Graphical Abstract

The impact of climate change on Brazil's agriculture

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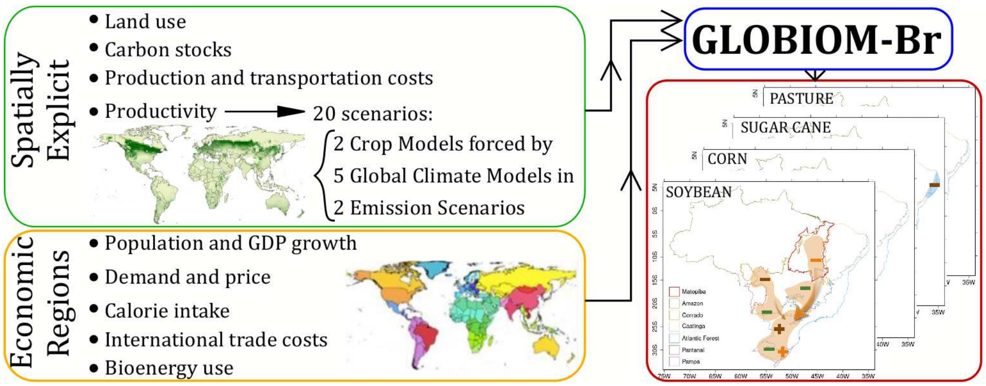

Highlights

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- Projections of climate change impacts on main Brazilian agricultural commodities
- Use of spatial explicit partial equilibrium global land use model adapted to Brazil
- Framework integrating land-use competition and biophysical and economic aspects
- Displacement of soybean and corn production toward subtropical regions of Brazil
- Decrease in soybean and corn production, especially in the Matopiba region

The impact of climate change on Brazil's agriculture

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Abstract

Brazilian agricultural production provides a significant fraction of the food consumed globally, with the country among the top exporters of soybeans, sugar, and beef. However, current advances in Brazilian agriculture can be directly impacted by climate change and resulting biophysical effects. Here, we quantify these impacts until 2050 using GLOBIOM-Brazil, a global partial equilibrium model of the competition for land use between agriculture, forestry, and bioenergy that includes various refinements reflecting Brazil's specificities. For the first time, projections of future agricultural areas and production are based on future crop yields provided by two Global Gridded Crop Models (EPIC and LPJmL). The climate change forcing is in-

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cluded through changes in climatic variables projected by five Global Climate Models in two emission pathways (RCP2.6 and RCP8.5) participating in the ISIMIP initiative. This ensemble of twenty scenarios permits accessing the robustness of the results. When compared to the baseline scenario, GLOBIOM-Brazil scenarios suggest a decrease in soybeans and corn production, mainly in the Matopiba region in the Northern Cerrado, and southward displacement of agricultural production to near-subtropical and subtropical regions of the Cerrado and the Atlantic Forest biomes.

Keywords: GLOBIOM-Brazil, land-use competition, change in production, soybean, corn, sugar cane

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1. Introduction

In its fifth Assessment Report (AR5), the Intergovernmental Panel for Climate Change (IPCC) stated that the warming of the climate system is evident and largely caused by the increase of atmospheric CO_2 concentration, mainly from anthropogenic sources (IPCC, 2013). According to the future climate projections in this report, expected increase in the length and intensity of extreme heat waves and changes in precipitation distribution, water availability, and drought, could reduce agricultural productivity and increase the risk of food insecurity (IPCC, 2014). In Brazil, climate change projections for the 21st century suggest an increase in average temperature, more intense over the central part of the country (Chou et al., 2016), including a rise in the number of days with temperature above 34°C (Assad et al., 2016a). In addition to warmer days, the number of consecutive dry days would also increase (Marengo et al., 2009, 2010, 2012), as well as the intensity and frequency of droughts south of 20°S (Penalba and Riveira, 2013). Total annual precipitation would increase over western Amazon and South Brazil (Marengo et al., 2012) and decrease over eastern Amazon and Northeast (Marengo et al., 2012, 2009), Center-West, and Southeast Brazil (Bombardi and Carvalho, 2009).

In this context, impacts of climate change in Brazilian agriculture should be assessed and quantified, especially because the agriculture sector directly contributed for 23.5% of the national gross domestic product (GDP) in 2017. The sector also accounts for 38.5% of the total national exports, placing the country as the world's third largest exporter of agricultural commodities (OECD, 2018). Brazilian main agricultural commodities are soybeans, corn, and sugar cane which, together, accounted for 84.4% of Brazilian cropland area in 2017 (PAM-IBGE, 2019). These are also the main Brazilian exports, with soybeans responding for more than 50% of the total agricultural exports in 2018, followed by sugar and sugar cane ethanol (8.7%) (OECD, 2018). Additionally, Brazil has the second largest cattle herd in the world and is the leader producer and exporter of beef, which accounted for 17.3% of the country's agricultural export in 2018 (OECD, 2018).

Several studies analyzed the impacts of climatic changes on the potential productivity of Brazilian agriculture (Margulis et al., 2011), and its main commodities, such as soybeans (Tavares et al., 2010; Zanon et al., 2016), corn (Resende et al., 2011; Costa et al., 2009), and sugar cane (Zullo, Pereira and Koga-Vicente, 2018; Marin, Jones, Singels, Royce, Assad, Pellegrino and Justino, 2013; Carvalho, Menezes, Nóbrega, Pinto, Ometto, von Randow and Giarolla, 2015). These studies focused on specific regions and only considered incremental changes (increase or decrease) on individual atmospheric variables (temperature, precipitation, CO_2 concentration). Lapola et al. (2011) produced one of the first spatial assessments of the impacts of climate change on land-use and land-cover changes in the Legal Amazon region (which encompasses the states within the Amazon biome). Using a modeling framework that simulates the interplay between anthropogenic and environmental system components (including climate change impacts), they found a reduction in soybeans, corn, and rice yield, in addition to a 10% reduction in pasture productivity in the region by 2050. The reduced productivity could potentially decrease farmer's profitability, shifting the crops toward the Cerrado biome.

By including future projections of temperature and precipitation, as estimated by global and regional climate models, into the definition of the agricultural zoning, Assad et al. (2016a) systematically evaluated the future climatic risk of main Brazilian commodities. They found a reduction of 65.7% in the area suitable for soybeans production, mainly in South Brazil, displacing the main producing regions to the southeastern portion of Amazon. Impacts on the area suitable for corn production would be even more intense, resulting in a 84.9% decrease by 2050, affecting mainly the corn produced as a second crop. Corn harvest during summer (as first crop) would be less affected, but would still have an area reduction in Northeastern and over west São Paulo and south Mato Grosso do Sul. Similar results were also identified in regional studies based on regression models between yield and climatic variables (Araújo et al., 2014) or on econometric models (Feres et al., 2010). On the other hand, the effects of warmer temperature could benefit sugar cane yield, mainly in South Brazil where the increase in temperature is projected to reduce the frequency of frosts (Assad et al., 2013).

Changes in yield due to changes in biophysical variables, such as temperature and precipitation, can also be evaluated through Global Gridded Crop Models (GGCMs). These models consist of spatially explicit global models that simulate agricultural variables based on climatic, soil, and management conditions. GGCM simulations forced by future scenarios of climate, as projected by Global Climate Models (GCMs), indicated a decrease in soybeans and corn yield in the tropical regions (Müller and Robertson, 2014; Rosenzweig et al., 2014; Müller et al., 2015), in agreement with the previously mentioned studies focused on Brazil (Assad et al., 2016a; Araújo et al., 2014; Feres et al., 2010). On the subtropics, some global studies indicate an increase in soybeans yield (Rosenzweig et al., 2014; Müller et al., 2015) while others suggest a decrease (Müller and Robertson, 2014). Part of these discrepancies could be related to the assumption of no CO_2 fertilization in Müller and Robertson (2014).

All studies mentioned so far described the impacts of climate change on the potential yield of agricultural commodities. However, it is also important to consider the interplay between these biophysical impacts and the economic outcomes, as well as to account for the various actors involved. Producers adapt to biophysical changes in productivity by moving to new areas, by growing more profitable and resilient crops, or by improving their management systems, such as increasing fertilization or implementing irrigation. Consumers also adapt to higher cost by shifting to cheaper and more resilient products. Additionally, change in climate have different impacts in different parts of the world, with the effects of climate change in productivity being, at least partially, overcome by international trade (Nelson et al., 2013; Leclère et al., 2014; Mosnier et al., 2014).

