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The potential of a bioeconomy to reduce Brazilian GHG emissions towards 2030: a CGE-based life cycle analysis

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Abstract: Brazil is one of the largest emitters of greenhouse gases in the world with most of its emissions coming from the land use, land use change, and forestry (LULUCF) sector. New commitments have been set by the Paris Agreement and are reflected in the country's Nationally Determined Contribution (NDC). The Brazilian NDC has three main pillars to reduce emissions: increasing the share of biomass in the total primary energy supply to 18%, reducing deforestation, and achieving 45% of renewable energy in the energy mix. It is important to enlarge the share of biomass in the Brazilian economy, but it is also important to assess the potential impacts on deforestation in order to set the right strategy eventually. This study is thus an effort to investigate the contributions of a biobased economy to reduce Brazilian emissions, considering the broader concept of the bioeconomy, using biomass for energy, chemicals, and materials. To satisfy the objectives of the project, especially those related to its interest in economy-wide changes in feedstock (from fossil to biobased), computable general equilibrium modeling (CGE) was chosen as the basic methodology integrated with an economic input–output life cycle analysis (EIO-LCA). Results show that the impacts of the bioeconomy scenarios are positive but not sufficiently high to reduce the estimated emissions drastically. Emissions by the energy sector produce the

highest reductions (7.5%) but the 12% increase in the LULUCF sector offsets those reduction.
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Keywords: bioeconomy; Brazil; economic input–output life cycle analysis; computable general equilibrium; greenhouse gases emissions; non-renewable energy use; NDC

Introduction

Brazil was the seventh largest emitter of greenhouse gases (GHG) in 2014.¹ Between 1990 and 2014, the country was able to reduce its GHG emissions by 29%,² mostly by cutting 54% of emissions from deforestation.³ In its Nationally Determined Contribution (NDC), as part of the Paris Agreement, the country committed to reducing its annual emissions to 1.3 GtCO₂e in 2025, with a target of 1.2 GtCO₂e by 2030. However, the country's recent record on deforestation shows a different trend. Since 2012, following the relaxation of the Forest Code,⁴ the reduction of deforestation has ceased, reaching 7900 km² in the Amazon region alone in 2018,⁵ the highest rate in 10 years. In Cerrado, deforestation reached 6600 km² in 2018.⁶

The 1.2–1.3 GtCO₂e targets were, in fact, defined relative to the emissions in 2005, officially estimated as slightly lower than 2.2 GtCO₂e, including removals, by the time the Brazilian compromise was presented. Some years after, Brazil declared that there was a mistake in its inventory, and the emissions in 2005 were 2.74 GtCO₂e. However, in this paper the basis for the assessment is the absolute emissions in 2025 and 2030, estimated at the time the Brazilian NDC is presented.

Figure 1 shows the historical GHG emissions in Brazil, after the corrections mentioned above. To reach the emissions predicted in the NDC, Brazil would need to cut 0.16 GtCO₂e from 2015 to 2030 in net emissions.

To reduce emissions, the Brazilian NDC has three main options: (a) increase the share of biomass in total primary energy supply to 18%, (b) reduce deforestation, and (c) achieve 45% of renewable energy in the energy mix. It would be crucial to enlarge the share of biomass in the Brazilian economy but it is also critical to assess the potential impacts on deforestation to, eventually, set the right strategy. Thus, this study is an effort to investigate the further contributions of a biobased economy to reduce Brazilian emissions, considering the broader concept of the bioeconomy, using biomass for energy, chemicals and materials.⁸ It is part of a larger project, focused on Brazil, which sought to develop a methodology able to analyze the impacts of a biobased economy on society, GHG emissions, resource use, and land use. To satisfy the objectives proposed by the project, especially its interest in economy-wide changes in feedstock (from fossil to biobased), computable general equilibrium modeling (CGE) was chosen as the basic methodology, integrated with an economic input–output life cycle analysis (EIO-LCA). The use of CGE models and EIO-LCA's to analyze the energy-environment nexus has continuously

Figure 1. Brazilian gross emissions from 1990 to 2017 in million tons of CO₂ equivalent (GWP-AR5).⁷

grown and has many examples to offer, mainly focusing on carbon emissions, and carbon price,^{9–12} emissions reductions and costs,^{13, 14} and, most important, land use and land-use change. For land-use change, an important publication dealing with deforestation and emissions¹⁵ found that food output can increase without land supply expansion.

In the context of the project mentioned above, a first study introducing the CGE model along with its macro and socioeconomic results was published earlier. The current study presents the methodology for the interregional EIO-LCA and the results, in 2030, of the contributions of a biobased economy to GHG emissions (including those from land use) and primary energy supply, considering the Brazilian NDC as the reference scenario. The biobased economy in this study is based on sugars (sugarcane), oil (soybean), and planted forests (short rotation coppice, or SRC).

In the bioeconomy analyzed in this study, there are four energy carriers, which include ethanol, biodiesel, renewable jet fuel, and bioelectricity. There are five chemicals namely ethylene, propylene, acrylic acid, polylactic acid, and *n*-butanol. Each product is produced by one or more feedstocks, from first- and second-generation (1G and 2G) technologies or both (1G2G). While ethylene, propylene, *n*-butanol and ethanol are produced from SRC and sugarcane, renewable jet fuel, acrylic acid, and polylactic acid are only produced from sugarcane. Biodiesel, is only produced from soy. Each of the biobased processes was modeled in this study to integrate energy-sufficient biorefineries and deliver the necessary products. This study considers two levels of technology: first and second generation. First-generation technologies use vegetable and animal oils or simple sugars to produce biofuels and bioproducts whereas second-generation products are produced from cellulose, hemicellulose, or lignin.

Methodology

CGE model

Computable, or applied, general equilibrium models (CGE) are simulations that combine the concept of market equilibrium with economic data, to numerically solve for the levels of supply, demand, and prices that support equilibrium across a set of markets. The empirical basis of CGE models is the interregional social accounting matrix (SAM), which records the revenues and expenses of all agents in the economy, classified as businesses, factors of production, households, government and the rest of the world (or the country), and provides the input–output coefficients of an economy.¹⁶ In this study, two main data sources feed the CGE model with balanced input–output coefficients: the

interregional SAM for the baseline year of 2009,¹⁷ which describes the current sectors of the economy, and economic modeling of the biobased processes.

The macroeconomic CGE model was used in combination with a spreadsheet tool containing the calculated GHG emission factors and primary energy supply factors for each sector in the economy and each biobased product analyzed. Each economic segment of the model (households, industries, government, exports, imports) is described through a specific function and is further explained in the supplementary material to this paper, Appendix S1D (model integration). Figure 2 shows a scheme to summarize the methodology applied in this study. The biobased processes database was created by modeling the biorefineries composed of the four energy carriers and five chemicals analyzed in this study. The modeling details of the biorefineries and the output of the model are presented in Appendix S1B, D, respectively.

The macroeconomic projections are shown in Table 1 and they serve as a basis for creating the baseline scenario (BAU), which is in accordance with the NDC. In this study, the baseline scenario is compared with two biobased scenarios. They are detailed below.

