Received: 6 July 2022 | Accepted: 4 October 2022

DOI: 10.1111/gcbb.13008

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access WILEY

RESEARCH ARTICLE

BLOEM: A spatially explicit model of bioenergy and carbon capture and storage, applied to Brazil

Isabela Tagomori[1] | **Vassilis Daioglou**[1] | **Pedro Rochedo**[2] | **Gerd Angelkorte**[2] | **Roberto Schaeffer**[2] | **Detlef van Vuuren**[1,3] | **Alexandre Szklo**[2]

[1]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands

[2]Energy Planning Program, Graduate School of Engineering, UFRJ, Rio de Janeiro, Brazil

[3]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, The Netherlands

Correspondence
Isabela Tagomori, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands.
Email: isabela.tagomori@pbl.nl

Funding information
Directorate-General for Development and Cooperation - EuropeAid, Grant/Award Number: 21020701/2017/770447/SER/ CLIMA. C.1 EuropeAid/1384; Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Grant/Award Number: 2016.00687.5 (Bolsa Doutorado Nota 10); H2020 Energy, Grant/Award Number: Grant Agreement 821471 (ENGAGE)

Abstract

Bioenergy could play a major role in decarbonizing energy systems in the context of the Paris Agreement. Large-scale bioenergy deployment could be related to sustainability issues and requires major infrastructure investments. It, therefore, needs to be studied carefully. The Bioenergy and Land Optimization Spatially Explicit Model (BLOEM) presented here allows for assessing different bioenergy pathways while encompassing various dimensions that influence their optimal deployment. In this study, BLOEM was applied to the Brazilian context by coupling it with the Brazilian Land Use and Energy Systems (BLUES) model. This allowed investigating the most cost-effective ways of attending future bioenergy supply projections and studying the role of recovered degraded pasture lands in improving land availability in a sustainable and competitive manner. The results show optimizing for limiting deforestation and minimizing logistics costs results in different outcomes. It also indicates that recovering degraded pasture lands is attractive from both logistics and climate perspectives. The systemic approach of BLOEM provides spatial results, highlighting the trade-offs between crop allocation, land use and the logistics dynamics between production, conversion, and demand, providing valuable insights for regional and national climate policy design. This makes it a useful tool for mapping sustainable bioenergy value chain pathways.

KEYWORDS

BECCS, bioenergy, Brazil, IAMs, land availability

1 | INTRODUCTION

Deep mitigation scenarios, including those aimed at limiting global average temperature increase to below 1.5°C, often indicate a prominent role for bioenergy as a mitigation option, especially when associated with carbon capture and storage (CCS) systems (Clarke et al., 2014; Fuss et al., 2018; Kriegler et al., 2013; Minx et al., 2018; Rogelj et al., 2016). Brazil is a major producer and consumer of bioenergy. Brazil is also projected to play a relevant role in bioenergy production in the future, according to scenarios consistent with ambitious mitigation targets (Daioglou et al., 2020; Köberle et al., 2022). For instance, the Brazilian Land Use and Energy Systems (BLUES)

Integrated Assessment Model (IAM) indicates that bioenergy would continue to supply a major share of energy demand (Rochedo et al., 2018). The projection suggests that the production of liquid biofuels would be the key route, including first- and second-generation ethanol, biodiesel, aviation biofuels, and green diesel (all associated with CCS, except for biodiesel).

However, large-scale bioenergy deployment (with or without CCS) faces many risks and challenges, including biophysical, technological, economic, social, and institutional ones. This includes the possible impacts on food security, on biodiversity and soils (via land use and land-use change), water requirements, emissions, and carbon debt. If developed adequately, bioenergy systems have the potential to contribute to climate change mitigation significantly. However, if inappropriately expanded, they can negatively impact climate, inducing direct and indirect land-use changes, causing damages to biodiversity and leading to water scarcity, as well as reducing food security (Hasegawa et al., 2020; Kemper, 2015; Samsatli et al., 2015; Smith et al., 2016).

Brazil is a major food producer and the location of some of the world's most pristine forests and natural lands, which have greatly suffered from large-scale deforestation in recent decades (Rajão et al., 2020; Rochedo et al., 2018). Additionally, the country has large low-productivity pasture areas with low stocking rates, which, if better managed, could improve land availability even for uses beyond pasture only (Bragança et al., 2022; Feltran-Barbieri & Féres, 2021; Strassburg et al., 2014). In this context, a prominent expansion of bioenergy needs to be carefully considered in the light of agricultural and land-use policies to prevent negative impacts on food production, biodiversity and water availability.

While IAMs offer a consistent framework to access these potentials, they normally lack details concerning bioenergy supply chains, not thoroughly representing regional specificities. This represents a crucial gap in the current literature on mitigation pathways. Köberle et al. (2022) highlight the need for comprehensive and flexible modelling tools that can translate aggregate global projections of IAMs into more robust spatially explicit local projections, giving valuable and actionable regional insights in the process. Moreover, better representing agricultural and land-use dynamics and bioenergy development strategies and how they are affected by regional characteristics and economic, social and political drivers can improve the appropriateness of IAMs for regional assessments and policy design. In this context, linking IAMs and regional models could provide the complementary interaction between global mitigation pathways since bioenergy, as a climate mitigation option, cannot be fully interpreted without the global context and regional strategies and aspects that influence potentials, costs, logistics, and system expansion (Gambhir et al., 2019).

This study proposes a methodological approach for a more detailed analysis of bioenergy value chains by developing and applying a spatial–temporal model. In the literature, there are several regional models to evaluate biomass supply chains in long-term climate change mitigation strategies (Fajardy et al., 2018; Samsatli et al., 2015; Zhang et al., 2019). However, to the best of our knowledge, none of the existing models has been applied to Brazil or accounts for land-use change emissions, direct or indirect. Furthermore, these models have not been directly linked to the outcomes of IAMs. Such a link allows for consistent projections within global resource and emission constraints while maintaining regional and spatial details, providing a downscaling of global and regional projections to a more relevant actionable level.

BLOEM uses a spatially explicit approach to land allocation for bioenergy production, accounting for both the spatial and temporal variations of biomass yields and land availability, transportation and storage costs, including the need for pretreatment of biomass for suitable storage options, imports and exports, and the availability, location and scale of conversion units. The model also describes stock, investments and retirement of technologies and captures the co-product and end-product values and their respective logistics, and carbon capture, transportation and sequestration.

In this study, we apply BLOEM to the Brazilian context. We link it to the BLUES model to evaluate the dynamics of bioenergy supply. We do this to better understand if bioenergy production targets in mitigation scenarios can be met without posing a threat to forests and protected natural areas, as well as to investigate the role of land availability for bioenergy expansion in Brazil.

This manuscript is structured as follows. Section 2 presents the methodology used. Section 3 presents the results. Section 4 provides a discussion of the results. Finally, Section 5 presents conclusions and future work recommendations.