Hence, a proper assessment of the impacts of climate change in the agricultural sector should also include these actors and their interactions, be it agricultural producers competing internally for land (and other resources), or external producers competing for a share in the global market. This could be achieved through the utilization of spatially explicit partial equilibrium economic models such as GLOBIOM (Havlík et al., 2011) and its Brazilian version, GLOBIOM-Brazil (Soterroni et al., 2018, 2019; de Andrade Junior et al., 2019). Using the global version of GLOBIOM, Leclère et al. (2014) demonstrated that, despite the adverse effects of climate change in biophysical productivity, Brazilian agricultural production could increase in 8% by 2050, when compared to a scenario without climate change. In this context, soybeans production would increase by 7%, mostly due to an increase in exports, highlighting the importance of international trade.

Building upon previous studies regarding the climate change impacts on Brazilian agriculture, our objective is to quantify the economic impacts, in terms of changes in area and production, of the main Brazilian commodities considering land-use competition and economic aspects as integrated in GLOBIOM-Brazil. Section 2 describes GLOBIOM-Brazil, the modeling framework, and necessary adjustments to represent the climatic scenarios. Projections of cropland and pasture area in 2050, resulting from land-use competition and economic adjustments, as well as the changes in the production of main crops and livestock are explored in Section 3. Section 4 contextualizes the main findings and discusses the modeling framework caveats and future developments. The main conclusions and final remarks are in Section 5.

2. Material and Methods

2.1. GLOBIOM-Brazil

Socioeconomic advancements, climate change impacts, and governance scenarios affect land-use competition and productivity, resulting in different pathways through which these impacts are absorbed into the economy. Here, we use GLOBIOM-Brazil, a Global Economic Model (GEM) based on IIASA's GLOBIOM (Havlík et al., 2011) and adapted to incorporate Brazil's specificities and local policies. GLOBIOM-Brazil is a global bottom-up economic partial equilibrium model that focus on the main sectors of the land-use economy (agriculture, forestry, and bioenergy). The production of 18 crop (listed in Table S2), 5 forestry, and 7 livestock products is adjusted to meet the demand for food, feed, fibers, and bioenergy at the level of 30 economic regions. Mathematically, the model simulates competition for land at pixel level (50km x 50km in Brazil and 200km x 200km for the other 29 regions of the world) by solving a constrained linear programming problem: the maximization of welfare (i.e.,the sum of producer and consumer surplus) subject to resources, technology, and policy restrictions. International trade is also considered and is based on the spatial equilibrium modeling approach, where individual regions trade with each other under the assumption of homogeneous goods and thus competition relies only on costs.

The current version of GLOBIOM-Brazil has been extensively validated against 2000-2015 Brazil's official agricultural and deforestation data (Soterroni et al., 2018, 2019). The initial year of integration is 2000, with the model running recursively each 5 years until 2050. The 5-years time step has been adopted to gain flexibility/accuracy in defining the starting dates of Brazil's local policies. A more in-depth description of GLOBIOM-Brazil specifications and input data can be found in de Andrade Junior et al. (2019); Soterroni et al. (2019) and Soterroni et al. (2018). In addition to the features described by these authors, the version of GLOBIOM-Brazil utilized in this study also includes the double-cropping system for corn and soybeans cultivated in succession during the same season, and the agro-ecological zoning (AEZ) for sugar cane in Brazil.

2.2. Modeling Framework

GLOBIOM-Brazil initial assumptions adopted here are described in Soterroni et al. (2018, 2019), and further includes the impacts of climate change in crop yields. The model's initial assumptions are related to governance, economic, and biophysical aspects as represented in Figure 1.

[Figure 1 about here.]

Restrictions in land-use changes resulting from governance assumptions are estimated based on the level of compliance with the Brazilian Forest Code, a set environmental laws designed to eradicate illegal deforestation. As demonstrated by Soterroni et al. (2018, 2019), land-use policies related to the deforestation control affect the land-use change dynamics. Among the scenarios proposed by those authors, the IDCImperfect3 scenario is the one that best represents the historical (2000-2015) deforestation rates in Brazil, particularly in the Amazon. Economic assumptions are based on the Shared Socioeconomic Pathways 2 (SSP2) which determines the population and economic growth and the changes in consumption habits. As our objective is to quantify the impacts of climate change on Brazilian agriculture, both economic and governance scenarios are kept constant.

Initial assumptions of agricultural productivity are based on productivity models for each sector: the average productivity of crops is estimated through EPIC (Williams, 1995); cattle growth rate and milk production is estimated using RUMINANT model (Herrero et al., 2008, 2013); and forestry mean annual increments and harvesting costs are estimated by the forestry model G4M (Kindermann et al., 2008). The impacts of climate change are included in GLOBIOM Brazil through changes in biophysical aspects related to the crop productivity, as modeled by crop models forced by a set of climate change scenarios based on different emissions assumptions (as represented in Fig 1), as detailed below. For the other sectors (livestock and forestry), the assumptions are kept constant along the integration.

In its AR5, IPCC defined four Representative Concentration Pathways (RCP), representing the global greenhouse gas (GHG) emissions, land-use change, and resulting climate tendencies for the 21^{st} century (Stocker et al., 2013). GHG emissions and land-use change defined by these RCPs are used as input to GCMs that project historical and future scenarios for climatic variables such as temperature and precipitation. These information are used by GGCMs to assess the biophysical impacts of climate change in crops and pasture yield as well as the regions where crops will be more or less affected by climate change (Rosenzweig et al., 2014). Finally, these changes in yield provide the necessary input to evaluate the impacts of climate change in land-use competition and other economic variables as modeled through GLOBIOM-Brazil. These steps are summarized in Figure 1.

In this study, we utilize changes in global yield provided by two GGCMs: EPIC (Environmental Policy Integrated Model) (Williams, 1995; Izaurralde et al., 2006) and LPJmL (Lund-Potsdam-Jena managed Land) (Bondeau et al., 2007; Fader et al., 2010; Waha et al., 2012; Sibyll et al., 2013).

Changes in yield from both GGMCs are obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) FastTrack platform (Rosenzweig et al., 2014; Elliott et al., 2015). ISIMIP provides spatially interpolated and bias-corrected projections of future climate change from five GCMs (listed in Fig 1) in four Representative Concentration Pathways (RCP) (Hempel et al., 2013). These GCMs are selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012) archive and are representative of the range of global mean precipitation and temperature changes (Warszawski et al., 2014). These GCM projections are then used as initial conditions in GGCMs, resulting in future changes in agricultural productivity, which are also available through the ISMIP platform. We make use of global results from two GGCMs (EPIC and LPJmL) forced by all 5 GCMs available in ISIMIP (listed in Fig 1), considering the highest and the lowest emission scenarios: RCP8.5 and RCP2.6, respectively. For both GGCMs, the levels of CO_2 vary according to the emission scenario and thus the results include effects of CO_2 fertilization and water use efficiency. It is important to keep in mind that this choice will produce optimistic scenarios, since GGCMs currently overestimate the beneficial effects of increased

CO_2 concentration (Rosenzweig et al., 2014). More information regarding the ISIMIP FastTrack platform and the GCMs considered here can be found in the Supplementary Material.

3. Impacts on Agricultural Output

The biophysical impacts of climate change on agricultural productivity are included in GLOBIOM Brazil's projections of land-use change through GGCMs projections of productivity, more specifically EPIC and LPJmL. Projections from these GGCMs represent the potential changes in yield resulting from changes in temperature, precipitation, solar radiation, among others. Here, we will use the term "changes in potential yield" to refer to these changes and to distinguish them from changes in agricultural productivity as project by GLOBIOM Brazil.

Over Brazil, the biophysical impact of climate change results in an increase (decrease) in soybean and corn potential productivity over subtropical (tropical) regions of the country, with a good agreement between EPIC and LPJmL results (Fig S5). On the other hand, changes in sugar cane potential productivity vary among the GGCMs, highlighting the large uncertainties regarding the impacts of increase CO_2 concentration in C4 crops, such as sugar cane (Rosenzweig et al., 2014; Havlík et al., 2015). Finally, pasture potential yield is not as heavily impacted by climate change as other crops. A more detailed description of these results can be found on the Supplementary Material.