To match the GHG emissions predicted in the Brazilian NDC, land use for livestock in 2030 (BAU scenario) was exogenously determined based on Moreira *et al.*,¹⁸ and was calculated as 1.57×10^4 km². The decrease in land use of 14% by the livestock sector, regarding 2010 (or 0.26×10^6 km²) provides almost all additional land required for the economy in the BAU scenario, leaving only 25×10^3 km² to be provided by expansion, due to deforestation, or an increase of 0.95% in arable land from 2009, as shown in Table 1. To analyze the contributions of the bioeconomy, no extra deforestation is allowed. This was imposed as a land restriction in the CGE model. This means that the agricultural sector will have to adjust to the higher demand for biomass in the bioeconomy, without increasing land availability.

From the results of the CGE model, four main variables are obtained for the calculation of the GHG emissions and primary energy supply in 2030: total energy supply, total fuel consumption, total land use and sectorial production of the other sectors of the economy (industry, public sector, services, etc.). Each of these variables is multiplied by its GHG emission and primary energy supply factors, generating their totals for the country. The next sections detail the procedure adopted for estimating emission factors.

GHG emission factors

In an EIO-LCA the specific system boundary is not required because the boundary is the entire economy. This

Figure 2. General equilibrium model set-up.

Table 1. Targets and input parameters for the Brazilian economy in 2030 in the reference scenario.

Parameter	2009–2030 change	2030 BAU target
GDP (billion US\$ of 2010)*	53.94%	3161.2
Economically active population (million people)**	17.96%	116.9
Households (consumption) (billion US\$)***	52%	1581
Government (consumption) (billion US\$)***	37%	489 998
Investments (billion US\$)***	76%	500 708
Livestock (land use) (km ²)****	–14%	1.57 × 10 ⁶
Land endowment increase (%)	0.95	2.53
* 48		
** 49		
*** 17		
**** 18		

also means that emissions are automatically divided into sectors; this resembles the monetary allocation method. In comparison with process-based LCA, EIO-LCA is considered quick and inexpensive.¹⁹ To calculate the

total environmental impacts of an activity, the EIO-LCA methodology uses technical coefficients, represented by the emission factors (GgCO₂e/MR\$) and primary energy-use factors (toe/MR\$).

For the calculation of emission factors, two approaches were used: one for the biosectors of interest, and another for the rest of the economy, except land-use change. For land-use change, the procedure is based on Approach 1 from the Intergovernmental Panel on Climate Change (IPCC),²⁰ and information is presented in the following section.

For the biosectors, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, were used for two operations: the combustion of biomass for heat and power generation, and the emissions due to leakage from biogas production. Equation (1) (based on Tier 1) shows the procedure for estimating emissions from combustion of biomass.²¹ Only two GHG are considered: CH₄ and N₂O, as CO₂ is considered biogenic.

$$E_{GHG, fuel} = F_{fuel} \cdot EF_{GHG, fuel} \quad (1)$$

where $E_{GHG, fuel}$ are the emissions of a given GHG by fuel (in mass units), F_{fuel} is the amount of fuel combusted (in energy units) and $EF_{GHG, fuel}$ is the default emission factor of a given GHG by type of fuel. In sugarcane-based biorefineries the fuels are bagasse, sugarcane straw and biogas. For eucalyptus-based biorefineries, bark and crown branches are used, while in pine-based biorefineries the fuels used in combined heat and power (CHP) plants are tops, branches, and leaves. Residues related to eucalyptus and pine trees were estimated

based on Brand *et al.*²² and Santiago.²³ Biogas is produced whenever biodigestible material is available (vinasse and unfermented juices). Estimates of biogas production are based on Moraes *et al.*²⁴

In biogas production, emissions of CH₄ from unintentional leakages during process disturbances or other unexpected events are generally between 0 and 10% of the amount of CH₄ generated. Considering that the International Energy Agency Task 47 (working group on energy from biogas) worst scenario is a leakage of 5.5%²⁵ and that IPCC uses a default value of 5%, the default of 5% was used (Tier 1).²⁶

When the own process emits GHG, as is the case of hydrogenation in jet fuel production and of biopropylene metathesis, the emission factors considered are based on literature (additional information presented in Appendix S1D. Table 2 presents the emission factors considered.

Finally, the emission factors in economic basis (GgCO₂e/MR\$) are calculated using Eqn (2). Resulting emissions factors are shown in Appendix S1B, Table B.3 (physical outputs for each facility).

$$E_{bio} = \frac{\sum_1^{fuel} \sum_1^{GHG} E_{GHG, fuel} \cdot GWP_{GHG} + \sum_1^I Q_i \cdot EF_i}{\sum_1^I p_i \cdot Q_i / 1000} \quad (2)$$

Table 2. Emission factors for different emission sources.

Item	Unit	Value
Biomass combustion – Residues*	Kg CH ₄ /TJ	30
Biomass combustion – Residues*	Kg N ₂ O/TJ	4
Biomass combustion – Biogas*	Kg CH ₄ /TJ	1
Biomass combustion – Biogas*	Kg N ₂ O/TJ	0.1
Biogas leakage**	%	5
Propylene production***	tCO ₂ e/t product	0.009
Renewable jet fuel production****	gCO ₂ e/MJ	9
* 21		
** 26		
*** 50		
**** 51		

where E_{bio} is the emission factor for each biosector (GgCO₂e/MR\$), $E_{GHG, fuel}$ is the total emission of each GHG by each fuel (GgGHG), GWP_{GHG} is the global warming potential of each GHG, base 100 years (IPCC AR5), EF_i is the emission factor from process i (presented in Table 4), Q_i is production (in mass or volume, depending on the product) by process i , and p_i is the price (in R\$/ unit) of product i . The parcel $\sum_1^n p_i \cdot Q_i$ is the annual value of production of each biorefinery in MR\$.

For the rest of the economy (except land use), the emissions per monetary unit (GgCO₂e/MR\$) of each emitting sector are estimated using Eqn (3).

$$EF_i = \frac{\sum_1^{GHG} E_{2009, i, GHG} \cdot GWP_{GHG}}{X_{2009, i}} \quad (3)$$

where EF_i is the emission factor of sector i of the economy, $E_{2009, i, GHG}$ are the emission of GHG (CO₂, CH₄ or N₂O), in 2009, by sector i , and GWP_{GHG} is the global warming potential of each GHG, 100 years (IPCC AR5). $X_{2009, i}$ (in MR\$) is the monetary value of production of sector i in 2009 taken from the Brazilian 2009 interregional SAM.

Future sugarcane production was considered to be entirely mechanized and emission factors were taken from Cardoso²⁷ and can be found in Appendix S1C, Table C.1, which shows the estimated emissions factors for different sectors of the economy.

