

Contribution of double-cropped maize ethanol in Brazil to sustainable development

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Contribution of Double-cropped Maize Ethanol in Brazil to Sustainable Development

Supplementary Material

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1. Evolution of double-cropped corn in Brazil

Figure S1 illustrates the changes in the areas of the first and second crops corn and soybean in the Brazilian Center-West region. The area of the second crop corn has shown significant growth in recent years, rising from 45 thousand hectares in 1990/91 to 11.4 million hectares in the crop season of 2022/23. This growth follows the curve of the soybean area, increasing from 3 million hectares to 20.5 million hectares in the same period. In contrast, the area of the first crop of corn has been declining from 1.5 million hectares in 1990/91 to 261 thousand hectares in the crop season of 2022/23 (CONAB, 2024). The increase in second-crop corn production can be attributed to better technology adoption and cultivation practices, leading to increased production and productivity in second-crop areas (MAGALHÃES et al., 2020; NOVELLI et al., 2023).

Additionally, in the last harvest season (2022/23) the first crop of corn represented only 2% of the total corn area in the Center-West region and only 1% in Mato Grosso state. On the other hand, the second crop of corn represented 98% of the total corn area in the Center-West region and 99% in Mato Grosso state. In the 1990/91 harvest, the first crop of corn represented 97% of the total corn area in the Center-West region and 100% in Mato Grosso state. Contrarily, in 1990/91, the second crop corn participation was practically zero, representing 3% of the total corn area in the Center-West region and 0% in Mato Grosso state (CONAB, 2024).

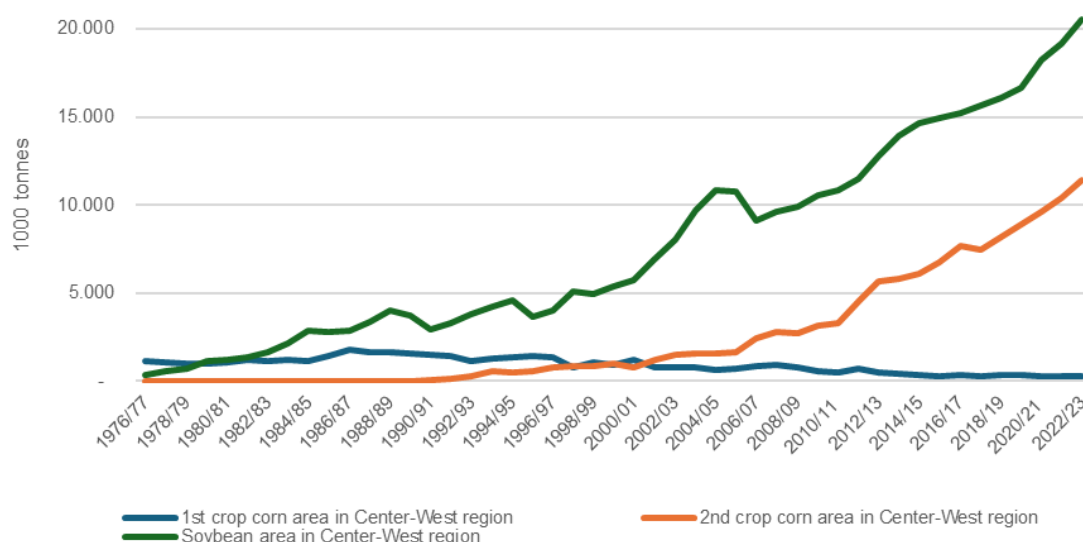


Figure S1. Evolution of the first and second corn crops and soybean areas in the Center-West region of Brazil

Source: CONAB (2024).

Second-crop corn planting began in Brazil in 1976, and in Mato Grosso state in 1989. Data from Mapbiomas Collection 6 and Agrosatélite (2022) reveals that in 2021:

- 79% of the total area used for planting second-crop corn in Mato Grosso was previously occupied by soybeans in 2015.
- 12.3% of the area was pasture.
- 5.5% was temporary.
- 2.1% was natural vegetation.
- 1.1% was used for other purposes.

As observed from literature references (CORBEEELS et al., 2016; ALLEN et al., 2016; EMBRAPA, 2021 and FUENTES-LLANILLO et al., 2021), 100% of second-crop corn in Mato Grosso state is planted in a sequential system after soybean, using the same area. In Mato Grosso, soybean is rarely grown as a single crop. Instead, farmers cultivate other crops during the off-season, such as cotton, dry beans, rice, peanuts, and more. This strategy maximizes land use in the off-season cultivation system. This allows for an extra cultivation window during the agricultural year. According to Garofalo et al. (2022), this method effectively uses the same area. Table S1 shows the increase of second-crop corn over the soybean area in Mato Grosso state, achieving 57% (CONAB, 2024; WAHA et al., 2020).

Table S1. Second-crop corn participation over soybean area in Brazilian regions and Center-West States

2nd CROP CORN AREA / SOYBEAN AREA (%)	2008/ 09	2009/ 10	2010/ 11	2011/ 12	2012/ 13	2013/ 14	2014/ 15	2015/ 16	2016/ 17	2017/ 18	2018/ 19	2019/ 20	2020/ 21	2021/ 22	2022/ 23	2023/24 (¹)
NORTH	8%	13%	13%	16%	14%	16%	19%	15%	22%	19%	24%	25%	27%	31%	31%	27%
NORTHEAST	22%	19%	19%	19%	13%	16%	20%	15%	12%	17%	14%	15%	13%	17%	20%	21%
CENTER-WEST	29%	28%	30%	31%	40%	44%	42%	42%	45%	50%	48%	51%	54%	53%	55%	56%
MATO GROSSO	29%	26%	31%	29%	38%	43%	37%	38%	41%	49%	47%	50%	54%	56%	58%	61%
MATO GROSSO DO SUL	51%	50%	48%	54%	66%	72%	73%	70%	69%	70%	64%	65%	61%	63%	61%	59%
GOIÁS	12%	16%	17%	21%	26%	29%	31%	33%	39%	38%	36%	41%	46%	39%	40%	38%
DISTRITO FEDERAL	17%	10%	14%	9%	16%	33%	69%	68%	55%	55%	50%	52%	51%	49%	59%	46%
SOUTHEAST	22%	21%	19%	24%	27%	26%	28%	30%	35%	36%	35%	36%	36%	34%	34%	29%
SOUTH	20%	18%	15%	19%	22%	22%	18%	17%	19%	21%	18%	19%	19%	20%	21%	19%
BRAZIL	24%	23%	22%	24%	29%	32%	30%	29%	31%	35%	32%	34%	36%	36%	38%	38%

¹Estimated

Source: CONAB (2024).

2. Additional Results from the Environmental Modeling (Life Cycle Assessment - LCA)

Table S2 shows well-to-wheel (WTW) performance indicators for multi-cropping corn ethanol and fossil gasoline, while Figure S2 brings a normalized comparison, differentiating the Well-to-Tank (WTT) and Tank-to-Wheel (TTW) phases. Table S2 presents a summary of net life cycle impact indicators (at the endpoint level) associated with the displacement of the traditional product system by implementing the multi-cropping corn-based system. A negative value in that table indicates an environmental benefit with the implementation of the corn-based systems (due to lower emissions/discharges), while a positive value means greater impacts. The normalization shown in Figure S2 considers the result of the worst-performing fuel (the highest indicator) as 100% for each category, making the result of the other fuel a percentage of the worst case. For example, in the Human carcinogenic toxicity category, gasoline had the worst WTW performance (100%), so the value of this indicator for ethanol is only 32% of what was seen for gasoline.

Table S2. WTW environmental profile of multi-cropping corn ethanol and gasoline (UF = 1 MJ)

Impact category	Units	Ethanol	Ethanol w/ BECCS	Gasoline
Human non-carcinogenic toxicity	kg 1,4-DCB	-8.18E-02	-8.30E-02	5.68E-03
Terrestrial acidification	kg SO ₂ eq	3.70E-04	3.70E-04	1.50E-04
Global warming ^a	kg CO ₂ eq	2.68E-02	-8.18E-03	9.49E-02
Ozone formation, Terrestrial ecosystems	kg NO _x eq	8.25E-05	8.36E-05	8.25E-05
Stratospheric ozone depletion	kg CFC11 eq	4.02E-07	4.07E-07	1.13E-07
Marine eutrophication	kg N eq	3.32E-05	3.37E-05	2.77E-07
Human carcinogenic toxicity	kg 1,4-DCB	6.60E-04	6.70E-04	2.06E-03
Land use	m ² a crop eq	3.97E-03	4.03E-03	2.40E-04
Water consumption	m ³	3.00E-04	3.10E-04	1.80E-04
Fine particulate matter formation	kg PM _{2.5} eq	6.45E-05	6.56E-05	5.14E-05
Marine ecotoxicity	kg 1,4-DCB	6.10E-04	6.20E-04	3.10E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.54E-01	1.56E-01	3.43E-02
Ozone formation, Human health	kg NO _x eq	7.28E-05	7.38E-05	7.35E-05
Freshwater eutrophication	kg P eq	3.28E-06	3.37E-06	2.39E-06
Freshwater ecotoxicity	kg 1,4-DCB	6.40E-04	6.50E-04	1.80E-04
Mineral resource scarcity	kg Cu eq	6.72E-05	6.87E-05	3.16E-05
Ionizing radiation	kBq Co-60 eq	6.00E-04	6.10E-04	1.05E-03
Fossil resource scarcity	kg oil eq	4.77E-03	4.85E-03	3.04E-02

^a LCIA results for IPCC (2013) GWP100 (no feedback) would be, respectively, 2.5E-02, -9.7E-03 and 9.4E-02.



