The impact of climate change on Brazil's agriculture

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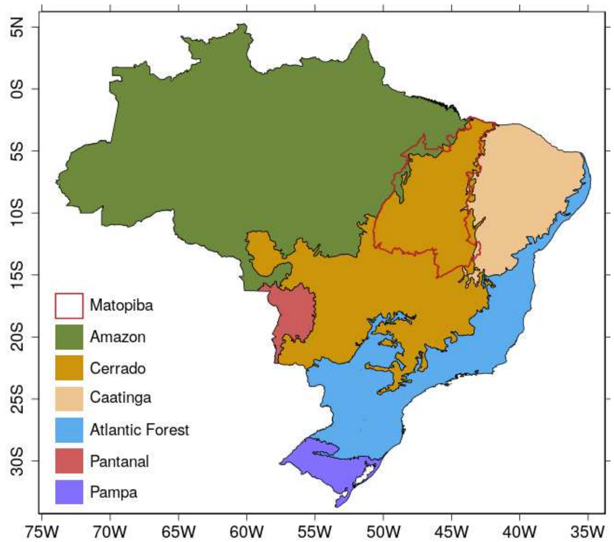

Figure S1: Brazilian main biomes (color key in the lower left) and Matopiba (dark red contour).

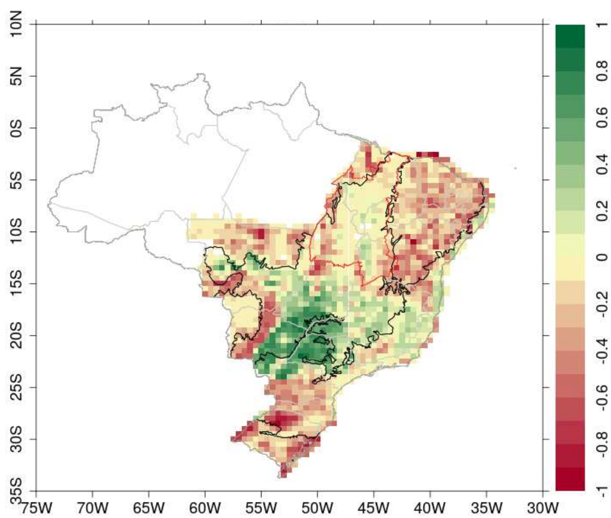

Figure S2: Fraction of each pixel considered as suitable (green shades) or unsuitable (red shades) for sugar cane production under the ZAE.

1. ISIMIP FastTrack and GCMs

ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) is a cross-sectorial initiative driven by the modeling community to facilitate intercomparison among various impact models. Models participating on this initiative cover sectors such as biodiversity, water, forest, agriculture, among others. Its first simulation round, FastTrack, aimed on providing a common set of climate change scenarios, resulting in a coherent set of impacts considering a range of 21^{st} global warming projections.

The climate change scenarios used as input in the FastTrack simulation round are provided by the CMIP5 (Coupled Model Intercomparison Project, Phase 5) archive. As the ISIMIP, all modelling centers participating on the CMIP5 provide scenarios and projections based on the same initial assumption, allowing for intercomparison among the results. Five Global Climate Models (GCMs) are selected as input to intersectoral models: HadGEM2-ES, IPSL-CM5-LR, GFDL-ESM2M, MIROC-ESM-CHEM, and NorESM1-M. These models were selected to best represent the range of global mean temperature and precipitation changes covered by the CMIP5 models (Warszawski et al., 2014). Atmospheric CO_2 concentrations were prescribed according to the four representative concentration Pathways (RCP): RCP2.6, RCP4.5, RCP 6.0 and RCP 8.5. GCMs projections of daily surface air temperature (minimum, maximum, and average), precipitation, solar radiation, near surface wind speed (total and its east- and north-ward components), surface air pressure, near-surface relative humidity, and CO_2 concentration were interpolated to a regular 0.5^o lat/long grid and bias corrected (Hempel et al., 2013) before being used as input in ISIMIP participant models. More information regarding ISIMIP and the FastTrack phase can be found in Rosenzweig et al. (2014) and at https://www.isimip.org/.

The GGCMs considered here (EPIC and LPJmL) are part of the ISIMIP FastTrack, with projections for both historical (1980-2005) and future scenarios (2005-2100) for all four RCPs. They also provide future scenarios with and without effects of increase CO_2 concentration. Here, we considered only the most optimistic and pessimistic scenarios (RCP2.6 and RCP8.5 respectively), including the effects of CO_2 fertilization due to its increased concentration. In the optimistic scenario, also known as mitigation scenario, the emission trajectory results in a stable radiative forcing of $2.6 W/m^2$ in 2100, after a peak of $3.1 W/m^2$ in 2050 (van Vuuren et al., 2011). In this scenario, the mean global temperature rise would be about 1^oC ($\pm 0.4^oC$)

Table S1: List of GMCs considered in ISIMIP, the Institutes responsible for their simulations and their references.

GCM	Institute and Country	Reference
HadGEM2-ES	Met Office Hadley Centre, UK	Collins et al. (2011); Jones et al. (2011)
IPSL-CM5A-LR	Institut Pierre Simon Laplace (IPSL), France	Dufresne et al. (2013)
GFLD-ESM2M	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration (GFDL/NOAA), USA	Dunne et al. (2012)
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Research, and Japan Agency for Marine-Earth Science and Technology, Japan	Watanabe et al. (2011)
NorESM1-M	Norwegian Climate Centre (NorClim), Norway	Bentsen et al. (2013)

by the end of the century (Collins et al., 2013). This is the only scenario where temperature projections would be within the goals established in the Paris Agreement. In the pessimistic scenario, the increase in the radiative forcing would reach 8.5W/m^2 by 2100 in an ascending trajectory, resulting in an average global temperature increase of 3.7°C (±0.7°C; Collins et al. (2013)). Current emissions already surpassed the RCP8.5 trajectory (Peters et al., 2012). More information about how individual models respond to these emission scenarios can be found in references in Table S1.

2. Potential Yield and Other Input Variables

Through the ISIMIP FastTrack platform, both EPIC and LPJmL have yearly data at 0.5^o geographical spatial resolution covering the entire world. EPIC provides information about yield, inorganic nitrogen application rate, and potential irrigation water withdrawal in two management systems, fully irrigated and not irrigated, for 15 crops: barley, beans, cassava, cotton, corn, millet, grass, ground nut, rapeseed, rice, wheat, sorghum, soybeans, sugar cane, and sunflower. LPJmL provides information only about yield and potential irrigation water withdrawal in the same management systems for 13 crops: cassava, maize, grass, millet, ground nut, field pea, rapeseed, rice, wheat, soybeans, sugar beet, sugar cane, and sunflower.

Before using the potential yield in GLOBIOM-Brazil, both EPIC and LPJmL data need to be adjusted. Here, we follow the methodology described by Leclère et al. (2014). The first step is to transform yield, as well as inorganic nitrogen application rate (initr) and potential irrigation water withdrawal (pirrw), into percentage changes in relation to the base year 2000. To avoid the large fluctuations resulting from the GCMs' interannual variability, we first estimate the climatological averages of each variable (yld, pirrw, and initr): one for the historical period (1980-2010 for EPIC and 1971-2005 for LPJmL) and three for future scenarios, considering 30-years intervals. The climatological averages, centered at the middle year of each interval, are interpolated (extrapolated after 2080), resulting in values each 5 years starting in 2000. Finally, all variables are normalized by their value in 2000, resulting in percentage changes where values smaller (larger) than 1 indicate negative (positive) impact of climate change on the variable. These values are capped at 10 (maximum 900% increase). The same procedure is adopted for all variables, crops, and management systems for both GGCMs.

These changes are used in GLOBIOM-Brazil as multipliers to the baseline productivity at the beginning of each time step, similarly to previous work (Meijl et al., 2018; Leclère et al., 2014; Havlík et al., 2015a; Nelson et al., 2013). Thus, it is necessary to have a value for each of the GLOBIOM-Brazil agriculture variables (yield, amount of nitrogen and phosphorus used as fertilizers – FTN and FTP, respectively – water requirements, and costs), management systems (subsistence– SS – low-input rain-fed – LI – high-input rain-fed – HI – and high-input irrigated – IR), and crop. The extension of the crops available in each GGCMs to GLOBIOM-Brazil's crops follows Meijl et al. (2018) and is described in Table S2.

Table S2: Mapping of EPIC and LPJmL main crops into GLOBIOM-Brazil 18 crops (based on Meijl et al. (2018)).

GLOBIOM Brazil	EPIC (except HadGEM2-ES)	EPIC HadGEM2-ES	LPJmL
Barley	Barley	Barley	Mean of Rice, Soybean, and Wheat
Dry Beans	Dry Beans	Dry Beans	Mean of Rice, Soybean, and Wheat
Cassava	Cassava	Cassava	Cassava
Chickpea	Mean of Rice, Soybean, and Wheat	Ground nut*	Ground nut*
Corn (Maize)	Maize	Maize	Maize
Cotton	Cotton	Cotton	Mean of Rice, Soybean, and Wheat
Ground nut	Ground nut	Ground nut	Ground nut
Millet	Millet	Millet	Millet
Oil of Palm	Sunflower	Mean of Rice, Soybean, and Wheat	Sunflower
Potato	Mean of Rice, Soybean, and Wheat	Mean of Rice, Soybean, and Wheat	Mean of Rice, Soybean, and Wheat
Rapeseed	Rapeseed	Rapeseed	Rapeseed
Rice	Rice	Rice	Rice
Soybean	Soybean	Soybean	Soybean
Sorghum	Sorghum	Sorghum	Millet
Sugar Cane	Sugar Cane	Sugar Cane	Sugar Cane
Sunflower	Sunflower	Sunflower	Sunflower
Sweet Potato	Mean of Rice, Soybean, and Wheat	Mean of Rice, Soybean, and Wheat	Mean of Rice, Soybean, and Wheat
Wheat	Wheat	Wheat	Wheat

* Only half of negative impact applied, representative of improved drought tolerance

The adaptation of EPIC and LPJmL variables and management systems to GLOBIOM-Brazil's are summarized in Figure S3. EPIC and LPJmL changes in potential yield in fully irrigated and not irrigated systems change GLOBIOM-Brazil's yield and costs of production in IR and HI management systems, respectively. For LI and SS management systems, GLOBIOM-Brazil's yield and costs are changed by EPIC and LPJmL yield changes in not irrigated systems. EPIC and LPJmL changes in potential irrigation water withdrawal are used to change the water requirements in GLOBIOM-Brazil IR system. EPIC changes in inorganic nitrogen application rate in fully irrigated and not irrigated systems are used to change both GLOBIOM-Brazil FTN and FTP in IR and HI management systems, respectively. As LPJmL only estimates changes in yield and potential irrigation water withdrawal, changes in yield in fully irrigated and not irrigated systems are also used to change GLOBIOM-Brazil's variables FTP and FTN in IR and HI management systems, respectively. Finally, GLOBIOM-Brazil values of FTN and FTP for LI and SS management systems are not affected.