2 | MATERIALS AND METHODS

2.1 | The bioenergy and land optimization spatially explicit model

BLOEM is a perfect foresight, spatially explicit, least-cost optimization model. The model is formulated as a linear programming model, accounting for both total system costs and greenhouse gas (GHG) emissions, aiming to comply with a given bioenergy production target at a minimum cost. The model is implemented in the GAMS modelling platform and solved using the CPLEX solver. Model documentation, including its detailed mathematical formulation, and the lists of parameters and variables, can be found in Tagomori (2022), BLOEM (2022), and in the Supplementary Material.

2.1.1 | Objective function

The objective function, to be minimized, accounts for the total system costs, as defined by Equation (1). It encompasses impacts of biomass production, biomass transportation, biomass conversion, final products transportation and distribution, CO_2 capture, transportation and storage, and GHG emissions.

$$Z = \sum_{t \in T} \left(I_t^{BP} + I_t^{BT} + I_t^{BC} + I_t^{ET} + I_t^{CC} + I_t^{TG} \right) \forall t \in T \quad (1)$$

where Z represents the total system cost (to be minimized), in unit of costs; I_t^{BP} represents the impacts of biomass production in time "t"; I_t^{BT} represents the impacts of biomass transportation in time "t"; I_t^{BC} represents the impacts of biomass conversion in time "t"; I_t^{ET} represents the impacts of bioenergy transportation (logistics and distribution) in time "t"; I_t^{CC} represents the impacts of carbon transportation and storage in time "t"; and I_t^{TG} represents the impacts related to GHG emissions in time "t". All impacts are measured in units of costs.

2.1.2 | Land availability

The amount of land available for bioenergy crops is an input to the model and can account for different constraints such as excluding protected land areas and factoring agriculture-dedicated areas (in a food-first concept, for example), among others. Land availability is grid cell specific and can vary across time. The fraction of a grid cell that is dedicated to produce bioenergy crops (A_{rlct}) is constrained by the amount of land available for bioenergy crop growth ($LdAv_{lct}$), as defined by Equation (2).

$$\sum_{r \in R^B} A_{rlct} \le LdAv_{lct} \forall r \in R^B, \forall l \in L, \forall c \in C, \forall t \in T \quad (2)$$

where A_{rlct} represents the fraction of land cover type "l" in grid cell "c" dedicated to bioenergy crop "r" in time "t"; and $LdAv_{lct}$ represents the fraction of land cover type "l" in grid cell "c" available for bioenergy production in time "t."

2.1.3 | Logistics of biomass and biofuels

The flows of bioenergy crops between grid cells are modelled according to the resource balance given by Equation (3), in which the consumption of bioenergy crops in a given grid cell (H_{rct}) accounts for crop growth in the grid cell (Brit)and flows into and out of the grid cell.

$$B_{rct} + \sum_{c' \in C} Bn_{rc'ct} = HB_{rct} + \sum_{c' \in C} Bn_{rcc't} \forall r \in R^B, \forall c \in C, \forall t \in T \quad (3)$$

where B_{rct} represents the production of bioenergy crop "r" in grid cell "c" in time "t," in unit of output; $Bn_{rc'ct}$ represents the flow of bioenergy crop "r" from grid cell "c'" to grid cell "c" in time "t" (the flow of bioenergy crop "r" into grid cell "c"), in unit of output, e.g., GJ; HB_{rct} represents the consumption of bioenergy crop "r" in grid cell "c", in unit of output; and $Bn_{rcc't}$ represents the flow of bioenergy crop "r" from grid cell "c" to grid cell "c'" in time "t" (the flow of bioenergy crop "r" out of grid cell "c"), in unit of output.

Similarly, bioenergy logistics accounts for the flows of bioenergy products from the conversion facilities to geographically explicit local demands. For the logistics of distribution of final products (liquid biofuels) no constraints on grid cell interconnections were added, so that grid cells can communicate with each other regardless of the distance between them.

$$E_{rct} + \sum_{c' \in C} En_{rc'ct} = HE_{rct} + \sum_{c' \in C} En_{rcc't} \forall r \in R^P, \forall c \in C, \forall t \in T \quad (4)$$

where E_{rct} represents the production of bioenergy product "r" in grid cell "c" in time "t"; in unit of output per time; $En_{rc'ct}$ represents the flow of bioenergy product "r" from grid cell "c'" to grid cell "c" in time "t" (the flow of bioenergy product "r" into grid cell "c"), in unit of output per time; $En_{rcc't}$ represents the flow of bioenergy product "r" from grid cell "c" to grid cell "c'" (the flow of bioenergy product "r" out of grid cell "c"), in unit of output per time; and HE_{rct} represents the amount of bioenergy product "r" consumed in grid cell "c" in time "t", in unit of output per time.

2.1.4 | CO_2 logistics and storage constraints

CO_2 logistics (transportation and storage dynamics) account for flows of CO_2 from the conversion facilities to the CO_2 storage sites, as shown in Equation (5).

$$Vcap_{ct} + \sum_{c' \in C} Vn_{c'ct} = Vseq_{ct}\big|_{c \in C^S} + \sum_{c' \in C} Vn_{cc't} \forall c \in C, \forall t \in T \quad (5)$$

where $Vcap_{ct}$ represents the amount of CO_2 captured in grid cell "*c*" in time "*t*", in unit of CO_2 emission; $Vn_{c'ct}$ represents the flow of CO_2 from grid cell "*c′*" to grid cell "*c*" in time "*t*" (the flow of CO_2 into grid cell "*c*"), in unit of CO_2 emission; $Vn_{cc't}$ represents the flow of CO_2 from grid cell "*c*" to grid cell "*c′*" (the flow of CO_2 out of grid cell "*c*"), in unit of CO_2 emission; and $Vseq_{ct}$ represents the amount of CO_2 sequestrated in grid cell "*c*" in time "*t*", in unit of CO_2 emission.

CO_2 storage is constrained by the cumulative storage capacity of each selected storage site $\left(c \in C^S\right)$, as seen in Equation (6).

$$\sum_{t \in T} Vseq_{ct} \leq MaxSt_c \, \forall c \in C^S, \forall t \in T \tag{6}$$

where $Vseq_{ct}$ represents the amount of CO_2 sequestrated in grid cell "*c*" in time "*t*," in unit of CO_2 emission; and $MaxSt_c$ represents the cumulative storage capacity of grid cell "*c*," in unit of CO_2 emission.

2.1.5 | Bioenergy production targets

Bioenergy production targets include domestic production targets and export targets, if applicable, and should meet the local bioenergy demands as follows.

$$Pb_{rct} + Ex_{rct} = HE_{rct} \, \forall r \in R^P, \forall c \in C, \forall t \in T \tag{7}$$

where Pb_{rct} represents the domestic production target for bioenergy product "*r*" in grid cell "*c*" in time "*t*"; in unit of output per time; Ex_{rct} represents the export target for bioenergy product "*r*" in grid cell "*c*" in time "*t*"; in unit of output per time; and HE_{rct} represents the local bioenergy demands, that is, the amount of bioenergy product "*r*" consumed in grid cell "*c*" in time "*t*," in unit of output per time. For accounting simplicity of the export dynamics, we consider that the bioenergy exported from a grid cell is consumed in that grid cell (therefore, part of the local bioenergy demand).

