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Biobased economy for Brazil: Impacts and strategies for maximizing socioeconomic benefits

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ABSTRACT

Fossil fuels dominate the current energy and chemicals' supply and this leads to a rapid growth in global greenhouse gas emissions. One mitigation option is using renewable feedstock for materials, chemicals (ethylene, propylene, acrylic acid and butanol) and, mostly, energy carriers (biodiesel, renewable jet fuel, ethanol and bioelectricity). This study demonstrates the effects of an economy based on biomass (bioeconomy) on macroeconomic aspects through a Computable General Equilibrium model. Three scenarios for 2030 were created to compare different levels of production (amount of chemicals and energy production through fossils versus biomass) for Brazil, based on sugarcane, soy and forest crops. Two important methodological aspects of this paper are the financial support provided by the government to enable the bioeconomy, and the limitations in comparing strategies to maximize the socioeconomic benefits of a biobased economy. The results show that a bioeconomy could result in almost irrelevant negative impacts on GDP and in small increases in unemployment rate comparing to the reference scenario. However, these effects could be reversed, even with no deforestation, if the livestock and agriculture sectors increased their efficiency regarding land. Most importantly, if the livestock sector worked as a source of land for other crops in the event of a bioeconomy, the socioeconomic response would be more positive than if deforestation took place.

1. Introduction

In its Nationally Determined Contribution (NDC), Brazil states the intention to reduce 37% of its emissions related to 2005 levels, by 2025, and 43% of them by 2030. An important share of this result would come from the increase in the share of sustainable bioenergy in the Brazilian energy matrix to approximately 18% by 2030, expanding the consumption of biofuels and increasing electricity generation from biomass [1].

Besides emission reductions, a bioeconomy has been claimed to resolve socioeconomic problems promoting income diversification [2,3], GDP growth and poverty reduction [4], depending on the production technology [5]. Furthermore, possible impacts on food security, including its availability, might arise due to large-scale biomass consumption [6], which can be prevented by combining biomass production with improved agricultural management, investing in agricultural production systems with management improvements [7,8], to induce more efficient land use [9]. In addition, linked to sound governance and well-established sustainability criteria, a bioeconomy may prevent income concentration and help reduce poverty.

In this context, this study describes a model developed to identify the strategies to maximize the socioeconomic benefits of a biobased economy, related to changes in land use, unemployment, labor remuneration, food security, and GDP growth.

Keeping in mind that the main goal of a bioeconomy is the reduction of GHG emissions, this study first considers its development under a no-
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deforestation policy and then proposes measures to attain the development of the bioeconomy without actual decrease in net forest area.

The scenarios in this study go beyond the bioenergy proposed in the NDC and are defined not only by energy carriers but also biochemicals. The analysis includes bulk chemicals, fine chemicals), and plastic resins. Taking into account the oil price scenarios considered, the viability of some biobased products vis-à-vis the conventional ones was not verified and, in this context, direct subsidies were considered in this study. Subsidies are one of the alternatives for equalizing biobased and petrobased prices, and this study analyzes the bioeconomy with and without subsidies thoroughly.

The text is divided in six sections, including this introduction. Section 2 is the methodology section in which the economic model and technologies considered are discussed; section 3 presents the results; section 4 reports discussions and further results on land use and subsidies; and, finally, the study is ends in section 5, with conclusions.

2. Materials and methods

2.1. Model set-up

Two approaches were used in the implementation of the CGE model: a bottom-up approach for the new biobased processes and a top-down for the rest of the economy. For the rest of the economy (encompassing the oil-based sectors), data from the Brazilian 2009 social accounting matrix [10] were used.

A selection of the products to be included in the economy was performed based on the available literature. These processes were then translated into technical coefficients, based on the biorefinery concept, considering the production of different products from some specific feedstock [11]. In doing so, both commercial and proposed routes were considered; in the latter case, whenever necessary, mass and energy balances were established based on computational models for the cases under analysis.

Fig. 1 shows the steps for the representation of each biorefinery and their ultimate inclusion in the basic structure of the Brazilian social

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Fig. 1. Flowchart on how hypothesis and process data were dealt and how monetary information was created to be inserted in the socioeconomic accounting matrix.
accounting matrix. The first two steps are the definition of feedstock and the product. For each product the required information was obtained from the literature, such as mass and energy flows, equipment, economic inputs, total investments, operational and maintenance costs, as well as labor inputs. Information used is presented in the appendices.

Efficiency improvements were applied to the processes efficiencies to obtain the appropriate figures for 2030. Thus, it was explored the potential for cost reduction of biobased products due to increases in efficiencies, using the same methodology as Jonker et al. (2015) [12], especially for 2nd generation biofuels.

The software Engineering Equation Solver (EES) was used for performing mass and energy balances for all industrial processes considered, and also for defining processes integration. In doing so, certain constraints were considered, such as biomass availability and energy requirements.

An example of the applied procedure, and also of the assessment of economic feasibility of biorefinery processes, can be found in Machado et al. (2016) [13] for the production of biopropylene. Each bio-sector operates with only one type of feedstock (i.e. sugarcane, eucalyptus or pine, or soybeans).

Industrial processes were classified according to their profile, hereafter called (technical) configuration. Four groups were considered: for sugarcane, the first generation (1G) route and the combination of first and second generation routes (2G); for eucalyptus and pine, the 2G route; and in the case of soybeans, the 1G route based on oil transesterification. Thus, each bio-sector is defined by a configuration and by a single feedstock.

A configuration can have one or more processes, and each process can have different outputs. For example, ABE fermentation is considered as one process, but generates three products (acetone, butanol and ethanol; thus, ABE). Depending on the configuration, more than one material stream can feed the process. For example, in a 1G2G basic configuration, both the streams of C6 sugars and sugarcane juice can go to fermentation, providing only one final product (ethanol).