Emissions from land use change

Here, total land use is a result of the CGE model, which provides the regional land use in 2030 (regional division is given in Fig. 3) by commercial crops of interest (i.e. corn, soy, sugarcane, other crops, silviculture and livestock). With that information, it is possible to use Approach 1 of the IPCC methodology.²⁰

Approach 1 requires only the net changes in land use area over time, indicating which land use type expands over what, which means that it does not require a transition matrix. This approach is used to estimate changes in biomass carbon stocks and changes in carbon stock in soils.²⁰

For biomass carbon stocks, the approach requires initial areas of native vegetation, agricultural areas and planted forests (in million hectares) and these are multiplied by their above-ground carbon content. Appendix S1C, Table C.2 shows information on the 2009 native vegetation area (in million hectares) and the above-ground carbon contents used in this study. Figure 3 shows Brazil and its five regions with their original biomes (the figure depicts only the

Figure 3. Brazilian biomes and 5 macro-regions.²⁸

original vegetation, not the land coverage remaining of each biome).

For carbon stock in soils, the approach uses the soil carbon stock change factors for different regions in Brazil and their initial soil carbon stock. Table 3 shows information on initial soil carbon stock and the soil carbon stock change factor for each region and each land use type.

The dynamics of land use change from 2009 and 2030 are given by the CGE model, based on the land price of each land use type. Results on land use are given without information about which land use type expanded over which. As mentioned, this type of data allows the analysis of emissions from land use change only through approach 1 of the IPCC,

using land endowments in two periods of time: 2009 (base-year data) and 2030 (model results). Soil carbon stock is calculated using the estimated original carbon stock by region and carbon stock change factor by crops. Equations (4) through (6) show how emissions were estimated.

$$ACS_i = \sum_{j=1}^J LAND_{j,i} \cdot AGCC_j \cdot CF_j \quad (4)$$

$$SCS_i = \sum_{z=1}^Z \sum_{j=1}^J LAND_{z,j,i} \cdot CCF_{z,j} \cdot OS_z \quad (5)$$

$$EL_{2030} = \frac{(ACS_{2030} + SCS_{2030}) - (ACS_{2009} + SCS_{2009})}{2030 - 2009} \cdot (-44/12)/1000 \quad (6)$$

where ACS_i is the above-ground carbon stock (tC) in year i , $LAND_{j,i}$ is the land use (in million hectares) of land use type j (i.e. the Brazilian biomes Caatinga, Cerrado, Atlantic forest, Amazon, besides planted forests and perennial crops). $AGCC_j$ is the above-ground carbon content (in tC/ha), CF_j is the carbon fraction of above-ground biomass per crop j . SCS_i is the soil carbon stock (in tons of carbon) in year i , $LAND_{z,j,i}$ is the land use (million hectares) in year i of land use type j in region z , $CCF_{z,j}$ is the carbon change factor by region z and land use type j and OS_z is the original carbon stock in region z . EL_{2030} is the emission from land use change in 2030 (in GgCO₂e); 44 and 12 are the molecular weights of CO₂ and carbon, respectively.

It is supposed that, until 2030, the livestock sector will have substantial increases in productivity (heads/ha), which changes its emissions.²⁹ Because of these structural changes, the emissions factors for livestock are not calculated using the same procedure than the other sectors of Brazilian economy. In its turn, emission factors for the livestock sector are calculated based on the methodology used in Gouvello,³⁰ a study by the World Bank that also deals with land-use change in Brazil. The estimated emission factors for livestock are

distinguished by production system and are shown in Table 4. Values in that table are very similar for emissions; however, the change lies on the yield of carcass produced per head of livestock.

Total emissions from livestock sector were calculated using Eqn (7):

$$E_{livestock,i} = \sum_1^{GHG} \sum_1^J \frac{Meat_{i,j}}{C} \cdot EF_{j,GHG} \cdot GWP_{GHG} \quad (7)$$

where $E_{livestock,i}$ is the emission in the livestock sector (GgCO₂e), $Meat_{i,j}$ is the production of meat in year i by management system j , $EF_{j,GHG}$ is the emission factor of each GHG by management system and GWP_{GHG} is the global warming potential of each GHG, base 100 years (IPCC AR5).

Reforestation versus no reforestation and removals

The estimated regional land use in 2030 provided by the CGE model only takes into consideration the commercial crops. Although land use only increases 0.95% nationally from 2009 to 2030 in the reference scenario because each region has a vocation for different crops, land use change in the model could represent an increase in land use in one region but a

Table 3. Soil carbon stock change factor for each region and each land use type, and original soil carbon stock per region.

Change factor	SE	S	CW	NE	N
Corn	0.45	0.55	0.45	0.50	0.45
Soy	0.45	0.55	0.45	0.55	0.45
Sugarcane	0.9	0.9	0.9	0.9	0.9
Other crops	0.85	0.85	0.85	0.85	0.85
Livestock	1	1	1	1	1
Abandoned land	0.8	0.8	0.8	0.8	0.8
Original C stock (mg/ha)	40.3	60.5	40.1	30.6	46.5

SE, Southeast; S, South; CW, Central-west; NE, Northeast; N, North.³⁰

Table 4. Livestock emission factors, yield, and share of production of each management system, in 2030.

Management system	Emissions per animal (kg/year)*		Yield (carcass/animal)**	Share of production in 2030 BAU (%)**
	CH ₄	N ₂ O		
Extensive pastures	51.71	0.22	52.5	81.0
Crop-livestock integration	51.73	0.21	61.3	7.5
Confinement	51.53	0.21	65.2	11.5

*Based on Gouvello.³⁰
 **Based on Moreira *et al.*¹⁸

decrease in another. This means that land requirements could be reduced in a region in absolute terms.

Two options were considered when land requirements reduce in a region: the first one would be to reforest that area with the region's native vegetation, while the second one would be to leave it as degraded land. In the first case, ACS_{2030} and SCS_{2030} , Eqns (4) and (5), are calculated using coefficients (soil carbon content and above-ground carbon content) for degraded land. In the second case, those variables are calculated using carbon content coefficients for native forests of the regions in which land requirements decrease.

For inventory purposes, the IPCC guidelines include anthropogenic GHG emissions and removals. Removals are negative emissions that consider the increases in carbon stocks in natural forests protected by law (when located in conservation units or indigenous lands), in addition to considering forest regeneration. A total removal of 208 MtCO₂e was estimated by the government in 2009⁷ and applied to this study when comparing the emissions from land use with and without removals (Fig. 10).

Primary energy use

Primary energy use is analyzed using, as reference, the National Energy Balance for 2009.³¹ First, the coefficient that reflects the total renewable and non-renewable energy consumption for the Brazilian economy is calculated dividing the energy consumption in each economic sector by their total production value in that year (Mtoe/MR\$, in 2009). Appendix S1C, Table C.3 shows renewable and non-renewable energy coefficients for different sectors of the economy. Equation (8) indicates the basis for estimating:

$$EnF_{s,i} = \frac{En2009_{s,i}}{X2009_i \cdot a_{s,i}} \quad (8)$$

where $EnF_{s,i}$ is the energy consumption indicator, in Mtoe/MR\$ of energy type i (renewable and non-renewable), $En2009_{s,i}$ is the energy consumption of each type of energy by sector s in 2009, $X2009_i$ is the total value of production in monetary terms (in million R\$) of energy type i and $a_{s,i}$ is the share of the energy type i that is consumed by sector s . Total energy consumption is then converted into EJ.