Figure S2. Comparative analysis of the environmental performance of multi-cropping corn ethanol (with and without BECCS) and gasoline

Figure S3 displays a sensitivity analysis of the net LCA endpoint indicators associated with implementing the multi-cropping corn-based system with BECCS. The sensitivity explored the indicators for the three areas of protection (human health, ecosystems, and resources) shown in Table 1 of the main text. These indicators quantify the net effect of

replacing conventional, fossil-based products with those derived from the corn-based system. This means that negative values indicate that there would be a net environmental benefit with the displacement, while positive ones point that the environmental burden would increase. Therefore, for the conditions explored in the sensitivity, despite the changes in magnitude, the indication of net environmental gains for all three areas of protection prevailed.

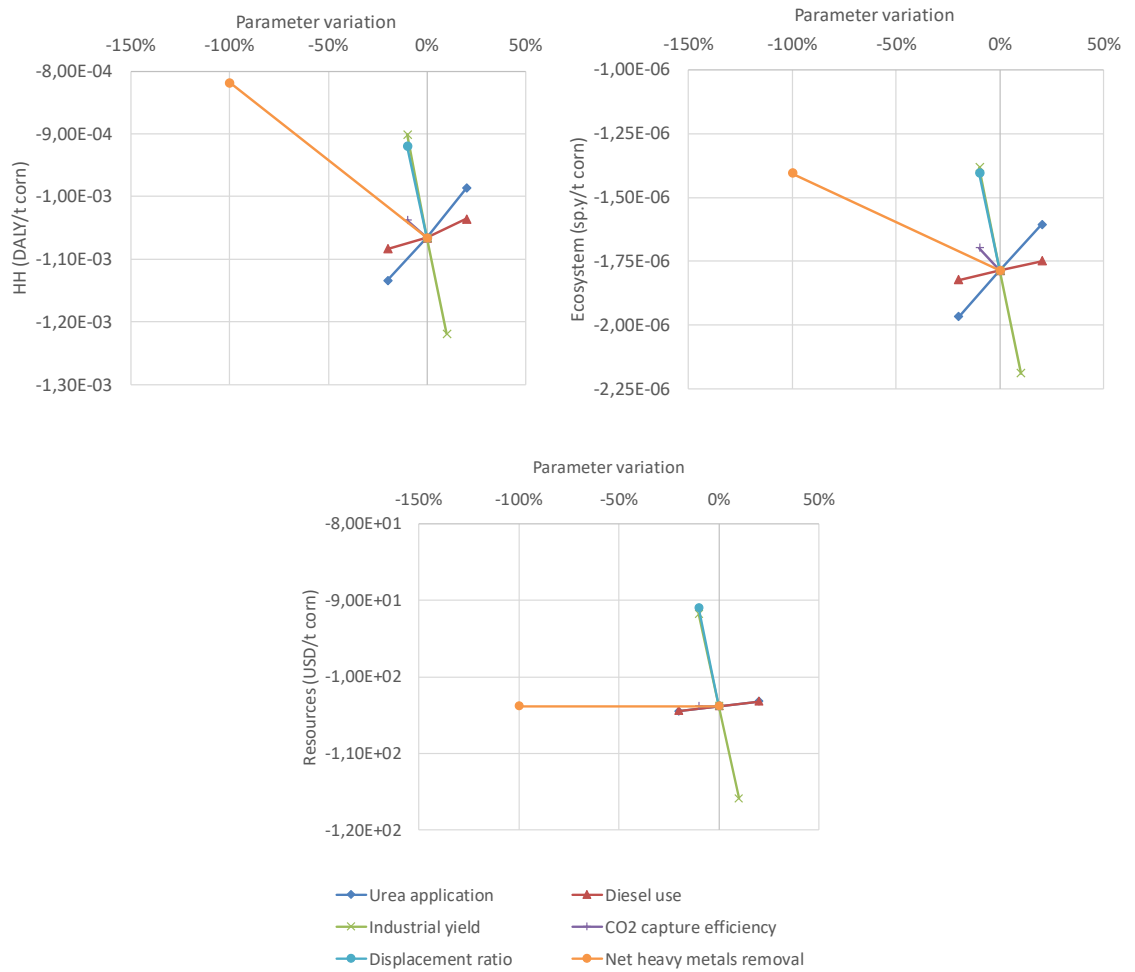


Figure S3. Sensitivity analysis of the net LCA endpoint indicators associated with implementing the multi-cropping corn-based system with BECCS

3. Additional details and assumptions in the Life Cycle Assessment

The product system based on the double-crop (multi-cropping) corn used in Brazil dedicated to producing ethanol, DDG, oil, power, and capturing CO₂ is illustrated in Figure S4. The environmental life cycle indicators were expressed as the difference compared to the conventional system featuring a single soybean crop, assuming the displacement of the traditional products, according to the equivalences shown in Supplementary Figure S5.

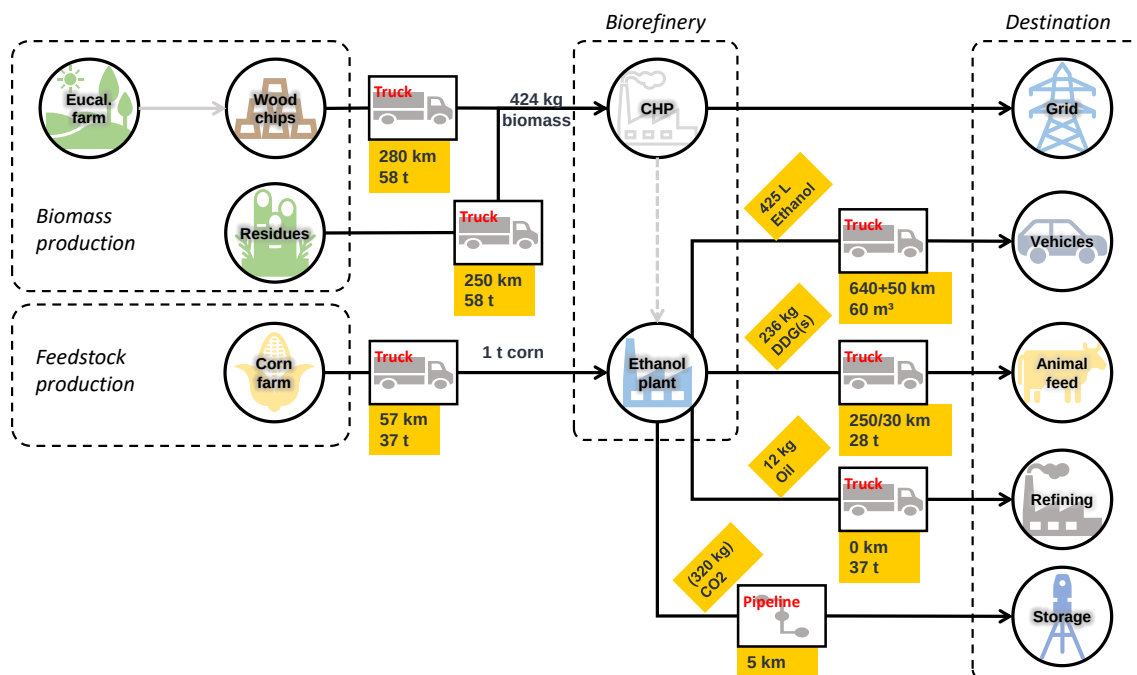


Figure S4. General representation and yields of the product system based on double-cropping corn

In brackets the yields of the configuration with BECCS.

Figure S4 Credit: icons from the Microsoft PowerPoint 2021.