2.2 | The Brazilian context

The model can be applied to suit the user's specification, such as coverage, and spatial and temporal resolution. In this study, the model is configured for Brazil: the Brazilian territory is divided into 2912 square grid cells of 50 km in length. The time frame goes from 2020 to 2050 in decadal time steps. The model was coupled with the BLUES model (BLUES, 2022; Köberle et al., 2022; Rochedo et al., 2018), developed by CENERGIA, COPPE/UFRJ.

2.2.1 | Bioenergy production targets

The bioenergy production levels for this study were based on the NDC scenario developed with the BLUES model. This scenario is based on an updated Brazilian Nationally Determined Contribution (NDC) (Brasil, 2022), assuming that it will be implemented by 2030 and reflecting a continuation of such measures from 2030. The updated Brazilian NDC aims at reducing GHG emissions by 37% and 50% in 2025 and 2030, respectively, compared to 2005 levels (Brasil, 2022). The degraded pastures recovery target of 30 million hectares by 2030 is based on the Plan for Adaptation and Low Carbon Emission in Agriculture (Plano ABC+) (MAPA, 2021).

The technologies' portfolio (Figure 1) includes first-generation ethanol from sugarcane (with and without carbon capture), biodiesel from oil crops, and lignocellulosic biofuels (biojet and green diesel, with and without carbon capture) from woody biomass. Further details regarding the technologies' portfolio, such as investments, operation

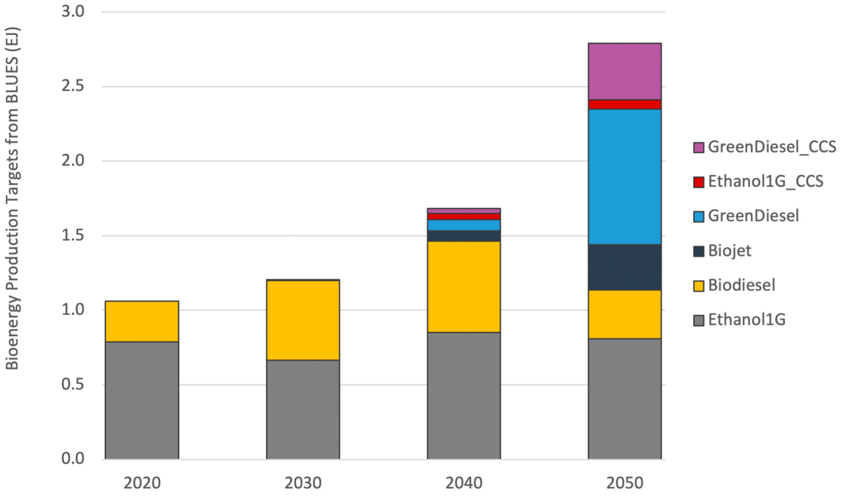

FIGURE 1 Bioenergy production levels and technologies portfolio for the NDC+ scenario according to the BLUES model.

and maintenance costs and conversion efficiencies, can be found in the Supplementary Material.

2.2.2 | Biomass yields, potentials, and costs

Potential biomass yields at the grid level were obtained from IMAGE (Integrated Model to Assess the Global Environment) LPJmL (Lund-Potsdam-Jena managed Land), which computes photosynthesis, maintenance and growth respiration (Doelman et al., 2018; IMAGE, 2022; PIK, 2022). Actual yields were calculated by applying a management factor to potential yields. Such factors represent management and farmer behaviour that, in turn, affect crop yields and ensure that the actual yields match empirical data (Daioglou et al., 2016). All yields were reported on dry basis. For oil crops, a small step of calibration combining the data from IMAGE (yields on a grid level) and the data from BLUES (regional level differences in yields) was necessary to better represent the expected behaviour of soybean since oil crops are a pool of different crops, including other crops with minor relevance for biofuel production.

The biomass supply potentials for each crop were determined based on actual yields and land availability. Supply costs for biomass include farm gate costs, land rent costs and costs for biomass collection (transportation within a given grid cell). Farm gate costs at a regional level were obtained from Angelkorte (2019). Costs for biomass collection within the grid cell were based on Tagomori et al. (2019) and adapted to different feedstocks. Land rent costs at the grid level were obtained from Doelman et al. (2020).

2.2.3 | Land availability scenarios

BLOEM accounts for five different types of land: forests, agricultural land, pastures, urban areas and other lands (including savannahs, grasslands and scrublands). The land-use dynamics and land cover calibration are based on projections from IMAGE-LPJml (Doelman et al., 2018). IMAGE provides maps indicating the portion of grid cells used for urban, agriculture, forest, and other natural lands. All urban areas were considered unavailable for bioenergy crops. Furthermore, a food-first principle is applied where agricultural areas are also deemed off-limits. For the remaining grid cell fraction, a cap of 25% was applied to savannahs and 90% to scrublands and/or grasslands. In all cases, no more than 75% of a grid cell can be used for bioenergy crop growth.

Food crops have priority over energy crops for land allocation. However, sugarcane and oil crops are both food and energy crops, already being partly directed to bioenergy production. Therefore, a fraction of agricultural land was deemed available for bioenergy (Daioglou et al., 2019; van Vuuren et al., 2021). The calculation of these fractions is based on comparing the Food and Agriculture Organization of the United Nations (FAO) numbers (FAO, 2018) with national statistics for ethanol and biodiesel production (ANP, 2020; UNICA, 2019). Furthermore, agricultural lands projected to be abandoned are also deemed available for bioenergy production (Doelman et al., 2018).

To evaluate the role of land availability in land allocation for bioenergy, we developed scenarios where a share of depleted pasture lands is deemed available. This share is based on Plano ABC+, which has a target of 30 million hectares of degraded pastures recovered by 2030 (MAPA, 2021). Forests were deemed unavailable for bioenergy crops, except for the weak governance scenario (WGV), where no forest and natural land protection policies were applied.

An overview of the land availability scenarios is presented in Table 1.

None of the Brazilian NDCs released so far explicitly refer to carbon prices. However, to evaluate the effects a

TABLE 1 Land availability scenarios.

Scenario name	Tag	Land availability	Carbon price
Reference	REF	Other land Bioenergy land	No
Reference with carbon price	REF_C	Other land Bioenergy land	Yes
Pasture recovery	PAS	Other land Bioenergy land Recovered pastures	No
Pasture recovery with carbon price	PAS_C	Other land Bioenergy land Recovered pastures	Yes
Weak governance	WGV	Other land Bioenergy land Forests (no forest protection)	No

carbon price could have on land allocation decisions, we also ran the reference and the pasture recovery scenarios assuming a carbon price trajectory consistent with 1.5°C global scenarios available in the AR6 Scenarios Database (Byers et al., 2022), as displayed in Table 2.

2.2.4 | Logistics interconnections

Biomass can be transported from one grid cell to another, depending on the location of the conversion facilities. The logistics interconnections for biomass transportation were constrained by a maximum distance of 300 km from the centroid of the grid cell where the crop is being grown to the centroid of the grid cell where the conversion facility is located. The costs for biomass and biofuel transportation were determined based on Tagomori et al. (2019) and Vera et al. (2020), adapting the load weight according to the feedstock or product being transported. Tortuosity factors were adapted from Fajardy et al. (2018).