In other cases, a process is in fact a set of processes. For example, the considered propylene route starts with ethanol production, followed by ethanol dehydration to ethylene, and finally the transformation into propylene. In this case, all three processes are represented by a single process.

By-products do not exist in all processes. In the cases considered, by-products are vinasse, in ethanol production, and the stream of C5 sugars in sugarcane and short rotation coppices (SRC) biorefineries. Residues include bagasse from sugarcane and forest residues from SRC.

After defining the scale of each biorefinery, information on the capital costs of the literature were adjusted based on the methodology presented in Towler & Sinnott [14], using equation (1) for taking into account scale effects.

$$C_2 = C_1 \left( \frac{S_2}{S_1} \right)^n$$  \hspace{1cm} (1)

Where $C_2$ is the capital cost of the plant with capacity $S_2$ and $C_1$ is the capital cost of a plant with capacity $S_1$. The exponent $n$ was also taken from literature and considered values are presented in Appendix A (Table A16).

In this study, it was considered only one production capacity for each feedstock. Table A1, in Appendix A, shows these capacities for soy (500 thousand tones), SRC (1.2 million tons) and sugarcane (2 million tons) based biorefineries, along with other basic economic parameters for biorefinery integration.

It was considered that the market price of the products is the same both for oil and biobased routes, i.e. there is no premium price for biobased products. Equation (2) shows the balance of expenses and earnings.

$$\sum Q_j \cdot p_j = \sum Q_j \cdot p_j + \sum \sum E_{n,m} \cdot HR_{n,m} \cdot h_{n,m} + EOB + T_e - Sub_d$$  \hspace{1cm} (2)

Where $Q_j$ is the amount of each product $i$ produced, $p_i$ is the price of each product produced, $Q$ is the amount of each product consumed, and $p_j$ is the price of each product $j$ consumed. $E_{n,m}$ is the number of employees $n$ in labor category $m$, and $HR_{n,m}$ is the hourly rate, multiplied by the annual number of hours worked by each employee in each category. $EOB$ represents the gross operating surplus, $T_e$ indicates the taxes paid, and $Sub_d$ the subsidies received. The technical parameters considered for each process are presented in Appendix A. Appendix A also shows the final output of each biorefinery configuration (Table A4), and their input-output coefficients in 2009 (Tables A2 and A3).

Despite the consideration of learning effects, biobased products could have higher costs in 2030 and, to close the balance, subsidies would be required. Subsidies were applied when there was imbalance between the total revenue and the costs of production (including capital, labor, taxes, etc.). Subsidies were considered due to the methodological choice of having one single price for both products, fossil and biobased. This choice is based on two main aspects. First, on the assumption that the same products generate the same utility for the consumer, who would pay equal prices regardless of their origin. Second, on the important message that subsidy carries, as they represent the social cost of a technology.

However, the choice for subsidies is not based on a realistic consideration. Currently, for instance, biodiesel and ethanol are not subsidized in Brazil. This, however, does not annul the importance of the scenario comparisons. In opposition to subsidies, a modeler could choose to explore that the extra cost of some biobased products would be covered by premium prices, reflecting the willing to pay for renewable products. This hypothesis was not included in this study, but is dealt with in the discussions.

In addition, in a context of high oil prices subsidies wouldn’t be necessary, as mentioned by Winchester & Ledvina [15]. However, in this study it was assumed a single oil price in 2030–80 US$/barrel –, based on the projections by International Energy Agency (IEA) in its World Energy Outlook [16]. This price is associated to a scenario with high GHG mitigation efforts and, consequently, a lower oil demand. This price level is similar to 2009 levels, which is the base year, and, therefore, the authors decided not to explore different oil prices within the scenarios. It was also assumed that the prices $p_1$ taken from the Brazilian Annual Industry Research [17] reflect oil prices in 2009, and were used for defining the oil-based counterparts’ prices in 2030.

With higher oil prices, higher the prices the counterparts are sold, reducing the required subsidy.

The need for subsidies is, therefore, uncertain, depending both on oil prices and on the costs of biobased products. For this reason, section 4.2 presents a sensitivity analysis on subsidies.

### 2.2. Biobased products and processes

The analysis focused on four main classes of products: bulk chemicals (represented by ethylene and propylene), fine chemicals (represented by butanol and acrylic acid), resins (substituted by polylactic acid), and energy, represented by liquid biofuels (biodiesel, ethanol and renewable jet fuel), plus bioelectricity (generated in combined heat and power – CHP – units). In the supplementary material, Appendix B shows a detailed description of each chemical and energy carrier.

### 2.3. Scenarios

The analysis includes three main scenarios: a reference (BAU) and two bioeconomy scenarios (BBEs). Variants of these scenarios allow the evaluation of impacts of land availability (in section 4.1) and of no subsidies (in section 4.2). With respect to land availability, assessments
include both the macroeconomic impacts of further livestock intensification and the extension of the area due to deforestation. In the latter case, land endowment was left endogenous in the model and it was supposed no change in land price between BAU and BBEs scenarios. Thus, with no restriction to land supply, the resulting expansion leads to a zero change in land prices. For the subsidies case, they were exogenously set as zero and new macroeconomic results were obtained.

The three scenarios differ on four main points: (1) amount of biobased chemicals; (2) amount of bioenergy; (3) presence of 2G technologies; and (4) use of SRC as feedstock. As an illustration, Fig. 2 shows the total consumption of liquid fuels in the transport sector, in 2009 and in the BAU scenario. In addition, the same figure shows the electricity generation mix in 2030, in the BAU scenario.