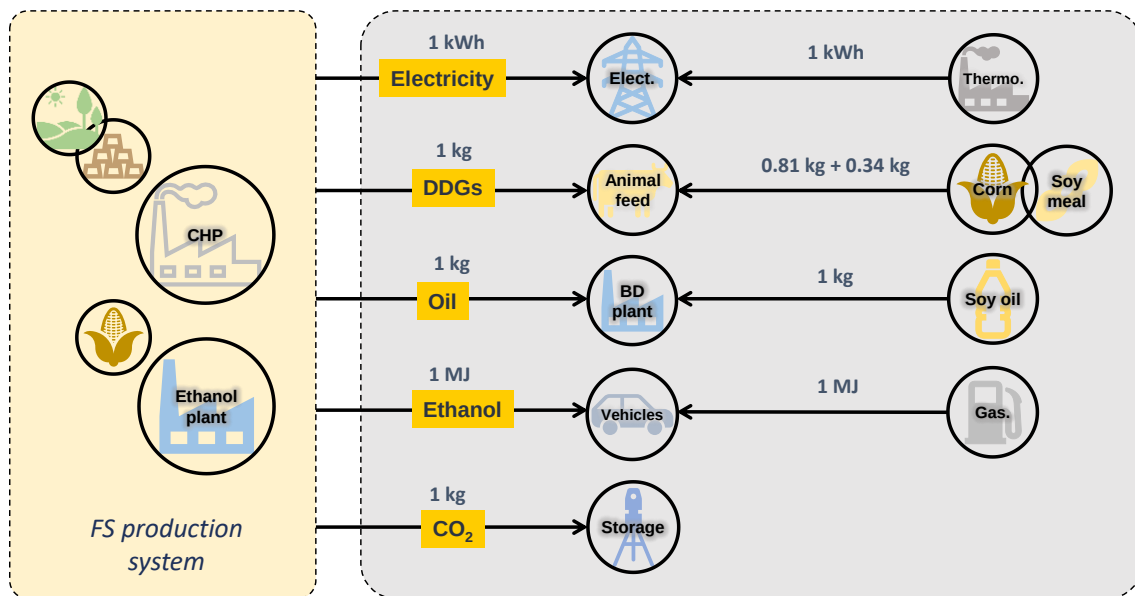


Figure S5. Considered equivalence in replacing conventional products

Figure S5 Credit: icons from the Microsoft PowerPoint 2021.

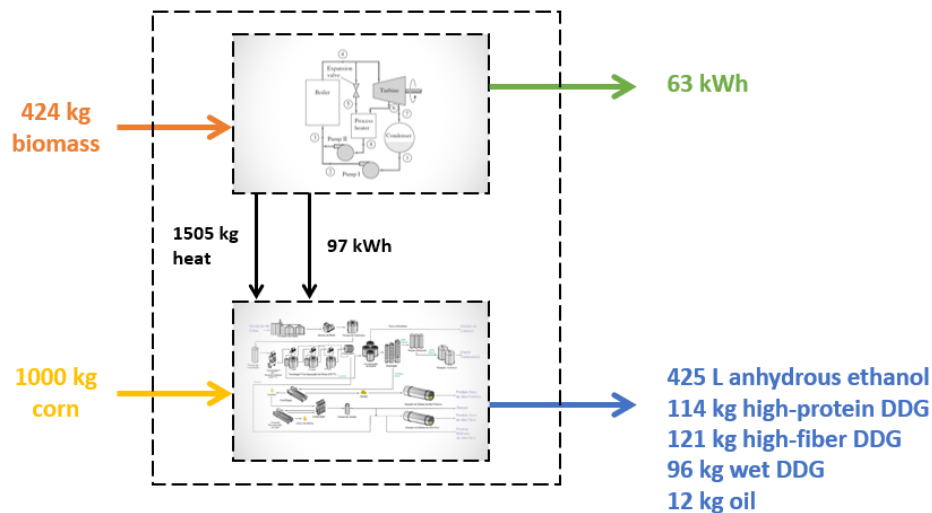
Parameters related to inputs for corn cultivation and industrial yields are shown in Table S3 and Figure S6, respectively. Discharges to the environment associated with corn cultivation were quantified according to Nemecek et al. (2014) and Folegatti-Matsuura and Picoli (2018).

Table S3. Inputs used for second crop (multi-cropping) corn cultivation (by kg of corn)^a

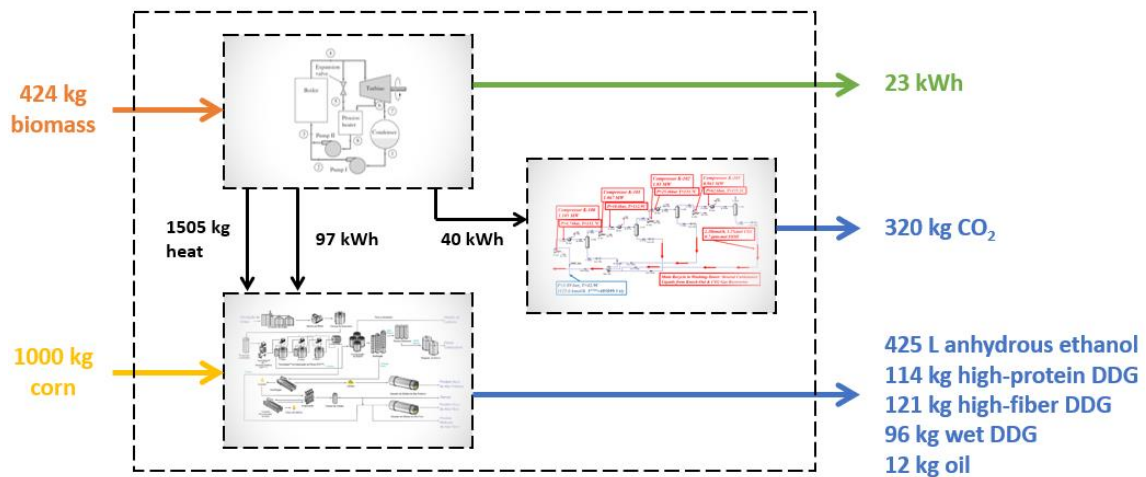
Parameter	Units	Quantity
ammonium nitrate, as N	kg	2.20E-04
ammonium sulfate, as N	kg	2.15E-03
annual crop, non-irrigated, intensive	m ² *a	4.61E-01
atrazine	kg	2.43E-04
calcium nitrate	kg	1.29E-03
diesel, burned in agricultural machinery	MJ	2.25E-01
electricity, low voltage	kWh	1.60E-04
glyphosate	kg	7.50E-05
lime	kg	6.00E-05
maize seed, for sowing	kg	3.44E-03
packaging, for fertilizers or pesticides	kg	1.12E-03
packaging, for fertilizers or pesticides	kg	9.98E-02
pesticide, unspecified	kg	2.40E-04
phosphate fertilizer, as P ₂ O ₅ (SSP)	kg	1.43E-03
phosphate fertilizer, as P ₂ O ₅ (MAP)	kg	2.00E-05
potassium fertilizer, as K ₂ O	kg	8.48E-03
tap water	kg	1.12E-01
urea, as N	kg	8.60E-03

^a Based on RenovaCalc – FS Lucas do Rio Verde (LRV), except for pesticide consumption, packaging, and water, which were based on the corn inventory (in MT) available at SICV Brasil. The NPK consumption informed in the “Other” synthetic fertilizer fields was arbitrarily considered as urea, MAP, and KCl, respectively.

According to information provided by FS, each 1,000 kg of corn produces 425 liters of anhydrous ethanol, 114 kg of high-protein DDG, 121 kg of high-fiber DDG, 96 kg of wet DDG (totaling 331 kg of DDG) and 12 kg of unrefined corn oil. For the same amount of corn, 424 kg of eucalyptus chips is needed to meet the plant's energy demand, which still allows exporting 63 kWh of surplus power to the grid in the configuration without BECCS (Figure S6a), or 23 kWh in the configuration with BECCS (Figure S6b). In the latter case, introducing the BECCS system enables capturing 320 kg of CO₂ for each ton of processed corn. The materials and energy flow diagram are shown in Figure S6.



(a)



(b)

Figure S6. Breakdown of biorefinery co-product yields: (a) reference scenario without CO₂ capture and (b) with CO₂ capture

Source: Primary data provided by FS Bioenergia.

Table S4 shows the relationship established between the Sustainable Development Goals (SDGs) and the impact indicators on each environmental impact category quantified at the endpoint level. Table S5 lists environmental impact categories and their relationship with the SDGs.

Table S4. Connections between Environmental Impact Categories and SDGs

	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND
Ozone formation, Human health		x			x				
Global warming, Human health		x			x		x		
Water consumption, Human health		x			x				
Human carcinogenic toxicity		x							
Human non-carcinogenic toxicity		x							
Stratospheric ozone depletion		x							
Ionizing radiation		x							
Fine particulate matter formation		x			x				
Ozone formation, Terrestrial ecosystems									x
Land use									x
Marine eutrophication			x					x	
Terrestrial acidification	x								x
Freshwater ecotoxicity			x					x	
Freshwater eutrophication			x					x	
Global warming, Freshwater ecosystems								x	
Global warming, Terrestrial ecosystems	x								x
Terrestrial ecotoxicity	x								x
Water consumption, Aquatic ecosystems								x	
Water consumption, Terrestrial ecosystem			x						x
Marine ecotoxicity			x					x	
Fossil resource scarcity				x					
Mineral resource scarcity						x			

Table S4 Credit: icons from the United Nations Sustainable Development Goals (<https://www.un.org/sustainabledevelopment>).

