et al. 2024). Therefore, producing ethanol from second crop corn can mitigate the competition with food production as well as price and trade implications. Second crop corn's economic viability and policy implications are key in understanding the potential as a SAF feedstock. This article offers insights into using second crop corn for energy production and outlines implications for climate change mitigation, sustainable agricultural production for food security, and policy. In this line, the article highlights the need to explicitly consider the possibility of expanding second crop corn production in Brazil as shown by its recent and significant growth into economic models assessing indirect land use change and GHG emissions.

Historical data show that Brazilian corn ethanol production and exports have increased simultaneously in recent years; however, this co-movement alone does not reveal how these variables would have evolved in the absence of ethanol expansion, as multiple factors jointly influence market outcomes. The baseline in this study reflects the recent joint growth of second-crop corn production, ethanol output, and exports, whereas the scenario analysis isolates the marginal effects of additional ethanol expansion on land use, prices, trade flows, and greenhouse gas emissions.

Changes in global cropland used depend critically on the ability of Brazil to limit its changes in corn exports as a result of expanded corn ethanol production. If corn exports are reduced, excess demand leads to higher world prices, and other countries will increase production leading to land-use change globally. While relative (percent) changes in supply are higher in Brazil than in other countries, total (absolute) area changes can be higher in other countries. This would be akin to "exporting land use change." The ability to expand second crop corn production

when demand increases (elasticity of supply) largely determine land-use change both in Brazil and globally.

Justus et al. (2024) find that Brazilian domestic corn prices largely respond to international price signals, reflecting strong global-to-local price transmission. Our modeling framework is consistent with this finding, as increases in ethanol demand result in shifts in the world market that raise international prices, which are then transmitted to domestic markets. These findings also align with previous studies highlighting agricultural intensification and double cropping as mechanisms that can mitigate land-use change (e.g., Moreira et al. (2020); Fiorini et al. (2023); Gurgel et al. (2024)). However, an important distinction of our analysis is the explicit treatment of export adjustments, showing that export dynamics play a central role in determining both international price responses and the distribution of land-use change across regions. If the supply elasticity in second crop corn production is "sufficiently high," changes in cropland use (indirect land use change and emissions) might be negative, as the additional supply of coproducts displaces the need for feed (e.g., corn and soybean meal) in Brazil and globally, thus reducing the area of soybeans. Beyond evaluating specific scenarios, the contribution of this study is in identifying the structural adjustment mechanisms, particularly supply elasticity, export responses, and global price transmission, through which increased biofuel-driven demand translates into land-use outcomes within an integrated global agricultural system. Future research could further investigate how alternative assumptions of price transmission dynamics and supply responsiveness influence the magnitude and distribution of land-use change under different biofuel demand scenarios.

Even in scenarios with large domestic expansion of the second crop corn, there is a substantial ability to expand corn as a second crop, which currently represents less than half of the soybean area. Depending on the stock of these areas and the conditions of the corn market in terms of demand and price, the opportunity cost of expanding corn over the area currently used for soybeans may be small. Additionally, existing large areas of degraded pasture can be recovered in Brazil, and released for crop production, without the need to bring new land into production (Colussi et al. 2025b; Bolfe et al. 2024; EPE 2024). Improved management practices can lead to higher livestock productivity and carbon sequestration (Bragança et al. 2022) or lower emissions (Cohn et al. 2014). The combined effects of better livestock practices and expansion of double cropping are not considered here but might be avenues for future research.

Most analyses of GHG emissions from corn ethanol production have been conducted for the United States, and there is limited information about the GHG implications of Brazilian corn ethanol. Brazilian corn ethanol differs from US ethanol in at least two aspects: (1) Reliance on a second crop of corn and (2) use of renewable energy to fuel ethanol plants. Most agricultural modeling systems do not explicitly incorporate the second crop corn, which prevents them from accurately capturing the dynamics of its expansion in areas already used by soybeans. Thus, this article explicitly represents second crop within an agricultural-economic modeling framework to demonstrate that agricultural practices, specifically multi-cropping, and the broader agricultural-economic context in which production

occurs, are often more decisive in shaping land-use change and GHG outcomes than the choice of feedstock itself.