The baseline scenario (BAU) does not include biobased chemicals. The total bioenergy (liquid biofuels and bioelectricity) in this scenario is based on projections by EPE (2016) [18], but corrected to take into account a more realistic economic growth (GDP projections based in USDA (2015) [19] were used), since the basic economic hypothesis in the reference study (EPE) is not compatible with the hypothesis assumed in this study. Regarding 2G technologies, SRC is not used as feedstock in the BAU scenario.

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 done and most of these studies predict market shares in ranges. Thus, in the BBE 1 the lower values in these ranges were assumed. Regarding liquid biofuels, the consumption 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 IEA [16]. The Brazilian share in the global consumption of biofuels was taken from a special chapter on Brazil in IEA 2013 Energy Outlook [20], and these shares were applied to the most recent projections (2015). Again, SRC was not considered as feedstock in this scenario.

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 production is equal to BBE 1. Thus, a basic difference between BBE 1 and BBE 2 is the production of biobased chemicals. Besides that, BBE 2 also reflects the feasibility of 2G technologies: all sugarcane-based 1G facilities incorporate 2G routes (i.e. 1G2G facilities) and ethanol production is complemented by stand-alone 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 1 shows the estimated production of biobased chemicals and biofuels, in 2030. In the bioeconomy scenarios bioenergy is presented as a share of total consumption: for instance, ethanol would represent 80% of the total consumption of gasoline equivalent. Modeling results for bioenergy are presented in section 3.

No projections are made for bioelectricity due to its co-product characteristic in the biorefinery design; calculations were done in each case. Electricity generation in each biorefinery depends on biomass availability and on steam demand; surplus electricity is the difference regarding industry’s demand.

### Table 1

<table>
<thead>
<tr>
<th>Chemicals</th>
<th>BAU</th>
<th>BBE 1 (%)</th>
<th>BBE 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene</td>
<td>–</td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td>Polylactic acid (PLA)</td>
<td>–</td>
<td>6.5</td>
<td>10</td>
</tr>
<tr>
<td>Acrylic acid</td>
<td>–</td>
<td>5.8</td>
<td>50</td>
</tr>
<tr>
<td>Propylene</td>
<td>–</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>–</td>
<td>5.8</td>
<td>100</td>
</tr>
<tr>
<td>Energy</td>
<td>(TJ)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>245.3</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>939.6</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Renewable jet fuel</td>
<td>0.7</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Electricity</td>
<td>884 (TWh)</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

* a Estimates vary considerably on the potential substitution of fossil for biobased ethylene. Dornburg et al. [21] indicate a 47% substitution, while OECD [22] indicates a minimum of 40% substitution. Haveren et al. [23] consider a 10–15% substitution in the short term for bulk chemicals, and Hoefnagels et al. [24] assume a 20% substitution in their analysis. Here, a minimum of 10% was considered, and a maximum of 47%.

* b Substitution of PLA for composite of resins. Lower values based on Shen et al. [25], and upper values based on Dornburg et al. [21], 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%.

* c USDA [26] 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 [27]. Here, a minimum of 5.8% was considered, and a maximum of 50%.

* d Lower values based on Haveren et al. [23] and upper values based on Deloitte [28]. Here, a minimum of 10% was considered, and a maximum of 30%.

* e USDA [26] 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. Bain & Company [27] considers a penetration of over 50% for n-butanol. Here, a minimum of 5.8% was considered, and a maximum of 100%.

* f Based on a 10% share regarding total diesel consumption (blend mineral diesel plus biodiesel). Figure for BAU scenario is based on EPE [18]. The share of biodiesel on total diesel was taken from Ref. [16] for the BBE scenario (20%).

* g Based on the share of ethanol regarding total gasoline equivalent. In the BAU scenario the share is based on EPE [18]. The share of ethanol on total gasoline equivalent was taken from IEA [16] for the BBE scenarios (80%).

* h Based on IEA [16] in all scenarios, regarding the total kerosene consumption: 8% for BBE scenarios and 0.4% for BAU scenario.

2.4. Model integration

In order to quantify the economic impacts of introducing biomass for
chemicals and increasing for energy in a higher level of biomass deployment, a macroeconomic CGE model was used in combination with a spreadsheet tool to translate the physical flow of each biobased process to the balanced input-output matrices of all transactions within the economy (new biobased and traditional fossil-based included).

The balanced input-output coefficients used in the CGE model derived from two data sources: the baseline Social Accounting Matrix [10], that describes current sectors (including the fossil-based counterparts to be partially substituted by bioproducts), and the results of the physical process modeling of each biobased process, that are translated into monetary units.

Each component of the model is described through a specific function. Regarding the final demand, household’s consumption and government consumption are modeled by a Linear Expenditure System (LES) function. The demand from investments (or the gross fixed capital formation) for product j is modeled as a function of total savings. Exports are modeled as a decision between external and internal market based on a Constant Elasticity of Transformation (CET) function, while the competition between domestically produced and imported goods is modeled by an Armington function [29].

The intermediate consumption of the sectors is modeled based on the fixed Leontief coefficients [30]. The primary factors of production, including land, on the other hand, are modeled by a Constant Elasticity of Substitution (CES) function [29]. More specifically to the biobased sectors, and based on the biorefinery concept, they have the ability to produce more than one product, which should be reproduced also in terms of fixed Leontief output coefficients. Taking into account different routes of production, the bioproducts are blended with their fossil-based counterparts in a “virtual sector”. More information on model integration is provided in the supplementary material, presented in Appendix B. Table 2 shows the targets for the BAU scenario used in the CGE model.