Table S5. List of environmental impact categories and their relationship with the SDGs

SDGs	SDG target¹	SDG indicator¹	Indicator
SDG 2: Zero Hunger	2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production that help maintain ecosystems that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality.	2.4.1 Proportion of agricultural area under productive and sustainable agriculture.	Terrestrial acidification (species.yr)
			Freshwater ecotoxicity(species.yr)
			Freshwater eutrophication (species.yr)
SDG 3: Good Health and Well-Being	3.4 By 2030, reduce by one-third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being. 3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.	3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes, or chronic respiratory disease. 3.9.1 Mortality rate attributed to household and ambient air pollution.	Ozone formation, Human health (DALY)
			Global warming, Human health (DALY)
			Water consumption, Human health (DALY)
			Human carcinogenic toxicity (DALY)
			Human non-carcinogenic toxicity (DALY)
SDG 6: Clean Water and Sanitation	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes.	6.4.1 Change in water-use efficiency over time. 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources. 6.6.1 Change in the extent of water-related ecosystems over time.	Stratospheric ozone depletion (DALY)
			Ionizing radiation (DALY)
			Fine particulate matter formation (DALY)
			Marine eutrophication (species.yr)
			Freshwater ecotoxicity (species.yr)
			Freshwater eutrophication (species.yr)
SDG 7: Affordable and Clean Energy	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix. 7.3 By 2030, double the global rate of improvement in energy efficiency.	7.2.1 Renewable energy share in the total final energy consumption. 7.3.1 Energy intensity measured in terms of primary energy and GDP.	Water consumption, Terrestrial ecosystem (species.yr)
			Marine ecotoxicity (species.yr)
SDG 11: Sustainable Cities and Communities	11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global	11.5.1 Number of deaths, missing persons, and directly affected persons attributed to disasters per 100,000 population.	Fossil resource scarcity (USD2013)
			Ozone formation, Human health (DALY)

	gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations. 11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	11.3.1 Ratio of land consumption rate to the population growth rate 11.6.2 Annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted).	Global warming, Human health (DALY) Water consumption, Human health (DALY) Fine particulate matter formation (DALY)
SDG 12: Responsible Consumption and Production	12.2 By 2030, achieve the sustainable management and efficient use of natural resources.	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP. 12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.	Mineral resource scarcity (USD2013)
SDG 13: Climate Action	13.2 Integrate climate change measures into national policies, strategies, and planning.	13.2.1 Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan that increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other).	Global warming, Human health (DALY)
SDG 14: Life Below Water	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, from land-based activities, including marine debris and nutrient pollution. 14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.	14.1.1 Index of coastal eutrophication and floating plastic debris density. 14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations.	Marine eutrophication (species.yr) Freshwater ecotoxicity (species.yr) Freshwater eutrophication (species.yr) Global warming, Freshwater ecosystems (species.yr) Water consumption, Aquatic ecosystems (species.yr) Marine ecotoxicity (species.yr)
SDG 15: Life on Land	15.1 By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater	15.1.1 Forest area as a proportion of total land area.	Ozone formation, Terrestrial ecosystems (species.yr)

ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line.	15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type.	Land use (species.yr)
15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally.	15.2.1 Progress towards sustainable forest management with obligations under international agreements.	Terrestrial acidification (species.yr)
15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world.	15.3.1 Proportion of land that is degraded over total land area.	
15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity, and, by 2020, protect and prevent the extinction of threatened species.	15.5.1 Red List Index.	Global warming, Terrestrial ecosystems (species.yr)
15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies, and accounts.	15.9.1 Progress towards national targets established in accordance with Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020.	Terrestrial ecotoxicity (species.yr)
		Water consumption, Terrestrial ecosystem (species.yr)

4. Additional Results from the Socio-economic Models

Figure S7 displays changes in energy prices paid by consumers and industries provided by the PAEG model due to the expansion of the corn ethanol output from 3 billion gallons to 8 billion gallons. Figure S8 shows the results from the EPPA model.

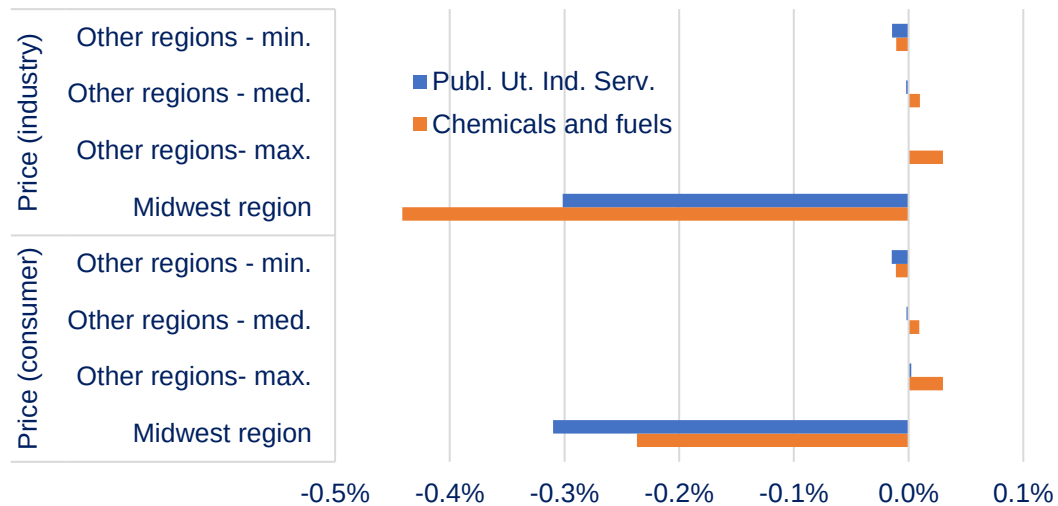


Figure S7. Price changes for consumers and intermediate demand in energy sectors in the PAEG model

Variations in the model's shock region (Midwest) are presented individually, while average, maximum, and minimum changes are shown for the set of other regions.

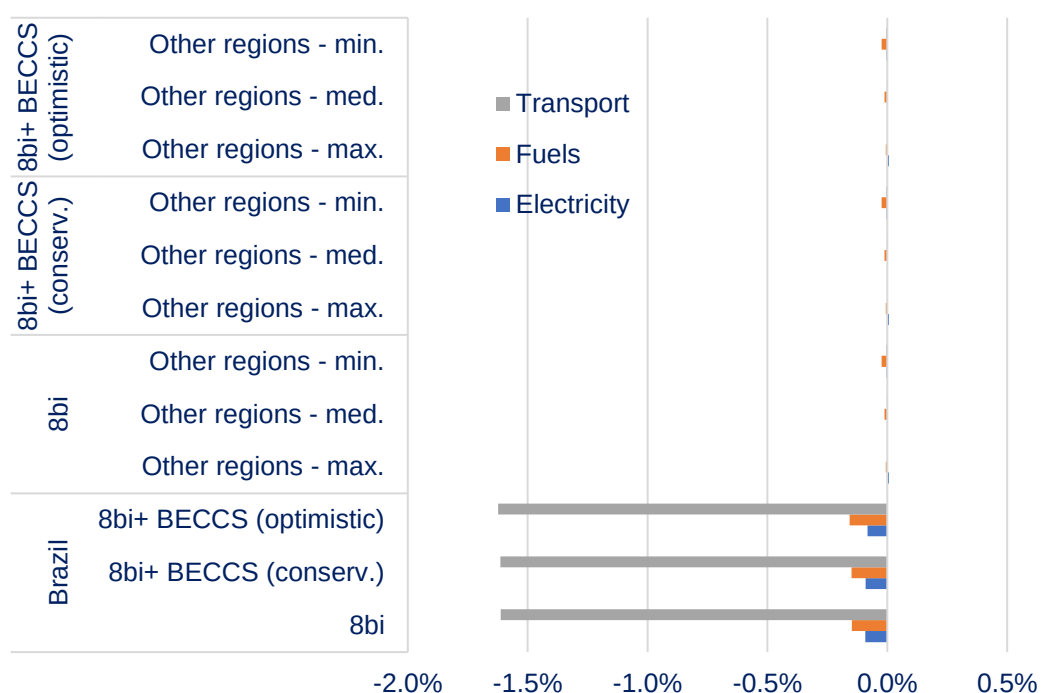


Figure S8. Price changes in energy and transportation in the EPPA model

Variations in the model's shock region (Brazil) are presented individually, while the average, maximum, and minimum changes are presented for the set of other regions.

Table S6 presents alternative parameter assumptions tested in the sensitivity analysis on results from the PAEG model. Figures S9, S10, and S11 display how income, utility index, and value of consumption are impacted in the sensitivity analysis.

