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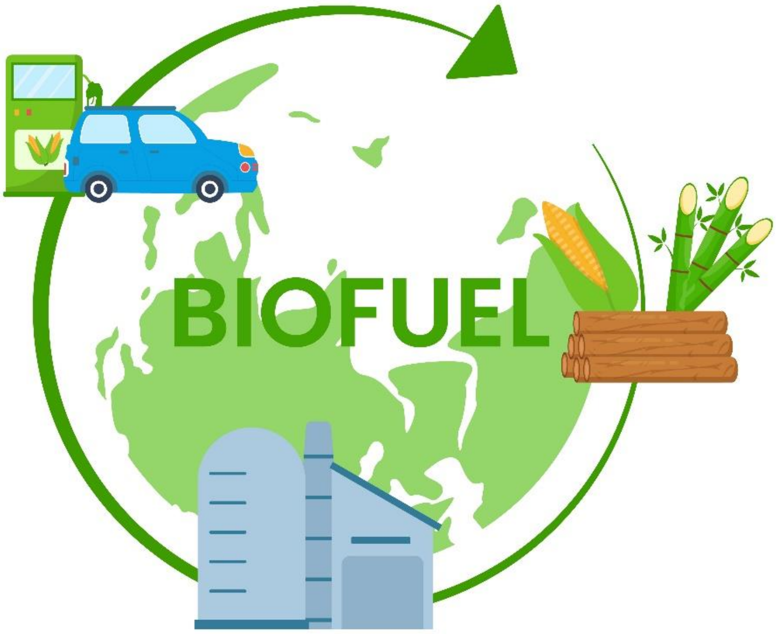

Evaluation of the Brazilian RenovaBio conversion-free criteria on land use change emissions

Brazilian Biofuel Program and the use of risk-management approach

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Executive Summary

Dealing with Land Use Change (LUC) emissions is the most challenging aspect of any bioenergy program in the context of climate change, and this has a central role in defining policy. Induced Land Use Change (ILUC) emissions cannot be measured, and there is no consensus on the best way to estimate a quantitative ILUC value. Programs that apply ILUC values as point estimates for specific pathways have been criticized due to the impreciseness of models, lack of convergence of results, and significant dependency on models and premises. The alternative to point estimates is to develop ILUC risk strategies, which are also challenged to demonstrate their effectiveness regarding induced emissions. This study focuses on the RenovaBio approach and evaluates the effectiveness of its risk-based approach, through the eligibility criteria, in reducing ILUC emissions in the Brazilian context. RenovaBio is based on certification and life cycle assessment, but LUC emissions are not accounted for. They are managed through three main criteria: "no conversion of natural vegetation." In our analysis, we merged the BLUM (Brazilian Land Use Model) with BRLUC 2.0 carbon stocks to evaluate how LUC emissions change in two different scenarios and thus evaluate the effectiveness of the conversion-free criteria by 2030. When direct deforestation is not allowed due to RenovaBio requirements, the stimulus of the expansion effect is reduced. Simulations show significantly lower emissions (-428 Mt CO_2e) with the no-conversion criteria compared to the no-criteria alternative, representing an additional reduction of 63% when the restriction is considered. Although we know the uncertainty associated with this value, its magnitude is sufficient to conclude that it is crucial to maintain these eligibility criteria in the RenovaBio Program. This observation is specific to the Brazilian context but highlights the need to keep policy efforts and traceability to avoid induced deforestation.

INTRODUCTION

The relationship between biofuels and Land Use Change (LUC) is a highly controversial issue and a sensitive point for the design of biofuel programs worldwide, mainly because the Induced Land Use Change (ILUC) associated with the production of biomass for biofuels can result in significant GHG emissions and undermine the carbon economy related to the biofuel use (Brandão et al., 2022; Lark et al., 2022).

Despite the development of various models, there are currently no widely accepted methodologies. The scientific community is engaged in significant debate regarding the most appropriate approaches based on specific geographical, production, and other factors (Plevin et al., 2014; Rosa et al., 2016). However, there is still no consensus on the subject in the scientific literature. The ILUC estimates are uncertain and depend on various assumptions, leading to diverse results based on the crop, region, production pattern, and the model used for analysis. Given the methodological complexity of estimating induced land use emissions, biofuel programs have assumed different strategies to address the issue (Daioglou et al., 2020; Prussi et al., 2021).

The Renewable Energy Directive (RED III), a European Union policy, only considers direct effects and does not assign default values to dLUC, using a risk management assessment approach for induced effects. On the other hand, the Low Carbon Fuel Standard (LCFS), a program run by the state of California in the United States, models direct and indirect effects together (CARB, 2021; ISCC, 2019). Within the International Civil Aviation Organization (ICAO) and in discussions to promote sustainable aviation fuels, the concept of low-

ILUC risk has been adopted along with a quantitative approach.

Overall, the main strategies adopted in biofuel programs worldwide are: (i) estimating LUC emissions (in gCO_2e/MJ) and adding them to the biofuel carbon footprint; (ii) not allowing the use of specific areas for biofuel production; (iii) applying risk management in combination with other policies related to land use; (iv) identifying and encouraging low-risk practices regarding ILUC (at an individual level); (v) restricting feedstock with high ILUC risks; and (vi) classifying advanced fuels with preferential access to the market.

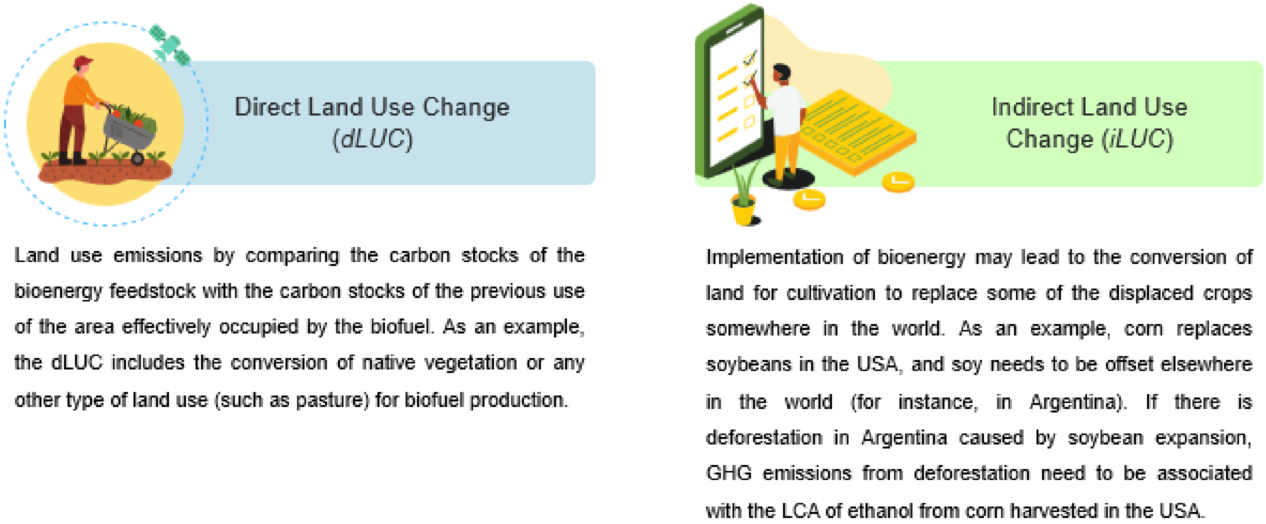
Brazil has an extensive biofuel industry that, since 2017, can be certified under the RenovaBio Program framework and rewarded for avoiding greenhouse gas (GHG) emissions, promoting sustainable development. RenovaBio intends to reduce the carbon footprint of fuels sold in Brazil by around 10% until 2030, corresponding to avoided GHG emissions of 678 $MtCO_2e$. The policy's objectives are (i) to provide a relevant contribution to achieving the Brazilian commitments under the Paris Agreement, (ii) to promote the adequate expansion of biofuels in the energy mix, with emphasis on the regularity of fuel supply, and (iii) to ensure predictability of fuel markets, introducing energy efficiency gains and reduction of GHG emissions during the production, commercialization, and use of biofuels (ANP, 2019; MME, 2020).