Secondly, the coefficients for the biosectors were calculated based on their biomass input, and their renewable energy use coefficients are shown in Appendix S1B, Table B.2. Biosectors were created to be energy sufficient and, therefore, are only fed with biomass and do not require any electricity or any other form of energy from the exterior. Appendix S1D

further explains the biorefinery integration. Coefficients for sugarcane-based biorefineries were calculated based on the energy content of sugarcane as primary energy.³¹ In case of SRC-based biorefineries, the total energy input is calculated using heating values presented in Brand²² and Santiago.²³ As for biodiesel production, primary energy inputs are calculated based on Cunha.³² Equation 9 shows the calculation of the primary energy use (renewable) in the biosectors:

$$EnF_{bio} = \frac{EnU_{bio}}{\sum_1^I p_i \cdot Q_i} \quad (9)$$

where EnF_{bio} is the energy consumption factor in each biorefinery (in EJ/MR\$), EnU_{bio} is the total energy consumption by the biorefinery in EJ and $\sum_1^I p_i \cdot Q_i$ is the total value of production of the biorefinery, where p_i Q_i is the price and the quantity of each product i , respectively.

As mentioned before, Brazil intends to reach 45% of renewables in total energy matrix, being 18% of bioenergy and between 28 and 33% of renewable energy other than hydropower. In the electricity matrix, the country intends to reach 23% of renewables, other than hydropower.

Scenarios

The analysis includes three main scenarios: a reference (BAU), in accordance with the Brazilian NDC, and two bioeconomy scenarios (BBEs). The three scenarios differ on four main points: (1) amount of biobased chemicals; (2) amount of bioenergy; (3) presence of second-generation biofuel (2G) technologies; and (4) use of SRC as feedstock. The biobased scenarios were chosen to present different frameworks in 2030 concisely. The first is a path in which second-generation processes are not yet feasible and sugarcane and soy remain as the main feedstock for bioenergy in the country. Chemicals also do not have high market penetration, which is a result of lower technological development in the biobased economy. In the second scenario, the use of second-generation technologies is more feasible. This enables the use of other feedstock, as is the case of SRC. In this second scenario, the development of processes for chemicals production is also higher and they have greater market penetration. Table 5 shows a summary of each scenario.

The baseline scenario (BAU) does not include biobased chemicals, because they are not considered in the NDC. The total bioenergy consumption (liquid biofuels and bioelectricity) in this scenario is based on projections by the Brazilian Energy Planning Company (EPE).³³ The results in these projections were corrected to more realistic

Table 5. Summary of the scenarios' differentiation.

	BAU	BBE1	BBE2
Biobased chemicals	No biobased chemicals	Biobased chemicals from sugarcane lower share	Biobased chemicals from sugarcane and SRC (except polylactic and acrylic acids) higher share
Bioenergy	Ethanol and jet fuel from sugarcane Biodiesel from soy Amount in the NDC	Ethanol and jet fuel from sugarcane Biodiesel from soy Double the amount from BAU	Ethanol and jet fuel from sugarcane and SRC Biodiesel from soy Double the amount from BAU
2G technologies	Only for ethanol production (5%), as is in the NDC	Only for ethanol production (5%), as is in the NDC	Sugarcane-based 1G facilities are substituted for 1G2G facilities. 2G SRC included.
SRC-based biorefineries	No SRC biorefineries are included.	No SRC biorefineries are included.	SRC-based biorefineries produce all additional ethylene, propylene and butanol in comparison with BBE1.

GDP projections (Table 1), due to the 2014–2016 Brazilian economic crisis.

In the first biobased economy scenario (BBE 1), one hypothesis is that the share of biobased chemicals will be a minimum. A literature review of technical and economic assessments was conducted and it was noted that most of these studies provide for ranges of market share. Thus, in the BBE 1 the lower values in these ranges were assumed. For example, Dornburg *et al.*³⁴ assumes a 47% substitution of ethylene, while the Organisation for Economic Co-operation and Development (OECD)⁸ assumes a minimum 40% substitution. Haveren *et al.*³⁵ consider a 10–15% substitution in the short term for bulk chemicals (ethylene is a bulk chemical), and Hoefnagels *et al.*³⁶ assume a 20% substitution in their analysis. In this study, a minimum of 10% was considered, and a maximum of 47%. Therefore, 10% of

bioethylene is considered in BBE 1 and a 47% substitution is considered in BBE 2. *N*-Butanol is a special case because it could be produced entirely from biobased sources, as mentioned in Dornburg *et al.*³⁴ On the other hand, United States Department of Agriculture (USDA)³⁷ projects a substitution of 5.8–10% for commodity chemicals (as in the case of *n*-butanol). Bain & Company³⁸ considers a penetration of over 50% for *n*-butanol. Consequently, the minimum share of 5.8% was considered for BBE 1, and the maximum share of 100% was considered in BBE 2. Regarding liquid biofuels, the predicted share in Brazil in 2030 is coherent with the worldwide figures in Scenario 450 (the most optimistic for biofuels, due to the efforts on climate mitigation) presented by International Energy Agency.³⁹ The Brazilian share in the global consumption of biofuels was taken from a special chapter on Brazil in IEA 2013 Energy Outlook,⁴⁰ and these shares were applied to the most recent projections (2015). Short rotation coppice was not considered as feedstock in this scenario. Second-generation ethanol from sugarcane lignocellulosic residues is set to 5% of total ethanol, which is in accordance with the Brazilian NDC.

Finally, in the second biobased economy scenario (BBE 2), the hypothesis is that the production of biobased chemicals is maximized (i.e., upper values in the previous mentioned ranges), while liquid biofuels shares are equal to BBE 1. Thus, as mentioned before, a basic difference between BBE 1 and BBE 2 is the production of biobased chemicals. The BBE 2 scenario also reflects the feasibility of technologies: all sugarcane-based first-generation (1G) facilities incorporate 2G routes (i.e. 1G2G facilities) and ethanol production is complemented by standalone 2G SRC-based biorefineries. The hypothesis is that SRC-based biorefineries would produce all additional ethylene, propylene and butanol, in comparison with BBE 1.

For the three scenarios considered, Table 6 shows the amount in the BAU scenario and the shares of biobased chemicals and biofuels, used in the bioeconomy scenarios in 2030. The total amounts of bioenergy and biochemicals are calculated as a share of total production: for instance, total ethanol produced is an output of 80% of the total production of gasoline equivalent. This means that the share is an exogenous variable to the model (the modeler provides the share to the model), while the total amount is a result of the model. As explained in Appendix S1D, the products are produced in integrated biorefineries, modeled to be energy sufficient and to deliver at least three products (as is the case today).

More data on the biorefineries and their biobased products (efficiencies, demand for electricity and steam, investment costs, production costs and process scale) can be found

Table 6. Share of biobased chemicals and bioenergy (%) regarding the predicted total demand in the scenarios considered for 2030.