2.2.5 | CO_2 storage sites

For this study, we have selected three potential carbon storage sites. All selected storage sites are mature oil and gas fields: one onshore and two offshore. The maximum storage capacity for all sites, onshore and offshore, was collected from Nogueira et al. (2022) and Oliveira et al. (2020). The costs of CO_2 onshore transportation via pipelines were based on da Silva et al. (2018). The costs of CO_2 offshore transportation were based on Nogueira et al. (2022). The choice of storage sites was based on data availability and the required experience regarding the geological structure, physical properties, feasibility, and safety of the potential sites. Saline aquifers were excluded due to geological uncertainties and limited seismic data availability.

2.2.6 | Spatial distribution of bioenergy production targets

Data on population density from the Brazilian Institute of Geography and Statistics were used to spatially distribute the demand for bioenergy products (IBGE, 2020). Municipalities under 300,000 inhabitants were excluded. The distribution according to population density was crossed and matched with data on states capitals' locations and the locations of fuels and biofuels distribution terminals (EPE, 2022).

TABLE 2 Carbon price trajectory.

	Carbon price [US$/tCO$_2$]			
Trajectory	**2020**	**2030**	**2040**	**2050**
1.5°C 50th percentile	0	100	250	400

Note: Based on Byers et al. (2022).

2.2.7 | Emission factors

A set of emission factors was used to represent all emissions along the production and use a chain of bioenergy. The emission factors at the grid level for land-use change were obtained from IMAGE, following the methodology proposed by Daioglou et al. (2016, 2017). These factors include the instantaneous emissions (emissions due to land clearing) and the gradual emissions over time (the differences in carbon stocks between the area used for crops and the natural vegetation counterfactual). For gradual emissions, this study has chosen a 30-year period. A second emission factor was applied for biomass production to represent the emissions from energy use during production (in this case, conventional diesel fuel). The factor of fuel consumption per crop, per region, was obtained from BLUES as proposed by Angelkorte (2019). The emission factor for conventional diesel fuel was obtained from the IPCC Guidelines for National Greenhouse Gases Inventories (IPCC, 2006). A third emission factor related to using fertilizers, per crop and region, was obtained from BLUES, as proposed by Angelkorte (2019). Fourth, the emission factors for biomass conversion in the use phase were obtained from IMAGE (Daioglou et al., 2015, 2019). These are specified per bioenergy product per technology. Finally, the emission factors for biomass and biofuel transportation were determined based on Vera et al. (2020), combining data on fuel consumption, load weight and the emission factor related to the fuel in use (in this case, conventional diesel fuel). More details can be found in the Supplementary Material.

3 | RESULTS

3.1 | Cost supply curves

Figure 2 presents cost supply curves for sugarcane, oil crops and woody biomass, assuming no competition between them. Potentials range from 6 EJ (oil crops) to around 14–18 EJ (woody biomass and sugarcane, respectively) in 2030, and from around 7 EJ (oil crops) to 14–20 EJ (woody biomass and sugarcane, respectively), in 2050. The stagnation in woody biomass potentials in 2050 compared to 2030 is due to a combination of the expansion of agricultural land and lower yields, where food crops

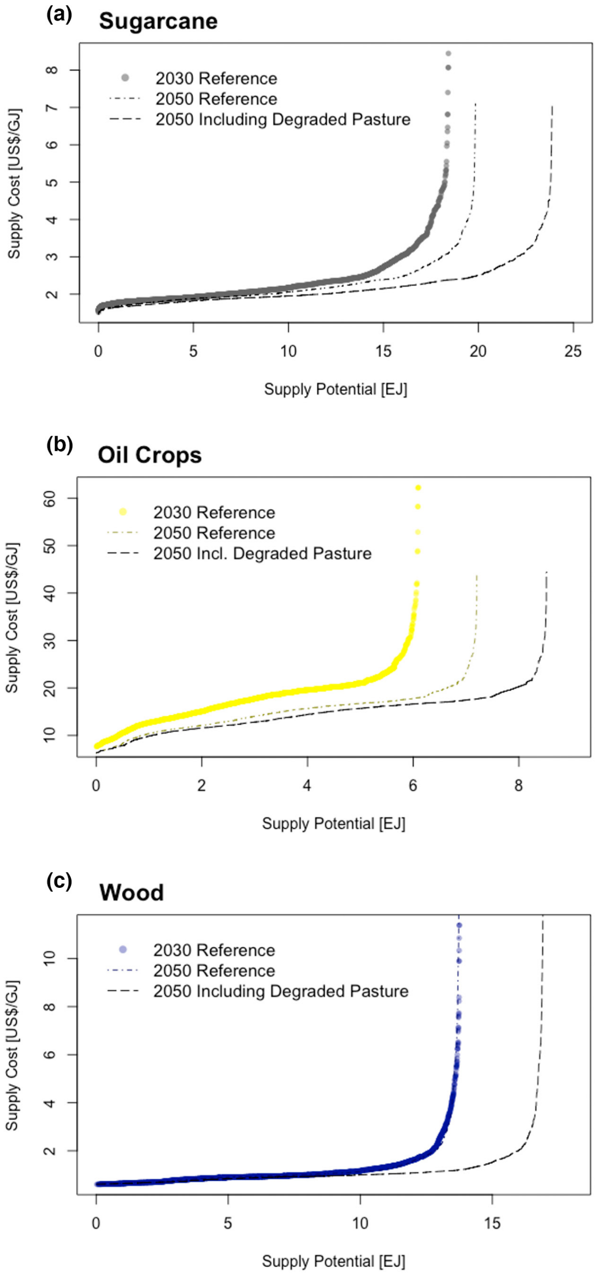

FIGURE 2 Cost supply curves for sugarcane (a), oil crops (b) and woody biomass (c).

move into the high-yield areas, leaving lower-yielding remaining lands. The availability of degraded pasture lands significantly increases the potential for biomass supply in all cases, reaching around 8 EJ for oil crops, 17 EJ for woody biomass, and 24 EJ for sugarcane in 2050.

3.2 | Land allocation, land-use change, and emissions

Figure 3 presents the results for land-use change and direct land-use change emissions, for the entire time frame (2020–2050). To put these figures into context, land allocation in Brazil, in 2020, accounted for approximately 371 Mha of forests, 75 Mha of agricultural land, 221 Mha of pasture lands and 172 Mha of other lands (IBGE, 2018).

As expected, the weak-governance scenario leads to higher land conversion of natural lands and, consequently, higher direct land-use change emissions: 18.5 million hectares of natural land converted, 80% of which are tropical forests, leading to around 60 $MtCO_2$ emitted from direct land-use change, in the period between 2020 and 2050. In this scenario (NDC_WGV), most (77%) of the converted land is utilized for oil crops and woody biomass. The availability of degraded pasture lands reduces the conversion of natural lands to some degree (NDC_PAS) while introducing a carbon price retracts such expansion significantly (NDC_REF_C). Combining both measures (NDC_PAS_C) leads to energy crops moving only toward pasture lands, resulting in no direct land-use change emissions. When comparing both reference (NDC_REF_C) and degraded pasture (NDC_PAS_C) scenarios with a carbon price, we observe a trade-off between direct land-use change emissions and land-use change, with NDC_PAS_C accounting for more land-use change (8 million ha vs. 6 million ha in NDC_REF_C), due to the lower productivity of degraded pasture lands, but lower direct land-use change emissions.