Finally, for both GGCMs, changes in soybean and corn yield in the double cropping system (summer soybean and winter corn) were based on changes in soybean and corn yield in HI management system:

- Yield: same as for corn and soybean in HI;
- FTP, FTN, and water requirements: same as for soybean in HI;
- Costs: costs of soybean plus 50% of the costs of corn, both in HI

3. Governance Scenario: IDCImperfect3

This scenario represents the historical compliance with Brazilian Forest Code through a probability of enforcement: in each grid cell, the probability value varies between 0 and 1, with 1 indicating full compliance and no illegal deforestation, and 0 representing no compliance and no ban on the conversion of native vegetation. Values between 0 and 1 represent some level of compliance, with only a fraction of the available native vegetation being subjected to illegal deforestation. More information about this governance scenario can be found in Soterroni et al. (2018) and references therein.

4. Representation of Results and Uncertainties

Projections from two crop models (EPIC and LPJmL) forced by two emission scenarios (RCP2.6 and RCP8.5) as modeled by five different climate

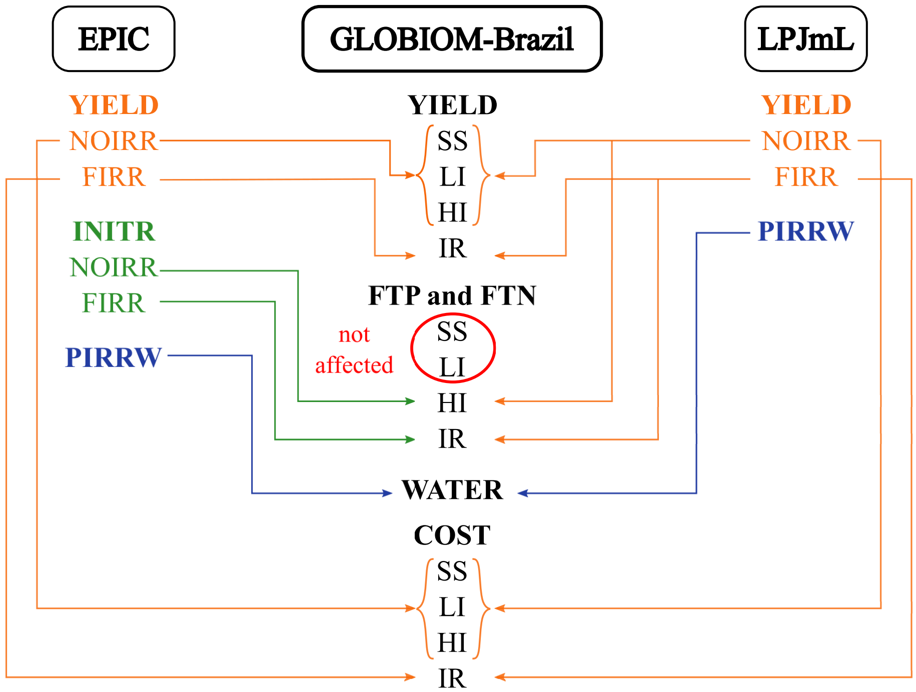

Figure S3: Schematic of the conversion from EPIC and LPLmL to GLOBIOM-Brazil variables. yld: yield; initr: inorganic nitrogen application rate; pirrw: potential irrigation water withdrawal; firr: fully irrigated; and noirr: not irrigated.

models results in 20 scenarios (Fig S4) and will be refer to as "individual scenarios". To facilitate their interpretation, these individual scenarios are aggregated by RCP and GGCMs, producing four sets with five individual scenarios each: RCP2.6-EPIC, RCP2.6-LPJmL, RCP8.5-EPIC and RCP8.5-LPJmL. This aggregation is used when describing the resulting GLOBIOM Brazil scenarios forced by the two GGCMs (Section 3) as well as the results of the GGMCs obtained from the ISIMIP Platform (Supplementary Material). Results regarding GLOBIOM Brazil scenarios for these four sets, and each of the 20 scenarios, are compared to a baseline (noCC), in which GLOBIOM Brazil is driven only by population growth and consumption, as defined by SSP2 scenario, with no impacts from climate change. The final impacts are quantified as the difference (either in absolute terms or as percentages) between scenarios (or set of scenarios) and the noCC at each 5-year time step, with focus on the year 2050.

For each set of scenarios, we estimated the median (50^{th} percentile), upper

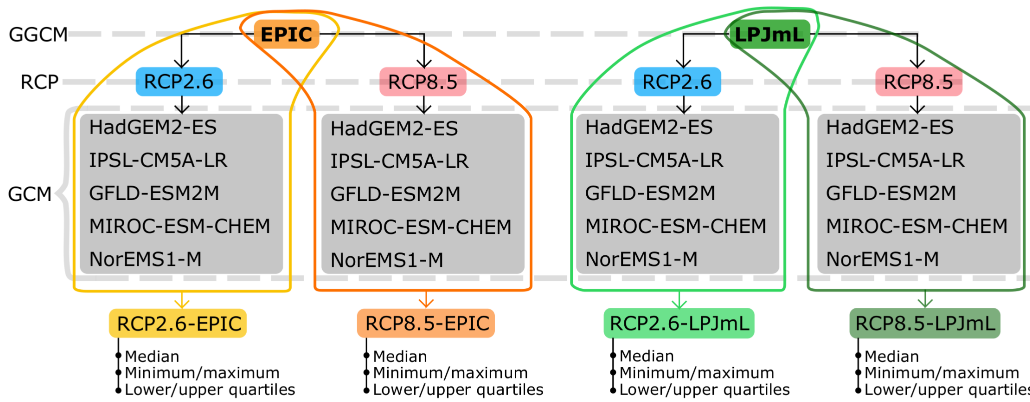

Figure S4: Representation of the combinations of RCPs and GCMs used as input for GGCMs as well as the combination of these 20 individual scenarios in two four sets.

and lower quartiles (25$^{\text{th}}$ and 75$^{\text{th}}$ percentiles, respectively), in each 50 km by 50 km pixel. The differences between the median in each set and the noCC scenario are presented as maps. Results from these maps (and also for each individual scenario) are summed over the entire over Brazil or its regions to produce aggregated results, which are presented as graphics. Uncertainties are assessed through the spread between the upper and lower quartiles, or maximum and minimum values, within a given set and also among all individual scenarios. Sets and scenarios are considered to display an increasing (decreasing) trend whenever the lower and upper quartiles have the same positive (negative) sign and/or whenever more than 90% of the 20 individual scenarios are in sign agreement. When the upper and lower quartiles display opposites signs and the median is close to zero, the set display a stability (or no-change) trend with regard to the noCC.

Figure 1 also identifies the main uncertainties related to each link of this impact modeling framework. Future emissions in each RCP scenario are based on coherent socioeconomic pathways and on historical concentration of GHG and other air pollutants, with uncertainties rising from the translation of emissions profiles into concentrations and radiative forcing (van Vuuren et al., 2011). We assess these uncertainties by considering the highest and lowest emission scenarios (RCP2.6 and RCP8.5, respectively). Additionally, each GCM responds differently to external forcing due to differences in their dynamic core (set of equation and parameterization), resulting in large uncertainties (Kirtman et al., 2013). Similarly, GGCMs simulations also incorporate uncertainties from the previous links of the modeling framework together with those related to the model's assumptions and performance (Elliott et al., 2015). The use of five GCMs and two GGCMs explores the possible impacts of these uncertainties in potential crop productivity. Thus, the resulting 20 scenarios (2 GGCMs forced by 5 GCMs in 2 RCPs) provide a sizeable sample to analyze the possible impacts of climate change on Brazilian agriculture with some level of confidence, specially on those cases where there is an agreement among them.

5. Impacts on Potential Yield

Figure S5 (and Tables S3-S6) shows the changes in potential yield (expressed as a percentage of increase or decrease) of the main crops and pasture aggregated over Brazil in 2050. For soybeans, the impacts of climate change on potential yield are positive and more intense for the pathway RCP8.5. For both the RCP2.6-EPIC and the RCP8.5-EPIC sets (Fig S5a), all aggregated statistics (median, lower, and upper quartiles, represented by the box), as well as the individual values for each GCM (represented by the colored upper and lower triangles) are positive, suggesting agreement among all scenarios. RCP2.6-LPJmL and RCP8.5-LPJmL soybeans results are slightly more optimistic but also with a larger spread (Fig S5b and Table S3). Considering each GCM and RCP individually, 7 out of 10 scenarios indicated positive impacts.

For corn, the spread of the statistics are similar to those for soybeans, but with less clear trends. In RCP2.6-EPIC and RCP8.5-EPIC (Fig S5a and Table S4), only 4 of 10 individual scenarios display a positive trend. On the other hand, RCP2.6-LPJmL and RCP8.5-LPJmL corn results aggregated over Brazil are mostly positive (Fig S5b and Table S4), with 9 out of 10 individual scenarios predicting a positive impact of climate change on corn potential yield.

Results from both GGCMs indicate an increase in soybeans and corn yield over subtropical regions (Pampa and Atlantic Forest) and a decrease over tropical areas (Amazon, Cerrado, and Matopiba; Fig S6a-d). These results are in agreement with previous studies based on GGCMs (Müller et al., 2015; Müller and Robertson, 2014; Rosenzweig et al., 2014), but they disagree with projections based in agricultural zoning, which indicated a reduction of suitability over Atlantic Forest and southern Cerrado biomes and an increase further north along the border of Cerrado and Amazon biomes (Assad et al., 2016).

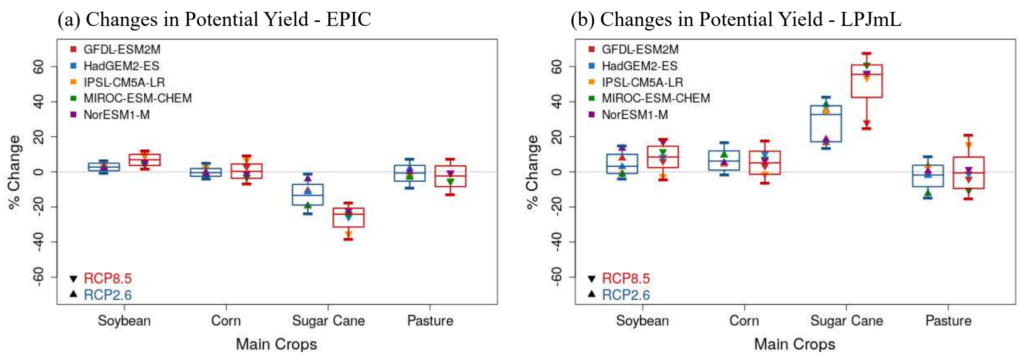

Figure S5: Changes in potential yield (represented as percentage) of main Brazilian crops and pasture in 2050 aggregated over Brazil for (a) EPIC, and (b) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers) for RCP2.6 (in blue) and RCP8.5 (in red) emission scenarios (values in Tables S3-S6). Upper (lower) triangles: aggregated value of the changes in potential yield in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left).