Table S6. Overall assumptions in the sensitivity analysis performed in the PAEG model

#	Parameter or Elasticity	Description	Base values	Source	Changes
1	Fuel substitution	Substitution between corn ethanol and other fuels from petrochemical industry	1	PAEG model	plus 50%, less 50%
2	DDG substitution	DDG substitution equivalence	1	Moreira et al. (2020)	plus 50%, less 50%
3	DDG initial	DDG initial value relative to ethanol output	14%	Moreira et al. (2020)	plus 50%, less 50%
4	Trade substitution	Trade elasticities (substitution between domestic and imported goods)	domestic x imported: 1.3 to 3.8; among imports from different partners: 2.6 to 7.6	Lanz and Rutherford (2016)	plus 50%, less 50%
5	Consump. substitution	Substitution among goods in household consumption	1	Wolf et al. (2021)	plus 50%, less 50%
6	Land substitution	Land transformation elasticity among alternative crops	0	Lanz and Rutherford (2016)	plus 50%, less 50%
7	K x L substitution	Substitution among primary factors (capital, labor, land, natural resources)	0.26 to 1.68	Lanz and Rutherford (2016)	plus 50%, less 50%
8	Corn oil substitution	Substitution between corn oil co-production from corn ethanol and food products	1	PAEG model	plus 50%, less 50%
9	Corn substitution	Substitution between corn from double cropping and corn from single cropping	2	PAEG model	plus 50%, less 50%
10	Electr. substitution	Substitution between electricity co-production from corn ethanol and utility services	1	PAEG model	plus 50%, less 50%

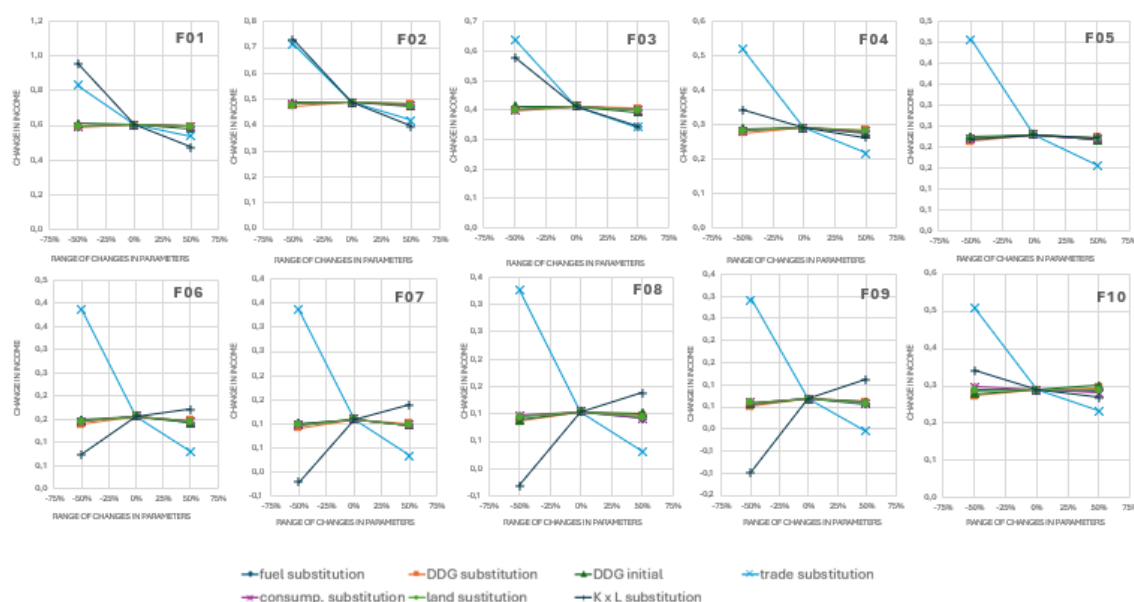


Figure S9. Sensitivity analysis for income

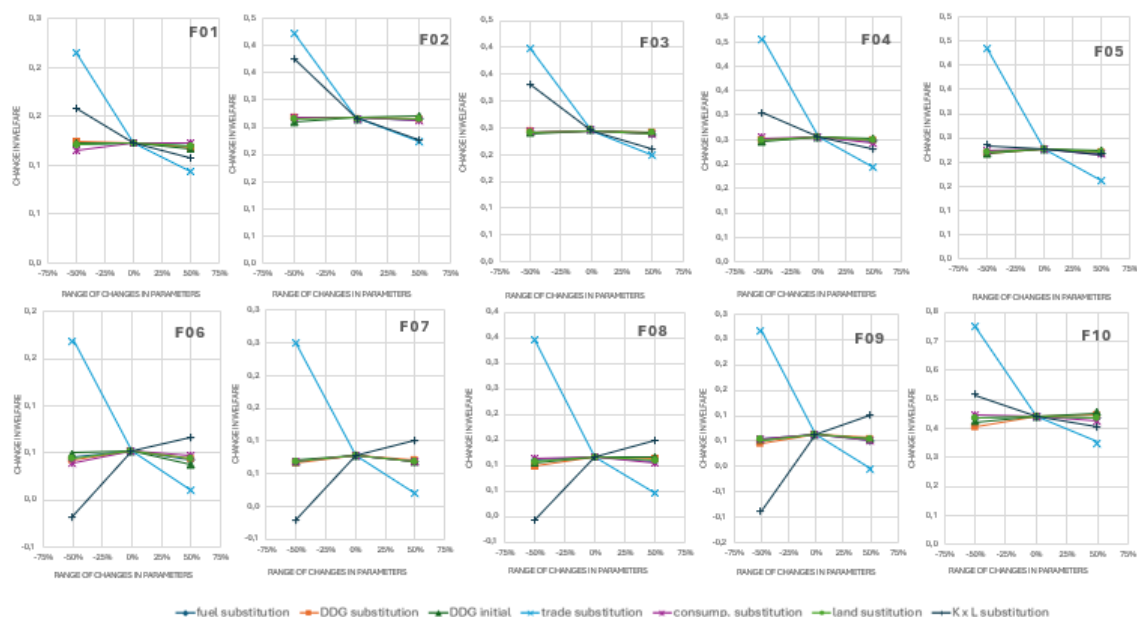


Figure S10. Sensitivity analysis for welfare

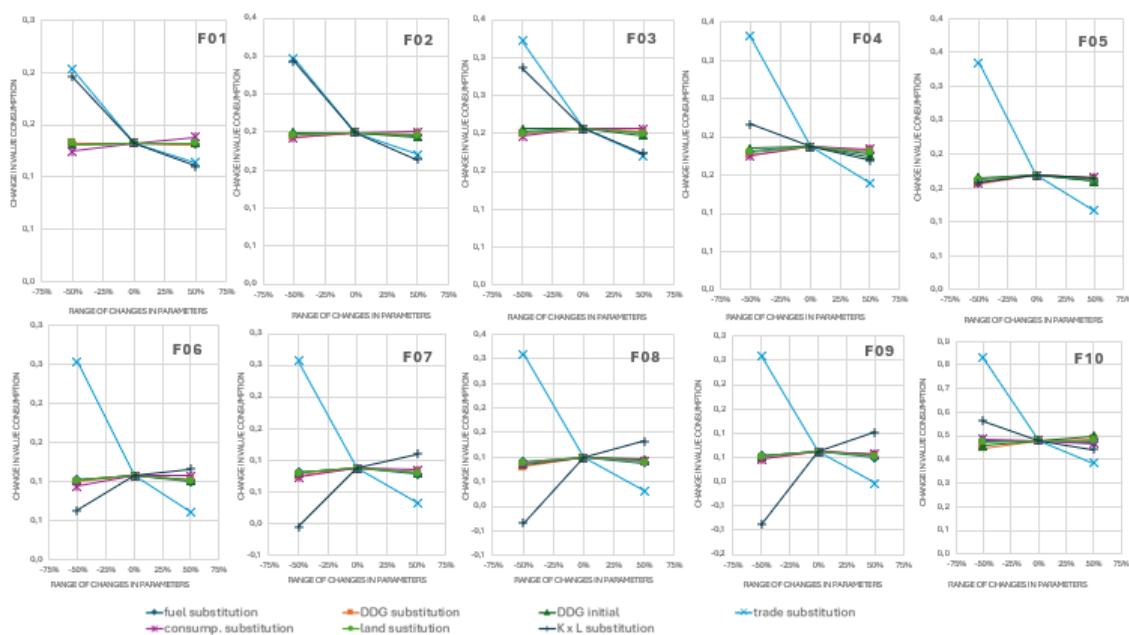


Figure S11. Sensitivity analysis for value consumption

Figures S12 and S13 display sensitivity analysis on EPPA model results regarding changes in land use in Brazil and changes in CO₂ and GHG emissions, by testing alternative assumptions on key model parameters (Table S7).