Figure 4 presents the differences in land allocation, in 2050, for all scenarios. Figure 5 presents installed capacities in 2050, per region, per technology, for all scenarios (top) and the geographic allocation of installed capacities in 2050, per technology, for NDC_PAS_C (bottom, similar figures for the other scenarios can be found in the Supplementary Material). These figures provide a spatially explicit perspective of the land-use changes displayed in Figure 3, capturing regional specificities and patterns. The scenarios with pasture recovery and enforced protection of forests indicate that land expansion moves toward degraded pastures, reducing the conversion of other natural lands. Land allocation is highly concentrated in the Center-South of the country, with moderate participation of the Northeast, especially around the coast where sugarcane production in the region already takes place. The production of biofuels with CCS is allocated to the coast, near the CO_2 storage sites, to minimize CO_2 transport costs.

In all scenarios, sugarcane and oil crop production remain prevalent in the Center-South region. When degraded pastures are made available and are more attractive due to the introduction of a carbon price (NDC_PAS_C), energy crops expand toward the Center-West, surpassing the installed capacities in the Southeast in 2050, and closing in on the borders of the Amazon region. However, under weak governance and the lack of protection of forests, this expansion shifts toward the Atlantic Forest, moving to the South and Southeast

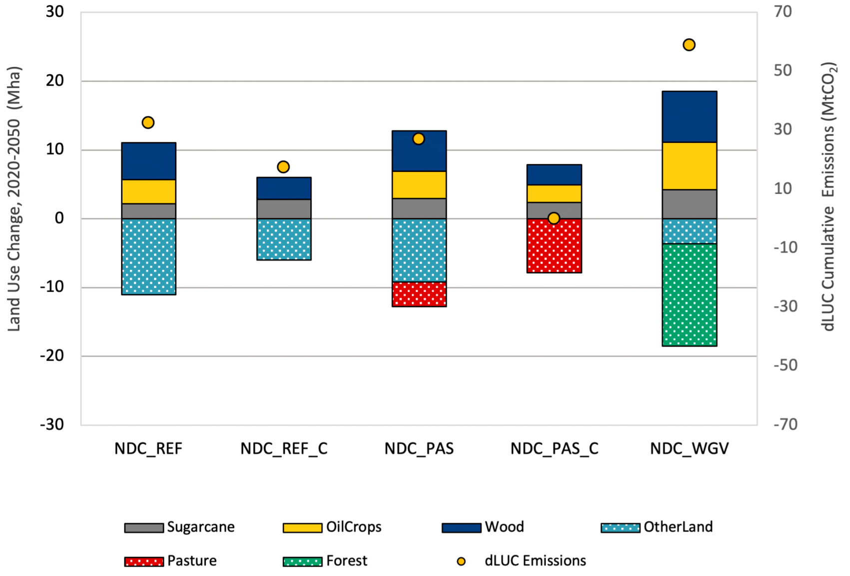

FIGURE 3 Land-use change and direct land-use change emissions (2020–2050), for bioenergy.

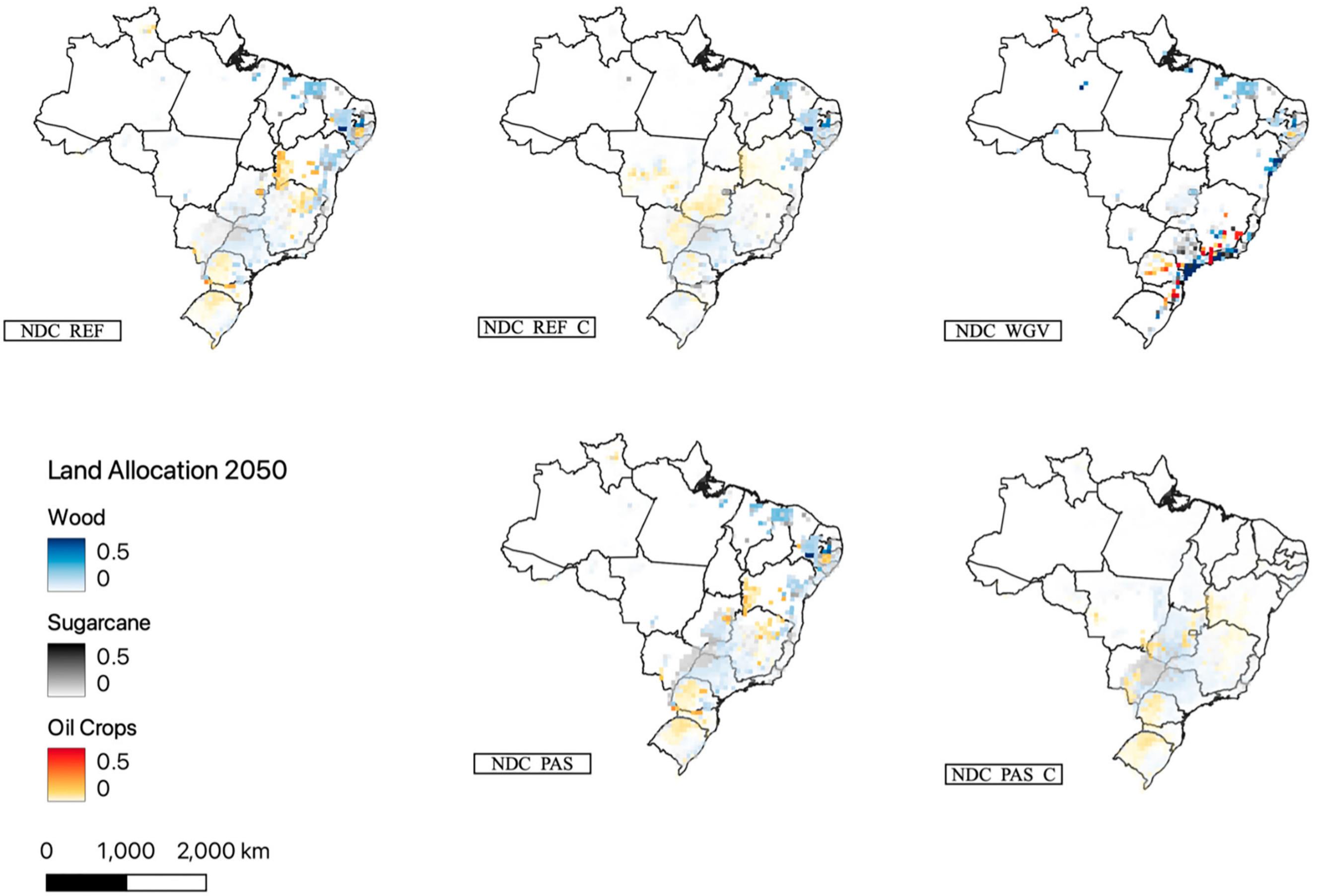

FIGURE 4 Land allocation for bioenergy crops, projections for 2050 for the reference scenarios, with and without carbon price (REF; REF_C), the scenarios with pasture recovery, with and without a carbon price (PAS; PAS_C), and for the weak governance scenario (WGV).

coastline. In all scenarios, the production of biofuels with CCS (BECCS) is concentrated in the Southeast and Northeast coasts due to the preferred proximity to the CO_2 storage sites, which reduces costs for CO_2 transportation.