RenovaBio is based on certification, life cycle assessment (LCA), and ILUC emissions, which are not accounted for but managed through three main criteria, including "no conversion of natural vegetation." The Program does not consider ILUC due to the challenge of directly measuring induced GHG emissions. Instead, it establishes eligibility criteria to prevent using biofuels sourced from high-carbon land or deforested areas. Only biofuels meeting the eligibility criteria can access the RenovaBio program. Besides protecting more sensitive areas, the objective of the eligibility criteria is to strengthen planning land use in Brazil. RenovaBio's fundamentals recommend updating the eligibility criteria following scientific progress and database availability (Moreira et al., 2018). This study focuses on the RenovaBio approach, evaluating the effectiveness of its risk-based strategy through eligibility criteria to reduce ILUC emissions in Brazil.

THE ISSUES OF LAND USE CHANGE

Different studies show that the carbon footprint of biofuels can vary significantly depending on the previous use given to the land (Fargione et al., 2008; Righelato & Spracklen, 2008). In literature, this type of conversion is conventionally called direct Land Use Change – dLUC. The dLUC calculates land use emissions by comparing the carbon stocks of the bioenergy feedstock with the carbon stocks of the previous use of the area effectively occupied by the biofuel. The dLUC includes the conversion of native vegetation or any other type of land use (such as pasture) for biofuel production. Depending on the land use conversion to biofuel, the production can generate "carbon debts" that can take decades or even hundreds of years to pay off. It is also possible that biofuels increase LUC-related carbon stocks when biomass occupies areas with low carbon stocks and cultivation adopts predominantly "conservation agriculture" practices (Cerri *et al.*, 2007; Junior *et al.*, 2018; Oliveira *et al.*, 2017).

The issue becomes more controversial when the indirect LUC (iLUC) effects are also considered. In a high-impact article, Searchinger *et al.* (2008) extended the dLUC emissions concept to include all induced effects of this change, creating the iLUC concept. For example, if corn replaces soybean in the United States, that soy needs to be offset elsewhere in the world (for instance, in Argentina), and if there is deforestation in Argentina caused by soybean expansion, GHG emissions from deforestation need to be associated to the lifecycle of ethanol from corn harvested in the United States (Figure 1).



Land use emissions by comparing the carbon stocks of the bioenergy feedstock with the carbon stocks of the previous use of the area effectively occupied by the biofuel. As an example, the dLUC includes the conversion of native vegetation or any other type of land use (such as pasture) for biofuel production.

Implementation of bioenergy may lead to the conversion of land for cultivation to replace some of the displaced crops somewhere in the world. As an example, corn replaces soybeans in the USA, and soy needs to be offset elsewhere in the world (for instance, in Argentina). If there is deforestation in Argentina caused by soybean expansion, GHG emissions from deforestation need to be associated with the LCA of ethanol from corn harvested in the USA.

Figure 1. dLUC versus iLUC in the context of CO_2 emissions
Source: Agroicone (2024).

Subsequent studies showed that the initial iLUC estimates might have been overestimated due to model simplifications, the feedstock, and the context in which biofuels are inserted (Prussi et al., 2021; Zilberman et al., 2018; Valin et al., 2015; USEPA, 2010; Dale et al., 2010). Depending on the context, iLUC values may even be negative (Kerdan et al., 2019; Moreira et al., 2020; Cherubin et al., 2021; Zhao et al., 2021; Naess et al., 2021; Fiorini et al., 2023).

Understanding the effectiveness of the current eligibility criteria for LUC is the main gap to be filled in the short term to improve the RenovaBio program. Some civil society groups criticize RenovaBio's option of not considering and accounting for induced emissions (Maia et al., 2022). On the other hand, the eligibility criteria require geoprocessing techniques and interpretation of satellite images, conducted individually for each rural property, regardless of its size (Grangeia et al., 2022), which is an additional production cost. Such cost is inversely proportional to the scale of production and can be a barrier for smallholders. It is therefore relevant to evaluate the need to maintain such criteria, analysing their real effectiveness in mitigating deforestation and understanding the impacts of this policy on the different types of producers. The analysis presented here will contribute to this discussion.

RenovaBio manages LUC emissions through risk management strategies and the establishment of eligibility criteria. The current eligibility criteria are summarised as follows: (1) traceability of the raw material; (2) prohibition of biofuels from areas of native vegetation after November 2018 in all Brazilian biomes and compliance with the Forest Code (FC); (3) mandatory enrolment in the Rural Environmental Registry (CAR, *Cadastro Ambiental Rural*, in Portuguese), and (4) compliance with the Agroecological Zoning for Palm Oil (ZAE-Palma, for Brazilian producers), which seeks to restrict the expansion of such cultivation in sensitive areas and over native vegetation (Strapasson et al., 2013) (Figure 2)).

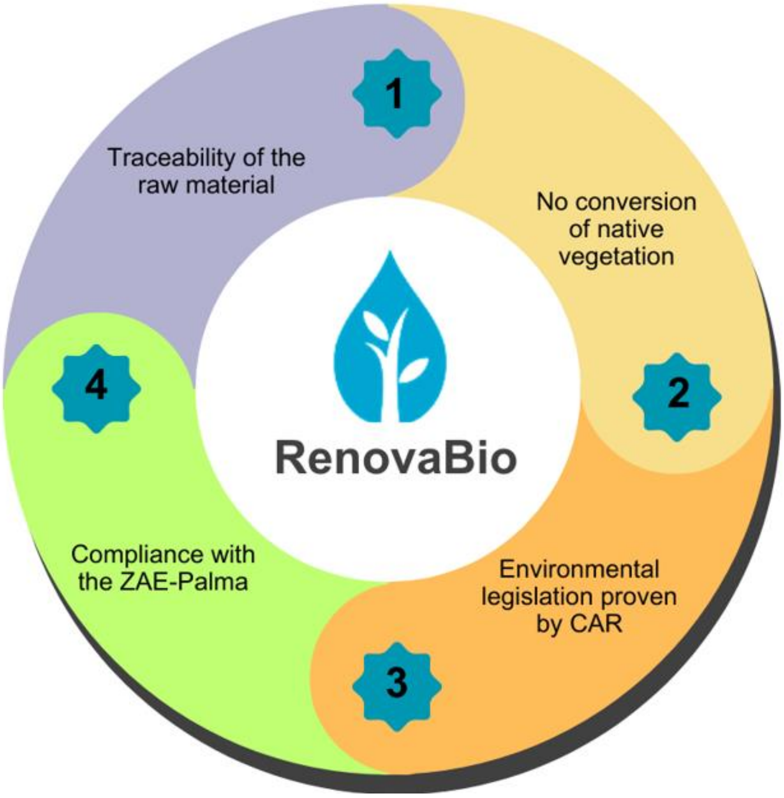


Figure 2. Eligibility Criteria for the RenovaBio Program
Source: Agroicone (2024).

The first and second criteria avoid the direct conversion of native vegetation. Criteria (3) reinforces the need to comply with the Brazilian Forest Code and other criteria verified by CAR. The fourth one strengthens the palm oil zoning (given the controversy regarding the use of this commodity for biofuel production). Additionally, the verification process is reviewed by a third party through a recognized inspector firm accredited by the ANP (in Portuguese, *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis)* (ANP, 2018; NOVAES et al., 2024). RenovaBio´s regulations require that the LUC theme be scientifically monitored and improved (Moreira et al., 2018; Matsuura et al., 2018).