Chemicals	BAU (%)	BBE 1 (%)	BBE 2 (%)
Ethylene*	0	10	47
Polylactic acid** (PLA)	0	6.5	10
Acrylic acid***	0	5.8	50
Propylene****	0	10	30
<i>n</i> -Butanol*****	0	5.8	100
Energy	(%)	(%)	(%)
Biodiesel*****	10	20	20
Bioethanol*****	45	80	80
Renewable jet fuel*****	0.4	8	8
Electricity*****	884 (TWh)	i	i

*Estimates vary considerably on the potential substitution of fossil for biobased ethylene. Dornburg *et al.*³⁴ indicate a 47% substitution, while OECD⁸ indicates a minimum of 40% substitution. Haveren *et al.*³⁵ consider a 10–15% substitution in the short term for bulk chemicals. Here, a minimum of 10% was considered, and a maximum of 47%.

**Substitution of PLA for composite of resins. Lower values based on Shen *et al.*,⁵² and upper values based on Dornburg *et al.*,³⁴ taking into account the shares of each resin in the total resin production (PE, PP, PVC, PS and PET). Here, a minimum of 6.5% was considered, and a maximum of 10%.

***USDA³⁷ projects a substitution of 5.8–10% for commodity chemicals (case of acrylic acid). Higher value is based on market penetration in the long term of biobased acrylic acid, as presented in Bain & Company.³⁸ Here, a minimum of 5.8% was considered, and a maximum of 50%.

****Lower values based on Haveren *et al.*³⁵ and upper values based on Deloitte.⁵³ Here, a minimum of 10% was considered, and a maximum of 30%.

*****USDA³⁷ projects a substitution of 5.8–10% for commodity chemicals (case of *n*-butanol). Dornburg *et al.* (2008) consider a 100% substitution potential in the high scenario. Here, a minimum of 5.8% was considered, and a maximum of 100%.

*****Based on a 10% share regarding total diesel consumption (blend mineral diesel plus biodiesel). Figure for BAU scenario is based on EPE.³³ The share of biodiesel on total diesel was taken from³⁹ for the BBE scenario (20%).

*****Based on the share of ethanol regarding total gasoline equivalent. In the BAU scenario the share is based on EPE.³³ The share of ethanol on total gasoline equivalent was taken from IEA³⁹ for the BBE scenarios (80%).

*****Based on IEA³⁹ in all scenarios, regarding the total kerosene consumption: 8% for BBE scenarios and 0.4% for BAU scenario.

*****Bioelectricity is an output of the model.

in Appendix S1A, Tables A.1 through A.17; production processes (with figures) are further detailed in Appendix S1D (products and processes). Surplus bioelectricity is an output of the model and depends on the biorefinery configuration and on the demands of heat and power in each case. More information on biorefineries outputs and their configurations can be found in Appendix S1B, Table B.3 – Physical outputs for each facility, where the reader can find the biorefineries' configurations used in this study.

Results

CGE model results

This section intends to summarize the results from the CGE model that are important for the calculation of the variables of interest in this paper. Details of the methodology are presented in Appendix S1D.

Table 7 shows results for GDP, total land use and total biomass requirements as well as the total demand for

crude oil and natural gas (fossil feedstock), and Table 8 shows the fossil and biobased products in each scenario, including information on SRC and 2G production.

The aggregated results that are presented are due to the production in eight major sectors: Petrochemicals, energy, oil, natural gas, sugarcane, silviculture, soy, and the introduction of new biosectors (i.e., the production of chemicals and energy carriers), which compose a bioeconomy.

As mentioned above and in Table 1, land use increases 0.95% from 2009, and total land available for agriculture and livestock is kept constant in the BBE scenarios (i.e. no extra deforestation is considered).

Table 7 shows that, in BBE 1, without much 2G technology, sugarcane production increases 30% in relation to BAU, while in BBE 2 the increase in silviculture is almost 80% compared to the BAU scenario. The biosector output increases 30% between BAU and BBE 1. On the other hand, the reduction of the primary fossil energy use is close to 15% both in BBE 1 and BBE 2. Crude oil use

and natural gas use falls 16% and 13% in both scenarios, respectively. Short rotation coppices are an important feedstock in BBE 2, producing 10.8 million liters of ethanol, or 13% of the total.

Table 8 shows the total output of each technology and each product. The total output of each product changes from scenario to scenario due to changes in GDP. As explained above, the shares are determined by the

Table 7. Results from the CGE model: GDP, total land use, total biomass and total fossil feedstock.

Variable	2009	BAU	BBE 1	BBE 2
GDP (billion US\$ of 2010)	2053.5	3161.2	3158.5	3146.5
Total land use ($\times 10^6$ km ²)	2.53	2.55	2.55	2.55
Livestock	1.83	1.57	1.46	1.43
Soy	0.22	0.44	0.54	0.54
Silviculture	0.06	0.10	0.10	0.16
Others	0.33	0.30	0.28	0.28
Total biomass requirements				
Soy ($\times 10^6$ ton)	64	127	163	163
Sugarcane ($\times 10^6$ ton)	612	1040	1308	1057
Silviculture ($\times 10^3$ m ³)	107	164	159	334
Fossil feedstock demand				
Crude oil ($\times 10^6$ m ³)	103.5	174.3	146.7	146.4
Natural gas ($\times 10^9$ m ³)	21.6	38	33	33

Table 8. Results from the CGE model: Total biobased and fossil-based products and 1G, 1G2G and SRC outputs.

	BAU				BBE 1				BBE2			
	Biobased		Fossil based		Biobased		Fossil based		Biobased		Fossil based	
	1G	1G2G	SRC		1G	1G2G	SRC		1G	1G2G	SRC	
Ethylene ($\times 10^6$ t)	0	0	0	7.9	0.7	0	0	6.7	0	0.72	2.6	3.8
Propylene (10^6 t)	0	0	0	4.9	0.5	0	0	4.2	1.4	0	0	3.2
Resins (10^6 t)	0	0	0	9.7	0.6	0	0	9.0	0.9	0	0	8.5
Acrylic acid (10^3 t)	0	0	0	220.9	12.6	0	0	205.4	107.4	0	0	107.4
n-butanol (10^3 t)	0	0	0	61.8	3.5	0	0	57.6	60.7	0	0	0.0
Diesel (10^6 m ³)	8	0	0	68	15	0	0	61	15	0	0	61
Gasoline (10^6 m ³)	0	0	0	32	0	0	0	12	0	0	0	12
Ethanol (10^6 m ³)	33.7	10.3	0	0	56.7	17.3	0	0	0	62.7	10.8	0
Jetfuel (10^6 m ³)	0.02	0	0	4.91	0.39	0	0	4.50	0	0.39	0	4.48
Electricity (TWh)	Bio		Other sources		Bio		Other sources		Bio		Other sources	
	194.5		689.5		155.6		726.1		82.2		800.2	

modeler and the model respond with the total amount of production.

Land use, primary energy supply, and GHG emissions

This section presents the results concerning this study, divided into three subsections: land use, primary energy supply, and GHG emissions; a summary of results is presented in Table 9. The BAU column shows the total amounts of each variable and columns BAU/BBE 1 and BAU/BBE 2 show the percentage changes ($\Delta\%$) compared to the BAU scenario.

Without considering reforestation, GHG emissions reach 1.72 Gt CO₂e, with an additional decrease of 1.1% in the first BBE scenarios and 1.63% in the second. In BAU, land endowment increases 0.95% from 2009, and no further deforestation is allowed in the bioeconomy scenarios. Finally, total non-renewable energy supply decreases 21.3% in BBE 1 and 20.14% in BBE 2 compared to BAU, while renewable primary energy supply increases 21.45% and 23.4% in BBE 1 and BBE 2, respectively. The next sections will further describe the results of each of these parameters.