4 | DISCUSSION

While considering both the spatial and temporal dynamics of bioenergy systems, assessing the availability and demand for resources, properly allocating available

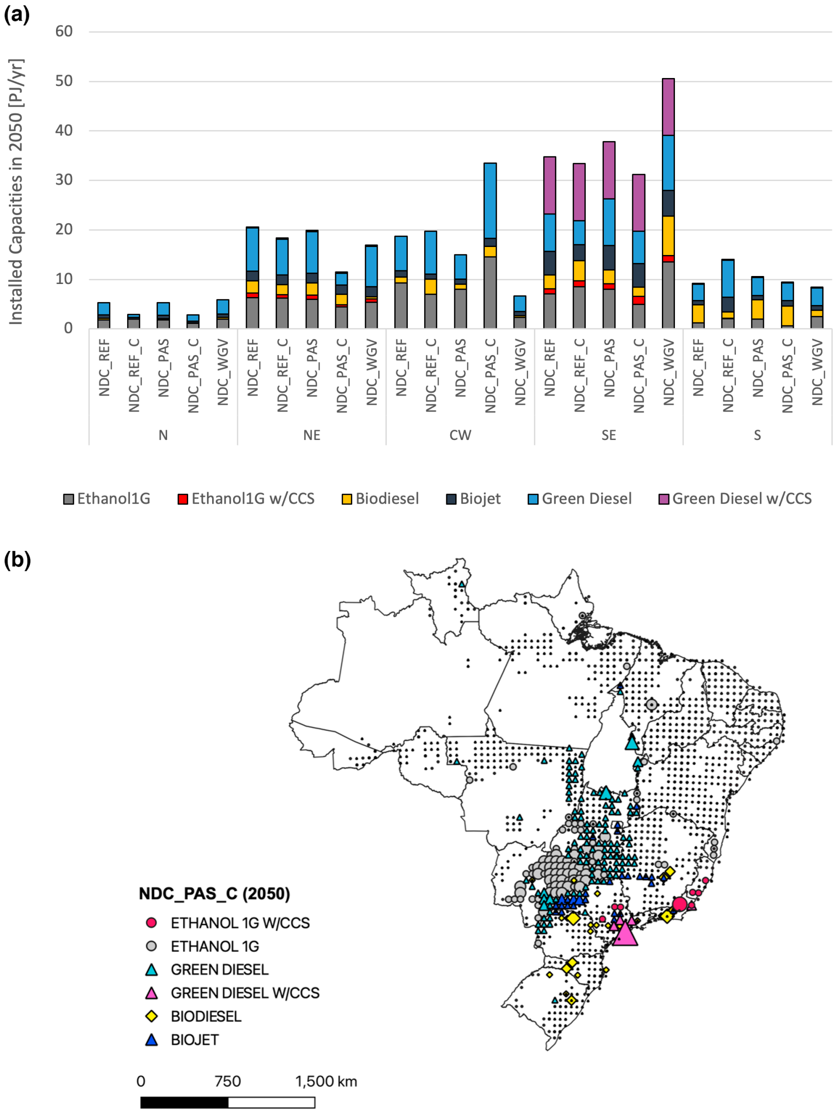

FIGURE 5 Installed capacities in 2050 per product, per region, for all scenarios (a) and geographic allocation of capacities in 2050, for NDC_PAS_C (b). Note: N = north; NE = northeast; CW = center-west; SE = southeast; S = south.

land, and establishing the necessary logistic interconnections, BLOEM provides a more robust evaluation of the role bioenergy can fulfil in terms of both energy supply and climate mitigation, as well as in offering support for policy-making in sustainable bioenergy expansion. This is especially relevant for Brazil, given the importance of biomass and bioenergy for the current energy matrix and their expected role in the future. It can also be a powerful tool for other regions where biomass potentials may be relevant. The model formulation can be applied to different regions, spatial resolutions, and time frames according to the availability of required data and computational effort and can be coupled with different IAMs at the national, regional, and global levels.

This study applied a food-first principle, where food crops have a preference over energy crops, with no economic interactions between bioenergy and food production. As this means that emissions for bioenergy are directly calculated, we do not calculate the possible impacts of replacing food production (so-called indirect land-use changes). Still, such patterns have been observed in the past (e.g., deforestation for low-intensity pasture turning, in time, into agricultural land for crops used to produce animal feeds). The results present physical potentials and the sensitivities of bioenergy-related land-use change and associated emissions in the presence of increasing bioenergy demand. It should be noted that an approach also accounting for indirect land-use change would not lead to higher emission factors as the direct emission factors would, in that case, be much lower.

Finally, IAMs scenarios usually use stylized assumptions about resource costs and logistical constraints for large regions. Using BLOEM, the feasibility of IAMs scenarios can be assessed at the regional level, accounting for logistical constraints, such as the logistics of feedstocks and final products, investments and conversion capital, hotspots for system expansion, location of conversion facilities and their connection to distribution and consumer centers. However, the cost-optimal outcomes are not necessarily true in the real non-cost-optimal world where, for various reasons, from the social and economic to the political spheres, large-scale deployments of bioenergy might induce shifts in agricultural areas, resulting in indirect land-use changes and endangering protected biomes and biodiversity due to illegal deforestation. Other current limitations include the lack of residues as feedstock and the lack of alternative practices, such as integrated systems. Future developments include expanding the model's capabilities to investigate impacts on other feedstocks (e.g., agricultural and forestry residues) and other resources such as water and biodiversity and incorporate competition with food production to evaluate indirect effects on land use, better encompassing the water–land–food–energy nexus.

5 | CONCLUSIONS

In this paper, we calculate in detail the land-use and emission consequences of detailed bioenergy scenarios that account for logistical considerations.

The results, first of all, show that in scenarios where the protection of forests is enforced and bans on the use of forest areas for bioenergy production are in place, degraded pasture lands become attractive for biomass production even without a carbon price in place. Our results indicate that using degraded pasture lands for bioenergy production is attractive from both logistics (i.e., proximity to distribution and demand) and climate (i.e., direct land-use change emissions) perspectives. This shows potential for pasture intensification and integrated systems (e.g., integrated livestock, forestry and pasture systems) that can improve land availability, reducing the conversion of other lands and relieving land pressures related to bioenergy.