Differently from the relative agreement among scenarios for soybeans and corn, the impacts of climate change on sugar cane potential yield vary among GGCMs. EPIC results (Fig S5a) indicate a reduction in potential yield over the entire country while, for LPJmL (Fig S5b) scenarios, climate change improves the crop yield (see also Fig S6e-f). For both GGCMs, the impact of larger CO_2 emissions (RCP8.5) is more intense, resulting in larger reduction (increase) in potential yield for EPIC (LPJmL). These results highlight 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., 2015b).

Finally, pasture yield is not as impacted by climate change as other crops, with medians close to zero and the first and third quartiles showing opposite signs for all sets. EPIC scenarios suggest a reduction in potential grassland yield in Pampa and Pantanal regions (Fig S6e and Table S6). Conversely, LPJmL suggest an increase in grassland potential yield in Pampa (Fig S6f and Table S6).

Table S3: Median, lower, and upper quartiles values of the changes in soybean potential yield (expressed as a percentage) in 2050 for EPIC and LPJmL GGCMs and RCP2.6 and RCP8.5 emission scenarios, aggregated over Brazil and main producing regions.

REGION	RCP2.6 Median (%)	RCP2.6 Lower quartile (%)	RCP2.6 Upper quartile (%)	RCP8.5 Median (%)	RCP8.5 Lower quartile (%)	RCP8.5 Upper quartile (%)
EPIC						
Brazil	2.7	0.6	4.9	6.9	3.6	10.0
Amazon	3.3	1.7	4.2	4.5	2.8	5.6
Cerrado	1.0	-2.0	4.0	3.9	-0.3	7.2
Matopiba	-19.5	-33.5	-5.5	-18.4	-36.1	-4.2
Atl. Forest	4.3	3.1	5.8	10.1	7.6	13.3
Pampa	4.0	3.2	6.9	7.2	5.1	9.2
LPJmL						
Brazil	3.2	-0.9	10.0	8.4	2.5	14.6
Amazon	2.1	-2.9	4.3	4.1	-0.1	8.2
Cerrado	0.2	-4.3	5.9	3.8	-1.3	10.1
Matopiba	-2.4	-6.4	5.2	2.3	-2.7	12.7
Atl. Forest	5.8	2.2	13.7	12.3	5.9	18.2
Pampa	8.4	3.7	18.7	20.0	7.7	28.6

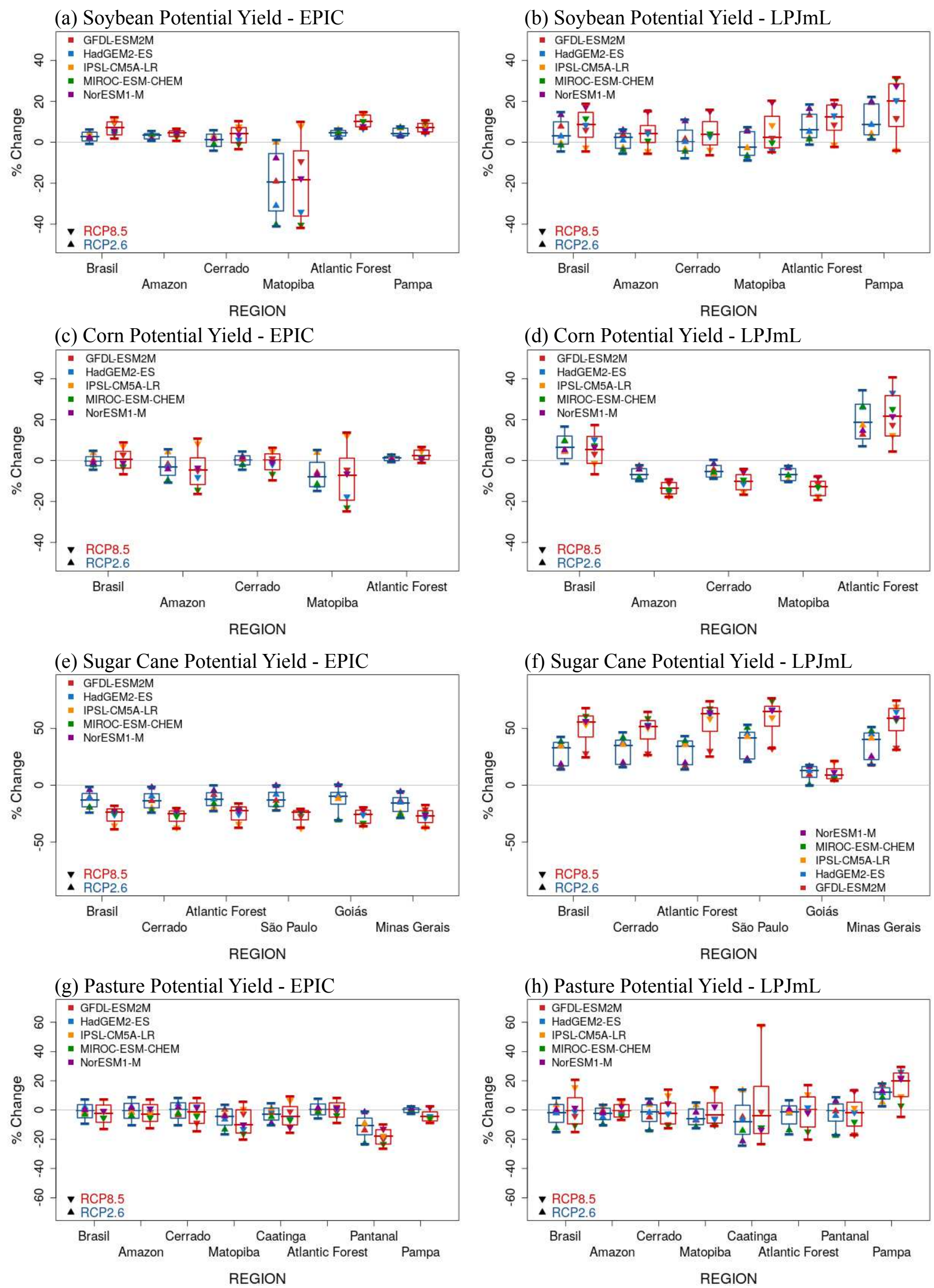

Figure S6: Percentage changes in potential yield of (a)-(b) soybean, (c)-(d) corn, (e)-(f) sugar cane, and (g)-(h) pasture in 2050 aggregated over Brazil, main biomes and producing regions, and Matopiba (Fig S1) for (a), (c), (e), and (g) EPIC, and (b), (d), (f), and (h) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers) for RCP2.6 (in blue) and RCP8.5 (in red) emission scenarios (values in Tables S3-S6). Upper (lower) triangles: aggregated value in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). Note: only biomes with more than 1% of the national production in 2050 are included.

Table S4: Median, lower, and upper quartiles values of the changes in corn potential yield (expressed as a percentage) in 2050 for EPIC and LPJmL GGCMs and RCP2.6 and RCP8.5 emission scenarios, aggregated over Brazil and main producing regions.

REGION	RCP2.6 Median (%)	RCP2.6 Lower quartile (%)	RCP2.6 Upper quartile (%)	RCP8.5 Median (%)	RCP8.5 Lower quartile (%)	RCP8.5 Upper quartile (%)
EPIC						
Brazil	-0.5	-2.5	1.9	0.3	-3.7	4.5
Amazon	-3.3	-7.2	1.8	-4.8	-11.7	1.3
Cerrado	0.1	-2.1	2.3	0.2	-4.5	3.3
Matopiba	-8.0	-12.8	-0.9	-7.5	-19.4	1.2
Atl. Forest	1.0	0.0	1.9	2.2	0.5	5.1
LPJmL						
Brazil	6.2	1.0	12.0	5.1	-1.4	11.8
Amazon	-7.2	-9.0	-4.0	-13.6	-16.2	-10.7
Cerrado	-5.6	-8.1	-2.4	-10.4	-14.3	-6.9
Matopiba	-7.0	-9.8	-3.9	-12.9	-17.2	-10.1
Atl. Forest	18.6	10.6	27.5	21.5	12.0	31.7

Table S5: Median, lower, and upper quartiles values of the changes in sugar cane potential yield (expressed as a percentage) in 2050 for EPIC and LPJmL GGCMs and RCP2.6 and RCP8.5 emission scenarios, aggregated over Brazil and main producing regions.

	RCP2.6			RCP8.5		
REGION	Median (%)	Lower quartile (%)	Upper quartile (%)	Median (%)	Lower quartile (%)	Upper quartile (%)
EPIC						
Brazil	-13.4	-19.0	-7.2	-24.2	-31.4	-20.8
Cerrado	-13.8	-19.8	-7.4	-25.4	-31.6	-22.5
Atl. Forest	-12.8	-17.8	-6.6	-22.6	-30.5	-19.0
São Paulo	-13.0	-18.6	-6.2	-24.0	-30.3	-22.2
Goias	-9.8	-16.6	-6.2	-25.8	-33.4	-21.9
Minas Gerais	-15.9	-23.0	-10.8	-27.5	-32.7	-22.3
LPJmL						
Brazil	32.7	17.2	37.7	55.6	42.5	61.0
Cerrado	34.6	18.3	39.8	51.6	40.7	56.9
Caatinga	0.6	-4.2	6.5	6.0	-0.7	16.3
Atl. Forest	34.0	18.1	38.9	62.8	47.4	68.2
São Paulo	41.4	23.2	46.6	64.9	52.0	69.4
Goias	12.4	7.0	16.4	8.9	5.8	14.6
Minas Gerais	40.0	22.6	46.0	59.0	48.0	67.6

Table S6: Median, lower, and upper quartiles values of the changes in pasture potential yield (expressed as a percentage) in 2050 for EPIC and LPJmL GGCMs and RCP2.6 and RCP8.5 emission scenarios, aggregated over Brazil and main producing regions.