METHODOLOGY

The Brazilian Land Use Model (BLUM)

This analysis uses the Brazilian Land Use Model (BLUM) to simulate contrafactual scenarios, with and without RenovaBio's conversion-free eligibility criteria, and compare their respective Land Use Change (LUC) emissions. Comparing these contrafactual scenarios isolates the contribution of the conversion-free criteria in reducing LUC emissions.

BLUM is a recognized model for analyzing Brazil's agricultural dynamics and land use. It was used in policy and academic arenas in Brazil and worldwide. For instance, the Renewable Fuels Standard 2 (RFS2) program (USEPA, 2017), the "Brazil Low Carbon Study" project (World Bank, 2010), the quantitative data for the Brazilian iNDC (Brazil, 2017a), the Brazilian NDC bioenergy strategy (Brazil, 2016) and the Partnership for Market Readiness (PMR) Brazil projects with their respective carbon market designs for agriculture and land use simulations (Rovere et al., 2020), all used BLUM as a quantitative tool. This model has been highly regarded in impactful articles and holds significant scientific importance (Grottera et al., 2022; Moreira et al., 2020).

BLUM Dynamics

BLUM is a one-country, multi-regional, multi-market, dynamic, partial-equilibrium economic model representing and detailing Brazil´s agricultural sectors, which comprises two sections: supply/demand and land use. The BLUM model is recognized for its ability to depict Brazil's land use changes. To distinguish this model from others, a comprehensive analysis of the Brazilian case was conducted, which includes: (i) an endogenous representation of multi-cropping; (ii) a representation of livestock technologies with the ability to switch between systems; (iii) a theoretical land use structure that can identify substitutions between uses; (iv) the use of Geographic Information System (GIS) tools to calibrate the elasticities governing land use dynamics; and (v) a regional analysis of the sugarcane sector's technological profile and the capacity to integrate innovative technological routes (ICONE, 2018). Figure 3 illustrates the land use dynamics in the BLUM model.

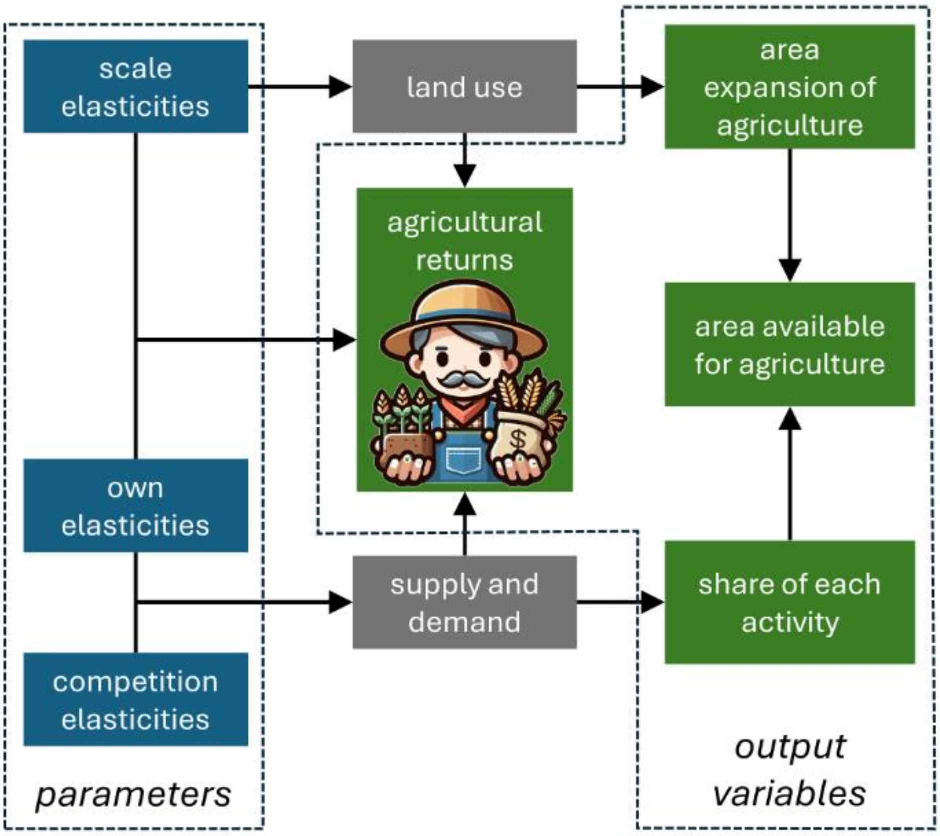


Figure 3 - Land use dynamics in the BLUM model
Source: Agroicone (2024).

Harfuch et al. (2017) and ICONE (2018) provide a detailed description of the BLUM model, which has been improved over time (additional information in Appendix).

Scale and substitution effects for agricultural areas

In the BLUM model, land use dynamics are influenced by two factors: competition and scale. The competition effect describes how agricultural activities compete for the same land resources. Meanwhile, the scale effects represent how this competition leads to additional agricultural land, which is assumed to reduce natural vegetation (ICONE, 2018).

The competition effect involves a mathematical system that assigns a portion of agricultural land to different crops and pastures based on their profitability and prices. This system shows that if one activity becomes more profitable, it will receive a larger share of the allocated land, causing a decrease in the share of competing activities. Conversely, if a competing activity becomes more profitable, it will receive a larger share of land, causing a decrease in the share of the first activity. To ensure theoretical consistency, we impose certain conditions, such as homogeneity, symmetry, and adding up, on the elasticity matrices and associated coefficients (Harfuch et al., 2017; ICONE, 2018).

With these coefficients, we can determine the own and cross impacts and competition among various activities. Using this structure, we can simulate land allocation and changes in land use through the BLUM model. These conditions allow us to identify each activity's exchanged area, considering the allocated agricultural land (Harfuch et al., 2017; ICONE, 2018).

Recent history has shown that market incentives (such as higher prices or profits) drive the expansion of agricultural land areas for crops, commercial forests, and pastures, which can lead to deforestation. There is a significant debate about the reasons for deforestation: whether it is due to the lack of a "command and control" policy or the increased profitability of agriculture. This effect is captured through the BLUM scale section, which is composed of equations that define how the returns of agricultural activities determine the total land allocated to agriculture.

More precisely, the total land allocated to agriculture is a share of the total area available for agriculture in each region, and this share responds to changes in the index of agriculture return regionally. Such an index is calculated based on the return of each agricultural use in the region weighted by the area of each activity. This methodological improvement is essential for representing the dynamics of Brazilian agricultural land use (Harfuch et al., 2017; ICONE, 2018).

Regarding the average profitability index, the regional land use elasticity (total area elasticity) is the sum of each activity’s scale elasticities. Thus, the competing elasticities can be calculated directly after total agriculture land elasticity, while total own elasticities were obtained through econometric analysis and literature review (Harfuch et al., 2017; ICONE, 2018). The average profitability index is calculated through the average return of each activity in the region weighted by a vector of deforestation rate caused by each agricultural activity obtained by satellite imagery and GIS modeling.

The scale and competition effects work together. When all other factors remain constant, an increase in the profitability of one activity has three effects: it increases the total agricultural area (scale effect), increases the activity's share of agricultural area (substitution effect of own profitability), and decreases the share of agricultural area for other activities (substitution effect of cross profitability). For competing activities, the cross effects of profitability on the area are negative (Harfuch et al., 2017; ICONE, 2018).