Our results indicate that carbon pricing alone is not enough to halt losses in natural land areas. The introduction of a carbon price reduces the expansion of energy crops toward other natural land areas, being most effective when combined with policies aiming at recovering degraded pasture areas. Such findings highlight the need for strategic energy and climate policies that combine the protection of natural areas and the recovery of degraded lands to develop bioenergy more sustainably. It also means that the protection of forests and other natural land areas, the commitment with zero illegal deforestation and the incentives to restore degraded lands are measures of utmost importance, as well as their proper enforcement. This is especially relevant given that the policies focusing on stopping illegal deforestation, reforestation and native forest management are no longer on track with the ambitions of the updated Brazilian NDC and the country's climate goals.

The trade-off between the costs of deforestation and the logistics costs/constraints plays a major role in the model's land allocation decisions. From a modelling perspective, due to logistics constraints, the biggest direct risk to deforestation is upon the Atlantic Forest: the proximity of such forest areas to current production (and therefore, current locations of conversion facilities), to CO_2 storage sites (most of which are offshore) and to the larger demand centers makes them more attractive than areas located further away from conversion, distribution, and consumption centers. Finally, it is important to reflect on the fact that BLOEM is a cost-optimal model, and the real world does not necessarily operate in a cost-optimal way. In this context, even if our results here indicate that expanding bioenergy production into the Amazon Forest is not, from a logistics and modelling perspective, the least-cost option, this does not mean there should be no concern in its regard since other drivers (social, economic, political) also play important roles in such decisions and their outcomes.

ACKNOWLEDGMENTS

We would like to thank Luiz Bernardo Baptista, from CENERGIA/COPPE/UFRJ for the support in running the BLUES model, to which BLOEM was linked in this study. This study benefited from the financial support of the European Union via the COMMIT (Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition pathways) project, funded by Directorate General Climate Action (DG CLIMA) and EuropeAid, under grant agreement No. 21020701/2017/770447/SER/ CLIMA.C.1 EuropeAid/138417/DH/SER/MuliOC (COMMIT). This study also benefited from the financial support of the European Union's Horizon 2020 research and innovation programme, via the ENGAGE project (Exploring National and Global Actions to reduce Greenhouse gas Emissions), under Grant Agreement 821471 (ENGAGE). This study was supported by the Carlos Chagas Filho Foundation for Research Support of the State of Rio de Janeiro (Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro – FAPERJ), under the Outstanding Candidate Scholarship (Bolsa Doutorado Nota 10), number 2016.00687.5. Finally, Alexandre Szklo and Roberto Schaeffer also want to thank CNPq (National Council for Scientific and Technological Development), from Brazil, for its financial support.

CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in itagomori/BLOEM at http://doi.org/10.5281/zenodo.7225602.

ORCID

Isabela Tagomori https://orcid.org/0000-0002-0469-6055
Vassilis Daioglou https://orcid.org/0000-0002-6028-352X

REFERENCES

Angelkorte, G. B. (2019). *Modelagem do setor agropecuário dentro de modelo de análise integrada brasileiro*. Universidade Federal do Rio de Janeiro, Rio de Janeiro. http://www.ppe.ufrj.br/index.php/pt/publicacoes/dissertacoes/2019/1442-modelagem-do-setor-agropecuario-dentro-de-modelo-de-analise-integrada-brasileiro

ANP. (2020). *Oil, natural gas and biofuels statistical yearbook 2020*. ANP, Brazil. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/oil-natural-gas-and-biofuels-statistical-yearbook-2020#Se%C3%A7%C3%A3o%202

BLOEM. (2022). Bioenergy and land optimization model (BLOEM). https://doi.org/10.5281/zenodo.7225602.

BLUES. (2022). *BLUES - IAMC model documentation*. BLUES. https://www.iamcdocumentation.eu/BLUES

Bragança, A., Newton, P., Cohn, A., Assunção, J., Camboim, C., de Faveri, D., Farinelli, B., Perego, V. M. E., Tavares, M., Resende, J., de Medeiros, S., & Searchinger, T. D. (2022). Extension services can promote pasture restoration: Evidence from Brazil's low carbon agriculture plan. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(12), e2114913119. https://doi.org/10.1073/pnas.2114913119

Brasil. (2022). *Nationally determined contribution*. https://unfccc.int/NDCREG

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromann, A., Winkler, H., Auer, C., Brutschin, E., Lepault, C., … Skeie, R. (2022). AR6 scenarios database. https://doi.org/10.5281/ZENODO.5886912

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., van der Zwaan, B. C. C., & van Vuuren, D. P. (2014). Assessing transformation pathways. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar5/wg3/assessing-transformation-pathways/

da Silva, F. T. F., Carvalho, F. M., Corrêa, J. L. G., Merschmann, P. R. d. C., Tagomori, I. S., Szklo, A., & Schaeffer, R. (2018). CO_2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks. *International Journal of Greenhouse Gas Control*, *71*, 168–183. https://doi.org/10.1016/j.ijggc.2018.02.018

Daioglou, V., Doelman, J. C., Stehfest, E., Müller, C., Wicke, B., Faaij, A., & van Vuuren, D. P. (2017). Greenhouse gas emission curves for advanced biofuel supply chains. *Nature Climate Change*, *7*(12), 920–924. https://doi.org/10.1038/s41558-017-0006-8

Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A., & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global Environmental Change*, *54*, 88–101. https://doi.org/10.1016/j.gloenvcha.2018.11.012

Daioglou, V., Rose, S. K., Bauer, N., Kitous, A., Muratori, M., Sano, F., Fujimori, S., Gidden, M. J., Kato, E., Keramidas, K., Klein, D., Leblanc, F., Tsutsui, J., Wise, M., & van Vuuren, D. P. (2020). Bioenergy technologies in long-run climate change mitigation: Results from the EMF-33 study. *Climatic Change*, *163*(3), 1603–1620. https://doi.org/10.1007/s10584-020-02799-y

Daioglou, V., Stehfest, E., Wicke, B., Faaij, A., & van Vuuren, D. P. (2016). Projections of the availability and cost of residues from agriculture and forestry. *GCB Bioenergy*, *8*(2), 456–470. https://doi.org/10.1111/gcbb.12285

Daioglou, V., Wicke, B., Faaij, A. P. C., & van Vuuren, D. P. (2015). Competing uses of biomass for energy and chemicals: Implications for long-term global CO_2 mitigation potential. *GCB Bioenergy*, *7*(6), 1321–1334. https://doi.org/10.1111/gcbb.12228

Doelman, J. C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D. E. H. J., Neumann-Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., & van Vuuren, D. P. (2018). Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, *48*, 119–135. https://doi.org/10.1016/j.gloenvcha.2017.11.014

Doelman, J. C., Stehfest, E., Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., Gernaat, D. E. H. J., Berg, M., Zeist, W., Daioglou, V., Meijl, H., & Lucas, P. L. (2020). Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Global Change Biology*, *26*(3), 1576–1591. https://doi.org/10.1111/gcb.14887

EPE. (2022). WEBMAP EPE - Energy Research Office (EPE). https://www.epe.gov.br/en/publications/publications/webmap-epe