REGION	RCP2.6 Median (%)	RCP2.6 Lower quartile (%)	RCP2.6 Upper quartile (%)	RCP8.5 Median (%)	RCP8.5 Lower quartile (%)	RCP8.5 Upper quartile (%)
EPIC						
Brazil	-0.7	-5.3	3.7	-2.4	-8.4	3.4
Amazon	-0.3	-5.6	4.6	-2.9	-7.7	3.7
Cerrado	0.1	-5.6	5.0	-1.6	-9.2	4.7
Matopiba	-4.6	-10.3	0.7	-10.4	-15.7	0.1
Caatinga	-2.9	-6.9	1.3	-4.5	-10.2	2.4
Atl. Forest	0.1	-3.3	4.1	0.3	-4.8	4.9
Pantanal	-10.6	-16.9	-5.5	-18.2	-23.2	-13.4
Pampa	0.0	-1.7	1.5	-4.7	-7.4	-1.3
LPJmL						
Brazil	-1.8	-8.4	3.8	-0.6	-9.5	8.4
Amazon	-2.7	-6.6	1.3	-0.4	-4.8	3.7
Cerrado	-1.5	-7.8	3.6	-2.7	-9.5	4.7
Matopiba	-5.9	-10.0	0.7	-3.4	-9.0	4.9
Caatinga	-8.3	-16.6	3.2	-4.0	-16.1	16.2
Atl. Forest	-1.7	-9.5	2.8	0.0	-11.6	9.0
Pantanal	-0.6	-7.6	4.2	-1.9	-11.0	5.4
Pampa	11.7	7.5	15.3	19.6	9.2	25.3

6. Impacts on Agricultural Output

6.1. Cropland and pasture area

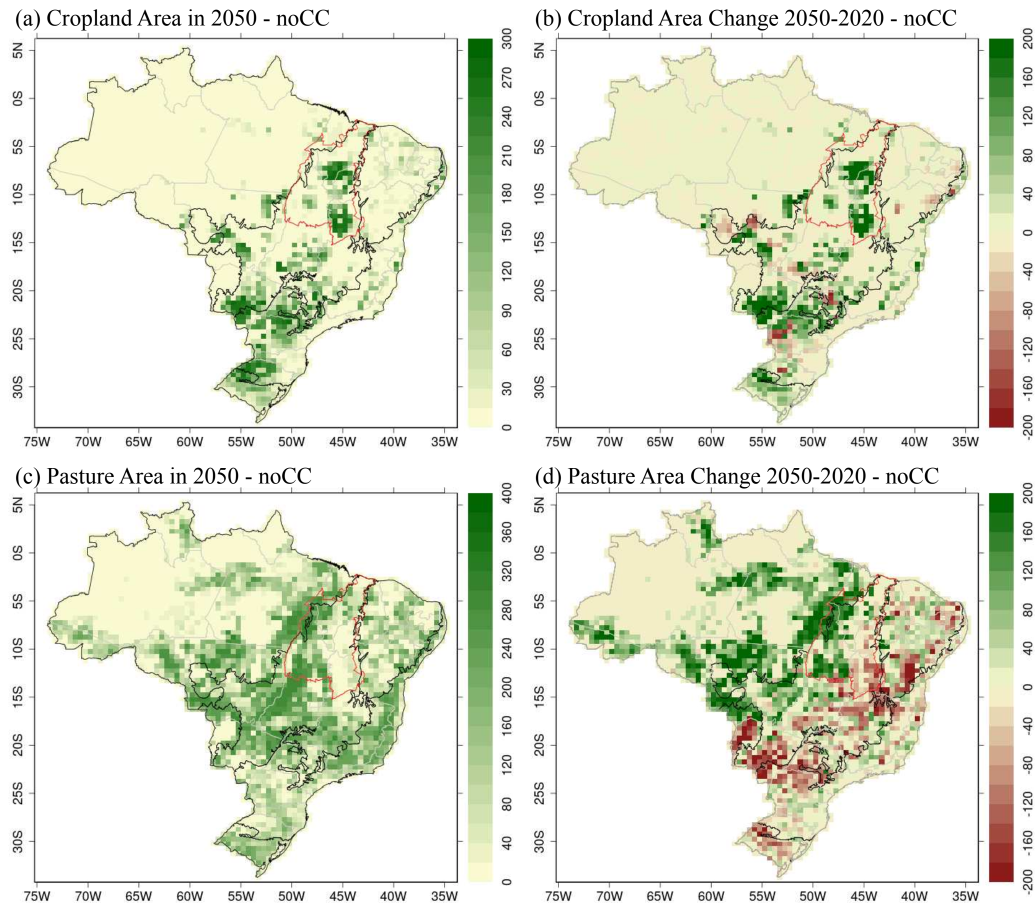

Figure S7: Area of (a) cropland (in kha) in 2050 and (b) its evolution compared to 2020, and (c) pasture (in kha) in 2050 and (d) its evolution compared to 2020 for noCC scenario. In (b) and (d), increase (decrease) is represented in green (red) shades.

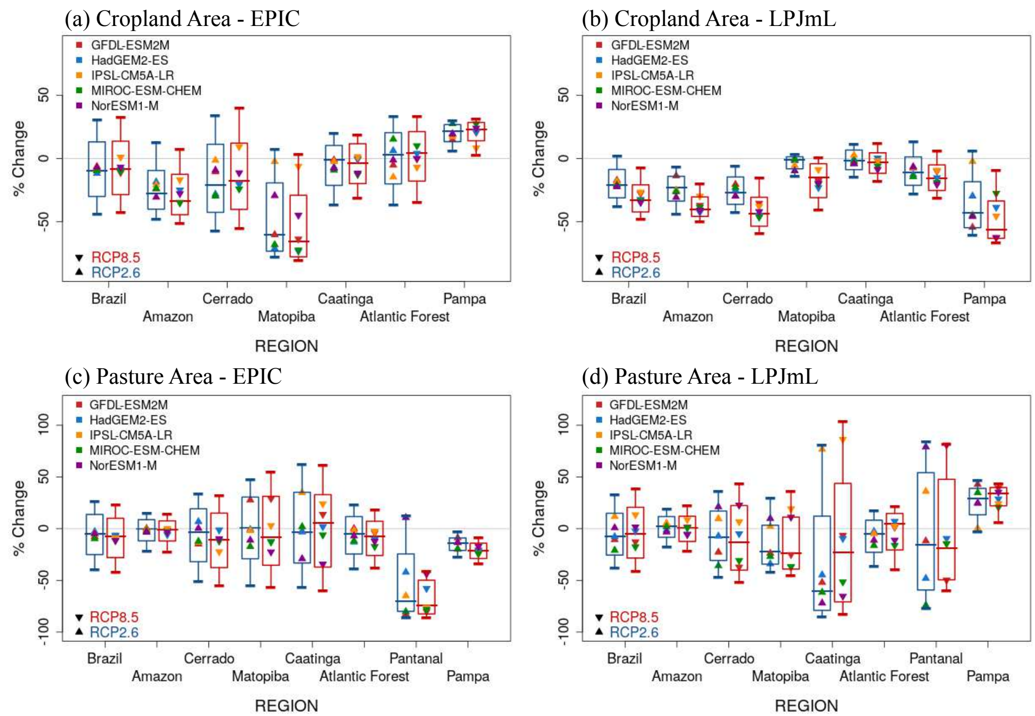

Figure S8: Percentage changes (compared to noCC in 2050) in the area of (a)-(b) cropland and (c)-(d) pasture aggregated over Brazil, main biomes, and Matopiba (see Fig S1 for location of biomes and Matopiba), for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S7. Upper (lower) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). Note: only biomes with more than 1% of the national production in the noCC scenario in 2050 are included.

Table S7: Median (lower and upper quartile) change in cropland and pasture area in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil, biomes, and Matopiba.

	RCP2.6		RCP8.5	
REGION	Cropland (%)	Pasture (%)	Cropland (%)	Pasture (%)
EPIC				
Brazil	-10.1 (-29.9; 13.2)	-5.2 (-25.0; 13.8)	-8.8 (-28.5; 13.8)	-7.8 (-27.9; 10.1)
Amazon	-27.7 (-40.0; -9.4)	-0.8 (-11.8; 8.7)	-33.8 (-44.4; -12.4)	-1.4 (-11.9; 7.6)
Cerrado	-21.2 (-42.5; 11.3)	-3.7 (-31.9; 19.2)	-17.9 (-40.2; 12.2)	-10.7 (-37.6; 15.0)
Matopiba	-60.5 (-73.2; -19.2)	0.6 (-29.0; 30.5)	-65.6 (-77.9; -29.0)	-8.3 (-35.4; 31.2)
Caatinga	-1.3 (-21.8; 10.4)	-4.1 (-33.2; 35.2)	-3.7 (-19.8; 11.8)	5.0 (-37.1; 32.9)
Atlantic Forest	2.7 (-20.0; 20.5)	-5.5 (-24.5; 11.7)	4.1 (-17.8; 21.4)	-7.8 (-25.9; 7.2)
Pantanal	-24.9 (-59.8; -0.2)	-70.1 (-79.9; -24.4)	-33.1 (-51.5; -13.3)	-74.5 (-82.4; -49.8)
Pampa	21.5 (13.4; 26.9)	-14.4 (-21.0; -8.9)	23.0 (14.0; 28.6)	-22.0 (-28.8; -14.0)
LPJmL				
Brazil	-21.5 (-31.0; -8.6)	-8.2 (-25.5; 14.9)	-33.4 (-42.2; -20.8)	-5.1 (-28.4; 20.7)
Amazon	-23.3 (-33.6; -14.0)	2.2 (-8.3; 11.7)	-40.3 (-45.7; -30.3)	0.3 (-12.3; 12.0)
Cerrado	-27.0 (-36.2; -14.5)	-8.9 (-30.7; 17.0)	-43.8 (-53.5; -30.6)	-13.2 (-40.0; 22.4)
Matopiba	-1.1 (-8.1; 1.4)	-22.3 (-34.3; 3.3)	-15.0 (-30.9; -4.0)	-23.9 (-39.0; 11.2)
Caatinga	-2.2 (-8.8; 6.8)	-60.9 (-78.9; 12.1)	-3.4 (-11.6; 4.5)	-23.6 (-70.7; 43.8)
Atlantic Forest	-11.5 (-21.2; 1.3)	-5.7 (-22.9; 8.2)	-15.9 (-25.2; -5.0)	4.7 (-20.5; 14.7)
Pantanal	-36.1 (-46.3; -22.7)	-16.2 (-59.2; 54.1)	-35.9 (-47.6; -24.1)	-18.9 (-49.4; 47.7)
Pampa	-43.0 (-54.6; -18.3)	29.2 (13.4; 38.9)	-56.8 (-63.0; -33.5)	33.6 (22.1; 39.8)