We should note that this structure only accounts for how profitability (because of supply and demand) changes agricultural areas. Other factors (such as logging, mining, land abandonment, changes in government policies and private initiatives, etc.) can also play an essential role in deforestation and are not endogenously considered by the current modeling structure. However, the current analysis is unaffected if such additional factors are not expected to change between baseline and contrafactual scenarios.

The original scale elasticities $e_{r_{li}}^{s_{l,i}\text{o}}$ of each region (*l*), which relate the total available area for agriculture with the profitability *(r)* of each crop type *(i)* were updated for scale elasticities with eligibility criteria $e_{r_{li}}^{s_{l,i,e}}$, according to the following equation (1):

$$e_{r_{li}}^{s_{l,i,e}} = e_{r_{li}}^{s_{l,i,0}} (1- \mathrm{e}_{li}) \tag{1}$$

in which

e_{li} is the share [0%, 100%] of crop *i* in region *l* that is subject to the eligibility criteria,
as discussed in the main reference of the model (Harfuch et al., 2017; ICONE, 2018).

LUC Emissions calculation

The regional land use emissions are calculated by multiplying the changes in land use by the specific emission factor. The model calculates a transition matrix internally, enabling us to track changes in land use over time or compare scenarios in the same year. The matrix results are expressed in hectares (ha), and within each BLUM region, the emission factor matrix displays GHG emissions for each land use change, expressed in tCO_2e/ha. Thus, in each of the *r* regions, LUC emissions of soil cover type *i* to *j* are expressed through equation (2) for each region r_1 to r_6 (p_k) and equation (3) for total emissions in the country (*P*) (Harfuch et al., 2017).

$$p_k = a_{ij}\ F_{ij} \tag{2}$$

$$P = \sum_{k=1}^{6} p_k = \sum_{r1}^{r6} a_{ij}\ \ F_{ij} \tag{3}$$

In these equations, a_{ij} represents the land use change from *i* to *j*, F_{ij} represents the emission factor of the change from *i* to *j*, and r represents the six regions classified in the BLUM model, named r_1 to r_6. In each region, the total emissions are the sum of all transitions i = 1...n. Brazil's total GHG emissions are calculated by adding up the GHG emissions of each region (Harfuch et al., 2017).

Emission factors of BRLUC Model

The BRLUC emission factors were used to obtain more accurate regional emission factors. This model was developed by *Empresa Brasileira de Pesquisa Agropecuária (Embrapa)* to estimate CO_2 emission rates associated with dLUC for 64 cultures, pastures, and silviculture in Brazil. The methodology was published in international journals (Novaes et al., 2017; Garofalo et al., 2022), with recent results that were integrated into the Brazilian products in *Ecoinvent* (Donke et al., 2020), the leading international lifecycle inventory database (Wernet et al., 2016).

The BRLUC carbon stock data were developed based on the leading international references on the subject, especially the Intergovernmental Panel on Climate Change Guidelines (IPCC, 2006, 2019) and the Renewable Energy Directive (RED II) of the European Union (EC, 2010). Additionally, data from the National Greenhouse Gas Inventory (Brazil, 2016), IBGE (Brazilian Institute of Geography and Statistics), and publications in scientific journals were used (e.g., Bernoux et al., (2001), Mello et al., (2014)). The structure of the original model is based on the recommendations of the IPCC and PAS2050.

Scenarios

This analysis evaluates the contribution of the conversion-free criteria of RenovaBio in reducing induced emissions compared to a scenario where such criteria are not considered. Since our objective is to evaluate the effectiveness of the conversion-free criteria, the levels of biofuel production are the same in both scenarios (46.6 billion liters of total ethanol - 38.6 billion liters of sugarcane ethanol and 8.0 billion liters of corn ethanol – and 11.2 billion liters of biodiesel, according to the Energy Research Office (EPE, *Empresa de Pesquisa Energética* in Portuguese) projection scenarios. The two scenarios were presented as follows:

- *Scenario 1 (Reference)* assumes no eligibility requirements and that the behavior of land use dynamics remains unchanged regardless of whether it comes from native vegetation or not (no change in land use patterns). This scenario maintains the BLUM elasticities at the same level as Harfuch et al. (2011) estimated.
- *Scenario 2* was designed to limit the conversion of natural vegetation to the exact proportion of biomass already certified by the program that is coming from areas without deforestation, already occupied by other crops, and released by pasture intensification.

In Scenario 2, the scale elasticity was reduced by 100% in the case of sugarcane and 33% for soybeans, which supports the analysis that resulted in this paper. The RenovaBio restrictions are only imposed on feedstock that uses agricultural land to produce, excluding waste and residues. Brazilian ethanol is primarily made from sugarcane (including second-generation) and second-crop corn. Soybean constitutes about 72% of the national biodiesel output, with the remaining portion mainly derived from other fatty materials (11.5%) and animal fats (11.3%). The residual amount is distributed among the residues. Palm and sunflower oils account for less than 1% of biodiesel production (ANP, 2021). Scenario 2 assumes that 100% of biodiesel and ethanol production will be certified.

The rationale for translating into a share of certified feedstock is described as follows:

Sugarcane: In Brazil, sugarcane is primarily used to produce ethanol and sugar, although other products derived from sugarcane (sugar, brandy, *cachaça*, bioplastics, etc.) and byproducts are also derived from it. The chain of custody system of RenovaBio requires that the share of certified sugarcane ethanol is equal to the proportion of certified sugarcane. Roughly, to achieve 100% certified sugarcane ethanol, all Brazilian sugarcane processed in sugarcane mills would need to be certified.

Soybeans: To produce 7.86 million cubic meters (m^3) of eligible soybean biodiesel (70% of the amount of biodiesel foreseen in the scenario), around 33% of current soybean production in Brazil must be certified. To meet eligibility requirements, around 39 million tonnes of soybean must be used, equivalent to roughly 25% of Brazil's soybean production in the last crop season (2023/24). Additionally, it is common for soybean producers to sell their products to multiple buyers, and interactions between corn ethanol and soy biodiesel can also impact this dynamic.

Corn: Most Brazilian corn ethanol production comes from a second crop. The BLUM model only considers the expansion of agricultural areas of the first crops. As a result, it was assumed that corn ethanol certification does not affect scale elasticities. This is a conservative premise, as reducing elasticity for corn tends to make the change between baseline and shock scenarios higher.

This assessment did not analyze the other two eligibility criteria of the RenovaBio program. The eligibility criteria regarding palm zoning were not included because palm cultivation is expected to be small and only expand over degraded areas (unused land). The eligibility criteria regarding compliance with the forest code through demonstration of the environmental registry was not simulated once different drivers (and not just RenovaBio) induced such compliance.

Contributions of conversion-free areas restriction

According to Scenario 1 (Reference), there will be a significant increase in agriculture activity levels up to 2030. Almost all agricultural commodities will expand between 2020 and 2030. Corn ethanol and biodiesel will grow most at 172% and 141% in the next ten years. Livestock and sugar will have the lowest production growth at 2% and 1%, respectively. Nevertheless, despite the slow growth in sugar production, sugarcane production will expand by 17%, primarily for biofuel production, as sugarcane ethanol production is expected to increase by 29%. Although cattle herd growth is projected to be low, beef production will grow 27% by 2030 due to yield increases in the livestock sector. Additional results of scenarios 1 and 2 are presented in Appendix (Table S4 and S5).

As per the difference between Scenarios 1 and 2, the conversion-free criteria imposed by RenovaBio had a minimal impact on the agricultural and livestock outputs. Production changes between scenarios are nearly 0% (see Table 1). There was a 260,000 cattle head reduction, but beef production remained the same, suggesting an induced yield increase. The same reduction movement can also be observed for soybean and first-crop corn, which decreased by 267,000 tonnes and 229,000 tonnes by 2030. However, this reduction is not significant in absolute terms.