The impacts of climate change on agriculture are quantified in terms of changes in area of cropland and pasture, and their corresponding spatial distributions, as projected by GLOBIOM Brazil. We also consider the changes in area and production of soybeans, corn, and sugar cane separately, as well as the impacts of climate change in livestock production. Yield and livestock density results are calculated by dividing the total production by the total area in Brazil (or region).

3.1. Total Cropland and Pasture Area

To measure the overall impact of climate change on Brazilian potential yield, values for individual crops were spatially averaged (weighted by the area of each crop), resulting in a value for all crops over the country. RCP2.6-EPIC and RCP8.5-EPIC results are presented in Figure 2a in which the first and third pair of box-plots display, respectively, the changes in potential yield for cropland and pasture by 2050 in Brazil, as projected by EPIC. The statistics represented in the box-plots were first estimated for each pixel individually and then aggregated over the country resulting in the values for minimum, maximum, lower and upper quartiles, and median scenarios, represented by the boxplots in Figure 2a. This figure also shows the median changes in each individual scenario (EPIC projections forced by one GCM in one RCP scenario), represented as the upward (for RCP2.6) and downward (for RPC8.5) triangles. The resulting changes in cropland and pasture areas, projected by GLOBIOM-Brazil, are presented in Figure 2a as the second and fourth pair of boxes. Similar results for RCP2.6-LPJmL and RCP8.5-LPJmL are presented in Figure 2b. Temporal changes in the median values for the four scenario sets and the corresponding results for the noCC baseline scenario are displayed in 2c and d, for cropland and pasture area, respectively.

[Figure 2 about here.]

Economic adjustments and land competition as modeled by GLOBIOM-Brazil result in a decrease in the median cropland and pasture area for both RCPs and GGCMs (Fig 2a and b). For the total cropland area in Brazil by 2050, this decrease, expressed as a percentage of the noCC scenario, ranges from -8.8% (-25.8%,13.8%) to -33.4% (-42.2%,-20.8%), for RCP8.5-EPIC and RCP8.5-LPJmL, respectively (Table S7). Note that from 2010 onward (Fig 2c) the impacts of climate change in potential yield result in a relative decrease in total cropland, more intense when considering LPJmL scenarios. For RCP8.5-LPJmL, there is even an absolute decrease in cropland area after 2035.

Uncertainties in GLOBIOM-Brazil projections are depicted as the orange (EPIC) and green (LPJmL) envelopes in Figure 2c and d, defined as the minimum and maximum scenarios of each GGCM, and by the spread between the lower and upper quartiles in Figure 2a and b. The large spread among these scenarios is related to their composition, with each of the scenarios estimated using the value in each individual pixel. For example: in the minimum scenario, we first identified the minimum value (among all 5 scenarios of each set) in each pixel and then summed it over the entire country to produce the statistic in Figure 2c. Consequently, values in adjacent pixels may come from different individual scenarios within that set. When aggregating over Brazil (or individual regions), the resulting statistics is larger (in absolute terms) than the value observed when considering individual scenarios (as represented by the triangles in Fig 2a and b). More details about the representation of the results and their uncertainties can be found in the Supplementary Material. Furthermore, this larger spread between the minimum and maximum scenarios (as well as between upper and lower quartile scenarios) suggest a large spatial heterogeneity of the climate change impacts over the country.

Despite the large uncertainties related to changes in cropland area for RCP2.6-EPIC and RCP8.5-EPIC aggregated results (Fig 2a and c), 9 of the 10 individual GCM indicate a decrease in area by 2050. In RCP8.5-EPIC median scenarios for 2050, cropland expansion will occur mostly in central-southern Cerrado, southern Atlantic Forest and Pampa regions (green shades in Fig 3a; see also Fig S8a). Areas the northwestern Cerrado biome and in the Matopiba region, considered as the next agriculture frontier (see Fig S7a and b for the projected cropland area in the noCC scenario), would not be as promising under the impact of climate change (red shades in Fig 3a, see also Fig S8a). The stippling in Figure 3a also represent the agreement between lower and upper quartiles scenarios (i.e., when both quartiles have the same sign), suggesting an agreement between these scenarios in areas with large changes (both positive and negative).

[Figure 3 about here.]

For the RCP8.5-LPJmL scenarios, reductions in the median cropland area are larger than for RCP8.5-EPIC projections (Fig 2b and c), with negative signs in both lower and upper quartiles (see also Table S7), as well as in all individual GCMs (Fig 2b), suggesting a larger agreement among scenarios. For this GGCM, the largest decrease in cropland area occur in Pampa, Cerrado, and Amazon biomes (Fig 3b; see also Fig S8b and Table S7).

For pasture, climate change scenarios based on both GGCMs indicate a decrease in the median area by 2050, when compared to the noCC (Fig

2a, b, and d). Historically, pasture area has been moving toward Cerrado and Amazon biomes (EMBRAPA and INPE, 2019). When considering impacts of climate change, areas of pasture along the border between Amazon and Cerrado biomes, a region known as the "deforestation arch", would be abandoned, with pasture moving south- and southeastward (Fig 3c and d). RCP8.5-LPJmL scenarios indicate an expansion toward Pampa biome (Fig 3d) while in RCP8.5-EPIC scenarios the pasture area decreases over this region (Fig 3c). Disagreements also occur in the Atlantic Forest, but not in the Amazon and Cerrado (Fig S8c and d).

3.2. Soybeans

Soybeans is Brazil's most important cash crop, with total production of 114.6 Mt in 2018 (PAM-IBGE, 2019), equivalent to 31% of the world's production. This ranks the country as the second largest producer, behind USA (TRASE, 2015). Approximately 70% of this production is exported (TRASE, 2015), which makes Brazil the world's largest exporter of the crop (EMBRAPA, 2018). Brazilian soybeans production is located mostly in the Cerrado biome and South Brazil (MAPA, 2018). Future economic projections suggest a northward displacement of the production toward Matopiba (see Fig S1 for its location), expanding mostly over pasture areas (MAPA, 2018).

Regardless the positive impacts of climate change on soybeans potential yield (Fig S5), land-use competition and market dynamics projected by GLOBIOM-Brazil result in a reduction of Brazilian soybeans area and production throughout 2050, compared to the noCC scenario (Fig 4a and b). On the trade side, Brazil's soybeans exports also decrease, both in volume and in share of the international market (Fig S21 and Table S12).

[Figure 4 about here.]

Until 2015, the difference between noCC and median scenarios for each set of projections for both area and production are close to the Brazilian official statistics (blue line with filled squares in Fig 4a and b; source: PAM-IBGE (2019)). From 2020 onward, GLOBIOM-Brazil projections for soybeans median area and production are increasingly smaller than those of the noCC scenario. Moreover, they are also below the area and production average (middle of the red vertical line) projected for 2028 by Brazil's government (MAPA) MAPA (2018). For RCP8.5-LPJmL and RCP2.6-LPJmL (green lines in Fig 4b), median production estimates are even below MAPA's lower limits. Both the reduction in area and in production are consistent among all 10 LPJmL scenarios (as shown by the green shaded envelope in Fig 4b). EPIC scenarios for both area and production are less pessimistic and within MAPA projections, despite the larger spread among them (orange envelope in Fig 4a-b; see also the first two boxes in Fig S11a and c, and Table S8).

By 2050, soybeans area would be -17.0% (-33.7%,11.5%) to -38.5% (-48.9%,-21.6%) smaller than in noCC scenario, resulting in a -6.3% (-26.3%,22.5%) to -36.5% (-47.0%,-14.7%) decrease in production (Fig S11 and Table S8). Compared to noCC, Brazil's soybeans exports also decrease in volume from -1.1% (-3.3%,2.8%) to -34.3% (-34.9%,-33.3%), with a median market share change ranging from a gain of 2.3% (RCP8.5-EPIC) to a loss of -40,0% (RCP8.5-LPJmL) (see Fig S21 and Table S12). In the RCP8.5-LPJmL scenario, most of the market share loss goes to Brazil's traditional competitors, USA and Argentina (figure not shown).

Even though GLOBIOM-Brazil median scenarios based on the two

GGCMs are not directly comparable, they indicate two pathways for soybeans in Brazil. The reduction in area is similar for both median scenarios (Fig 4a), and is followed closely by a reduction in production in LPJmL median scenarios (Fig 4b). Thus, median yields (estimated as the total Brazilian production divided by the total area) based on LPJmL scenarios are similar to the yield of the noCC scenario (Fig 4c). On the other hand, the reduction in area in EPIC median scenarios (Fig 4a) is offset by an increase in yield (Fig 4c) which brings the production numbers close to the noCC. These results suggest that Brazilian soybeans production can still grow despite the adverse effects of the economic adjustments to climate change, as long as the necessary technological development is achieved.