6.2. Soybean

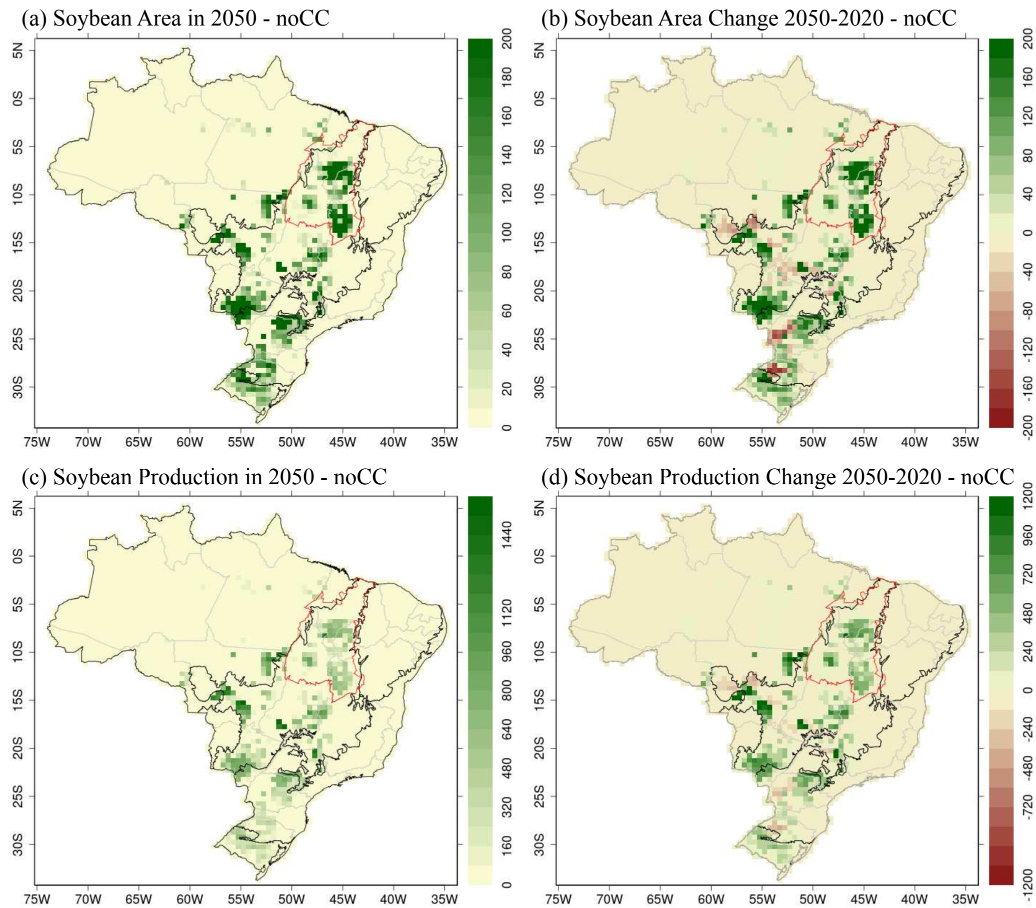

Figure S9: Soybean (a) area (in kha) in 2050 and (b) its evolution compared to 2020, and (c) production (in kt) in 2050 and (d) its evolution compared to 2020 for noCC scenario. In (b) and (d), increase (decrease) is represented in green (red) shades.

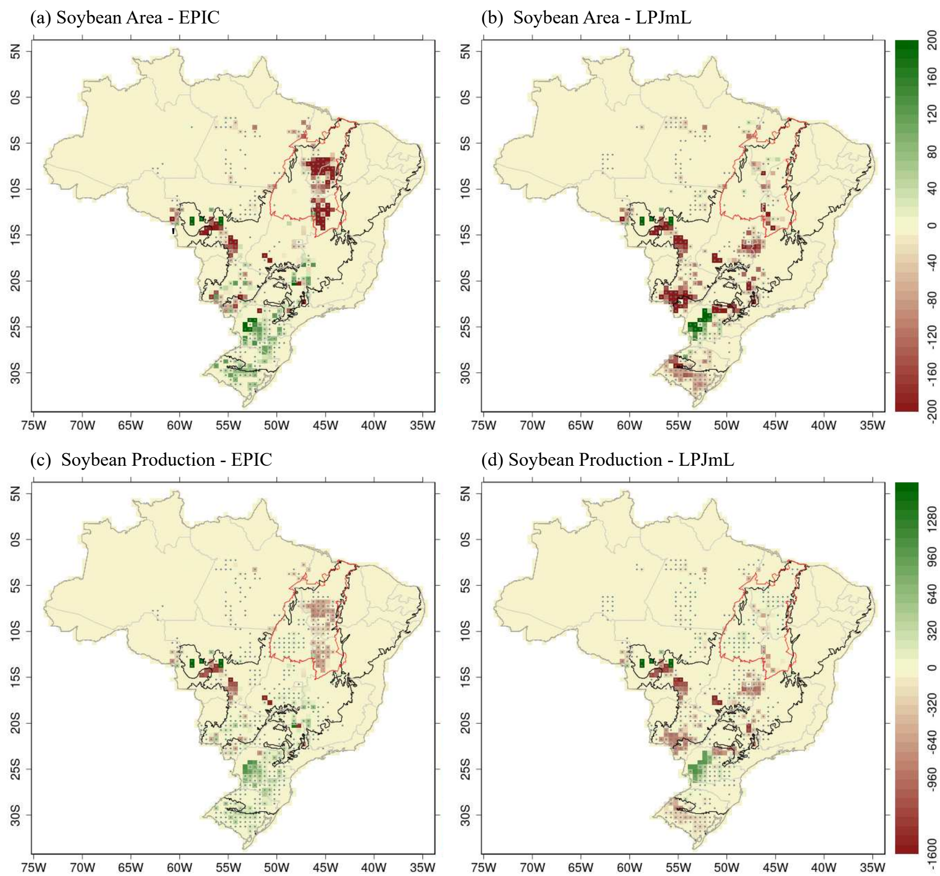

Figure S10: Median changes in soybeans (a)-(b) area (in kha) and (c)-(d) production (in kt) for (a) and (c) EPIC and (b) and (d) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Pixels where the difference between the median and the noCC scenarios are positive (negative) are shaded green (red); Stippled pixels indicate areas where the lower and upper quartiles have same sign.

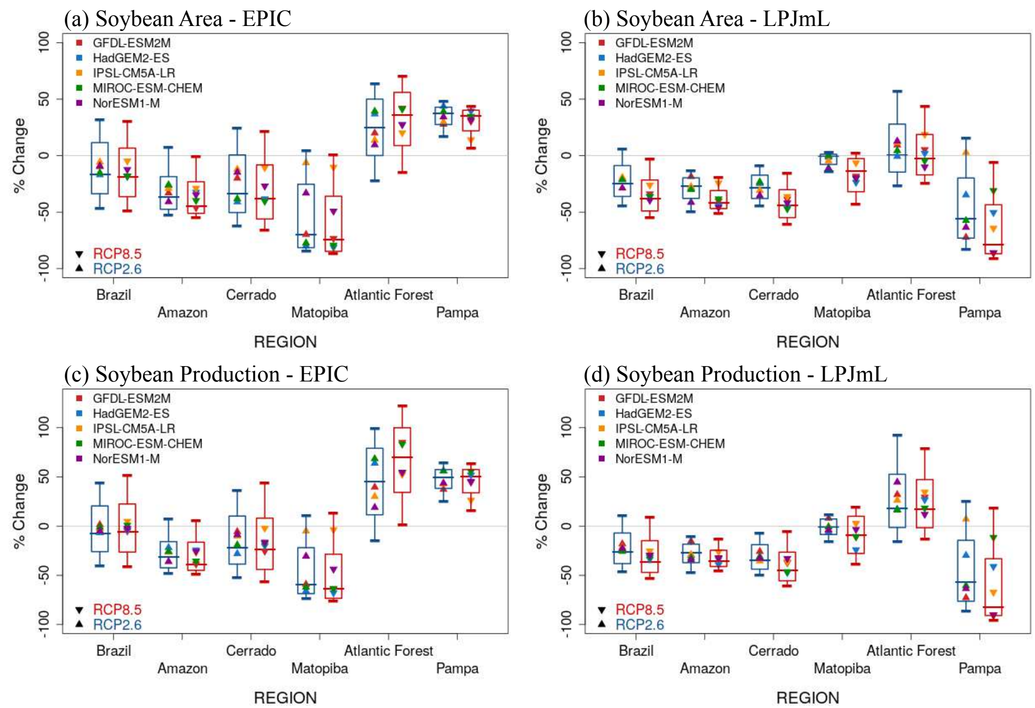

Figure S11: Percentage changes (compared to noCC in 2050) in soybean (a)-(b) area and (c)-(d) production aggregated over Brazil, main biomes, and Matopiba (see Fig S1 for location of biomes and Matopiba), for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S8. Upward (downward) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). Note: only biomes with more than 1% of the national production in the noCC scenario in 2050 are included.

Table S8: Median (lower and upper quartile) change in soybean area and production in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil and main producing regions.

	RCP2.6		RCP8.5	
REGION	Area (%)	Production (%)	Area (%)	Production (%)
EPIC				
Brazil	-17.0 (-33.7; 11.5)	-8.2 (-25.9; 20.5)	-18.9 (-36.6; 6.7)	-6.3 (-26.3; 22.5)
Amazon	-36.7 (-47.4; -18.5)	-31.4 (-42.4; -15.7)	-45.1 (-51.0; -23.1)	-38.9 (-44.9; -16.3)
Cerrado	-34.2 (-50.3; 0.6)	-22.5 (-38.6; 10.2)	-38.8 (-56.; -8.2)	-24.0 (-44.0; 8.1)
Matopiba	-70.2 (-81.4; -25.3)	-59.6 (-68.6–21.9)	-74.3 (-84.6; -35.9)	-63.7 (-73.3; -28.5)
Atlantic Forest	24.8 (0.1; 50.0)	44.4 (11.5; 79.1)	35.4 (8.9; 56.0)	69.5 (34.3; 99.9)
Pampa	37.4 (27.5; 42.9)	49.4 (38.3; 57.4)	34.9 (21.9; 40.2)	50.1 (33.8; 57.5)
LPJmL				
Brazil	-25.0 (-36.1; -8.8)	-26.8 (-38.1; -7.0)	-38.5 (-48.9; -21.6)	-36.5 (-47.0; -14.7)
Amazon	-27.2 (-37.8; -19.6)	-27.3 (-37.1; -18.4)	-41.9 (-46.8; -30.9)	-36.1 (-41.0; -24.5)
Cerrado	-28.7 (-37.9; -17.2)	-34.8 (-43.7; -18.9)	-44.1 (-54.8; -30.1)	-45.5 (-55.6; -26.5)
Matopiba	-0.7 (-7.7; 1.2)	-1.3 (-8.5; 7.2)	-14.3 (-31.9; -2.6)	-9.2 (-27.7; 10.0)
Atlantic Forest	0.1 (-14.5; 27.9)	17.5 (-1.4; 52.6)	-3.2 (-17.0; 18.7)	17.2 (-1.6; 47.3)
Pampa	-56.3 (-73.0; -19.8)	-57.3 (-76.3; -14.4)	-78.8 (-86.7; -43.5)	-83.2 (-90.8; -33.1)