Land use

Currently, most of the arable land in Brazil is used, in decreasing order, for livestock, soy, sugarcane, and corn production. The livestock sector, however, takes over 72% of the $2.53 \times 10^6 \text{ km}^2$ of total arable land (or $1.83 \times 10^6 \text{ km}^2$ in 2009). To match the GHG emissions predicted in the Brazilian NDC, land use for livestock in 2030 (BAU scenario) was exogenously determined, calculated as $1.57 \times 10^6 \text{ km}^2$. Further increases in the productivity of other crops are endogenously determined by the model to fit all land use types without deforestation (Table C.4 in Appendix S1C shows these endogenous increases in productivity). This

decrease in land use by the livestock sector ($0.26 \times 10^6 \text{ km}^2$) provides almost all land required for the economy in the BAU scenario.

In the BBE scenarios, soy and sugarcane are the main drivers for land-use change. While silviculture (in BBE 1) and other cultures are forced to shrink in area in comparison to BAU, soy and sugarcane expand with the increase in demand for biobased products. Coupled with livestock exogenous intensification, land-use reaches equilibrium. The production of soy-based biodiesel induces the greatest impact on land use since an increase in $8 \times 10^6 \text{ m}^3$ of biodiesel requires an expansion of around $100 \times 10^3 \text{ km}^2$ of soy. The impacts resulting from the additional production of $30 \times 10^6 \text{ m}^3$ of ethanol, besides different chemicals (ethylene, propylene, *n*-butanol, acrylic acid and polylactic acid) and jet fuel, are lower ($30 \times 10^3 \text{ km}^2$) due to the higher productivity of the routes based on sugarcane.

Silviculture has lower land productivity than sugarcane, so the pressure on land due to eucalyptus and pine expansion (BBE 2) is higher than the pressure of sugarcane in BBE 1, which is the feedstock for ethanol production. In that case, all other land use types are required to decrease their land use, which is given endogenously by the model based on their elasticity of substitution between factors of production. Figure 4 shows the land use in 2009 and in 2030 in all three scenarios.

As explained above, although land use increases only 0.95% from 2009 to 2030 in all three models, regionally the dynamics change for each crop. While sugarcane, soy and silviculture increase in all regions in the BAU scenario in relation to 2009, livestock reduces in all regions with different intensities, except for the north region. Other crops vary between the regions. For example, other crops decrease in the southeast by 9.5 thousand km² and increase in the central west by 11 000 km². Table 10 shows the dynamics of land use in absolute terms, comparing the three scenarios with 2009.

Table 9. Results for BAU, BBE 1 and BBE 2 for 2030 regarding GHG emissions, land use, non-renewable and renewable energy use.

	2009	BAU	BAU/BBE 1 ($\Delta\%$)	BAU/BBE 2 ($\Delta\%$)
GHG emissions (Gt CO ₂ e)	1.28	1.72	−1.1	−1.63
Land endowment increase (% from 2009)	—	0.95	0	0
Total land use (10^6 km^2)	2.53	2.55	0	0
Non-renewable primary energy supply (EJ)	5.38	11.69	−11.6	−7
Renewable primary energy supply (EJ)	4.76	8.47	16.2	23.5

Figure 4. Land use in 2009 and in 2030 (in BAU and in the two bioeconomy scenarios), by the main land claimants.

The total land available for reforestation used to calculate GHG emissions from land use change with reforestation, which will be presented below, derive from results presented in Table 10. Table 10 shows that livestock is the main provider of land for reforestation (except the north), followed by other crops (except the central west).

In the BAU scenario, 112 000 km² of land would be available for reforestation due changes in regional land use in the southeast (32×10^3 km²) and in the northeast (80×10^3 km²). In case of BBE 1 and BBE 2, land available for reforestation are estimated at 114 and 104 thousand km², respectively. The area of gross reduction resulted by the model is compatible and slightly higher than the area proposed by Brazilian NDC to be reforested in order to achieve the desired emissions reductions. The area resulting from the model is, however, concentrated in the northeast and southeast, as previously mentioned. If reforestation took place in the north region, carbon sinks would be higher due to higher carbon contents of the vegetation in that region in comparison to the vegetation in the northeast and southeast.

Primary energy supply

It is estimated that Brazil would increase its total primary energy supply regarding BAU, by 0.09% in BBE 1 and 5.7% in BBE 2. Figure 5 shows the differences in total primary energy supply for each scenario, aggregated for the national level. The participation of renewable energy increases from 33.5% in the BAU scenario to 43.7% in BBE 1 and BBE 2.

The bioeconomy scenarios impact the national energy matrix, in general, and the electricity matrix, in specific. Figure 6 shows the different shares of renewable energy in both matrixes.

On the other hand, in case of BBE 2 the introduction of 2G ethanol on a large scale displaces the residual biomass from

sugarcane previously used for electricity generation, which reduces the share of renewables in the electricity matrix, compared to the BBE 1 matrix. As a consequence, the share of non-renewables in the electricity matrix increases in BBE 2 compared to BBE 1.

The primary energy supply in the biobased economy helps reach the targets of renewable shares in the energy matrix, mentioned in the Brazilian NDC, with a good margin. This proposes 45% of renewable energy in the energy matrix. It also contributes to attainment of the 33% target for renewables, besides hydro, in the energy matrix, and of the 23% target for renewable electricity, besides hydro, in the electricity matrix. The increases in renewable energy differ among the bioeconomy scenarios specially in electricity generation, due to the trade-off between electricity and other products in the scenario with higher 2G.

GHG emissions

It is estimated that total Brazilian GHG emissions would decrease 1.1% from BAU to BBE 1, and 1.63% between BAU and BBE 2. Additional reductions in industrial processes and residues treatment can be considered marginal: 0.33% for residues and 0.19% for industrial processes in BBE 1. In BBE 2, the estimated reduction in industrial processes is 1.6% due to higher production of biochemicals. Most of the GHG emissions in Brazil in the industrial processes are not in the petrochemical plants but in industries in which the process involves limestone calcination, as in the cement and lime industries, and also in the steel and metallurgy industries. The production of chemicals from fossil feedstock contributes with less than 0.5% of the total GHG emissions in the BAU scenario.

In the bioeconomy scenarios, the energy sector gives the largest contribution for emissions reductions. The greater use

Table 10. Regional absolute land use change from 2009 in three scenarios, in 10³ km².