3. Results

3.1. Main results

The results of the reference scenario (BAU) are induced by the exogenously determined macroeconomic variables (GDP, economically active population, consumption by final demand and land use by livestock sector), combined with the expected production of bioproducts. The BAU scenario is fully realized when key macroeconomic variables (endogenous), presented in Table 2, reach the defined targets.

It is important to bear in mind that in the BAU scenario both bioenergy and fossil energy production are defined as targets, while in the BBE scenarios what is previously defined is the share of biobased products. In the case of BBE scenarios, the total production is a model result, depending on the level of economic activity.

Table 3 shows the total amounts of biobased products and their fossil-based counterparts in the three scenarios. Fig. 3 shows the total demand of liquid fuels and electricity estimated for 2030, also in each of the three scenarios, while for the chemicals addressed in this study, Fig. 4 shows the predicted total demand (biobased + fossil-based products).

Comparing the estimated consumptions in 2030, the main difference between BAU and both BBE scenarios is regarding ethanol and gasoline demand. The increase of ethanol consumption – and, consequently, the reduction of gasoline consumption – was induced by the change in shares of total gasoline equivalent. Increasing the substitution of gasoline for ethanol is one of the objectives of the Brazilian NDC (BAU result, in 2030), while the greater consumption in both BBE scenarios is due to the hypothesis that the consumption of biofuels will be enhanced in a context in which biobased products will be a priority.

The estimated total demand of the chemicals of interest varies a bit in the three scenarios considered because of the synergic effects. Among the scenarios, the most impacted products are ethylene and propylene, due to indirect impacts of the substitution of plastic resins. Since ethylene and propylene consumption is concentrated in resins manufacture, the direct substitution of resins for polyactic acid will directly impact their demand. In BBE 2, with the increase in polyactic outputs, ethylene and propylene consumption declines even further. Compared to BAU, the impacts on the consumption of other products are mostly due to the reduction in overall economic activity (see section 3.3).

3.2. Impacts on the demand of biomass feedstock and fossil feedstock

Compared to BAU, the impacts of the BBE scenarios on the demand of biomass feedstock and on the demand of fossil feedstock (i.e. crude oil and natural gas) are reported below.

Fig. 5 shows the estimated total consumptions of the major agricultural feedstock, in 2030, i.e. not just for producing the chemicals and energy carriers considered. The differences between scenarios rely on the assumptions regarding technologies used and, less important, on the amount of chemicals produced. For instance, from BBE 1 to BBE 2 there is a partial shift from sugarcane to eucalyptus and pine aiming the additional production of chemicals (in 2G-based biorefineries).

Additionally, although the production of chemicals is small (mass basis), a considerable amount of ethanol is produced as co-product in butanol SRC-based facilities. Since butanol is only produced from C5 sugars in 2G facilities, the remaining sugars are forwarded to ethanol production. Therefore, the production of biobased butanol will require considerable amounts of SRC, and ethanol will consequently be produced in a reasonable quantity (14% of total volume produced).

Reductions in sugarcane production in BBE 2 are due to technology changes (i.e. dissemination of 2G from sugarcane residues), and are also associated to ethanol production in SRC-based biorefineries. The impact is a reduction of 250 million tons in sugarcane production.

The increase in soybean production is driven by the change in the share of biodiesel, from 10% in BAU to 20% in BBEs. From 2009 to 2030 (BAU) the growth in silviculture is due to the evolution of traditional sectors (e.g. furniture, pulp and paper) driven by GDP growth. However, from BBE 1 to BBE2 scenario, silviculture increases 110% only to produce more chemicals and, as consequence, to partially satisfy the ethanol demand.

On the other hand, as expected, the impact of BBE scenarios on the demand of fossil feedstock is not negligible: a drop of 16% and 13% between BAU and the biobased scenarios, in case of crude oil and natural gas, respectively. Fig. 6 illustrates these impacts: in 2030, 27.5 million m³ of crude oil and 5 billion m³ of natural gas are spared. The difference between the demands in BAU and in the BBE scenarios is mainly due to the changes in the energy sectors, since the consumption as feedstock of chemicals is relatively small.

3.3. Impacts on land use

As far as land use is concerned, since no expansion in total land endowment is allowed between scenarios, the model manages to fit all...
production into the same amount of land. In this case, compared to the BAU scenario, the model shifts the agricultural and livestock yields. Fig. 7 shows the land requirement for each land use type, in 2030, for the three scenarios considered.

Since silviculture has lower land productivities comparing to sugarcane, the pressure on land due to eucalyptus and pine expansion (BBE 2) is higher than in BBE 1, in which ethanol production (and of derivatives) is based on sugarcane. In this 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. Section 4 elaborates on this topic.

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 $2.53 \times 10^6$ km$^2$ of total arable land (or $1.83 \times 10^6$ 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 based on the work of Moreira et al. (2016) \[32\], calculated as $1.57 \times 10^6$ km$^2$. This decrease in land use by the livestock sector ($0.26 \times 10^6$ km$^2$) provides almost all land required for the economy in the BAU scenario, leaving only $25 \times 10^3$ km$^2$ for deforestation, or an increase of 0.95% in arable land.