Table 1 - Scenarios comparison of absolute and percentage change of agriculture and livestock production for the 2025-2030 period in Brazil, considering Scenario 2 versus Scenario 1

Agriculture Production	Absolute Change 2025	Absolute Change 2030	% Change 2025	% Change 2030
Sugarcane ethanol (1000m^3)	0	0	0%	0%
Corn ethanol (1000m^3)	0	0	0%	0%

Agriculture Production	Absolute Change 2025	Absolute Change 2030	% Change 2025	% Change 2030
Total ethanol (1000m^3)	0	0	0%	0%
Biodiesel (1000m^3)	0	0	0%	0%
Biodiesel from soybean (1000m^3)	0	0	0%	0%
Sugarcane (1000 tonnes)	8	-12	0%	0%
Sugar (1,000 tonnes)	-11	-13	-0.03%	-0.03%
Soybean (1,000 tonnes)	-208	-267	-0.13%	-0.15%
Soybean Meal (1,000 tonnes)	-24	-36	-0.05%	-0.07%
Soybean Oil	-6	-10	-0.05%	-0.07%
1st crop corn (1,000 tonnes)	-165	-229	-0.48%	-0.63%
2nd crop corn (1,000 tonnes)	52	77	0.05%	0.06%
Total Corn (1,000 tonnes)	-113	-152	-0.08%	-0.09%
Other first-crop cultures (1,000 tonnes)	-22	-27	-0.10%	-0.12%
Cattle (1,000 heads)	-337	-260	-0.15%	-0.12%

Agriculture Production	Absolute Change 2025	Absolute Change 2030	% Change 2025	% Change 2030
Beef (1,000 tonnes)	7	-3	0.06%	-0.03%
Swine Meat (1,000 tonnes)	-1	0	-0.02%	-0.01%
Poultry Meat (1,000 tonnes)	-4	-3	-0.03%	-0.02%

In 2030, the total agriculture and livestock area will be 1.25 million hectares (ha) smaller in Scenario 2 compared to Scenario 1 (see Table 2). About 88% of the reduction is expected to occur in pasture areas (1 million ha by 2030), which face more significant pressure from crops that cannot expand over native vegetation anymore. The decrease in the cultivation of annual crops is relatively insignificant, with soybean and first-crop corn cultivation seeing the most significant reduction (81,000 ha and 44,000 ha, respectively), potentially affecting other grain demands. Brazilian historical data shows that first-crop corn cultivation is reduced, but corn production shifts toward second-crop corn areas.

Table 2 – Scenarios comparison of absolute and percentage agricultural area change for the 2025-2030 period in Brazil, considering Scenario 2 versus Scenario 1

Agriculture Area (1000 hectares)	Absolute Change 2025	Absolute Change 2030	% Change 2025	% Change 2030
Sugarcane	-2	-5	-0.02%	-0.04%
Soybean	-64	-81	-0.15%	-0.18%
Corn 1st crop	-34	-44	-0.55%	-0.78%
Corn 2nd crop	4	4	0.03%	0.02%
Others 1st crop	-12	-16	-0.24%	-0.32%

Agriculture Area (1000 hectares)	Absolute Change 2025	Absolute Change 2030	% Change 2025	% Change 2030
Pasture	-1,001	-1,102	-0.58%	-0.65%
Planted forest	0	0	0%	0%
Restoration	0	0	0%	0%
Total Agriculture Activities and Livestock	-1,113	-1,247	-0.45%	-0.50%

The conversion-free criteria of RenovaBio play a significant role in reducing induced GHG emissions in Brazil, reducing by 428 $MtCO_2e$ in different regional impacts (Table 3). In general, the Cerrado region has the most significant reduction in used land when the conversion-free criterion is applied (total of 590,000 ha), followed by the reduction in the North-Amazon region (478,000 ha), which has the highest number of avoided GHG emissions, since native vegetation carbon stocks of that region are higher. The other regions have smaller changes in area, although the South and Southeast regions are responsible for a representative share of sugarcane and soybean production.

Table 3 - Regional changes in agricultural areas and GHG emissions in scenario 2 compared to scenario 1 (2030)

Region	Agricultural area (1000 ha)	Agricultural area (% Brazil)	GHG Emissions ($MtCO_2e$)	GHG Emissions (%Brazil)
South	0	0%	-175	0%
Southeast	-82	7%	-24,8	6%
Centre-West Cerrado	-342	27%	-66,9	16%

Region	Agricultural area (1000 ha)	Agricultural area (% Brazil)	GHG Emissions (MtCO$_2$e)	GHG Emissions (%Brazil)
North Amazon	-478	38%	-282	66%
Northeast Coast	-97	8%	-5,84	1%
Northeast Cerrado	-248	20%	-48,1	11%
TOTAL	-1,247	100%	-428	100%

In the sensitivity scenario, using different emission factors, results show a significant reduction in LUC emissions when adopting RenovaBio conversion-free criteria, reducing by 218 MtCO$_2$e when comparing Scenario 1 and 2. The North-Amazon region accounts for 76% of the GHG emission reduction and the Cerrado region 20%. On the other hand, the South, Southeast, and Northeast Coast regions have a smaller share in GHG emissions reduction (see Table S5 in Appendix).

DISCUSSION

Researchers have expressed concerns about the RenovaBio program's capacity to address induced emissions, which could potentially compromise its environmental objectives (Maia et al., 2022; Grangeia et al., 2022). The deforestation rates in the Amazon region and the revocation of the Agroecological Zoning of Sugarcane (ZAE-Cana), which regulates the expansion and production of sugarcane, avoiding deforestation, have made these criticisms even more apparent. In this context, this study aimed to assess the effectiveness of RenovaBio's conversion-free criteria in reducing LUC emissions of biofuels in Brazil. As explained in section 2, RenovaBio currently addresses LUC by four eligibility criteria: (1) traceability of the raw material; (2) prohibition of biofuels from areas of native vegetation after November 2018; (3) mandatory enrolment in CAR and (4) compliance with the ZAE-Palma. This is the first study that evaluates the effectiveness of RenovaBio deforestation-free criteria in reducing LUC with a quantitative approach. Our results indicate that the conversion-free criteria could reduce LUC emissions in the 218-428 MtCO$_2$e range between 2020 and 2030, having different regional impacts according to biome but without compromising agricultural output. The GHG reduction achieved with the implementation of the non-conversion criteria indicates that it is effective in reducing GHG emissions compared to a scenario without it.

These findings provide quantitative support to Moreira et al. (2018) premises regarding the appropriateness of land use conversion-free criteria and align with Novaes et al. (2024), who also considered that the eligibility criteria used in the RenovaBio Program are essential to reducing LUC emissions and deforestation. The other two criteria (not assessed in this study) could further reduce LUC emissions.

The most significant contributions to reducing the expansion of agricultural and livestock areas on native vegetation occur in Cerrado regions. At the same time, the most substantial reductions in CO_2e emissions are observed in the North Amazon region. Our result, however, is not sufficiently robust to recommend higher or lower regional enforcement, as this would require future studies. Internationally, some biofuel programs quantify LUC emissions. However, economic models that support such programs often do not account for the impact of “no deforestation” criteria.

RECOMMENDATION

Alongside studies that use modelling to estimate induced land use impacts, this study also has uncertainties. ILUC estimates are uncertain and quite disparate depending on the crop, region, production parameters, and data considered. However, our effort is a pioneering initiative that tries to estimate the impact of RenovaBio’s conversion-free criteria, supporting policy decisions instead of being part of the GHG accounting of the fuel. Similar to this exercise, a risk-based or low-LUC risk could be supported by ILUC models, resulting in a hybrid policy approach (risk-based and quantitative). It can be more practical for managing uncertainty and ensuring consistency. While implementing this approach may be challenging, combined assumptions can help mitigate ILUC risk.