Table S7. Overall assumptions in the sensitivity analysis performed in the EPPA model

#	Parameter or Elasticity	Description	Base values	Source	Changes
1	Land supply elast.	Land supply elasticity	0.16 to 0.39 in developing countries, 0.01 to 0.05 in developed countries	Gurgel et al. (2016)	plus 50%, less 50%
2	Land transf. elast.	Land transformation elasticity	1 among alternative crops	Lanz and Rutherford (2016)	plus 50%, less 50%
3	Subst. land x other inp. (agri)	Substitution between land x other inputs in agricultural sectors	agricultural sectors: 0.3	Chen et al. (2016)	plus 50%, less 50%
4	Subst. K, L, land+other inp. (agri)	Substitution between capital & labor bundle and land & other inputs bundle in agricultural sectors	agricultural sectors: 0.7	Chen et al. (2016)	plus 50%, less 50%
5	Subst. dom. x imp.	Trade elasticities (substitution between domestic and imported goods)	domestic x imported: 3; among imports from different partners: 5	Chen et al. (2016)	plus 50%, less 50%
6	Subst. energy x K,L	Substitution between energy bundle and capital & labor bundle (all sectors)	agricultural sectors: 0.6; fossil energy sectors: 0.8; all other sectors: 1	Chen et al. (2016)	plus 50%, less 50%
7	Subst. inputs x energy	Substitution between energy bundle and other inputs (all sectors)	all sectors: 0.5	Chen et al. (2016)	plus 50%, less 50%
8	Subst. energy, inputs, K&L	Substitution between energy bundle, inputs bundle and capital & labor bundle (all sectors)	All assumptions in scenarios 5, 6 and 7 together	Chen et al. (2016)	plus 50%, less 50%
9	Land yield improv.	Long-run trend on land yield improvements	1% per year	Ray et al. (2013)	plus 20%, less 20%
10	Economic growth	Economic growth	Varies by region and by year	Chen et al. (2016)	plus 20%, less 20%
11	Population growth	Population growth	Varies by region and by year	Chen et al. (2016)	plus 20%, less 20%

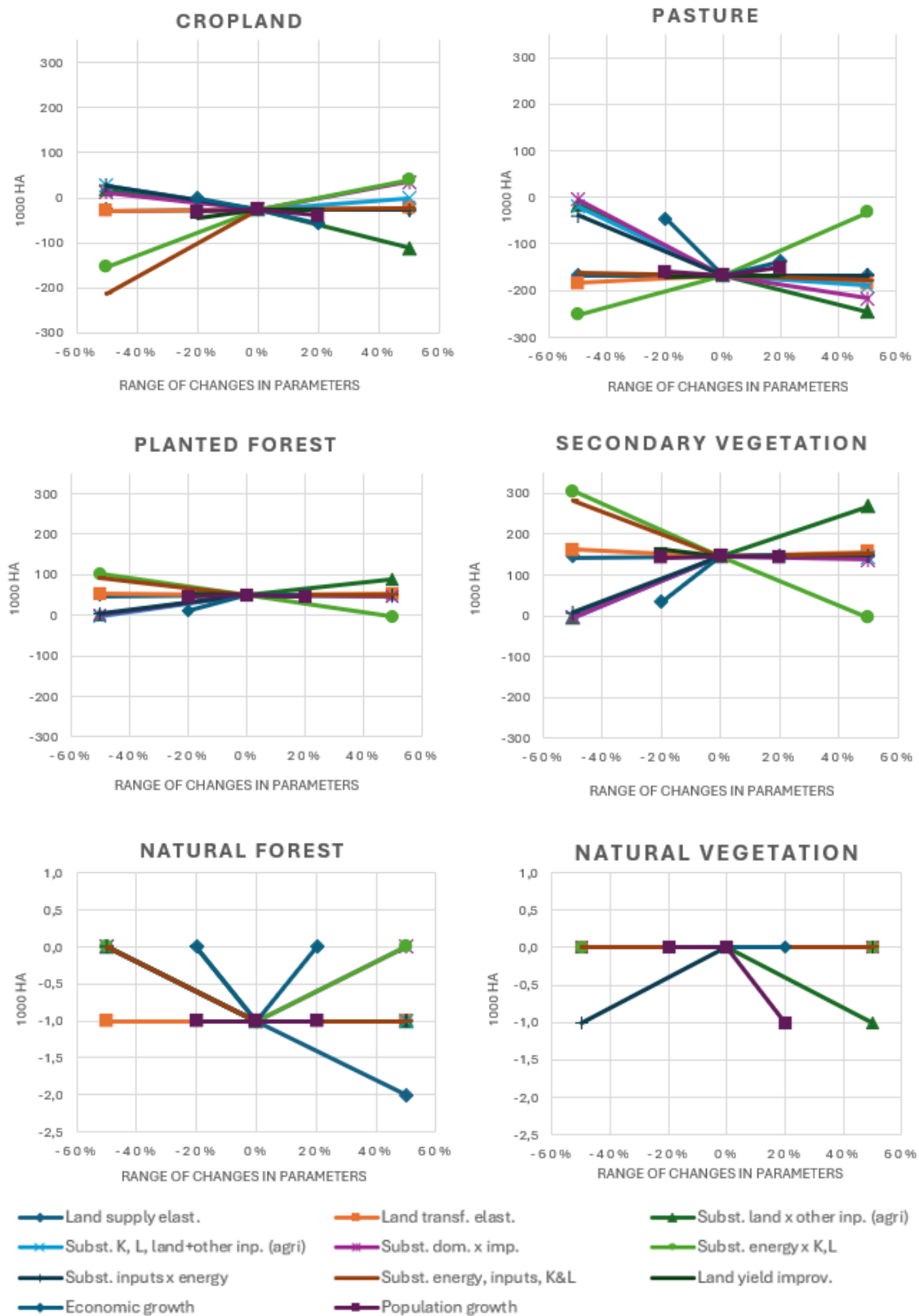


Figure S12. Land use change sensitivity

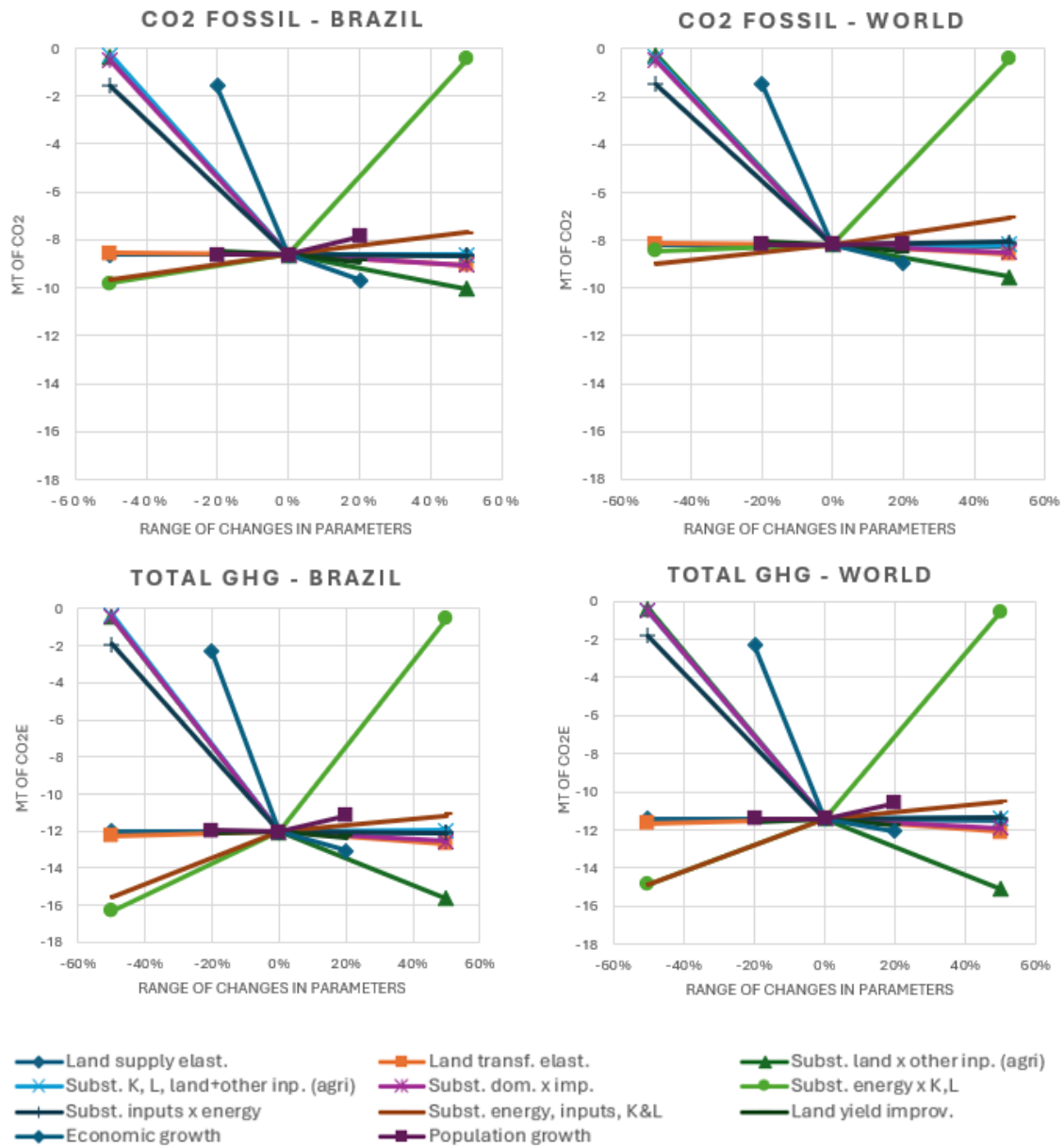


Figure S13. Sensitivity analysis: CO₂ fossil and GHG emissions for Brazil and the World

5. Regions represented in the economic models

Table S8 lists the regions and sectors represented in the PAEG model. Table S9 shows regions and sectors in the EPPA model.