On the other hand, in the bioeconomy scenarios land available for livestock is endogenously determined, following the increase in the demand for land by sugarcane and soy (and SRC in BBE 2). This is

Table 3

<table>
<thead>
<tr>
<th>Product Type</th>
<th>BAU</th>
<th>BBE 1</th>
<th>BBE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene ($x10^6$ t)</td>
<td>0</td>
<td>7.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Propylene ($x10^6$ t)</td>
<td>0</td>
<td>4.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Resins ($x10^6$ t)</td>
<td>0</td>
<td>9.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Acrylic acid ($x10^3$ t)</td>
<td>0</td>
<td>220.9</td>
<td>12.6</td>
</tr>
<tr>
<td>n-butanol ($x10^5$ t)</td>
<td>0</td>
<td>61.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Diesel ($x10^6$ m$^3$)</td>
<td>8</td>
<td>68</td>
<td>15</td>
</tr>
<tr>
<td>Gasoline ($x10^6$ m$^3$)</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>Ethanol ($x10^6$ m$^3$)</td>
<td>44</td>
<td>0</td>
<td>74</td>
</tr>
<tr>
<td>Jet fuel ($x10^6$ m$^3$)</td>
<td>0.02</td>
<td>4.91</td>
<td>0.39</td>
</tr>
<tr>
<td>Electricity (TWh)</td>
<td>Bioelectricity</td>
<td>Other sources</td>
<td>Bioelectricity</td>
</tr>
<tr>
<td>194.5</td>
<td>689.5</td>
<td>155.6</td>
<td>726.1</td>
</tr>
</tbody>
</table>

Fig. 3. Energy demand of liquid fuels and electricity in BAU and BBEs scenarios, in 2030.

Fig. 4. Estimated total Brazilian demand of the chemicals of interest in 2030, in each of the three scenarios considered.

Fig. 5. Estimated total requirements of biomass, in 2030, in the three scenarios considered.
consistent with the hypothesis that land for livestock is used flexibly, and in the case of higher land prices due to increased demand, livestock intensification is an alternative.

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

3.4. Changes in GDP

In this section the direct and indirect impacts on GDP and on investments are assessed, comparing the results of BAU and BBE scenarios. Structural changes and the option of considering subsidies, whenever necessary, to assure the strict viability of all biobased products, influence the results. Fig. 8 shows the changes in total GDP between the BAU and the biobased economy scenarios.

The results can also be seen as a small reduction in GDP growth between 2009 and 2030, since the expected increase in the period is 53.94% (BAU). In 2009, the growth over the period would be 0.17% lower in the case of BBE 1, and 0.75% in the case of BBE 2.

In decreasing order, most of the subsidies are destined to biodiesel, followed by propylene, ethylene and aviation fuel, besides ethanol 2G based on SRC (in the case of BBE 2 scenario). In the BBE 2 scenario, for instance, 60% of all subsidies are due to biodiesel, and in BBE 1 this share is much higher. In the biodiesel case, the opportunity cost of the soy oil, as an edible product, explains the differences between production costs, while the large volumes in 2030 (see Table 3) explains the high absolute values.

Fig. 9 shows the total estimated subsidies, in 2030, in each scenario. Comparing the total subsidies with a more updated figure for Brazil, it can be concluded that the requirement in the case of scenario BBE 1 is quite similar to the subsidies applied in 2016 [10]. Moreover, compared to the gross fixed capital formation (i.e. investments), shown in Fig. 10, the estimated subsidies would be marginal in both BBE scenarios. Comparing Figs. 9 and 10, it is possible to conclude that subsidies are equivalent to 0.35% of the total amount of investments.

However, the increase in subsidies affects the investments in the economy. Investing capacity is calculated as the sum of households, government and foreign savings, and in both BBE scenarios the investments (as a component of final demand) drop, following a drop in government savings (which are directly affected by subsidies). Fig. 10 shows the estimated total investments in each scenario, in 2030. With lower savings by the government, the demand for gross fixed capital formation is affected and, consequently, there is a negative impact in the total final demand.

3.5. Changes in employment and in households’ consumption

Changes in employment were analyzed based on the unemployment rate in each scenario in 2030. The rationale behind the assessment of unemployment rate is the concept known as Phillips curve, presented in Fig. 6.
the supplementary material (Appendix B) [33,34].

The decrease in the price of the labor factor, which shows the changes in labor remuneration, happens due to the relative availability of production factors (i.e. capital, land and labor). In one hand, with the increase in required subsidies, government will not be able to save as much as in the BAU scenario, which reflects in the final demand from investments, and this lowers the number of jobs in sectors like civil construction and machinery. With fewer workers demanded, labor factor becomes less scarce in the economy, and so its price goes down. In the case of BBE 1, labor prices go down 0.97% in relation to the CPI, resulting in an increase in unemployment (based on Phillips curve). The same happens in BBE 2, with a decrease of 1.18% in labor prices, generating an even higher unemployment rate. Fig. 11 shows the estimates of unemployment rate in 2030 in the three scenarios considered. Comparing BBE 1 to BAU, there is a tiny increase of the unemployment rate – less than 0.05%, and the same is observed comparing BBE 2 to BBE 1 – in fact, an even lower increase of the unemployment rate.

Although it has been pointed out by some authors that a bioeconomy generates employment [35,36], this statement is related to a ceteris paribus situation. As stated in Thornley et al. (2014) [36] the shift from fossil-based products to biobased ones can generate net jobs, and this is the result got in this research, as can be seen in Fig. 12 (left). The graph shows the dynamics in jobs creation among the sectors involved in the substitution process. While the number of jobs created in the biosectors increase, the number of jobs in the fossil-based counterparts reduces, but the total sum (of biosectors and counterparts) rises in both biobased scenarios. The same is valid for the comparison of agriculture and fossil feedstock (in oil and natural gas sectors).

However, the several possible indirect impacts of a biobased economy, as reduction in investments, can cause an overall reduction of employment in the rest of the economy (ROE) and, consequently, in the total economy (see the right side of Fig. 12). The economic sectors more impacted are those that demand more investments (e.g. machinery and civil construction), following the decline in government savings. As mentioned, these results are due to the hypothesis applied in this study; in this regard, see also other results and comments presented in section 4.2.