As observed for total cropland area, GLOBIOM-Brazil projections for soybeans production and area, based on EPIC values, are also spatially variable, resulting in a relative southward displacement of soybeans from tropical to subtropical regions (Fig S10a and c and Fig S11a and c). This displacement would require investments and adaptations since in some regions in Southern Brazil the appropriate logistics for large-scale soybean production is currently lacking and rural properties are highly fragmented. Cerrado, and particularly Matopiba, currently considered as the main production region and the future expansion region, respectively (Fig S9), would not thrive under the impact of climate change. In Matopiba, for RCP8.5, the median decrease in soybeans area and production by 2050 will be -74.3% and -63.7%, respectively (Fig S11a and c, and Table S8). Part of the soybean is displaced southward, being produced in Southern Atlantic Forest and in the Pampa biome (Fig S10a and c and S11a and c), where it would replace areas previously occupied by pasture. All these results are robust among EPIC scenarios (changes in lower and upper quartiles have the same sign) and for each GCM and RCP individually (see triangles in Fig S11a and c).

Projections based on LPJmL scenarios also indicate a reduction in soybeans area and production in the Cerrado (Fig S10b and d; see also FigS11b and d and TableS8). As previously mentioned, LPJmL projections are more pessimistic, with a reduction in soybeans area and production on all main soybeans production areas, except in the Atlantic Forest biome (Fig S10b and d). Contrary to EPIC projections, LPJmL soybeans production estimates in Matopiba are not affected by climate change. On the other hand, there would be substantial decrease in area and production in Pampa, with median decrease of -78.8% in area and -83.2% in production for the RCP8.5 scenario (Fig S11b and d and Table S8).

3.3. Corn

Corn is the second most important crop in Brazil, that currently produces 89.2 Mt, 74.6% of which in the states of Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais, and Paraná (MAPA, 2018). Differently from soybeans, corn production is almost completely consumed in the country. The majority of corn area and production in Brazil occurs as a second crop in succession to soybeans. Although historically this was considered a marginal management system mostly because of the climatic risk, currently more than 70% of the Brazilian corn production is as a second crops, with similar productivity as to the first crop (CONAB, 2019b).

GLOBIOM-Brazil projections of corn area from 2000 to 2015 (Fig 5a), in both noCC (black line with filled circles) and median climate change scenarios (orange and green solid and dashed lines with filled triangles), are similar to the official Brazilian statistics (blue line with filled squares), even though GLOBIOM-Brazil underestimates production (Fig 5b) and, consequently, yield (Fig 5c). From 2025 onward, GLOBIOM-Brazil projections for noCC and median scenarios are optimistic, located within the upper half of the MAPA official projections for corn in 2028 (red vertical line in Fig 5a and b). Also after 2025, corn area and production in the median scenarios are projected to be smaller than in the noCC scenario, with larger agreement among LPJmL scenarios. The impacts of climate change on corn production for scenarios using LPJmL are not as pronounced as in area, resulting in a small increase in yield (Fig 5c). For EPIC scenarios, reduction in area and production are commensurate, resulting in no change in yield after 2035. Notice that, under climate change conditions, to achieve the projected noCC production level, it would be necessary a substantial increase in corn yield, whose current Brazilian average is about 5.6 t/ha (CONAB, 2019b). This would demand heavy investments in technology.

[Figure 5 about here.]

By 2050, the median percentage reduction of Brazil's corn area is -14.6% (-30.4%,2.5%) and -37.5% (-43.4%,-23%), for RCP8.5-EPIC and RCP8.8-LPJmL, respectively (Table S9), with production results displaying similar reductions. These results are robust among all 20 individual scenarios (Fig S14), with agreement in the sign of the lower and upper quartiles in LPJmL scenarios for both RCPs. The volume of corn exports decreases by -13.0% (-18.4%,-12.7%), for RCP8.5-EPIC, and by -31.9% (-32.9%,-31.4%) (see Fig

S21 and Table S12). The median market share loss of Brazil's corn exports compared to noCC ranges from -0.5% to -16.2%.

Regionally, the largest reduction occur in Amazon, with -37.9% area and -39.8% production in RCP8.5-EPIC scenarios, and Cerrado, with a reduction of -60.2% in corn area and -62.6% in production in RCP8.5-LPJmL scenarios (Table S9). In the noCC scenario, Brazilian corn production migrates from South Brazil to the Cerrado biome, with this tendency projected to persist until 2050 (Fig S12). However, climate change impacts would affect this trend, resulting in a displacement of the production from tropical biomes to the subtropics (Fig S13 and Fig S14).

Differently than for soybeans, corn production in Matopiba would not be affected by climate change. Still, part of the corn production (and area) is displaced southward to the southern portion of the Atlantic Forest biome (Fig S13), with a median increase of 21.0% (74.6%) in area (production) in RCP8.5-LPJmL scenario (Table S9). Individually 18 (19) of the 20 scenarios indicated an increase in area (production) in Atlantic Forest biome (Fig S14), with agreement among LPJmL scenarios larger than among EPIC's. The reduction in production over central Brazil is also identified by Assad et al. (2016a), who attributed the changes in suitability to temperature increase and water availability reduction, which would affect mainly the corn cultivated as a second crop.

3.4. Sugar Cane

Currently, Brazil is the main producer of sugar cane in the world (FAO, 2017). In 2018/19 season, Brazil harvested 8.6 Mha and produced 620.4 Mt of sugar cane. Most of this production is located in the states of São Paulo, Goiás, and Minas Gerais. Even though both the national area and production growth have leveled off since the 2014/15, Brazilian sugar cane is expected to grow in the next decade mostly due to the RenovaBio, a national program that stimulates the use of biofuels (MAPA, 2018). Currently, about two thirds of the Brazilian sugar cane production is transformed in ethanol and the remainder third is transformed in sugar. (CONAB, 2019a).

GLOBIOM-Brazil projections for sugar cane area and production are able to correctly reproduced the official statistics (PAM-IBGE (2019), represented as the blue line with filled square in Figure 6a-b). However, projections for the noCC scenario for 2030 are more optimistic than the MAPA projections (red vertical line in Fig 6a-b; MAPA (2018)). When considering climate change scenarios, changes in sugar cane area and production have opposite sign for each GGCM. By 2050, EPIC scenario projections are close to the noCC scenario for both area and production (Fig 6a-b, respectively). Compared to the noCC, sugar cane area change varies between a loss of -7% (RCP2.6) to a gain of 5.4% (RCP8.5); for production, the respective values are -1.1% and 1.4%. For RCP8.5, the median gains in export volume and in export market share are, respectively, 26.3% and 9.9% (Fig S21 and Table S12). RCP8.5-EPIC scenarios indicate that sugar cane production would migrate towards Goiás and Western Minas Gerais, in Central Cerrado (Fig S16a and c; see also Fig S17a and c), partially occupying areas of pasture.

[Figure 6 about here.]

Opposite to EPIC, LPJmL scenarios project a decrease in area, from -26.1% (-38.9%;-10.2%) to -40.4% (-50.1%;-28.2%), and, to a lesser extent, in production, from -7.8% (-33.0%;18.2%) to -9.6% (-32.6%;15.9%) (see Fig 6a and b, respectively). LPJmL scenarios also project concomitant reduction in export volume and international market share (mainly to Australia and the Southern Africa region). For RCP8.5-LPJmL, the median losses in export volume and market share are -22.7% and -10.2%, respectively (Fig S21 and Table S12). Possible reasons for these discrepancies between EPIC and LPJmL GGCMs will be discussed in Section 4.

In RCP8.5-LPJmL scenarios, sugar cane production is displaced southward from Cerrado to Atlantic Forest biome (Fig S16b and d), in opposition to what is projected by RCP8.5-EPIC. In Central Cerrado, specially in the state of Goiás, sugar cane area and production decline by more than 50% in the RCP8.5-LPJmL scenario (Fig S17b and d and Table S10). These results are in agreement with the findings of Zullo et al. (2018), who attributed the increase in the climatic risk of sugar cane production in the area to a reduction in water availability.