210 *6.3. Corn*

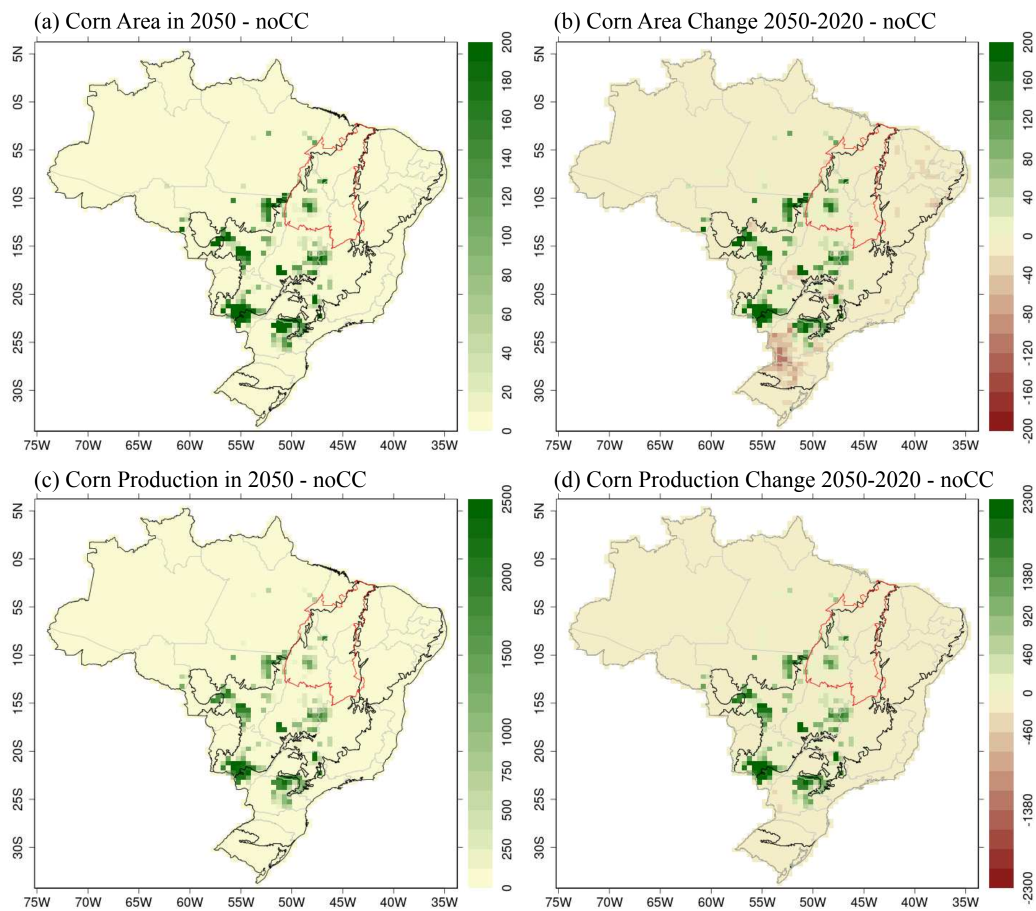

Figure S12: Corn (a) area (in kha) in 2050 and (b) its evolution compared to 2020, and (c) production (in kt) in 2050 and (d) its evolution compared to 2020 for noCC scenario. In (b) and (d), increase (decrease) is represented in green (red) shades.

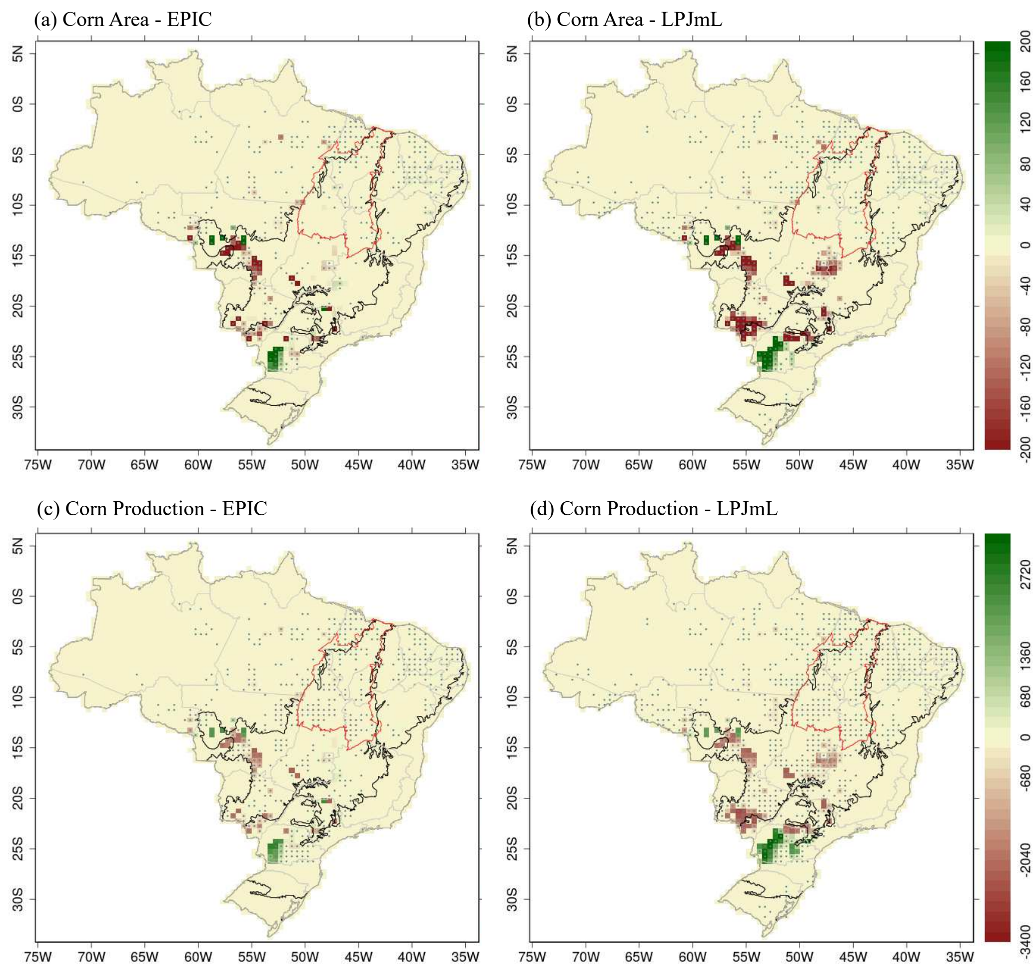

Figure S13: Median changes in corn (a)-(b) area (in kha) and (c)-(d) production (in kt) for (a) and (c) EPIC and (b) and (d) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Pixels where the difference between the median and the noCC scenarios are positive (negative) are shaded green (red); Stippled pixels indicate areas where the lower and upper quartiles have same sign.

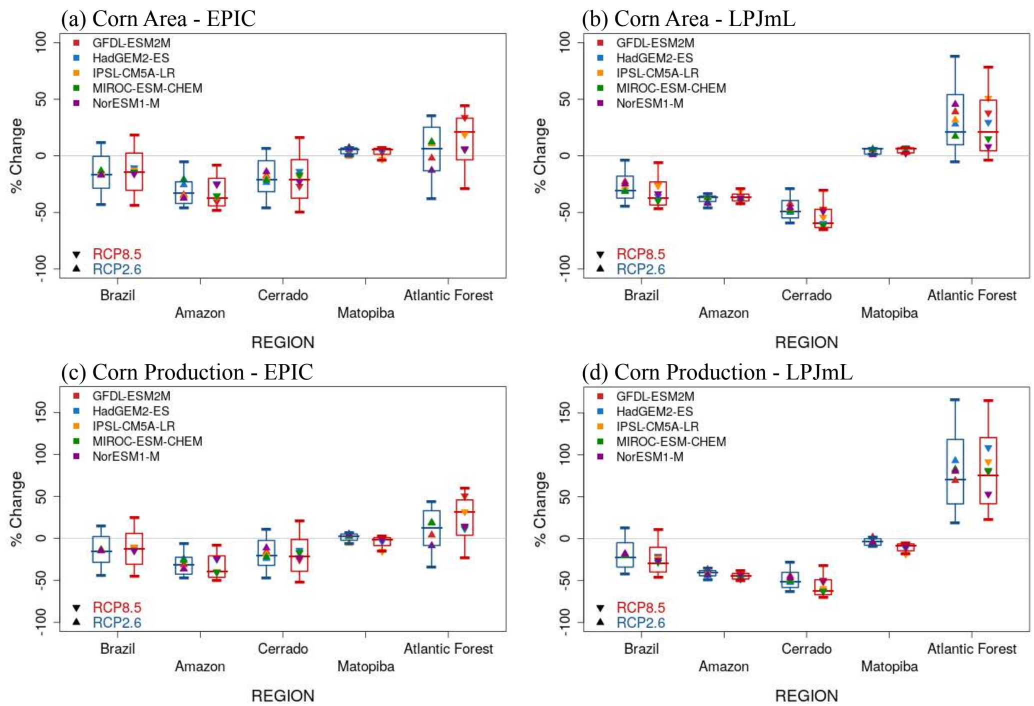

Figure S14: Percentage changes (compared to noCC in 2050) in corn (a)-(b) area and (c)-(d) production aggregated over Brazil, main biomes, and Matopiba (see Fig S1 for location of biomes and Matopiba), for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S9. Upward (downward) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). Note: only biomes with more than 1% of the national production in the noCC scenario in 2050 are included.

Table S9: Median (lower and upper quartile) change in corn area and production in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil and main producing regions.

	RCP2.6		RCP8.5	
REGION	Area (%)	Production (%)	Area (%)	Production (%)
EPIC				
Brazil	-16.6 (-28.6; -0.4)	-15.4 (-28.4; 2.2)	-14.6 (-30.4; 2.5)	-12.9 (-30.7; 6.0)
Amazon	-32.9 (-42.0; -23.0)	-32.0 (-42.6; -22.4)	-37.9 (-44.2; -19.8)	-39.8 (-46.3; -20.7)
Cerrado	-21.3 (-31.7; -4.3)	-20.9 (-32.0; -2.4)	-21.6 (-37.4; -3.3)	-21.5 (-39.0; -1.2)
Matopiba	5.6 (1.8; 6.9)	2.3 (-2.2; 5.3)	5.3 (1.5; 6.5)	-1.9 (-8.5; 1.1)
Atlantic Forest	5.8 (-13.2; 25.3)	11.9 (-8.4; 33.1)	20.7 (-3.5; -33.3)	31.0 (3.9; 45.9)
LPJmL				
Brazil	-31.0 (-37.4; -17.9)	-23.2 (-33.8; -4.8)	-37.5 (-43.4; -23.0)	-29.4 (-39.7; -10.2)
Amazon	-36.9 (-40.3; -35.6)	-41.1 (-44.2; -38.0)	-37.3 (-39.8; -33.8)	-45.1 (-48.1; 41.5)
Cerrado	-49.3 (-54.9; -39.4)	-51.8 (-58.1; -40.0)	-60.2 (-63.3; -47.2)	-62.6 (-66.7; -48.9)
Matopiba	5.7 (1.6; 6.1)	-4.1 (-7.8; 0.0)	6.0 (2.6; 7.1)	-8.8 (-14.4; -6.2)
Atlantic Forest	21.1 (9.8; 54.1)	70.1 (41.6; 118.3)	21.0 (4.5; 49.2)	74.6 (41.7; 120.7)