When it comes to food consumption, here understood as a proxy for food access, the increase in land prices affects directly food prices, and consequently, the consumption of food products. Table 4 shows that land prices increase significantly in both bioeconomy scenarios in comparison with BAU due to the hypothesis that land endowment is constant among the three scenarios.

The impacts on the total consumption of foodstuff by households due to higher food prices were estimated. Fig. 13 shows the impacts on consumption comparing both bioeconomy scenarios with BAU. The stronger impacts in case of BBE 2 are due to the larger land demand, in which SRC-based biorefineries produce a large amount of chemicals and ethanol. When it comes to land use, the lower yields of eucalyptus and pine, compared to sugarcane, causes the higher demands. It can be seen that the consumption of food products is affected in either scenarios. On the other hand, the “other products” sector shows increase in demand in BBE 1 – and a small reduction in BBE 2 – since as an aggregation of products it is less sensitive to changes in land prices.

Since it is estimated that land availability and, consequently, land prices could be important factors to the change of foodstuff consumption were assessed in section 4.1.

4. Other results and discussions

The literature on bioeconomy and biofuels has deeply studied its impacts on society, economy and the environment. It has been pointed out that the bioeconomy has potential reducing energy independence [37], increase income generation [2,3], growth in GDP and poverty reduction, [4]. On the other hand, some authors have seen minimal negative social impacts of the bioeconomy and biofuels production [38], impacts on food security, including its availability [6]. Several of the authors mentioned before have made important contributions for the reduction of negative impacts, nonetheless, showing how these impacts can be avoided [7-9,29].

This section brings the required actions to prevent the negative impacts previously shown, through the analysis of land expansion options, yield increases, price changes, investments and subsidies.

4.1. The bioeconomy under different land expansion hypothesis

In the previous section, the total land endowment (total land used in the economy) was kept constant in all scenarios considered. In this case, land prices would rise considerably, with an increase of 24% in BBE 1.
Keeping land constant was a choice by the authors based on the premise that, to understand the impacts of substituting fossil-based products for biobased ones, all other variables should be kept constant, in a *ceteris paribus* analysis. However, Brazilian government has recently (2012) reviewed its forest act (the major legal framework for conservation of natural vegetation on private land) and, according to Sparovek et al. (2015) [40], the legal apparatus has become weaker when it comes to protection of natural vegetation, and less demanding in terms of the requirements for the restoration and for keeping natural vegetation in agricultural land. This creates an inconsistency when affirming that, in the case of an increase in land prices, no deforestation would occur, since it would be legal to deforest, at a certain extent, which is the cheapest choice for the producer. The amount of land available for legal deforestation is yet unknown, but Sparovek et al. (2015) [40] found that a substantial increase in crop production is possible, using an area 1.5–2.7 times larger than the current cropland area.

On the other hand, several studies show that livestock production in Brazil has increased considerably its productivity. Dias Filho (2014) [41] shows that from 1975 until 2006 the stocking rate rose 92%, with highest intensification in the Center-West region. Even with such increase, further intensification is possible and other authors, as Moreira et al. (2014) e Gouvelo (2010) [32,42], consider higher stocking rates even in the mid-term. It is important to keep in mind that this study only considers one type of land, and all land is exchangeable among crops. This is not the reality, since crops require different types of land and nutrients. Ideally, land should be split into land types in order to identify limitations to land use change regarding crop adaptability.

In order to assess the economic impacts when total land endowment is no longer kept constant, two modeling alternatives were considered: increasing land endowment through deforestation, or increasing land available for other crops, with intensification of the stocking rate in livestock production. Fig. 14 shows the results in these two cases. To reach a land price variation equal to zero, compared with BAU, land endowment would have to be 9.6 and 10.6% higher in the BBE 1 and BBE 2 scenarios, respectively; these percentages can be understood as deforestation. In the case of stocking rate, in heads/1000 km², an increase from 13 to 15.7 in BBE 1, and from 13 to 15.9 in BBE 2, are required to reach a nil increase in land prices, also when comparing to the BAU scenario. Comparing these results with the information presented in the cited literature, it seems clear that it will not be likely to keep the land endowment constant in a context where land prices would increase considerably.

As consequence, new results on economic impacts were obtained, now supposing no constrains on land availability; they were compared with those presented in section 3.4. As for GDP and unemployment rates, Fig. 15 shows the comparison with the results of the BAU scenario. As for GDP and unemployment rates in the whole economy, the results are better for increasing stocking rates (SRI) in both BBE scenarios. Strictly discussing based on model’s assumptions and its results, this

### Table 4: Relative changes in production factors – comparison between bioeconomy scenarios and BAU.

<table>
<thead>
<tr>
<th>Production factors</th>
<th>BBE 1/BAU</th>
<th>BBE 2/BAU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Labor</td>
<td>-0.97</td>
<td>-1.18</td>
</tr>
<tr>
<td>Land</td>
<td>24.62</td>
<td>30.88</td>
</tr>
</tbody>
</table>

Fig. 12. Net employment generation in Brazil, between 2009 and 2030, in biosectors and counterparts (left side) and in the rest of the economy (ROE), plus the total number of jobs in the economy (right side).

Fig. 13. Changes of foodstuff consumption by households in 2030, in percentage, comparing biobased scenarios with BAU.
happens because more land is made available when stocking rates are raised: approximately $300 \times 10^3$ km$^2$ compared to $250 \times 10^3$ km$^2$ with land expansion (basically, due to deforestation), being both cases compared to BAU, in 2030.

Another aspect to be assessed is the potential impacts on food prices. Compared to BAU, as shown in Fig. 16, foodstuff consumption by households grows when land availability is enlarged (LEI or SRI cases), due to the lower land prices and increase in household’s income.