As observed for soybeans, the impacts of climate change on sugar cane production as projected by LPJmL are partially offset by an increase in yield (Fig 6c). However, this increase, as well as that projected by the noCC scenario, are above MAPA projections (represented as the red vertical line in Fig 6c; MAPA (2018)). In fact, the MAPA projected sugar cane yield for 2028 is close to the current value of 72.5 t/ha.

3.5. Livestock

Brazil has the second largest cattle herd in the world, with 214.9 million animals in 2017 (PPM-IBGE, 2019). This places the country among the world's leader producer and exporter of beef, which accounted for 17.3% of the country's agricultural export in 2018 (OECD, 2018). More than one third of this herd is raised in the Center-West region of Brazil, with 29.7 million heads in Mato Grosso and 21.5 million heads in Mato Grosso do Sul (PPM-IBGE, 2019).

The impacts of climate change on pasture yield considered here affect the livestock sector through losses in productivity and, to a lesser extent, through losses in soybeans and corn production used as livestock feed. Climate change impact on Brazilian herd size is not as pronounced due to an increase in herd intensity (Fig 7a and b; Table S11). For RCP8.5-EPIC and RCP2.6-EPIC, the median change in cattle herd size in Brazil 2050, expressed as a percentage of the noCC scenario, is -2.7% (-20.7%,19.3%) and 0.2% (-18.4%,19.4%), respectively. As for RCP8.5-LPJmL and RCP2.6-LPJmL, the median change in cattle herd size is -3.8% (-19.9%,16.4%) and -2.5% (-16.5%,12.7%), respectively. Overall, these results project no sizable impact of climate change on the Brazilian median herd size (viz-à-viz the noCC scenario). However, the associated uncertainty is large and there is no clear trend of growth or decline (signs of lower and upper quartiles are always opposite). On the trade side, Brazil's beef exports decrease in volume by -2.5% (-8.2%,-2.4%), for RCP8.5-EPIC, to -20.6% (-28.2%,-11.0%), for RCP8.5-LPJmL (Fig S21 and Table S12). Brazil losses on its share of exportation range between -10.7% and -28.6% compared to the noCC scenario.

[Figure 7 about here.]

As observed for pasture, livestock partially moves southeastward, from the deforestation arch region toward the border of Cerrado and Atlantic

Forest biomes (Fig S19). RCP8.5-LPJmL scenarios suggest an increase in herd size in Pampa biome (FigS19b and FigS20b) whereas RCP8.5-EPIC indicate a decrease (FigS19a and FigS20a). Note, however, that the LPJmL scenarios project a robust decrease of the herd size in the Matopiba region, from -23.9% to -28.4% in median (Table S11).

4. Discussion

Large-scale agriculture, cattle ranching, logging, and colonization are the main drivers of land-use change in Brazil (Lapola et al., 2014). Here, we focus only on the interplay between Brazil's agricultural production and land-use change, under the constrains of global and regional climate change. GLOBIOM-Brazil projections of land-use change and trade in response to climate change indicate an increase in internal competition for resources among different crops and products, and in external competition for market shares. For soybeans and corn, two of Brazil's major crops, GLOBIOM-Brazil scenarios project a displacement (relative to the baseline) toward subtropical or near-subtropical regions of Cerrado and Atlantic Forest biomes. Despite this reallocation, production of both crops is expected to decrease when compared to the noCC scenario in 2050, with reduction ranging between -6.3% and -36.5% for soybeans and between -12.9% and -29.4% for corn. Soybeans reduction occurs mostly in Matopiba region. In eastern Cerrado and Matopiba, these crops are substituted by pasture and livestock, with a corresponding decrease in cattle ranching in some regions of the Amazon (Fig 8). Along the border of Cerrado and Atlantic Forest, over central and southeastern Brazil, soybeans and corn are replaced by sugar cane production.

However, uncertainties regarding the expansion of sugar cane and pasture are large.

[Figure 8 about here.]

All scenarios considered in this study suggested a reduction of soybeans production in the Cerrado biome and a southward displacement of the crop, toward subtropical areas of Atlantic Forest (Fig 8a). In Matopiba, this represents a reduction from 13.2 Mha of soybeans in the noCC scenario in 2050 to a median area of 3.4 Mha (11.4 Mha) when considering EPIC (LPJmL) RCP8.5 projections.

Part of the impact of climate change in soybeans could be offset by an increase in yield, as suggested by scenarios based on EPIC results. Currently, soybeans average yield in Brazil is around 3 t/ha with projections indicating a stagnation tendency (MAPA, 2018). To attain a production of 156 Mt by 2028, as projected by Brazilian Ministry of Agriculture (MAPA, 2018), soybeans yield would have to reach 3.4 t/ha to 3.9 t/ha, which is considered as a challenge by the producers (MAPA, 2018). GLOBIOM-Brazil projections considering EPIC scenarios are within this yield range. However, to reach the production projected by EPIC median scenarios in 2050, soybeans productivity would have to be 4.1 t/ha. Sentelhas et al. (2015) demonstrated that it is possible to have a productivity of 4.0 t/ha in Cerrado and as high as 4.5 t/ha in South Brazil. This would demand investments in technology and management processes such as adaptation of the sowing calendar, utilization of drought resistant cultivars, implementation of irrigation, and investments in fertilization, soil improvement, and precision agriculture. GLOBIOM-Brazil projections discussed here partially account for technological improvements through changes in the management system (from low input, i.e., with low amount of fertilizer, to high input agriculture, for example).

As observed for soybeans, national corn production is also projected to decrease under climate change scenarios, with the producing areas migrating southward (Fig 8b). Cerrado biome would still produce more than 50% of Brazilian corn, mainly in Mato Grosso and Mato Grosso do Sul states, even though the participation of these regions in the total Brazilian production would decrease. Part of the production would shift toward the Atlantic Forest biome, which would be responsible for more than 25% of the national production. However, these results have to be carefully considered due to the absence of climate change impacts for the corn yield in a double cropping management system. As mention before, more than 70% of the corn produced in Brazil is as a second crop after soybeans (CONAB, 2019b). In the noCC scenario (as well as in all climate change scenarios considered here), all corn will be produced in a double cropping system by 2050. Corn in this system is planted between January and February and harvested no later than August, which is the dry season in most parts of Brazil. As future changes in climate across seasons might be different, and not taken into account by the GGCMs corn potential yield, our projections for the corn production in Brazil might be accordingly affected.

GLOBIOM-Brazil scenarios forced by both GGCMs indicate a westward displacement of sugar cane toward areas that would be occupied by soybeans and corn in the noCC scenario (Fig 8c). In scenarios forced by EPIC, sugar cane production would be concentrated over central Brazil (Goiás and Minas Gerais) states, over the northern part of the main production area in central Brazil (Fig 8c), despite the negative changes in potential yield over this region. In scenarios forced by LPJmL, sugar cane production would be located further south, over São Paulo and Minas Gerais states, equivalent to the southern part of the main production area in central Brazil (Fig 8c).

Sugar cane potential yield increases with warmer temperature and increased CO_2 concentration due to reduced water demand (Pinto and other, 2008; Marin et al., 2013). However, higher temperatures and longer and more intense dry spells results in larger losses in tropical regions without irrigation (Araújo et al., 2014; Zullo et al., 2018). LPJmL explicitly accounts for the C3 and C4 photosynthesis pathways (Weindl et al., 2015), and thus it is more sensitive to changes in temperature than water availability. Thus, under climate change scenarios, LPJmL favor the development of sugar cane over the subtropics, where the increase in temperature is not as pronounced, and over South Brazil, where changes in temperature will reduce the risk of frost. LPJmL scenarios of potential productivity also favors the development of sugar cane over eastern tropical Brazil (eastern Cerrado and Atlantic Forest biomes) while GLOBIOM-Brazil scenarios project a decrease in production over these areas. In these regions, GLOBIOM-Brazil is responding to restrictions imposed by the sugar cane agro-ecological zoning (AEZ), which favors its development over central Brazil, mostly over western São Paulo, southwestern Minas Gerais, south Goiás and eastern Mato Grosso do Sul (Fig S2).

GLOBIOM-Brazil projections of sugar cane production forced by EPIC crop model also have a similar response to the AEZ, despite the negative response of sugar cane potential productivity to climate change over this region. As a site-based crop model, EPIC responds to other limiting factors, such as heat and nutrients, in addition to temperature and water availability. Furthermore, it also accounts for changes in wind speed and relative humidity to calculate evapotranspiration. Thus, sugar cane potential productivity, as projected by EPIC, increases only over South Brazil, where changes in temperature and precipitation are mild and the risk of frosts is reduced. Over tropical Brazil, EPIC responds to the projected increase in temperature and in the risk of longer dry spells, resulting in a reduction of sugar cane potential yield.