Fajardy, M., Chiquier, S., & mac Dowell, N. (2018). Investigating the BECCS resource nexus: Delivering sustainable negative emissions. *Energy and Environmental Science*, *11*(12), 3408–3430. https://doi.org/10.1039/c8ee01676c

FAO. (2018). *OECD-FAO Agricultural Outlook 2018-2027*. OECD. https://doi.org/10.1787/agr_outlook-2018-en

Feltran-Barbieri, R., & Féres, J. G. (2021). Degraded pastures in Brazil: Improving livestock production and forest restoration. *Royal Society Open Science*, *8*(7), 201854. https://doi.org/10.1098/rsos.201854

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions - part 2: Costs, potentials and side effects. In *Environmental research letters* (Vol. *13*, Issue 6, p. 063002). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/aabf9f

Gambhir, A., Butnar, I., Li, P.-H., Smith, P., & Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies*, *12*(9), 1747. https://doi.org/10.3390/en12091747

Hasegawa, T., Sands, R. D., Brunelle, T., Cui, Y., Frank, S., Fujimori, S., & Popp, A. (2020). Food security under high bioenergy demand toward long-term climate goals. *Climatic Change*, *163*(3), 1587–1601. https://doi.org/10.1007/s10584-020-02838-8

IBGE. (2018). *Land use and cover in Brazil*. IBGE https://www.ibge.gov.br/en/geosciences/environmental-information/land-use-and-cover/18428-land-use-and-cover-in-brazil.html?=&t=acesso-ao-produto

IBGE. (2020). *Estimates of resident population for Municipalities and Federation Units*. IBGE https://www.ibge.gov.br/en/statistics/social/population/18448-estimates-of-resident-population-for-municipalities-and-federation-units.html?edicao=28688&t=resultados

IMAGE. (2022). IMAGE - IAMC model documentation. https://www.iamcdocumentation.eu/IMAGE

IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. IPCC. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, *40*, 401–430.

Köberle, A. C., Daioglou, V., Rochedo, P., Lucena, A. F. P., Szklo, A., Fujimori, S., Brunelle, T., Kato, E., Kitous, A., van Vuuren, D. P., & Schaeffer, R. (2022). Can global models provide insights into regional mitigation strategies? A diagnostic model comparison study of bioenergy in Brazil. *Climatic Change*, *170*(1–2), 1–31. https://doi.org/10.1007/s10584-021-03236-4

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., & Klein, D. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, *118*(1), 45–57. https://doi.org/10.1007/s10584-012-0681-4

MAPA. (2021). ABC+ plan for adaptation and low carbon emission in agriculture.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions - part 1: Research landscape and synthesis. In *Environmental research letters* (Vol. *13*, Issue 6, p. 063001). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/aabf9b

Nogueira, T., Rochedo, P. R. R., & Szklo, A. (2022). Evaluation of offshore CO_2 transport alternatives in Brazil. *International Journal of Greenhouse Gas Control*, *116*, 103629. https://doi.org/10.1016/j.ijggc.2022.103629

Oliveira, R. D. d., Silva, F. T. F. d., Nogueira, T. d. F., & Rochedo, P. R. R. (2020). CO_2 injection of ethanol distilleries in mature northeastern fields. *Rio Oil and Gas Expo and Conference*, *20*(2020), 547–548. https://doi.org/10.48072/2525-7579.rog.2020.547

PIK. (2022). *LPJmL - Lund-Potsdam-Jena managed Land*. Potsdam Institute for Climate Impact Research https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml

Rajão, R., Soares-Filho, B., Nunes, F., Börner, J., Machado, L., Assis, D., Oliveira, A., Pinto, L., Ribeiro, V., Rausch, L., Gibbs, H., & Figueira, D. (2020). The rotten apples of Brazil's agribusiness. *Science*, *369*(6501), 246–248. https://doi.org/10.1126/science.aba6646

Rochedo, P. R. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A. F. P., Koberle, A., Davis, J. L., Rajão, R., & Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. In *Nature climate change* (Vol. *8*, Issue 8, pp. 695–698). Nature Publishing Group. https://doi.org/10.1038/s41558-018-0213-y

Rogelj, J., Schaeffer, M., Friedlingstein, P., Gillett, N. P., van Vuuren, D. P., Riahi, K., Allen, M., & Knutti, R. (2016). Differences between carbon budget estimates unravelled. In *Nature climate change* (Vol. *6*, Issue 3, pp. 245–252). Nature Publishing Group. https://doi.org/10.1038/nclimate2868

Samsatli, S., Samsatli, N. J., & Shah, N. (2015). BVCM: A comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation–mathematical formulation. *Applied Energy*, *147*, 131–160. https://doi.org/10.1016/j.apenergy.2015.01.078

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016). Biophysical and economic limits to negative CO_2 emissions. In *Nature climate change* (Vol. *6*, Issue 1, pp. 42–50). Nature Publishing Group. https://doi.org/10.1038/nclimate2870

Strassburg, B. B. N., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., & Assad, E. D. (2014). When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, *28*(1), 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001

Tagomori, I. (2022). *Bioenergy and carbon capture and storage spatially explicit modelling in Brazil*. Universidade Federal do Rio de Janeiro http://www.ppe.ufrj.br/index.php/pt/publicacoes/teses-e-dissertacoes/2022/2315-bioenergy-and-carbon-capture-and-storage-spatially-explicit-modelling-in-brazil

Tagomori, I. S., Rochedo, P. R. R., & Szklo, A. (2019). Techno-economic and georeferenced analysis of forestry residues-based Fischer-Tropsch diesel with carbon capture in Brazil. *Biomass and Bioenergy*, *123*, 134–148. https://doi.org/10.1016/j.biombioe.2019.02.018

UNICA. (2019). Observatório da Cana–Production data: sugarcane planted area. https://observatoriodacana.com.br/sub.php?menu=producao

van Vuuren, D., Stehfest, E., Gernaat, D., de Boer, H.-S., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., van Zeist, W.-J., van den Berg, M., Dafnomilis, I., van Sluisveld, M., Tabeau, A., de Vos, L., de Waal, L., van den Berg, N., Beusen, A., Bos, A., Biemans, H., … Zapata Castillo, V. (2021). The 2021 SSP scenarios of the IMAGE 3.2 model. https://doi.org/10.31223/X5CG92

Vera, I., Wicke, B., & van der Hilst, F. (2020). Spatial variation in environmental impacts of sugarcane expansion in Brazil. *Land*, *9*(10), 397. https://doi.org/10.3390/land9100397

Zhang, D., Bui, M., Fajardy, M., Patrizio, P., Kraxner, F., & mac Dowell, N. (2019). Unlocking the potential of BECCS with indigenous sources of biomass at a national scale. *Sustainable Energy and Fuels*, *4*(1), 226–253. https://doi.org/10.1039/c9se00609e

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Tagomori, I., Daioglou, V., Rochedo, P., Angelkorte, G., Schaeffer, R., van Vuuren, D., & Szklo, A. (2023). BLOEM: A spatially explicit model of bioenergy and carbon capture and storage, applied to Brazil. *GCB Bioenergy*, *15*, 116–127. https://doi.org/10.1111/gcbb.13008