In these cases, also compared with BAU, the results of BBE 2 scenario are worse than BBE 1 mainly because the option of producing ethanol (and also chemicals) from SRC demands more land than producing the same amount only from sugarcane. Leal et al. (2013) [43] show that ethanol from lignocellulosic crops require more land than first generation sugarcane ethanol, which reflects in the higher demand for land.

However, the hypothesis in the model used is that all crops compete for the same land, and this is a simplification. In reality, not all land is suited for sugarcane, for instance, and in the case of less or non-suitable land for that crop, perennial crops could be options.

4.2. The bioeconomy without subsidies

Fig. 17 shows the results of GDP and unemployment rate, in 2030, in three cases: BAU, the BBE 2 with subsidies (see sections 3.3 and 3.4) and BBE 2 under zero subsidies. Compared to BAU, it is possible to see that subsidies and their impacts are only one factor to cause reduction in GDP and increase in unemployment. The other factor, as seen before, is land prices and its economic impacts. Without subsidies, GDP would reduce 0.35% compared to BAU, in contrast with an estimated 0.46% reduction when subsidies are included. And even without subsidies unemployment rate would still be slightly higher than BAU scenario.

Subsidy was the option chosen by the authors to ensure the viability of all biobased products by 2030. However, as shown in Fig. 10, most subsidies would be due to a few products (i.e., biodiesel, bioethylene and biopropylene), while the production of others would be viable under the hypothesis assumed. Disregarding the hypothesis of higher oil prices, an alternative to be explored is the existence of premium markets. i.e., the consumers would be willing to pay more for biobased products. Table 5 shows the estimated margin of premium prices vis-à-vis the counterparts based on fossil, comparing BAU and BBE 2.

The existence of premium prices will possibly also have an effect on the economy, with some decline in final demand due to higher prices. This could also have a negative impact on GDP, as happens with subsidies. Here, this case was not tested, nonetheless.

As seen in Table 5, the higher estimated premium price is for biopropylene, and for this product a feasibility study was previously published [13]. In that paper the production route is similar to the one considered here, based on ethanol from sugarcane. The authors concluded that the minimum selling price would be 90% higher than the average price for propylene in Europe, from 2010 to 2014, and this is strongly impacted by oil prices. In that study the authors explored hypothesis for reducing production costs, and concluded that with a combination of learning effects, scaling in the industrial phase, higher agricultural productivity for reducing sugarcane prices, and less ambitious expectations on capital return (the basic case was for a minimum attractive rate of return of 15% per year) it would be possible to reach viability. Here, it was considered the production in a sugarcane mill with capacity of 2 million tons of sugarcane crushed per year (an average mill), but there are some mills in Brazil with crushing capacity 3–4 times higher; Machado et al. (2016) [13] shows that only with scaling effect it would be possible to reduce 25–30% the minimum selling price.

Here, aspects like learning effects and increasing of agricultural yields (see next section) were considered, but it would be possible to foresee a more favorable scenario – but still realistic – for reaching the viability of biobased products in medium term. Thus, it would be fair to conclude that for many biobased products their viability is possible without subsidies.

The need for subsidy has also been studied in other articles, such asSadhuukan (2018) [44], which found that ethanol production in second generation plants is not economically feasible without subsidies or government support and state that high value added materials and chemicals have an important role for economic viability and independence from government policies. Subsidies and economic viability are intrinsically connected to sustainability issues as pointed out by Van Schouwenhove et al. (2018) [45]. The authors show that securing a profitable chemical product by efficient low-cost management is one of the main sustainability criteria in a biobased economy.

4.3. Agricultural yields

It is clear that land availability is a key factor for providing large-scale production of biobased products, even in a country with a large extension, such as Brazil. As seen, the larger demand for land induces higher land prices and this is an opportunity for substituting it for other factors of production. In practice, producers would do efforts for increasing yields. As land availability was established among the three
In the BAU scenario, and the assumptions were based in specialized literatures, heads/km². For instance, according to Strassburg et al. (2014) [51], livestock productivity in cultivated pasturelands is only 32–34% of its potential, and productivities are projected around 132 heads/km², which are similar to the results for the BBE scenarios (133 heads/km²). For silviculture, increases of 48% in yields are expected, according to Stape et al. (2010) [49]. Sugarcane also has room for improvements to reach average yields above 9130 t/km², which are similar to the results for the BBE scenarios (288 t/km²). As the assumed values are not a theoretical maximum, therefore there is room for further improvements.

Table 6 shows the estimated gains in productivity in both biobased scenarios that are imposed by the model, regarding those assumed in BAU. The results in Table 6 are an output of the model, and these in turn is only 32% of its potential, and productivities are projected around 132 heads/km², which are similar to the results for the BBE scenarios. For silviculture, increases of 48% in yields are expected, according to Stape et al. (2010) [49]. Sugarcane also has room for improvements to reach average yields above 9130 t/km², as discussed in Cardozo et al. (2016) [52].

The most challenging improvements are in the production of soybeans. As mentioned in MAPA (2016), the average productivity has been stagnated at 300 t/km². On the other hand, FIESP (2016) [53] foresees that the barrier of 300 t/km² will be surpassed in 2020, with an increase of 12% until 2026 (reaching 336 t/km²), more than would be required to reach the results presented in Table 6.