Table S8. Regions and industries represented in the PAEG model

Symbol	Region	Symbol	Sectors/Commodities
NOR	Brazilian North region	PDR	Paddy rice
NDE	Brazilian Northeast region	GRO	Cereal grains
COE	Brazilian Midwest region	OSD	Oil seeds
SDE	Brazilian Southeast region	C_B	Sugarcane and sugar beet
SUL	Brazilian South region	OAP	Animal products
RMS	Rest of Mercosur	RMK	Raw milk
USA	USA	AGR	Other agricultural products
CAN	Canada	FOO	Food products
MEX	Mexico	TEX	Textiles
ROA	Rest of Americas	WAP	Wearing apparel leather products
EUR	European Union	LUM	Wood products
REU	Rest of Europe	PPP	Paper products publishing
JPN	Japan	CRP	Chemical rubber plastic prods
RUS	Russia	MAN	Other manufacturing
CHN	China	SIU	Public utility industrial services
IND	India	CNS	Construction
ANZ	Australia and New Zealand	TRD	Trade
ASI	Fast development Asia	OTP	Transport
AFR	Africa	SER	Services
MES	Middle East		
RAS	Rest of Asia		

Table S9. Regions and Industries represented in the EPPA model

Symbol	Region	Symbol	Sectors/Commodities
USA	United States	PDR	Paddy rice
CAN	Canada	WHT	Wheat
MEX	Mexico	GRO	Corn and other cereal grains
JPN	Japan	V_F	Vegetables - fruit - nuts
ANZ	Australia - New Zealand	OSD	Soy and other oil seeds
EUR	Europe	C_B	Sugar cane - sugar beet
ROE	Eastern Europe	PFB	Plant-based fibers
RUS	Russia Plus	OCR	Other crops
ASI	East Asia	CTL	Bovine cattle, sheep and goats, horses
CHN	China	OAP	Poultry and swine
IND	India	OLIV	Other livestock
BRA	Brazil	FORS	Forestry
AFR	Africa	LUM	Wood products
MES	Middle East	OTH	Other industries
LAM	Latin America	FOOD	Food products
REA	Rest of Asia	COAL	Coal
KOR	South Korea	OIL	Crude oil
IDZ	Indonesia	ROIL	Refined oil
		GAS	Gas
		ELEC	Electricity
		NMM	Non-metallic minerals, cement, lime, gravel, concrete
		I_S	Iron & steel basic production and casting
		NFM	Non-ferrous metals production and casting
		OEIN	Other energy-intensive industries (includes chemicals)
		CNS	Construction
		OSER	Other services
		TRAN	Transport
		DWE	Ownership of dwellings

6. Data Sources Used on the Socio-Economic Modeling

Several data sources are used to build the socio-economic models. Physical information for energy, agriculture, and natural resource markets, was based on data from the United Nations Food and Agriculture Organization (FAO, 2020), the Organization for Economic Co-operation and Development (OECD-FAO, 2019), the International Energy Agency (IEA, 2012, 2015), and domestic statistics (in Brazil's case: the *Companhia Nacional de Abastecimento* (CONAB, 2023), the *Instituto Brasileiro de Geografia e Estatística* (IBGE, 2010, 2014, 2020) and the *Empresa de Pesquisa Energética* (EPE, 2021). Macroeconomic projections by the International Monetary Fund (IMF, 2021) are used as a reference for projecting future scenarios.

The household income classes in the PAEG model are grouped by monthly household income, based on the Brazilian IBGE Household Budget Survey (IBGE, 2014). These are defined as: household F01: income up to US\$ 240; F02: more than US\$ 240 up to US\$ 360; F03: more than US\$ 360 up to US\$ 599; F04: more than US\$ 599 up to US\$ 719; F05: more than US\$ 719 up to US\$ 958; F06: more than US\$ 958 up to US\$ 1,198; F07: more than US\$ 1,198 up to US\$ 1,796; F08: more than US\$ 1,796 up to US\$ 2,395; F09: more than US\$ 2,395 up to US\$ 3,593; F10: more than US\$ 3,593. Per capita monthly income in Brazil in the benchmark year was US\$1,006 at current prices and market exchange rate. Per capita monthly income at power parity purchase (PPP) was US\$1,305. PPP equalizes the purchasing power of different currencies by eliminating the differences in price levels between countries allowing comparison among them. There are different institutions defining income groups in Brazil. Using the definition by Brazil-SAE (2012), F01 to F03 are low-income households, F04 to F07 are middle-income households, and F08 to F10 are high-income households.

7. Methodological innovations for representing second cropping

Both PAEG and EPPA models were enhanced to represent the energy and food production system from the raw material corn, as well as the two-crop production system (double-cropping) for the case of rotation between soybean and second-crop corn. Production functions representing the amounts of inputs and energy used and the amounts of products generated by a typical multi-cropping corn ethanol plant (ethanol, DDG, power, and corn oil) were introduced in the model, according to data provided by the industry (see quantitative coefficients in Figure 6 of the paper and cost and value assumptions on Table S10).

Table S10. Cost assumptions and amounts used for introducing second-crop corn ethanol in the PAEG and EPPA models – costs for processing 1 ton of corn and producing 425 liters of ethanol

Item	US\$
Corn (2nd crop)	82.85
Biomass	13.35
Labor	9.11
Chemical inputs	5.67
Enzymes	5.95
Other production costs	11.73
Depreciation	7.57
Total	136.23

Source: Information provided by an industry company.

In the PAEG model, the multi-cropping corn ethanol production system was introduced in the Brazilian Midwest region, as 95% of the volume currently produced nationally comes from that region. In the EPPA model, the system was considered for all Brazilian regions. Figure S14 presents the correspondence between the original PAEG products and the products generated by the multi-cropping corn ethanol industry.

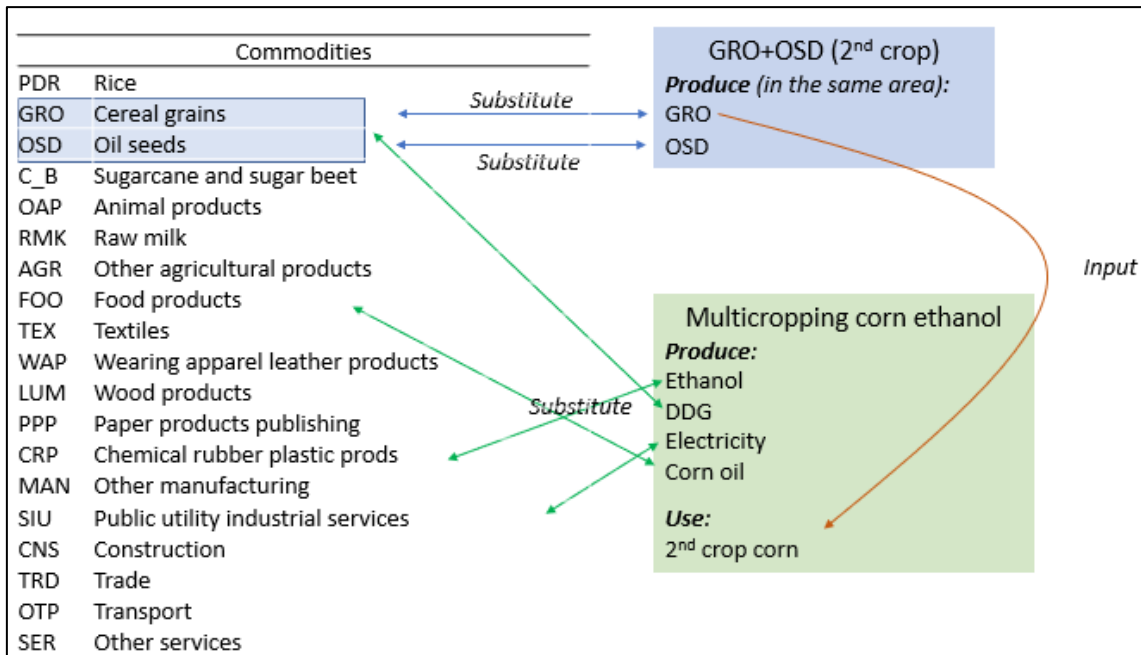


Figure S14. Industries and products originally represented in PAEG (left), and industries and products introduced for representing the corn ethanol production system and corn plus soybean double cropping, with the respective correspondence to the original GTAP products

Regarding modeling the multi-cropping corn production, in the case of the PAEG model, Figure S15 illustrates the functions of soybean and corn production and land use allocation, before the introduction of double-crops in the model, which follows the formulation of the GTAP-BIO model (Golub and Hertel, 2012; Taheripour and Tyner, 2013). In this figure, soybeans and corn are produced separately, based on the combination of productive factors, land, labor, capital, and domestic and imported intermediate inputs. The various σ parameters establish farmers' ability to substitute factors and inputs in the production process.