Finally, the impacts of climate change in pasture and livestock production, although displaying a larger uncertainty than crops, indicate rather robustly no sizable depart from the baseline (noCC), with no discernible increase or decrease trend. In this case, uncertainties arise from all links of the modeling chain, with small agreement among individual GCMs and RCPs. In addition to the large uncertainties, these results also did not account for the direct impact of climate change on the livestock due to water availability or heat stress. Regionally, projections on pasture and livestock production suggest a south- and southeastward shift from the border between the Amazon and the Cerrado biomes toward Eastern Cerrado and Southern Brazil, occupying areas that were previously used for soybeans and corn production (Fig 8d).

Regional shifts in production within Brazil, observed in all crops considered, raise concerns regarding the availability of infrastructure and resources to accommodate them, specially water availability. Currently, between 4 and 7 Mha of Brazil's cropland is irrigated, with most of the areas located in South, Southeast, Center-West regions (ANA, 2017). For 2030, the National Water Agency (ANA) projects 10 Mha of irrigated crops, mostly over central region of Brazil (ANA, 2017). The adoption of irrigation could help closing the yield gap between noCC and climate change scenarios described previously. On the other hand, even with the low participation of irrigation in agriculture, this sector is currently responsible for 67% of the total water consumption, with the projected expansion increasing this participation in 42% (ANA, 2017). Even though GLOBIOM-Brazil accounts for irrigated management systems, their representation in the model is still simplistic, with no costs associated with the implementation of the necessary infrastructure.

Along with the uncertainties related to each step of the framework, already discussed previously, it is also important to mention the uncertainties that arise from GLOBIOM-Brazil scenarios. One example is the uncertainties regarding the impacts of CO_2 concentration on each crop, including the water use efficiency, which could affect each crop's productivity and how producers eventually adapt to these changes. Other adaptations on the production side of the framework, such as the adoption of more resilient cultivars or changes in the crop cycle and sowing calendar, could also affect the impacts of climate change in crop reallocation. Even though the GGCMs utilized here are able to emulate these adjustments, the scenarios provided through the ISIMIP platform do not account for them. Similarly, the development of more resilient agriculture practices, such as multiple crops per year and integrated crop-livestock-forestry, should also be considered when estimating future scenarios of potential yield.

5. Conclusions

Despite all uncertainties discussed above, the main changes in crop and pasture presented here are robust among individual scenarios and are in agreement with previous studies focusing on the biophysical impacts of climate change on specific crops (e.g. Pinto and other (2008); Assad et al. (2013, 2016a,b)). The use of GEMs such as GLOBIOM-Brazil provides a framework to dynamically evaluate the interaction among biophysical impacts of climate change, land-use competition, and economical adjustments, adding an economic dimension to the physical-based models previously used. Furthermore, its flexibility allows the inclusion of different governance scenarios, providing an useful tool for policy decision making. Its spatially explicit projections also allows the evaluation of the impacts of these scenarios both on regional and global scales, through land-use competition and production and through trade adjustments, respectively.

Scenarios are possible futures. The 20 scenarios presented and discussed here offer a glimpse into the potential state of the Brazilian agricultural sector by 2050 under the constraints and impacts of climate change. Bad or good, for this potential state to become reality, it depends on the choices made now by landowners, stakeholders, and policy makers in Brazil. The spectacular growth of Brazil's agriculture over the past decades, in terms of volume and diversification, was heavily founded upon the availability of resources (suitable land and water), new technologies adapted to tropical agriculture, and the adoption of modern management methods (Müller and Robertson, 2014). As our results have shown, the future of Brazilian agriculture depends on growing productivity quickly enough to avoid (or to adapt to) the most nefarious impacts of climate change. This approach, which involves the use of new, genetically adapted cultivars and the expansion of irrigation (Margulis et al., 2011), requires time (8 to 12 years to put a new cultivar in the market Margulis et al. (2011)) and heavy investment (US$480–570 million per year until 2050, Lapola et al. (2014)). This pathway is probably outside the reach of smallholder and subsistence farmers, who will certainly be heavily impacted by climate change (Lapola et al., 2014). Another option for making the Brazilian agriculture more resilient is through the large-scale adoption of environmentally sustainable practices. Rigorously abiding to the existing legislation, such as the 2012 Forest Code which regulates land-use change in private properties, would stop illegal native vegetation conversion and help recovering and preserving valuable ecosystem services (water availability, local temperature control, pollination, etc), resulting in improved resilience to climate change and contributing to its mitigation.

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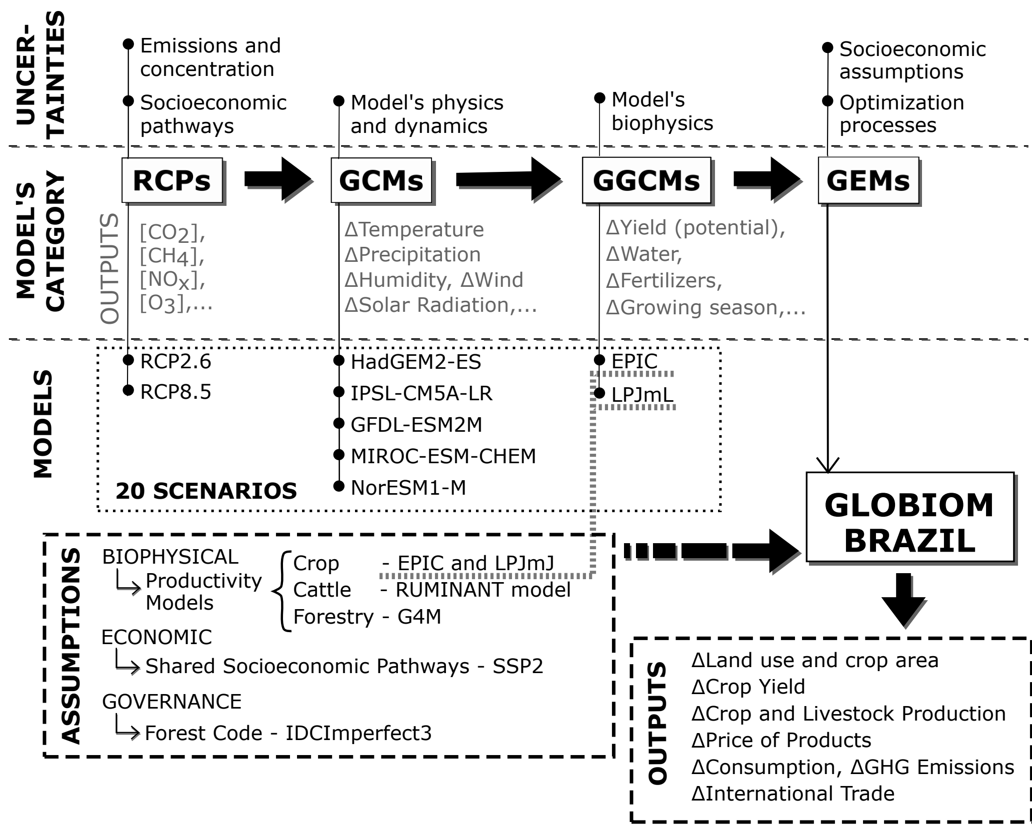

Figure 1: Impact modeling framework from RCP scenarios and GCM through crop and economic impact models (GGCM and GEM, respectively), resulting in 20 scenarios. The bottom part emphasizes the GLOBIOM Brazil's initial assumptions, in special the role of GGCMs, and main outputs.