The present study is not exhaustive and does not include all the research needed to make a final decision on LUC management under the RenovaBio program. It would be interesting to develop ways to evaluate all eligibility criteria considered in the RenovaBio Program, change the feedstock mix, consider other models, and analyse the effects of LUC outside Brazil. Beyond the RenovaBio case, this study identifies that no-conversion restrictions can be essential in reducing land use change emissions. It offers a possible method to replicate this evaluation in other jurisdictions and circumstances.

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Appendix

Methodology

The model covers around 95% of the agricultural area in Brazil, with various products included, such as soybeans, corn (first and second crops), cotton, rice, dry beans (first and second crops), sugarcane, wheat, barley, dairy and beef cattle, beef, pork, and poultry (eggs and chicken). The second and winter crops, such as corn, dry beans, barley, and wheat, do not require additional land as they are planted in the same area as first-season crops. Moreover, their production is already accounted for in the national supply. Corn and sugarcane ethanol, biodiesel from soybeans, and waste are included separately in the model for biofuels. These commodities can be broadly classified as agricultural and pasture, while commercial forests are considered exogenous projections, according to ICONE (2018).

BLUM considers the relationships between different sectors. For instance, the grain and livestock sectors are interconnected through feed consumption, mainly corn and soybean meal. In the soybean industry, soybean meal and oil are integral parts of the domestic demand for soybeans and are determined by grinding demand. The biodiesel mandate in Brazil also affects soybean demand. The demand for sugarcane includes sugar and ethanol components. Corn ethanol production involves corn and eucalyptus agricultural inputs and generates co-products such as DDG. Figure S1 illustrates the model's dynamics.

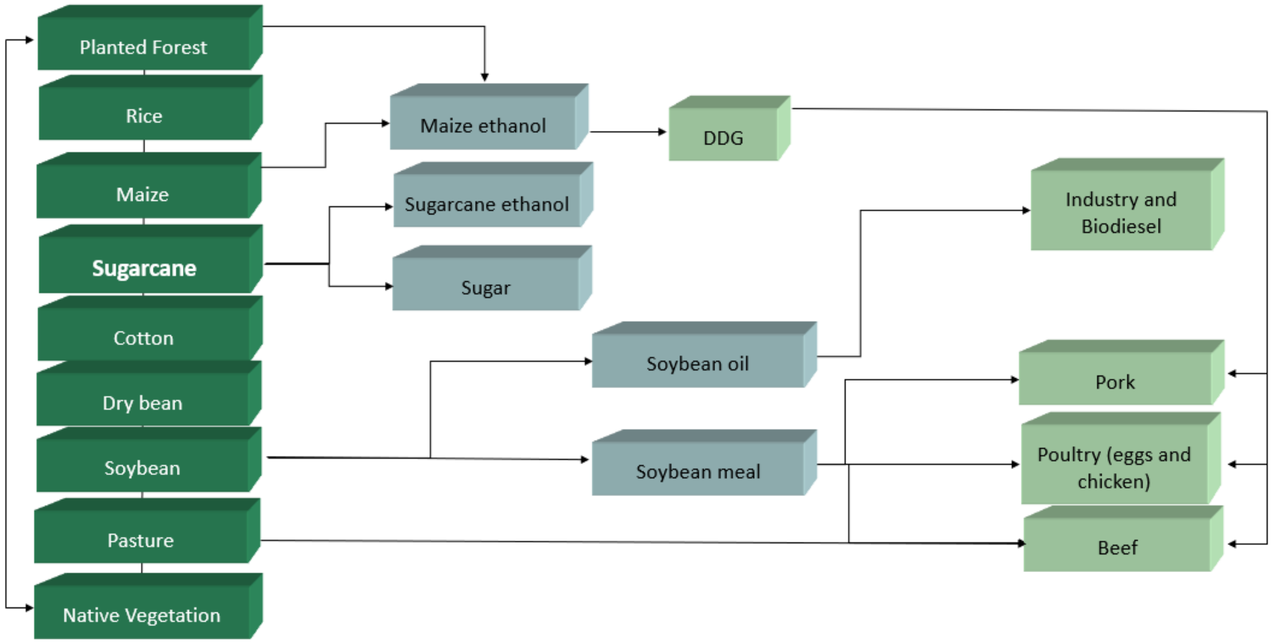

Figure S1 – Interaction between BLUM sectors
Source: Adapted for this study based on ICONE (2018).

The BLUM version of this analysis departs from the version used in the PMR Brazil study but with some updates. All databases, including prices, areas, supply, demand, and net exports, have been updated from 2016 to 2020 to include COVID-19 pandemic data and recovery scenarios. In addition, the corn ethanol sector has been included based on the mass balance published by Moreira et al. (2020).

The macroeconomic assumptions were taken from the National Energy Plan (EPE, 2021), while the exchange rate was based on Central Bank projections until 2024. After that date, the nominal exchange rate was calculated to maintain the fundamental exchange rate constant, considering OECD domestic and international inflation projections (OECD, 2021). Table S1 lists the main exogenous variables considered in the scenarios.

Table S1 - Exogenous Variables considered in each scenario

Variables	Unit	2020	2030: Scenario 1	2030: Scenario 2
Macroeconomic				
GDP Brazil	%	-4.06	3.50	
Population BR	Million	209	224	
Crude Oil price	USD/barrel (nominal)	41	95	
World GDP	Growth (%)	-3.59	3.40	
Fuels				
National ethanol supply (1000m^3)	Sugarcane ethanol	29,936	38,657	
	Corn ethanol	2,946	8,000	
	2G ethanol	0	0	
	Ethanol Imports	581	1,050	
	Total	**32,882**	**46,657**	

Variables	Unit	2020	2030: Scenario 1	2030: Scenario 2
National ethanol demand (1000m^3)	Hydrous	18,842	33,903	
	Anhydrous	9,625	10,365	
	Industrial	1,246	1,246	
	Exports	2,901	2,193	
	Stock Change	0	0	
Biodiesel (1000m^3)	Total Supply	4,664	11,233	
Soybean based biodiesel	% of total biodiesel	70	70	
Compliance with Eligibility Criteria				
Deforestation-free criteria	Change in Model Elasticity	Yes	No	Yes
Sugarcane	Reduction (%)	0	0	100
Soybean	Reduction (%)	0	0	33
Corn	Reduction (%)	0	0	0

Source: EPE (2021) and DBIO/MME and ANP contributions.

Land allocation for agriculture and pasture is determined for six primary regions. Each region is characterized by its agricultural production patterns, land use, political boundaries, biomes, and environmental regulations. Annual production is the crop area multiplied by the respective yield (ICONE, 2018) (Figure S2 and Table S2).