Absolute change (10 ³ km ²)		BAU-2009	BBE 1-2009	BBE 2-2009
Southeast	Sugarcane	14.1	29.3	8.9
	Soy	12.0	20.3	19.6
	Livestock	-56.9	-74.0	-78.7
	Others	-9.5	-11.2	-10.6
	Silviculture	8.2	6.6	22.9
	Total	-32.1	-29.0	-37.9
South	Sugarcane	1.9	3.6	1.3
	Soy	50.0	77.2	75.1
	Livestock	-9.1	-18.2	-20.8
	Others	-22.4	-26.5	-26.5
	Silviculture	8.0	6.5	22.2
	Total	28.4	42.6	513.9
Central-west	Sugarcane	31.4	40.8	28.3
	Soy	93.9	126.0	123.5
	Livestock	-115.4	-154.5	-165.3
	Others	11.0	6.7	6.1
	Silviculture	0.8	0.4	5.3
	Total	21.9	19.4	-2.0
Northeast	Sugarcane	3.5	6.7	2.5
	Soy	37.3	58.3	56.6
	Livestock	-114.6	-137.1	-143.4
	Others	-20.2	-24.2	-23.1
	Silviculture	13.8	10.8	43.2
	Total	-80.1	-85.6	-64.1
North	Sugarcane	3.6	4.4	3.3
	Soy	32.4	41.4	40.7
	Livestock	36.5	19.4	14.6
	Others	10.6	9.2	9.3
	Silviculture	2.9	2.3	8.8
	Total	86.0	76.6	76.7
Total gross reduction*		-112.2	-114.5	-104.1

*Used to calculate emissions for scenarios with reforestation. It is the sum of all negative values in the table.

of ethanol, biodiesel and renewable jet fuel in BBE 1 reduces GHG emissions by 7.5% in the energy sector, compared to BAU, while the reduction in BBE 2 is 4% (small changes due to less sugarcane bagasse available for electricity due to its use in 2G technologies).

The emissions classified as land use, land use change, and forests (LULUCF) are the second most impacted, with a 12.8% increase in BBE 1, regarding BAU, and a decrease of 13.3% in BBE 2. The increases in BBE 1 are due to the changes in the carbon content of the

Figure 5. Total primary energy supply and share of renewable energy share in 2009 and in 2030 for BAU, BBE 1 and BBE 2 scenarios.

original vegetation in different regions of the country. With greater demand for sugarcane and soy, the land expansion occurs differently among the regions, with an increase in the north (where there is higher carbon content) and a decrease in the northeast (with lower carbon content). In BBE 2 the decrease in GHG emissions in this category is due to the increase in planted forests, which have a higher carbon content. Comparing the bioeconomy scenarios with BAU, agriculture and livestock have a decrease in emissions by 1.8% (mostly due to reductions in livestock) in BBE 1 and a net increase of 11.9% in BBE 2, due to emissions in silviculture. Figure 7 shows the emissions split into sectors as proposed in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Figure 8 shows the allocation of emissions into the most GHG-emitting sectors of the economy, except LULUCF. First, in the BAU scenario, livestock emissions account for 60% of emissions in the agricultural sector and for 15% of total emissions but this estimate is based on the premise that productivity will increase considerably regarding land requirements until 2030 (in all scenarios). Compared to BAU, in BBE 1 emissions in this sector fall 4.5% and 6.5% in BBE 2.

The emissions due to diesel consumption represent 12% of total emissions in 2030 and 30% of those of the entire energy sector; currently, they represent 5% of the total and 25% of the energy sector.⁴¹ In both bioeconomy scenarios, emissions from diesel reduce 9.9% and 10.2% in BBE 1 and BBE 2, respectively, in comparison with BAU. Emissions due to natural gas would be reduced 13% in BBE 1 and BBE 2, from 116.1 TgCO_{2e} in the BAU scenario, in 2030, which includes its extraction and its use. As for GHG emissions in the energy sector the largest impact in relative terms would be due to

Figure 6. Share of renewables in 2009 and 2030 for BAU, BBE 1, and BBE 2 scenarios.

Figure 7. Total GHG emissions by sector in 2009 and in 2030 for the BAU, BBE 1, and BBE 2 scenarios.

Figure 8. Most GHG-emitting sectors in the BAU, BBE 1, and BBE 2 scenarios in 2030, without considering those related to land use and land use change.

gasoline consumption, with 60% reduction in bioeconomy scenarios compared to BAU.

Emissions from the agricultural sector, except those from livestock, would be relatively low in 2030. Emissions

related to sugarcane production would be lower due to full mechanization and no straw burning. Emissions due to soy and sugarcane represent 4% of the agricultural sector in the BBE 1 scenario, with an increase of 29% from the BAU scenario.

Discussion – NDC, land use and emissions

Land-use profile and GHG emissions in the BAU scenario are based on the Brazilian NDC. However, the country's current actions are not consistent with its commitments. Figure 9 shows a projection using the trend of land use of forests and agriculture (crops and livestock), using data from MapBiomas from 1985 to 2018.⁴² The figure on the left shows the projections using a linear trend, and the one on the right shows a comparison with the business-as-usual scenario and the trend.⁴⁴

In a path where the country follows the historical trend, additional 0.5 million km² of forests would be lost and 0.37 million km² of agriculture and livestock would be necessary. It is important to keep in mind that MapBiomas and data used in this study differ by 90 000 km² in forest land in 2009 (MapBiomas estimate a total land of 5.2 million km² in 2009), while agriculture land data differ by 80 000 km² (MapBiomas

estimate a land use by the agricultural sector -agriculture + livestock – of 2.44 million km²).

Reducing land use in the livestock sector by encouraging intensification and the recuperation of low-productivity pasturelands is an important action to reduce emissions. As mentioned, the assumption in this paper is towards the adoption of more efficient livestock management systems regarding the use of land. However, since in the general equilibrium model, there is no land set aside, with the yields of livestock set as exogenous and the other yields of the agricultural sector set as endogenous, lower demand by the livestock sector induces reductions in land prices, which will induce a reduction in yields by the agricultural sector. The displaced land due to livestock intensification, if not reforested, will therefore be made available for other crops, which will increase total emissions instead of decreasing. Figure 10 shows the predicted slight increase in emissions in BBE 2 due to the increase of yields in livestock.

Only intensifying livestock is not enough for emissions reductions, and for that reason, reforestation is also necessary.

Figure 9. Forest and agriculture land use linear trend from 1985 to 2030 (left) and land use comparison between trend, BAU and BBE scenarios in 2030 (right).

However, the increase in yields in agriculture and livestock is also required to avoid potential increases in deforestation and, consequently, higher increases in GHG emissions. The main driver of bioeconomy is, after all, reducing GHG emissions and its contribution is only possible if deforestation is constrained.

In Brazil, deforestation is much more important than energy and chemical production when it comes to emissions.⁴¹ Carvalho *et al.*⁴³ confirmed, in their model, that the restriction for land expansion through deforestation brings economic drawbacks (resulted from the model equilibrium), and one way to prevent it is to increase yields in

agriculture and livestock. In addition, De Oliveira Silva *et al.*⁴⁴ show that the livestock sector has a major role in achieving the Brazilian NDC, if understood the technical, economic and policy feasibility of pasture intensification.

Figure 11 shows the impacts of emissions related to reforestation. In the BAU scenario, reforestation alone could reduce 5.7% of GHG emissions, which is five times higher than reductions in BBE 1. The same figure shows the impacts of removals, supposing that their contribution in 2030 can be similar to the one in 2009.⁷ It can be seen that the targets of the Brazilian NDC are not reached with the set of actions related to BAU, including reforestation and removals.