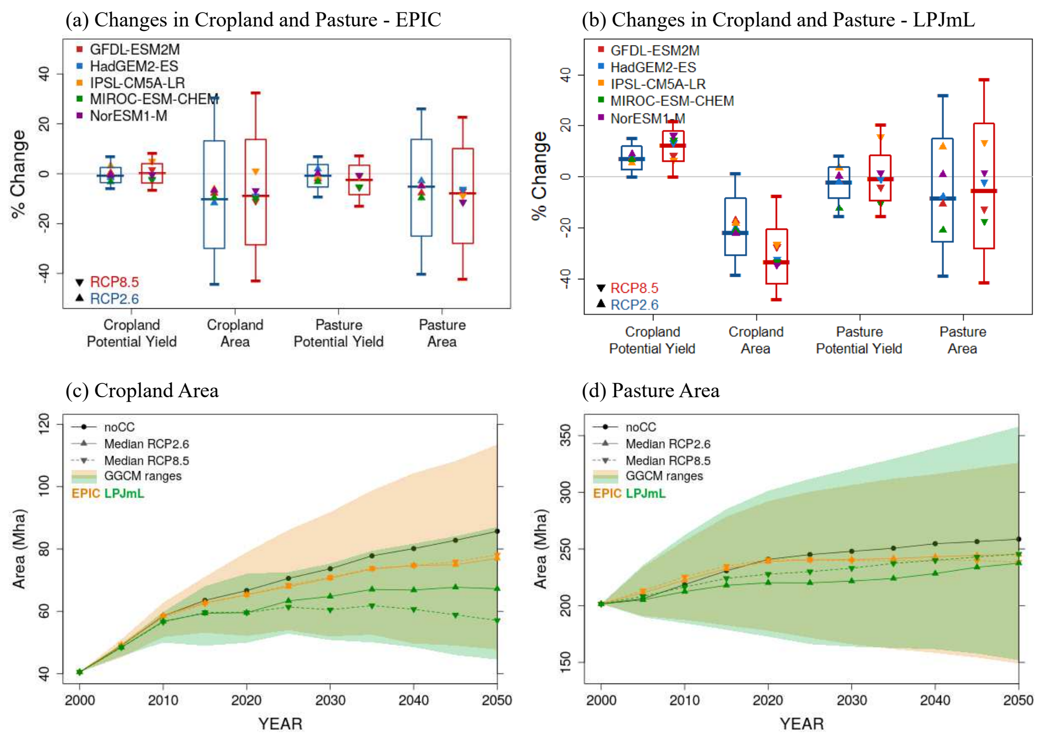

Figure 2: (a) and (b): Percentage changes in potential yield (1st and 3rd pair of boxes) and in total area of cropland and pasture (2nd and nth4 pair of boxes) in Brazil for (a) EPIC and (b) LPJmL GGMCs. Upper (lower) triangles: changes in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). (c) and (d): Projection of (c) cropland and (d) pasture area (both in Mha) aggregated over Brazil for noCC (black solid line with filled circle), EPIC (orange), and LPJmL (green) scenarios. Solid (dashed) lines and upward (downward) triangles: median values for RCP2.6 (RCP8.5) in each GGCM. Orange (green) shaded area: envelope of minimum and maximum scenarios for EPIC (LPJmL).

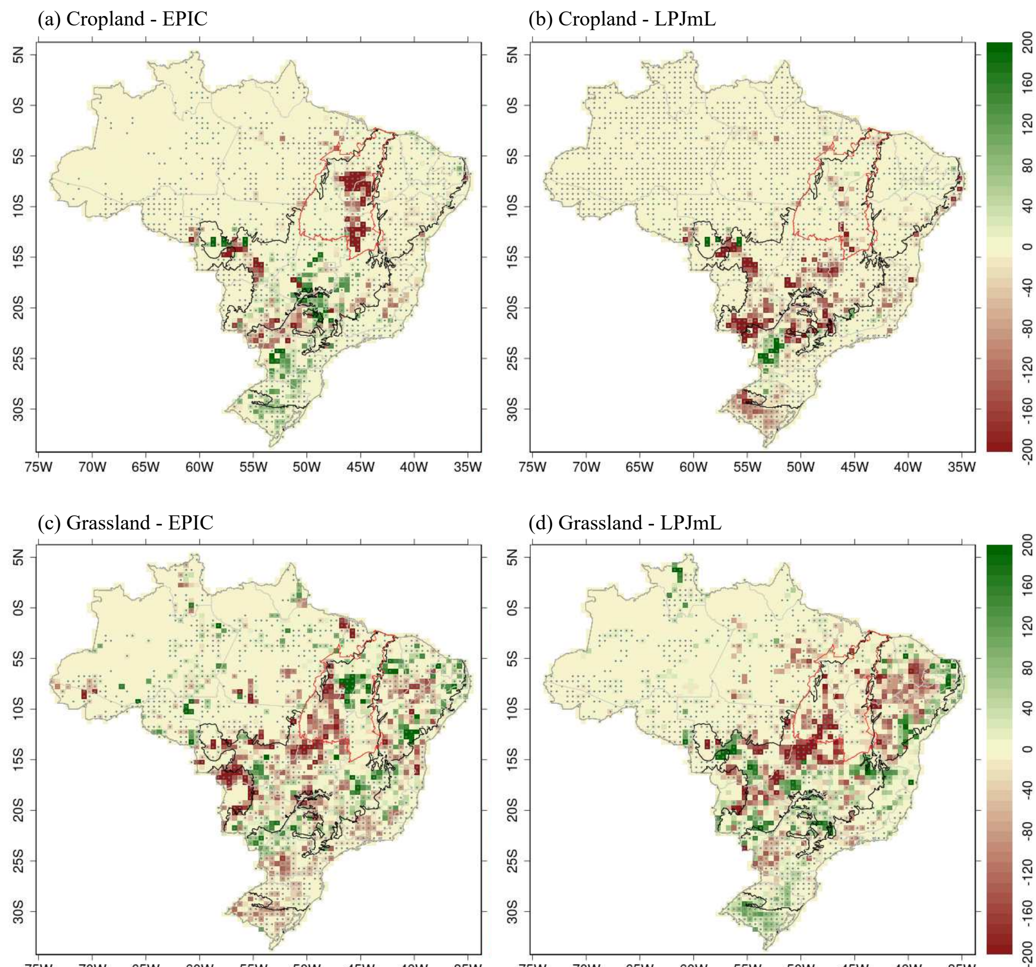

Figure 3: Median changes in the area of (a)-(b) cropland and (c)-(d) pasture (both in kha) for (a), (c) EPIC and (b), (d) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC 2050. Stippled pixels indicate areas where the lower and upper quartiles have same sign.

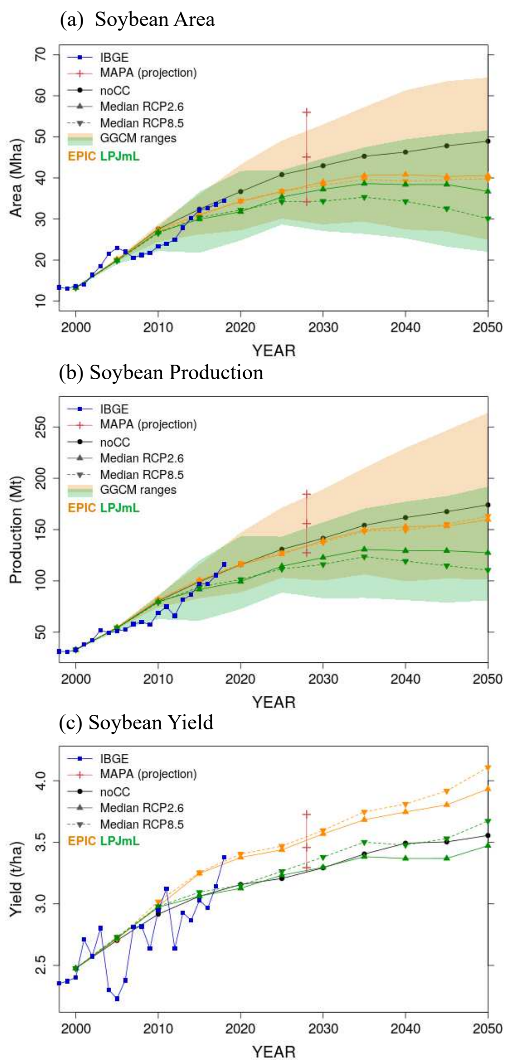

Figure 4: As in Figure 2c and d for soybeans (a) area (in Mha), (b) production (in Mt), and (c) yield (in t/ha). Blue line with filled squares: IBGE annual soybeans statistics (source: PAM-IBGE (2019)). Red vertical line with crosses: MAPA average projections for soybeans in 2028 and its lower and upper limits (source: MAPA (2018)).