6.4. Sugar Cane

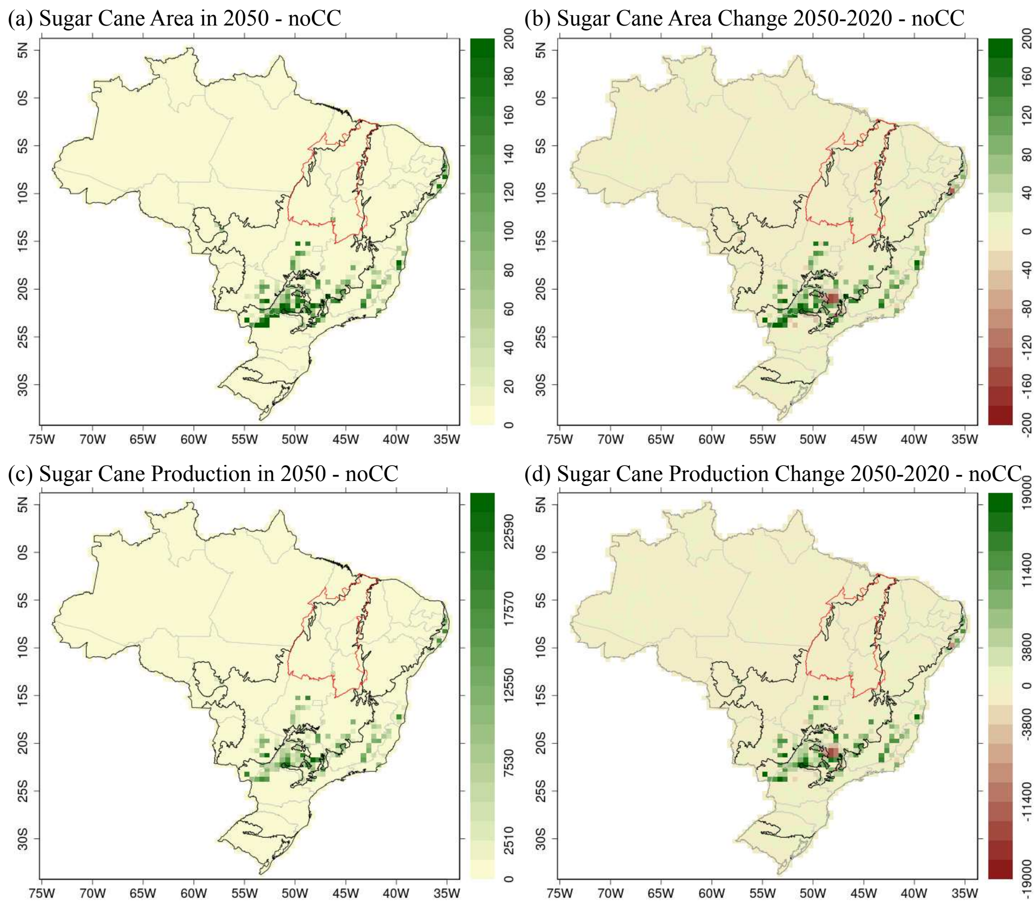

Figure S15: Sugar cane (a) area (in kha) in 2050 and (b) its evolution compared to 2020, and (c) production (in kt) in 2050 and (d) its evolution compared to 2020 for noCC scenario. In (b) and (d), increase (decrease) is represented in green (red) shades.

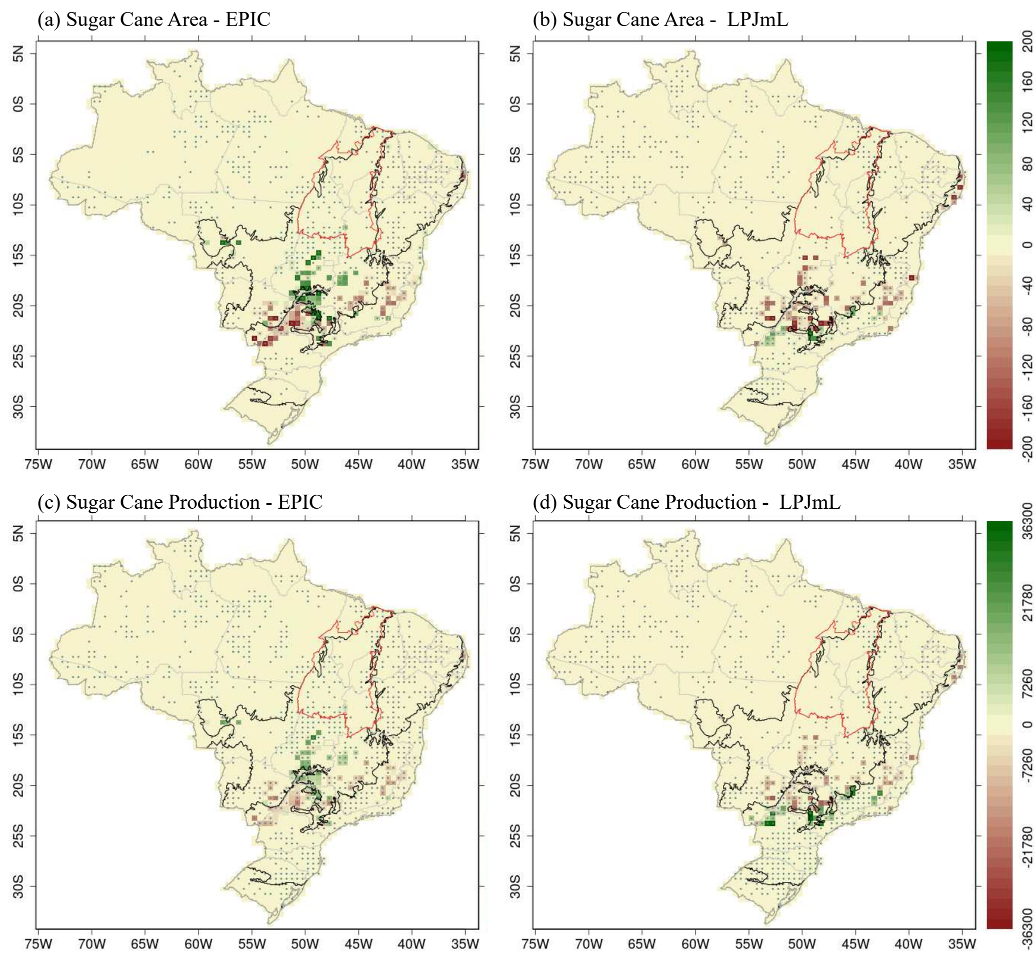

Figure S16: Median changes in sugar cane (a)-(b) area (in kha) and (c)-(d) production (in kt) for (a) and (c) EPIC and (b) and (d) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Pixels where the difference between the median and the noCC scenarios are positive (negative) are shaded green (red); Stippled pixels indicate areas where the lower and upper quartiles have same sign.

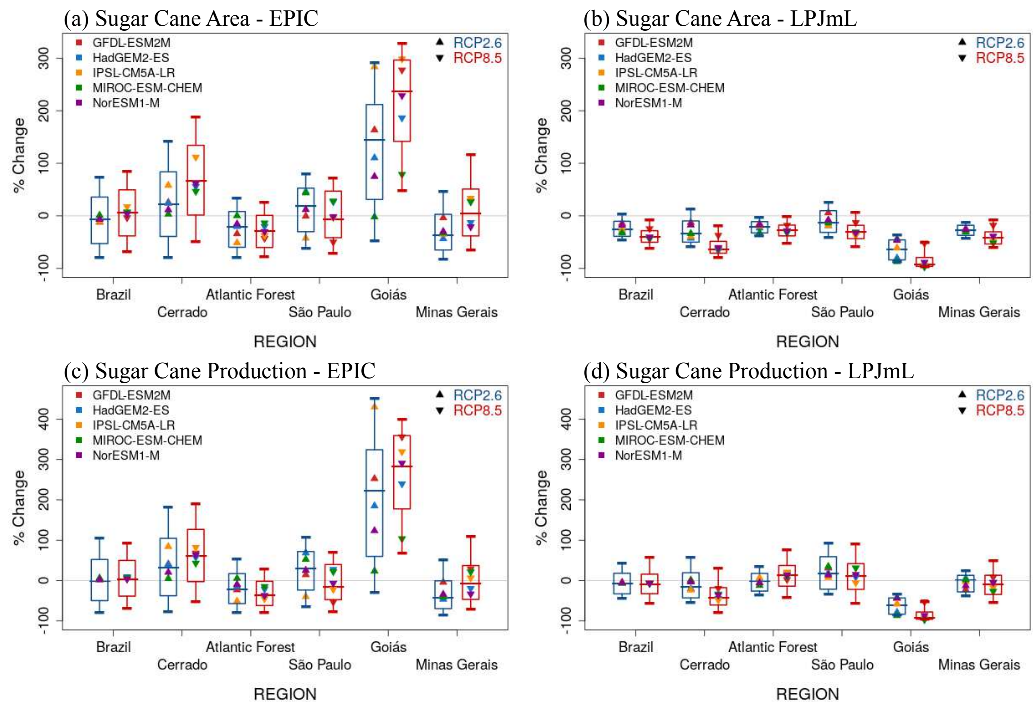

Figure S17: Percentage changes (compared to noCC in 2050) in sugar cane (a)-(b) area and (c)-(d) production aggregated over Brazil, main biomes, and Matopiba (see Fig S1 for location of biomes and Matopiba), for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S10. Upward (downward) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left). Note: only biomes with more than 1% of the national production in the noCC scenario in 2050 are included.

Table S10: Median (lower and upper quartile) change in sugar cane area and production in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil and main producing regions.