Figure 10. Emissions in 2030 supposing different levels of livestock intensification, for the BBE 2 scenario.

Figure 11. Total GHG emissions with and without reforestation, and CO₂ removals (estimated equal to 2009 values) in BAU, BBE 1, and BBE 2 scenarios.

In the absence of strict regulation and control, it would be unrealistic to imagine that no deforestation will occur in the event of a bioeconomy. However, to keep emissions reductions comparable to the BAU, land-use expansion was limited in this paper.

Reforestation, in this paper, has been set to happen using native forests. This is a simplification that is not impossible. A recent publication with a summary of actions to restore ecosystems says that forest restoration may reduce some of the damage caused by deforestation by enabling recovery of 12 million hectares of native vegetation nationwide by 2030, as set out in the National Ecological Restoration Plan.⁴⁵

According to Crouzeilles *et al.*,⁴⁵ in the Amazon, for example, meeting all the goals of agricultural and forestry production, zero illegal deforestation and restoration of native vegetation, aiming at legalizing rural properties and enhancing ecosystem services, means increasing productivity from the current level of 46% to 63–75% of its sustainable potential in 15 years. In the Atlantic Forest, this same process needs to increase from its current 24% to 30–34% of its potential, and such an increase is possible only by applying the basic knowledge of pasture management. In the Cerrado it would be sufficient to move from 35% to 65% of its sustainable potential by 2050 to harmonize sustainable agricultural expansion, restoration in priority areas, and zero illegal deforestation. Native forest restoration, however, comes with high cost, which sets up substantial economic barriers. The Ministry of Science and Technology estimated average cost per hectare of US \$3000 and abatement cost of US \$ 9.22 per tonne of CO₂e avoided. It was found that to achieve the mitigation potential of 414 MtCO_{2e} between 2012 and 2050, it would be necessary to invest US \$3.8 billion to restore an

additional 4.1 million hectares to the benchmark scenario used in the report.⁴⁶

Land restrictions imposed in this study for the biobased economy are, nonetheless, a representation of a desired outcome, not necessarily a reproduction of reality. Taking land endowment as constant was a modeling decision based on the idea that a bioeconomy cannot cause more net deforestation, or else it would lose its purpose of reducing GHG emissions. However, to demonstrate what would happen if land endowment was freely expandable, Fig. 12 shows the increase in net emissions, in comparison to those in BAU, as function of the increase in land endowment due to bioeconomy and how the increase of land use would overshadow actions in other sectors. In case of BBE 1, the breakeven in net emissions is a 1.8% increase in land endowment compared to the figure in 2009. In the BBE 2 case, the breakeven is around 1.5% compared to 2009; 0.95% was the endowment increase considered from 2009.

This discussion is highlighted by Rochedo *et al.*⁴⁷ who found that the recent increases in deforestation make it impossible to meet targets consistent with Brazil's contribution to a 2 °C world and show that recent trends in deforestation governance would require other sectors to deploy technologies that are not yet economically viable to compensate for higher emissions from land-use change and deforestation. This is even more evident in the bioeconomy scenarios, which depend on land availability. As shown in Fig. 11, the bioeconomy cannot come with higher increases in land use by deforestation, or emissions reductions would not take place. The Brazilian Greenhouse Gas Emission and Removal Estimation System (SEEG, in Portuguese) is also attentive to the increase of emissions due to deforestation. The organization indicates a list of actions required to accomplish

Figure 12. Increase in net emissions due to land expansion in the BBE 1 and BBE 2 scenarios, from land use figure in 2009.

the level of deforestation established in the Brazilian NDC and shows that the Brazilian government is not following the directives to prevent deforestation properly.³ The Climate Action Tracker (CAT) also shows that Brazil is moving away from fulfilling its commitments under the Paris Agreement, due to increases in deforestation.

Conclusions

This study reports an assessment of the impacts of bioeconomy scenarios on the Brazilian GHG emissions in the context of the compromises assumed by the country before the Paris Agreement. The methodology is based on computable general equilibrium modeling (CGE) integrated to an economic input–output life cycle assessment (IO-LCA) procedure. Results were obtained for the whole country, and also for the five main regions of Brazil. Three scenarios were considered, BAU being a scenario in which bioenergy (i.e. liquid biofuels and bioelectricity) would already be widely deployed, as predicted in the NDC. Regarding BAU, in the two BBE scenarios the most important differences are the production of biomaterials and the adoption of new technologies in a large extent (e.g. 2G biofuels).

The deployment of bioenergy would be crucial to reducing GHG emissions in 2030 (e.g. reductions related to gasoline and diesel use, to the natural gas supply chain and the electricity matrix), and this is the main reason for the already good results related to BAU. For the hypothesis assumed in this paper, the impacts of the BBE scenarios are positive (1.1 and 1.63% additional reduction compared to BAU), but not significantly high to reduce the estimated emissions drastically. Emissions by the energy sector are those with the highest reductions (7.5% in BBE 1), but the 12% increase in the LULUCF sector offsets those reductions.

In all cases, even in the BAU scenario, and considering the additional contributions of reforestation and removals, the total emissions would still exceed 1.3 GtCO₂e, compared to the 1.2 GtCO₂e target. Reforestation actions need to be planned to maximize emissions reduction. Although the model identifies areas to be reforested in the northeast and southeast, the highest carbon stocks are in the north region in the Amazon forest. If reforestation took place in that region, emissions reduction could be significantly higher than those given by the model. To explore reforestation in different regions, the model would require further modifications.

Improving livestock management and avoiding land-use changes are central issues in this study, once the bulk of reductions in GHG emissions could be achieved with livestock intensification, combined with no deforestation and reforestation. In Brazil, due to the large land area used

for livestock, its intensification results less pressure on deforestation and also on land available for reforestation. It is already known that when it comes to bioeconomy scenarios, it is crucial to avoid deforestation, or the benefits of displacing non-renewables energy and materials would be vanished. In the case of this study, the basic assumption is that the land available for agriculture and livestock in 2030 would be 0.95% higher than 2009 (the reference year), regardless of the scenarios considered, and this would be possible due to the higher yields both in agriculture and livestock, determined exogenously.

As for deploying bioeconomy, the advantage of Brazil is that a large stock of already anthropized land is available, but the conclusions regarding the importance of land use policies and regulations are not different than for many other countries. In this regard, a negative particularity of Brazil is that the country has gradually lost control over deforestation and, since 2012, it has increased to levels higher than 2009. With deforestation, as GHG emissions tend to grow significantly, it would be even more difficult – and more expensive – to achieve the goals of its NDC.

A limitation of the current version of the economic model (CGE + IO-LCA) imposes an important drawback on the analysis, as land that is made available due to, for instance, livestock intensification, is automatically occupied by agricultural crops. In this sense, the benefits of increasing yields both in agriculture and livestock have not been fully evaluated. Another issue to be further explored is related to the assumptions made at the beginning of the project as a whole, as large-scale production of biodiesel based on soy reduces the benefits of bioeconomy scenarios, due to the large extension of land required (8 million m³ of biodiesel requires an expansion of around 10 million hectares of soy). A new version of the model should be developed to overcome these constraints.

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