The assessment of GHG emissions associated with land-use change in this article highlights the complexity of not only market feedback in terms of coproduct substitutions and international trade but also in terms of supply elasticity in determining the carbon intensity of corn-based ethanol from Brazil and its viability as a feedstock for SAF production. The documented availability of land to expand second crop corn production in Brazil and the assumption of a high supply elasticity scenario have implications not only for corn ethanol production in Brazil, but also for the expansion of corn demand globally. In particular, if high supply elasticities are confirmed, global corn demand might increase (within certain limits) with small effects on the need to bring additional land into production and equally important with limited price impacts. While the former is indicative of reduced changes in GHG emissions locally, the later point to reduced emissions leakages (as there are no incentives to increase production in the rest of the world) and reduced food price changes, limiting food security concerns from increased demand for corn ethanol demand. Given its importance, future research should focus on robustly estimating the supply elasticity of Brazilian second crop corn and further integration of multi-cropping systems into land-use and bioenergy modeling frameworks.

Acknowledgments

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Endnotes

- ¹ However, some initial studies like Searchinger et al. (2008) and Fargione et al. (2008) estimated higher GHG emissions from corn ethanol production when accounting for indirect land-use change.
- ² See [Global Ethanol Production by Country and Region](#) from the Alternative Fuels Data Center maintained by the U.S. Department of Energy.
- ³ See [Sectorial data](#) from the União Nacional do Etanol de Milho (UNEM)
- ⁴ RenovaBio, established by Law 13.576/2017, is Brazil's national biofuel policy aimed at reducing GHG emissions in the transport sector while enhancing energy security and market predictability, in line with Brazil's Paris Agreement commitments.
- ⁵ Carbon intensity (CI) Score quantifies the environmental impact by measuring GHG emissions associated with producing a product throughout its entire life cycle, expressed in grams per CO₂ equivalent per megajoule for fuels or per unit for commodities.
- ⁶ This is possible if the United States lifts its restriction of limiting incentives such as the 45Z tax credit only to North American-sourced feedstock for SAF production, and Brazil meets the EU feedstock eligibility and sustainability criteria.
- ⁷ The predecessor of the LRLU Model has been an outlook model covering a shorter time period (10–15 years) and 58 countries/regions.

A detailed description of the initial FAPRI/CARD agricultural model system is provided in Fabiosa et al. (2010). FAPRI is the Food and Agricultural Policy Research Institute, that used to be a division in Center for Agricultural and Rural Development (CARD) at Iowa State University.

- ⁸ For crops, the year refers to the starting marketing year. For example, 2023 refers to the 2023/24 marketing year for crops.
- ⁹ The countries/regions modeled are Argentina, Australia, Brazil, Canada, Chile, China, Egypt, the European Union, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Nigeria, Peru, Russia, South Africa, Ukraine, the United States, Vietnam, and the aggregate rest of the world region required to close the model.
- ¹⁰ Refer to Figure S1 in the Supplementary Material for a diagram of the land-use structure.
- ¹¹ The scenario was released in December of 2023
- ¹² See the Supplementary Material for a graph of baseline projections for harvested area of first and second crop corn and soybeans (Figure S2).
- ¹³ For the evolution of soybean and corn harvested area for soybeans and corn over time in Brazil, refer to Figure S3 in the Supplementary Material.
- ¹⁴ Note that the results for “All Other Countries” after adjusting for second crop corn do not change as we account for the change in second crop area only in Brazil (the sole country in which double cropping is modeled).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Figure S1: Components and structure of the land-use categories in the CARD Model. Figure S2: Baseline projections of harvested area for soybeans, first-crop corn, and second-crop corn, crop years 2000/01-2033/34 (thousand hectares) Figure S3: Evolution of harvested area for soybeans and corn by cropping system (first crop vs. second crop) in Brazil, crop years 1976/77-2024/25 (thousand hectares)