	RCP2.6		RCP8.5	
REGION	Area (%)	Production (%)	Area (%)	Production (%)
EPIC				
Brazil	-7.0 (-52.7; 35.8)	-1.1 (-49.7; 52.2)	5.4 (-38.1; 49.5)	1.4 (-38.5; 50.0)
Cerrado	20.7 (-39.1; 83.8)	31.5 (-37.5; 104.5)	66.2 (1.5; 134.2)	59.1 (-2.6; 126.9)
Atlantic Forest	-22.0 (-59.7; 8.4)	-22.2 (-57.1; 17.2)	-28.8 (-60.1; 1.0)	-36.7 (-61.9; -1.8)
São Paulo	17.5 (-30.0; 52.7)	28.6 (-23.5; 72.0)	-6.8 (-41.5; 47.1)	-15.8 (-47.4; 39.7)
Goiás	144.0 (31.2; 211.8)	222.3 (59.9; 324.0)	236.5 (141.7; 296.4)	282.4 (177.5; 359.1)
Minas Gerais	-37.5 (-64.9; 3.0)	-44.3 (-69.5; -0.5)	4.1 (-38.1; 51.0)	-8.8 (-46.7; 37.2)
LPJmL				
Brazil	-26.1 (-38.9; -10.2)	-7.8 (-33.0; 18.2)	-40.4 (-50.1; -28.2)	-9.6 (-32.6; 15.9)
Cerrado	-34.6 (-50.0; -9.6)	-17.5 (-42.9; 19.4)	-63.9 (-70.9; -48.4)	-44.1 (-60.5; -17.4)
Atlantic Forest	-21.6 (-32.4; -10.9)	-1.1 (-26.0; 17.8)	-27.4 (-38.0; -17.5)	13.1 (-13.9; 37.3)
São Paulo	-13.5 (-31.4; 9.8)	15.6 (-21.4; 59.2)	-31.9 (-43.4; -18.0)	11.0 (-21.9; 41.9)
Goiás	-63.8 (-83.8; -45.7)	-61.7 (-83.2; -43.0)	-93.8 (-96.1; -79.1)	-92.6 (-95.6; -77.9)
Minas Gerais	-28.0 (-37.1; -17.9)	-0.7 (-28.1; 13.0)	-42.9 (-53.5; -30.4)	-11.0 (-34.3; 13.1)

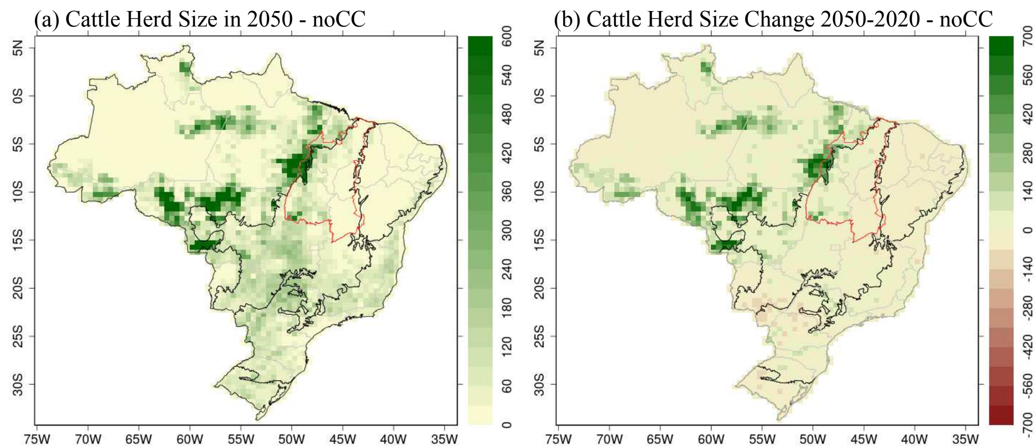

Figure S18: (a) Cattle herd size (in kLTU) in 2050 and (b) its evolution compared to 2020 for noCC scenario. In (b), increase (decrease) is represented in green (red) shades.

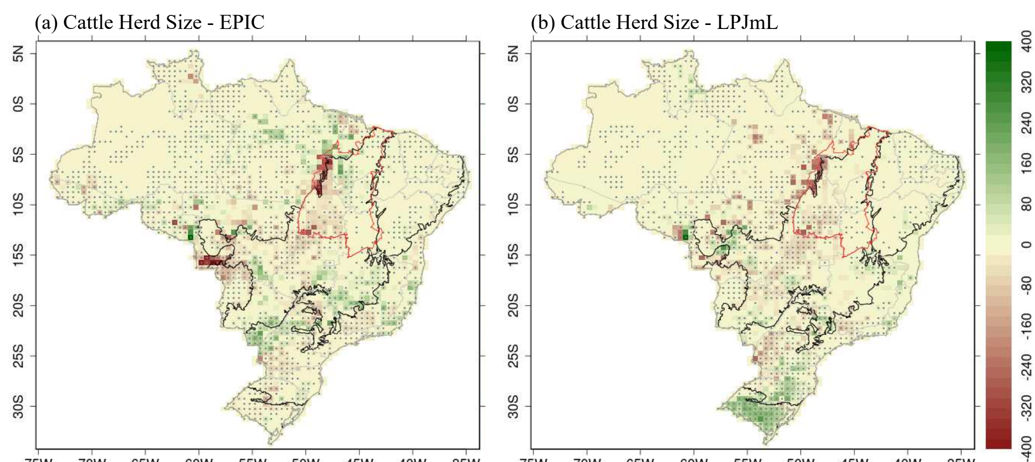

Figure S19: Median changes in cattle herd size (in kTLU) for (a) EPIC and (b) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Pixels where the difference between the median and the noCC scenarios are positive (negative) are shaded green (red); Stippled pixels indicate areas where the lower and upper quartiles have same sign.

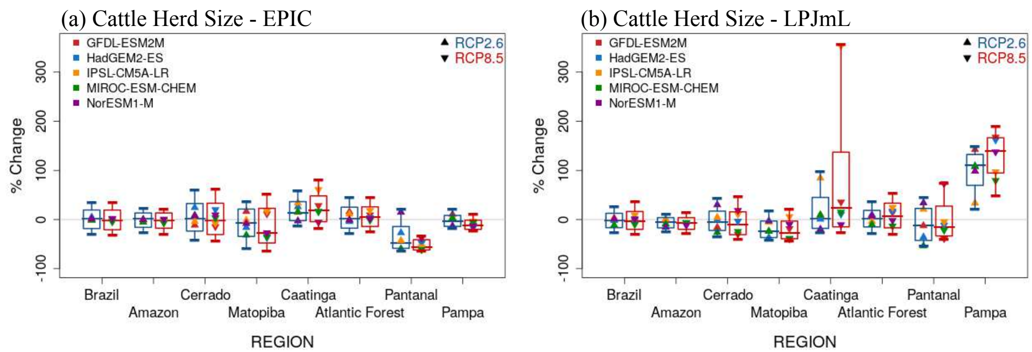

Figure S20: Percentage changes (compared to noCC in 2050) in cattle herd size aggregated over Brazil, main biomes, and Matopiba (see Fig S1 for location of biomes and Matopiba), for (a) EPIC and (b) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S11. Upper (lower) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left).

Table S11: Median (lower and upper quartile) change in cattle herd size in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil, main biomes, and Matopiba.

REGION	RCP2.6 Herd Size (%)	RCP8.5 Herd Size (%)
EPIC		
Brazil	0.2 (-18.4; 19.4)	-2.7 (-20.7; 19.3)
Amazon	1.0 (-15.9; 13.4)	-2.9 (-17.6; 13.5)
Cerrado	1.2 (-23.5; 32.6)	-3.0 (-30.5; 33.2)
Matopiba	-8.3 (-34.3; 21.4)	-27.4 (-47.7; 22.8)
Caatinga	12.0 (-2.3; 36.5)	17.4 (-4.2; 48.1)
Atlantic Forest	0.1 (-17.5; 25.1)	4.3 (-14.1; 25.9)
Pantanal	-48.3 (-58.6; -14.2)	-57.2 (-61.9; -41.1)
Pampa	-3.7 (-13.9; 8.4)	-13.0 (-19.9; -1.4)
LPJmL		
Brazil	-2.5 (-16.5; 12.7)	-3.8 (-19.9; 16.4)
Amazon	-5.8 (-16.9; 4.0)	-8.4 (-19.9; 3.9)
Cerrado	-6.0 (-22.2; 17.1)	-11.3 (-30.8; 15.8)
Matopiba	-23.9 (-36.6; -3.0)	-28.4 (-39.0; -3.2)
Caatinga	0.9 (-18.0; 45.0)	22.2 (-14.9; 137.1)
Atlantic Forest	1.4 (-15.0; 18.7)	5.7 (-16.8; 33.4)
Pantanal	-12.9 (-42.5; 22.6)	-16.0 (-33.4; 27.3)
Pampa	109.6 (69.6; 132.4)	138.7 (94.7; 166.4)

6.6. Trade

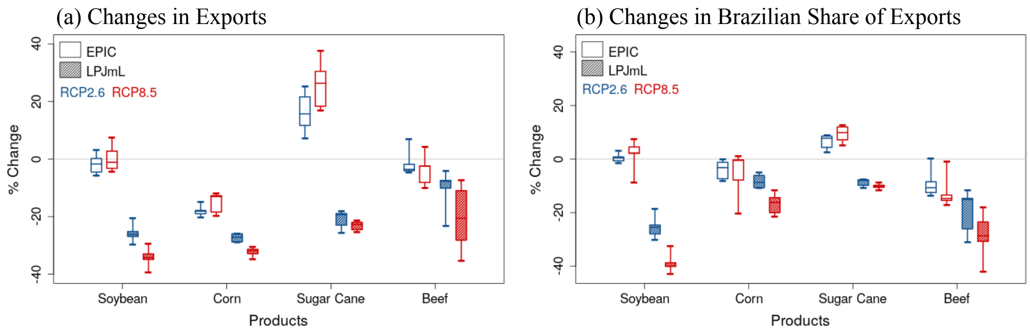

Figure S21: Percentage changes (compared to noCC in 2050) in Brazilian exports (a) and its share of the global exports (b) of soybean, corn, sugar cane, and beef, aggregated over Brazil for each GGCM and emission scenario. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table S12.

Table S12: Median (lower and upper quartile) change in Brazilian exports and in its share of the global exports of soybean, corn, sugar cane and beef, expressed as a percentage of the noCC scenario in 2050. Values aggregated for Brazil.

	RCP2.6		RCP8.5	
PRODUCT	Export (%)	Brazilian Share (%)	Export (%)	Brazilian Share (%)
EPIC				
Soybean	-1.7 (-4.5; 0.2)	0.4 (-0.7; 0.8)	-1.1 (-3.3; 2.8)	2.3 (2.1; 4.5)
Corn	-18.1 (-19.0; -17.9)	-3.2 (-7.4; -1.2)	-13.0 (-18.4; -12.7)	-0.5 (-7.9; -0.3)
Sugar Cane	15.7 (11.7; 21.6)	7.8 (4.4; 8.6)	26.3 (18.4; 30.5)	9.9 (7.2; 12.0)
Beef	-3.6 (-4.1; -1.8)	-10.7 (-12.5; -8.5)	-2.5 (-8.2; -2.4)	-14.7 (-15.4; -13.4)
LPJmL				
Soybean	-26.2 (-26.9; -25.2)	-25.5 (-28.0; -24.7)	-34.3 (-34.9; -33.0)	-40.0 (-40.1; -38.8)
Corn	-27.2 (-28.8; -26.0)	-8.7 (-10.7; -6.1)	-31.9 (-32.9; -31.4)	-16.2 (-20.0; -14.4)
Sugar Cane	-19.3 (-23.0; -18.9)	-8.0 (-9.8; -7.8)	-22.7 (-24.5; -22.0)	-10.2 (-10.5; -9.8)
Beef	-7.7 (-10.1; -7.4)	-15.1 (-26.1; -14.7)	-20.6 (-28.2; -11.0)	-28.6 (-30.7; -23.5)

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