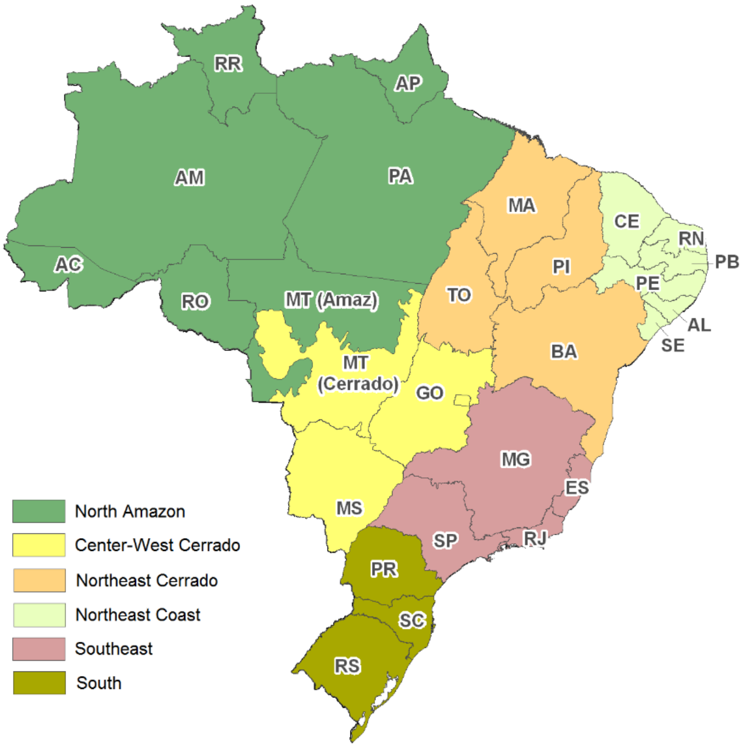

Figure S2 - Regions considered in the BLUM Model
Source: ICONE (2018).

Table S2 - Brazilian states and microregions considered in each BLUM Region

BLUM Regions	Brazilian States considered in BLUM regions
South	Microregions of South state
Southeast	Microregions of Southeast state
Centre-West Cerrado	Microregions of the states of Mato Grosso do Sul, Goiás, and Distrito Federal + microregions of Mato Grosso outside of the Amazon biome*

BLUM Regions	**Brazilian States considered in BLUM regions**
North Amazon	Microregions in the North of Brazil, except microregions Tocantins + of the state of Mato Grosso inserted in the Amazon biome*
Northeast Coast	Microregions of the Northeast, except for the states of Bahia, Maranhão, and Piauí.
Northeast Cerrado	Microregions of the states Maranhão, Tocantins, Piauí e Bahia

*Mato Grosso state has two different biomes (Amazon and Cerrado). The area of each biome was calculated using Geographic Coordinate System (GCS).

The demand is projected at the national level and is influenced by factors such as domestic consumption, net trade (exports minus imports), and final stocks. All demand equations respond negatively to prices, meaning that when the price of a product goes up, the demand for that product goes down. The demand equations also respond to external factors like Gross Domestic Product (GDP), population, and exchange rate (ICONE, 2018).

Conversely, the supply comprises national production, projected regionally (area multiplied by yield), and initial stocks (only considered for grains and sugarcane-based products). Regional area is influenced by each commodity's potential profitability, which depends on the costs, prices, and yields. However, if other crops compete for the same land, regional production may decline due to competition for land (ICONE, 2018).

The model closure is achieved when the price vector balances the supply and demand in all markets and for all years. In simple terms, the model reaches a stable equilibrium when the equation "Initial stock + Production + Imports = Final stock + Consumption + Exports" is satisfied simultaneously across all sectors and years. Every year, a sequence of price vectors is determined, enabling the assessment of the market's trajectory over time. The model generates relevant indicators such as regional land use, national and regional production, prices, consumption, net exports, and direct and indirect GHG emissions from land use in agriculture (Figure S3).

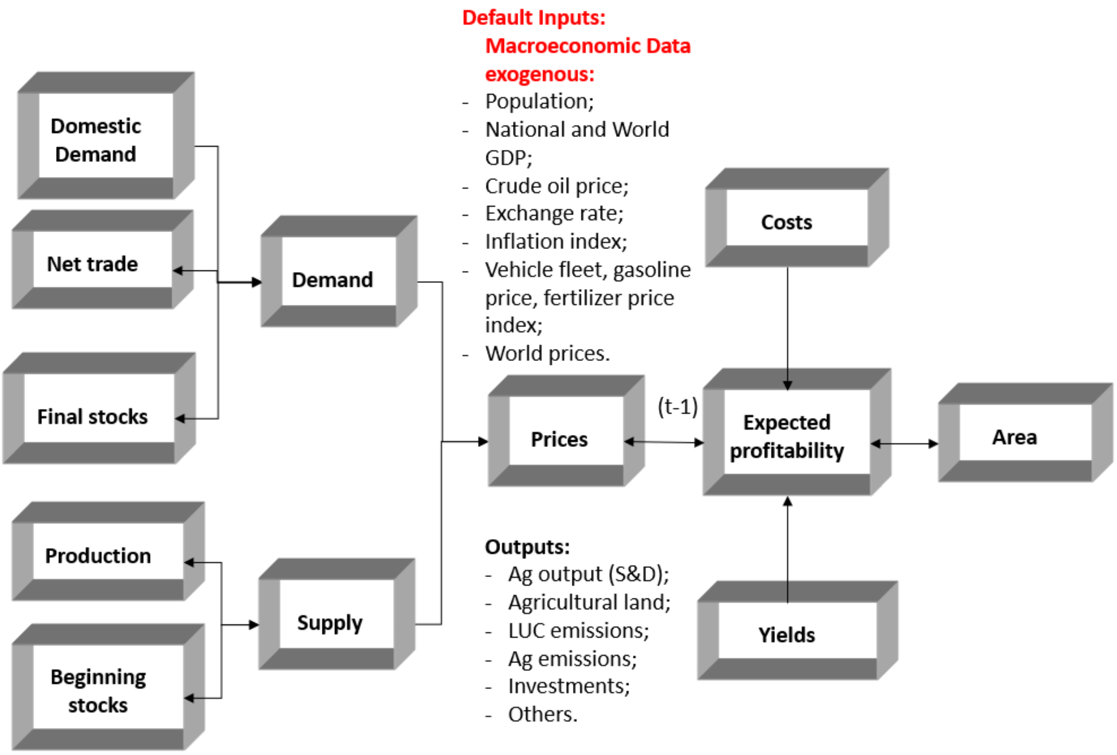

Figure S3 – BLUM model structure
Source: Agroicone (2021).

The premises and sources associated with carbon stock data from different land uses can be critical to the results of the BLUM model. The main assumptions and data sources included in BRLUC 2.0 to estimate land use carbon stocks (Garofalo *et al.*, 2022) are given below:

- Soil carbon stocks were counted for Brazilian microregions, following the political limits defined by IBGE and the climatic limits defined by the Joint Research Commission (JRC).
- The leading land carbon stocks contained in IPCC (IPCC, 2006b, 2019b) were considered biomass carbon stock (CVEG) and soil carbon stock (SOC). The total carbon stock in a particular area is CS = CVEG + SOC.
- According to IPCC guidance, biomass carbon stocks (CVEG) comprise stocks above ground (ABG), below ground (BGB), and dead organic matter (DOM).
- The biomass stocks of agricultural land uses were based on data from the European Commission (RED, 2010), and natural vegetation C stocks are averages of the Phyto physiognomies of the III National Inventory of Greenhouse Gases (Brazil, 2016) (refer to Novaes et al., 2017).
- Soil carbon stocks (SOC) are also estimated based on IPCC guidance and comprise the following components: soil carbon reference stock (SOCref), multiplied by the factor of land-use (FLU), by the management factor (FMG) and by the organic matter input factor (FI).
- Soil carbon reference stocks (SOCref) were taken from Bernoux et al. (2002).
- Factors from soil stock changes (FLU, FMG, and FI) followed IPCC guidance.
- Annual agriculture management was assumed to use no-till.
- Pasture degrading level was assumed as “moderately degraded.”

- Sugarcane carbon stocks were assumed to be equivalent to the "perennial cultures" in the original BLUM version. For BRLUC, biomass stock data from the European Commission were adopted (RED, 2010), and soil management factors were assumed to be intermediate between temporary and perennial culture, according to Novaes et al. (2017) and Garofalo et al. (2022).

Figure S4 shows the steps to integrate the BRLUC 2.0 carbon stock data into the BLUM database. The Brazilian micro-regions were grouped into BLUM regions (Table S2) using a geographical information system (GIS) and dynamic tables from Excel®.