Each industry uses land factor amounts that are specific to that industry, which is offered by allocating the total area for the different agricultural uses. Under this representation, a shock that increases demand for the corn product will cause an increase in the use of productive factors and inputs applied in producing corn, including land, which is only possible by reducing the land use factor in other industries, including soybeans, as represented by the land use allocation panel at the extreme right of Figure S15.

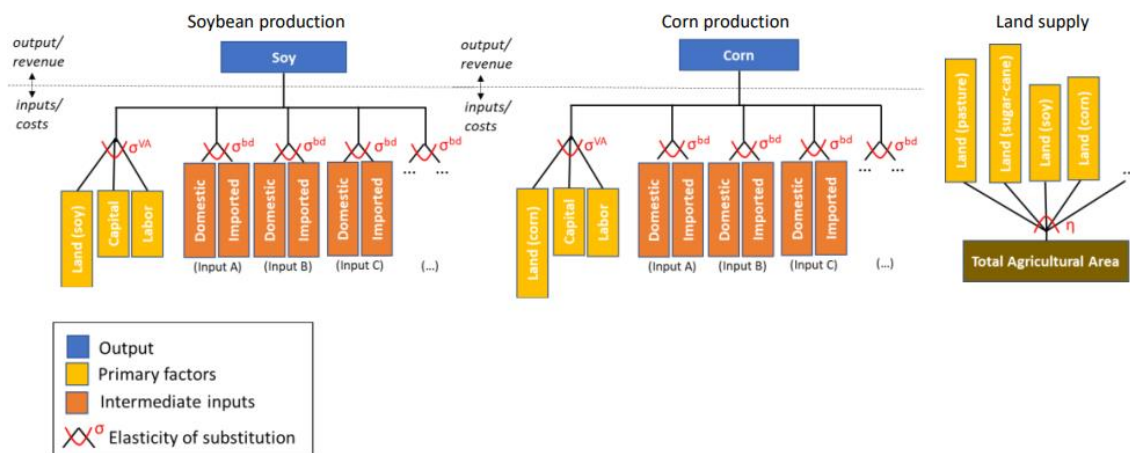


Figure S15. “Technological trees” for soybean and corn production as single-cropping sectors, industries, and land use allocation in the PAEG model, before introducing double-cropping modeling

Figure S16 shows how the soybean-corn production system in the same area was introduced into the PAEG model, as well as the changes made to the original functions of corn production and land use allocation. Soybeans and corn can now be produced by the same sector, and the remuneration of the land factor from producing second-crop corn is associated with the same physical area used for soybean production.

This way, shocks from increases in demand for corn can lead to growth in producing second-crop corn, which will require expansion of the corn area over the area previously used for producing single soybeans, thus preventing the two cultures from competing for land use. On the other hand, first-crop corn production considers only the physical area used for its production, while the land use allocation function distinguishes the economic return from the first-crop corn area from what is obtained by the soybean-corn production system. The “single” soybean production function does not require any change.

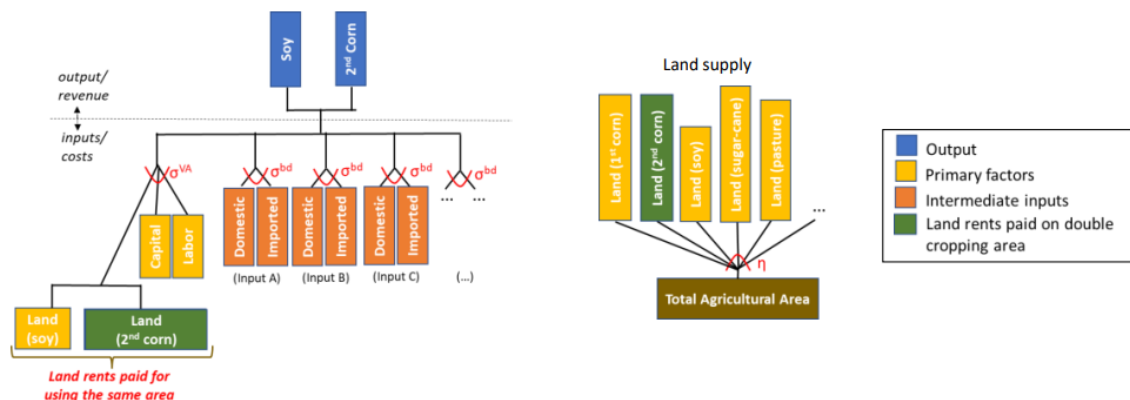


Figure S16. Representation of the soybean-corn, first-crop corn production system and land use allocation in the PAEG model, through explicit double-cropping modeling

8. Scenarios applied in the socio-economic models

Figure S17 shows the scenarios applied to the PAEG model. We simulate a 5-billion-liter multi-cropping maize ethanol increase. Production in 2020, before the shock, was 2.9 billion liters, reaching 8 billion liters in 2030. Additionally, DDG, corn oil, and bioelectricity are produced as co-products.

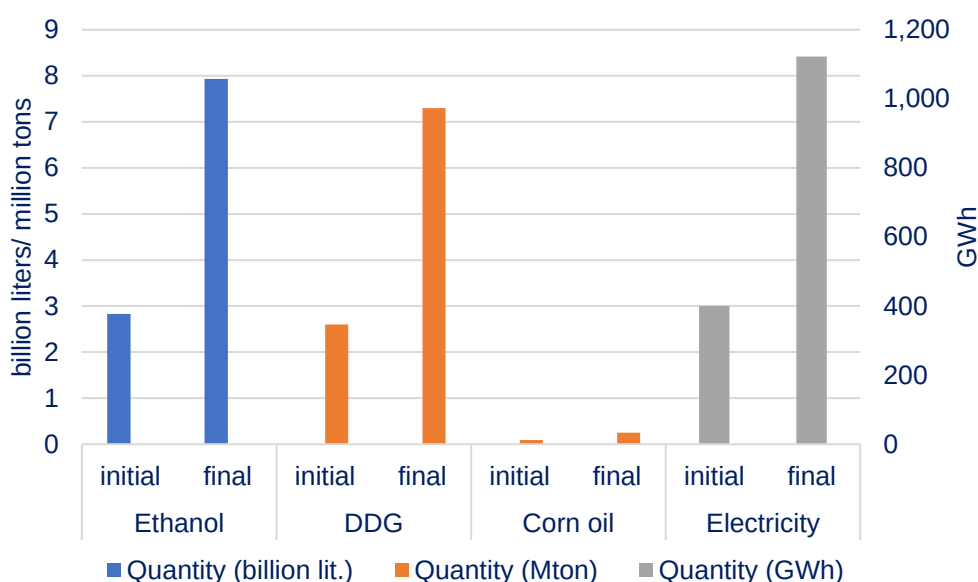


Figure S17. Shock applied on the PAEG model

Energy inputs (steam and power) are provided by an adjacent thermoelectric (cogeneration) plant using biomass as fuel. The electricity column is an excess electricity (co-product) that is usually sold to the power grid.

Table S11 describes scenarios applied to the EPPA model, their assumptions, and fundamentals.

Table S11. Scenarios applied to the EPPA model

Scenario	Multi-cropping maize ethanol (2030) (Billion liters)	Sugarcane ethanol (2030) (Billion liters)	Description
3bi	2.9 (Observed in 2020)	38.6 (MME projection)	Multi-cropping maize ethanol production constant at levels seen in 2020 + MME sugarcane ethanol projection
8bi	8.0 (MME projection)	38.6 (MME projection)	MME multi-cropping maize and sugarcane ethanol projection – multi-cropping maize ethanol grows from 2.9 billion to 8 billion liters (via efficiency gains), but BECCS does not develop.
8bi+ BECCS (conservative)	8.0 (MME projection) (0.78 w/ BECCS)	38.6 (MME projection)	Same as Scenario 8bi + adding BECCS (2025: 0.53 billion liters; 2030: 0.78 billion liters) (Sequestration of 0.59 million tons of CO ₂ at US\$ 73/ton)
8bi+ BECCS (optimistic)	8.0 (MME projection) (5.05 w/ BECCS)	38.6 (MME projection)	Same as Scenario 8bi + BECCS, but considering greater volume expansion with BECCS, as follows: 2025 = 2.5 billion liters and 2030 = 5.05 billion liters) (Sequestration of 3.8 million tons of CO ₂ at US\$ 73/ton)

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