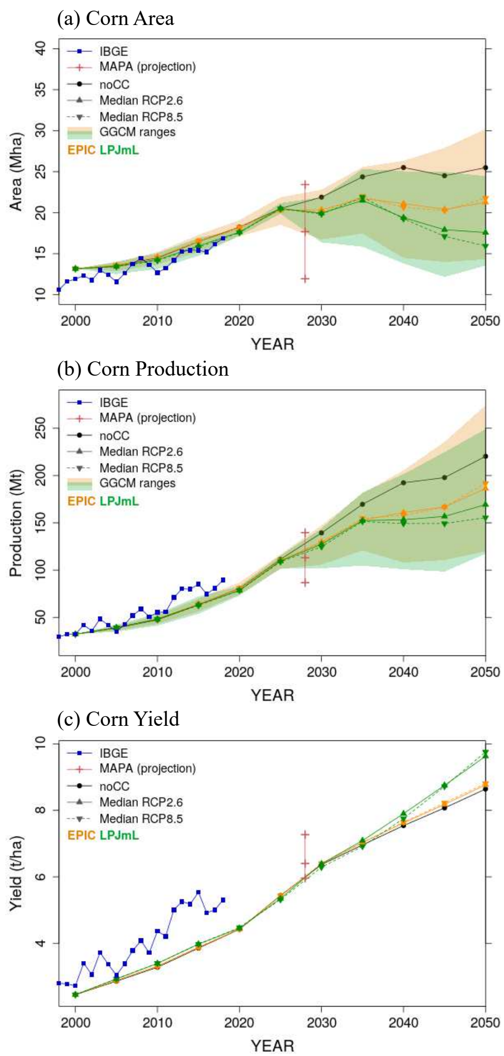

Figure 5: As in Figure 4 for corn.

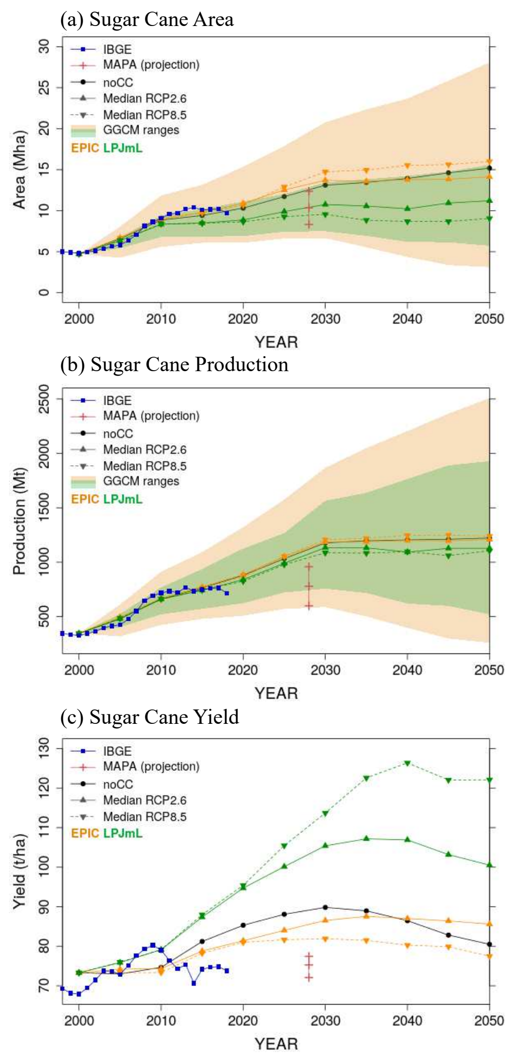

Figure 6: As in Figure 4 for sugar cane.

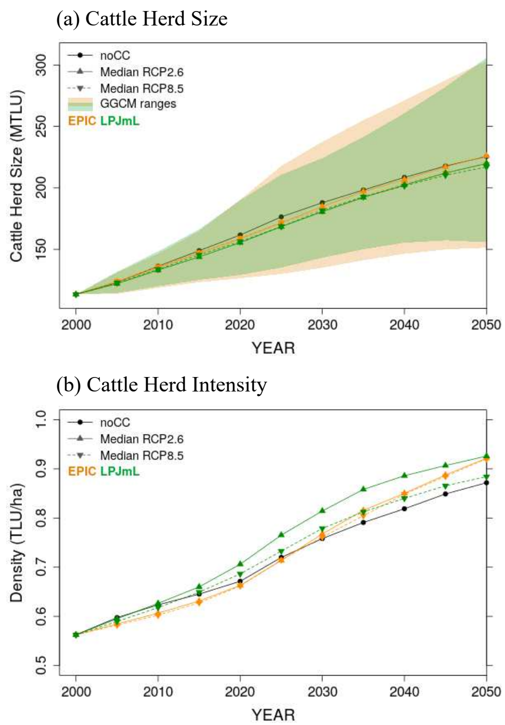

Figure 7: As in Figure 4 for cattle herd (a) size (in MTLU), and (b) intensity (in TLU/ha).

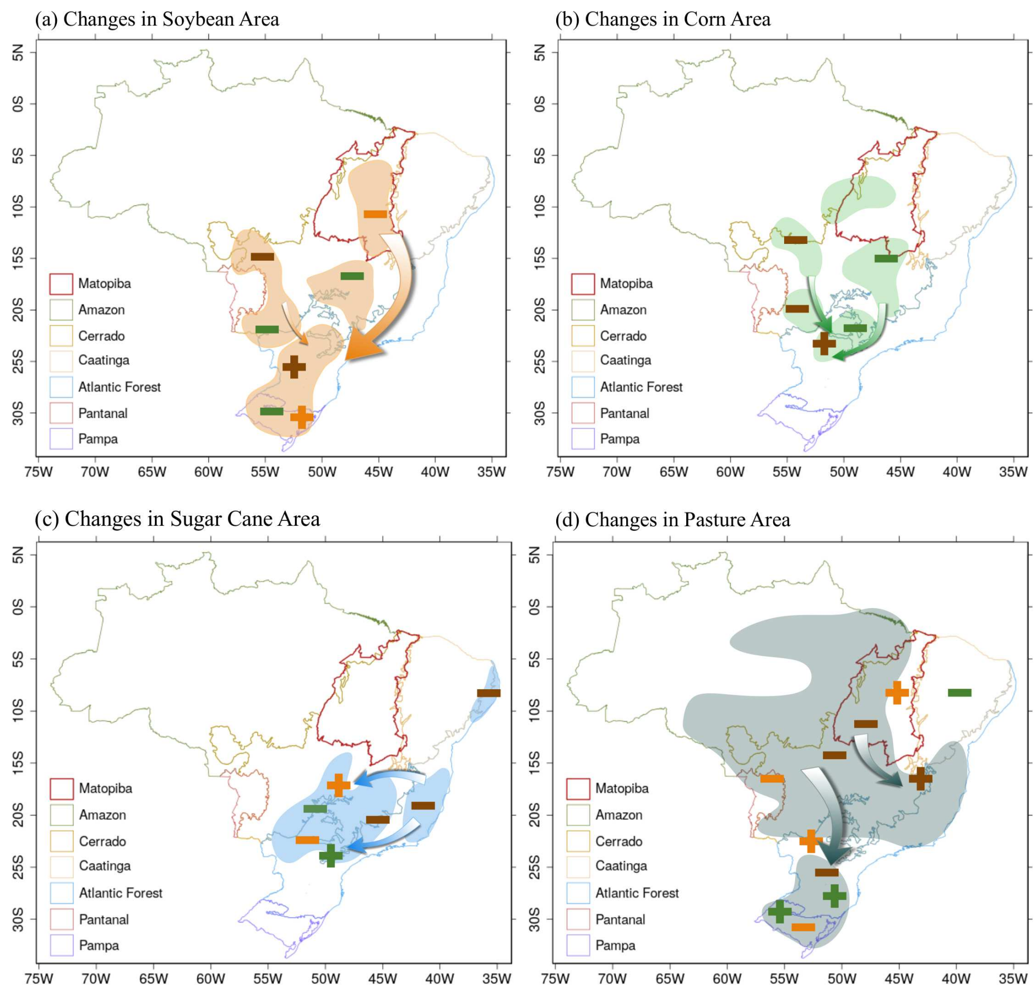

Figure 8: Scheme with main producing areas (shades; according to the noCC scenario) and changes in (a) soybeans, (b) corn, (c) sugar cane, and (d) pasture projected by EPIC and LPJmL considering RCP8.5. "+" and "-" represent regions where either EPIC (orange symbols), LPJmL (green symbols), or both GGCMs (brown symbols) indicated a median area increase or decrease, respectively. Large arrows indicate displacement of the main producing regions.