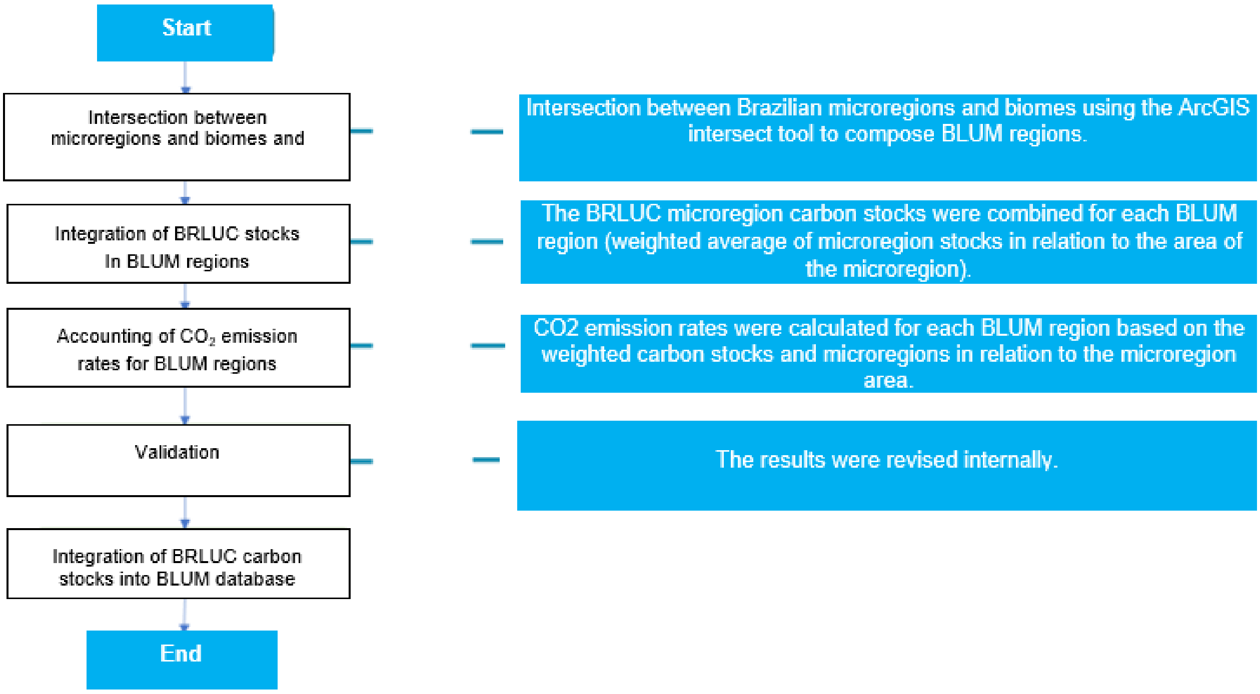

Figure S4 - Step by step to introduce BRLUC carbon stock data into the BLUM database

Composing the BLUM regions requires an appropriate grouping of the Brazilian microregions. For this aim, shapes (.shp) files of Brazilian microregions were used (IBGE, 2020), as well as Brazilian biomes (IBGE, 2019). Both files are referenced in the Geographic Coordinate System (GCS), Datum SIRGAS 2000. The two files were integrated using the GIS ArcGIS Software Intersect tool. Subsequently, the file's geographic coordinate system was transformed, changing from GCS SIRGAS 2000 to South America Albers Equal Area Conic to enable the calculation of microregion areas. The result was exported to the electronic spreadsheet format (.xls) using Excel® software, with a tab containing each land-use category's carbon stocks (tC/ha) for the 558 Brazilian microregions. For each BLUM region, the weighted average of carbon stocks of the microregions was calculated concerning the micro-region area (Table S3).

Finally, the carbon stock values obtained were converted into emission factors for use in the BLUM model by applying the following formula:

*(CSprevious – CSpresent) * 44/12 * 44/12 (carbon conversion rate to* CO_2*).*

Table S3 - Emission factors of the BRLUC method disaggregated in BLUM regions (tCO_2e/ha)

BLUM Regions	Annual to perennial	Pasture to perennial	Pasture to annual	Pasture to planted forest	Native vegetation to annual	Native vegetation to perennial	Native vegetation to pasture
South	-44	7	51	-124	388	344	337
Southeast	-31	7	38	-78	341	310	303
Centre-West Cerrado	-29	9	38	-77	220	191	182
North Amazon	-31	9	39	-160	626	596	587
Northeast Coast	-13	8	21	-85	77	64	56
Northeast Cerrado	-13	17	30	-84	220	206	190

*The category “Perennial Culture” refers to sugarcane. According to Novaes et al., 2017, sugarcane stocks were used instead of perennial culture stocks in this version.

Results

Table S4 - Agricultural production results for Scenario 1 and Scenario 2 (2025-2030)

Production	Scenario 1 2025	Scenario 1 2030	Scenario 2 2025	Scenario 2 2030
Sugarcane Ethanol (1,000m^3)	34,475	38,657	34,475	38,657

Production	Scenario 1 2025	Scenario 1 2030	Scenario 2 2025	Scenario 2 2030
Corn Ethanol (1,000m^3)	5,410	8,000	5,410	8,000
Total Ethanol (1,000m^3)	39,885	46,657	39,885	46,657
Biodiesel (1,000m^3)	9,923	11,233	9,923	11,233
Soy Biodiesel (1,000m^3)	5,233	5,934	5,233	5,934
Sugarcane (1,000 tonnes)	817,091	897,411	817,098	897,399
Sugar (1,000 tonnes)	38,093	41,887	38,082	41,874
Soybean (1,000 tonnes)	154,364	177,484	154,156	177,217
Soybean meal (1,000 tonnes)	48,035	54,509	48,011	54,473
Soy Oil	12,324	13,850	12,317	13,841
Corn 1st crop (1,000 tonnes)	34,688	36,268	34,522	36,040
Corn 2nd crop (1,000 tonnes)	102,937	126,140	102,989	126,217
Total Corn (1,000 tonnes)	137,625	162,408	137,512	162,256

Production	Scenario 1 2025	Scenario 1 2030	Scenario 2 2025	Scenario 2 2030
Other 1st crop cultures (1,000 tonnes)	21,774	22,996	21,752	22,969
Cattle (1,000 heads)	223,241	221,509	222,904	221,249
Beef (1,000 tonnes)	12,092	13,108	12,099	13,105
Pork Meat (1,000 tonnes)	4,886	5,210	4,885	5,210
Poultry Meat (1,000 tonnes)	16,460	17,586	16,455	17,582

Source: Original survey results.

Table S5—Changes in Agricultural Areas, using FAPRI/BLUM emission factors to estimate LUC emissions. Regional results of the agricultural area and GHG emissions variations show changes between Scenario 1 and Scenario 2 and respective LUC emissions in 2030 (adopting the standard BLUM method).

BLUM Regions	Agricultural area (1000 ha)	Agricultural area (%Brazil)	GHG Emissions ($MtCO_2e$)	GHG Emissions (%Brazil)
South	0	0%	-589	0%
Southeast	-82	7%	-3,282	2%
Centre-West Cerrado	-342	27%	-25,156	12%
North Amazon	-478	38%	-165,653	76%

BLUM Regions	Agricultural area (1000 ha)	Agricultural area (%Brazil)	GHG Emissions ($MtCO_2e$)	GHG Emissions (%Brazil)
Northeast Coast	-97	8%	-4,633	2%
Northeast Cerrado	-248	20%	-18,514	8%
Total	-1,247	100%	-217,828	100%

Source: Original survey results.

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