The increase in yields in agriculture and livestock is necessary to avoid the negative impacts of the bioeconomy and at the same time to avoid potential increases in deforestation and, consequently, GHG emissions. The bio-economy serves, after all, to reduce emissions. The bio-economy also contributes to a 2°C world. 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 the level of deforestation established in the Brazilian NDC and shows that the Federal Government is not following the directives to properly prevent deforestation [56]. Carvalho et al. (2017) [57] confirmed in their model that the restriction for land expansion through deforestation brings economic drawbacks (resulting from the model equilibrium), and one way to prevent it is to increase yields in agriculture and livestock. Finally, Silva et al. (2016) [58] show that the livestock sector has a

<table>
<thead>
<tr>
<th>Land use type</th>
<th>2009</th>
<th>2030</th>
<th>Increases in yields</th>
<th>BAU</th>
<th>BBE 1/BAU (%)</th>
<th>BBE 2/BAU (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn (t/km²)</td>
<td>484</td>
<td>576</td>
<td>3.0</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soy (t/km²)</td>
<td>8100</td>
<td>9130</td>
<td>0.7</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugarcane (t/km²)</td>
<td>288</td>
<td>300</td>
<td>8.4</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other crops (t/km²)</td>
<td>338</td>
<td>389</td>
<td>5.2</td>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silviculture (m³/km²)</td>
<td>4000</td>
<td>4070</td>
<td>0.7</td>
<td>24.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Livestock (heads/km²)</td>
<td>1.1</td>
<td>1.3</td>
<td>2.6</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Current and BAU productivity values taken from Ref. [46].
b Current productivity values taken from Ref. [47]. BAU productivity values taken from Ref. [46].
c Values for grains (except soy and corn). Current and BAU productivity values based on Ref. [46].
d Current productivity based on [48] and BAU productivity values based on [49,50].
major role in achieving the Brazilian NDC, if understood the technical, economic and policy feasibility of pasture intensification.

5. Conclusions

This study focuses on the national economic impact of large-scale substitution of fossil resources by biomass. It takes into consideration the production of energy in the form of ethanol, electricity, diesel and jet-fuel, besides chemicals represented by butanol, ethanol, propylene and resins derived from biomass. In this study, the bioeconomy scenarios are built within a framework of GHG emission reductions, its primary objective, which includes the premise of no deforestation. Subsidies were considered to allow products to enter the market that would not be economically viable compared to their competitors of fossil origin, but other economic strategies were also considered.

Overall, the results indicate that pursuing a substitution of fossil energy with biomass could result in almost irrelevant negative impacts on GDP and in small reductions in unemployment rate comparing to the reference scenario. The results depend on the impact of land demand on overall prices, and on the economic action – subsidies among them – that would be applied to support the entrance into the market or the consumption growth of some products. This slight reduction in GDP represents in fact the social cost to develop the bioeconomy. Considering that it would bring GHG emissions reductions, society must decide if this is a fair price and compare options based on their abilities to reduce emissions. If government was to bear the costs of the economic unviability of part of the bioeconomy through subsidies, the general equilibrium theory requires a reduction on investments, which would cause, in a country like Brazil, overall reduction in economic activity. If no subsidy is required, in the case of reducing bioproducts costs, the reduction in GDP would be annulled.

Results also show that, to guarantee sustainable biomass supply in large scale with little or no deforestation, the livestock and agriculture sectors must increase their efficiency regarding land. Most importantly, if the livestock sector worked as a source of land for other crops in the event of large-scale deployment of biomass, the socioeconomic response of the economy would be more positive than the alternative, which would be deforestation. Moreover, in a bioeconomy society would also benefit environmentally if the livestock sector increased its efficiency, reducing deforestation and potentially reducing GHG emissions. Thus, livestock intensification not only enhances the positive impact of the bioeconomy, but also leads to the desired GHG emissions reductions in the Brazilian NDC.

The results also indicate that, from a technological perspective, biorefineries producing multiple outputs could be cost effective along the years, but some processes still need other cost-reducing strategies, like up-scaling, in order to reduce investments costs. It is clear that the feasibility of bioproducts would depend of a set of factors, mainly in short to mid-term, as is the case considered in this paper.

It is important to bear in mind that models are by nature a simplification of reality and is not intended in this study to predict the future. The discussion presented here can be further improved if some modeling approaches are better addressed, such as:

- Capital expenditures were modeled based on literature review. However, many processes are described as a single purpose, and an effort has been made to integrate them. A better description of integrated production processes would lead to reduced investment and more efficient installations. In addition, in this study the industrial capacity is also fixed, which reduces the benefits of sizing.
- The SAM (Social Accounting Matrix) used for this study was derived from 2009 data. Obviously that reality has changed and many improvements in the economy occurred, with new economic sectors and impacts on land and energy use efficiencies. When available, more recent data should be used as base year.
- Ideally, land should be split into land types in order to identify limitations to land use change regarding crop adaptability, most likely integrating the economic model with a physical model.
- This study does not include CO₂ prices, which is common in macroeconomic studies using general equilibrium [24].
- General equilibrium model is static in this study and the treatment of consumption and the assumption of the general equilibrium are examples of simplification of potentially powerful variables. The dynamization of the model could bring more realistic results.

Finally, to provide concrete directions to policy-making and a broader analysis on the sustainability of the bioeconomy beyond macroeconomic issues, the group has published results on emissions reductions taking into account the scenarios dealt with in this article in Ref. [59] and intends to publish a paper on the regional impacts on income and inequality, deepening the understanding of the role of a bioeconomy in helping Brazil to achieve the sustainable development goals and its NDC with minimum negative environmental, macro and socioeconomic impacts.

CRediT authorship contribution statement

P.G. Machado: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing. M. Cunha: Conceptualization, Data curation, Methodology, Resources, Software, Supervision, Validation. A. Walter: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing. A. Faaij: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing. J.J.M. Guilhoto: Data curation, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References