Nature-based solutions are critical for putting Brazil on track towards net zero

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Supplementary Information

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GLOBIOM-Brazil model

The GLOBIOM-Brazil is a regional version of the GLobal BIosphere Management Model GLOBIOM [47] from International Institute for Applied System Analysis (IIASA) and has been developed at Brazil’s National Institute for Space Research (INPE), in collaboration with IIASA, since 2012 [32,33]. GLOBIOM-Brazil has been used to evaluate public and private policies, such as the trade-offs of the Forest Code [32] and the expansion of the soy moratorium to Brazil's

Cerrado [33], as well as the land use implications of various biofuels demands [48] and the climate change impacts on Brazilian agriculture [49]. GLOBIOM-Brazil has also provided science-based results to Brazil's intended nationally determined contribution (iNDC) [61].

More than 30 commodities are represented in GLOBIOM-Brazil, including 18 crops (such as soybeans, maize and sugarcane), meat and milk for five animal types, biofuels (such as sugarcane ethanol), and wood products (like sawnwood and pulpwood). The production is endogenously adjusted at the pixel level to meet the demand for food, feed, fibres and bioenergy of 30 different regions, including Brazil, interconnected through international trade. The production is determined by agricultural or forestry profitability, market prices, and costs, such as land conversion costs, internal transportation costs, production costs and trade costs. Since goods are assumed to be homogeneous, trade is based purely on cost competitiveness. The demands for all regions and products are endogenously calculated based on exogenous drivers such as gross domestic product (GDP), population growth and dietary trends. These drivers are derived from the Shared Socioeconomic Pathways (SSPs) [50] and we are using SSP2 for Brazil. The exogenous biofuels demand is based on the 2010 World Energy Outlook projections [62]. The demand for sugarcane ethanol in Brazil comes from the Energy Research Enterprise (EPE) projections of the Ministry of Mines and Energy (MME) [63].

Information on yield, harvesting costs and carbon stocks are also defined at the pixel level based on biophysical models. The model EPIC (Environmental Policy Integrated Climate) [64] is used to estimate potential crop yields for each crop and management system (subsistence, low-input rain-fed, high-input rain-fed, and high-input irrigated). A double cropping system for soy and maize was included in GLOBIOM-Brazil on the basis of standard EPIC runs for high-input systems to better capture the country's soybean dynamics [33]. The RUMINANT model [65,66] is used for bovines and small ruminant productivity and feed requirements. Eight livestock production systems for ruminants vary from grazing to humid to mixed arid. Final pasture productivity for Brazil for the year 2000 is based on the pasture area from the initial land cover map and official yearly surveys on livestock (PPM/IBGE) [67]. A semi-intensive cattle ranching production system is also implemented for Brazil through an increase in pasture yield, which is used to define the recovery of degraded pastures [52]. Harvesting costs and annual mean increments are defined by the forestry model G4M [68]. Productivity can endogenously increase in the model in response to market signals through shifts between management systems (e.g., from low to high input) or reallocation to more suitable areas. An exogenous yield increase due to technological progress such as breeding is also applied, and it is based on the economic growth projections given by the SSPs. Internal transportation costs in Brazil are defined at the pixel level for different products and different destinations (nearest state capital and nearest seaport) based on the national transport infrastructure plan [32].

GLOBIOM-Brazil optimises, at the pixel level, over six land use classes, including unmanaged native vegetation, pastures, croplands and nonproductive lands (see **Table S16**). A land use class for native vegetation restoration is available in GLOBIOM-Brazil [32]. The possible land use conversions and land conversion costs are defined by a matrix of endogenous land-use change [32]. Protected areas in Brazil are a subset of unmanaged native vegetation and take into account conservation units, indigenous territories and public forests amounting to, approximately, 243 million ha (Mha) [69]. Here, we have a conservative assumption where land-use changes are not allowed within protected areas. Although deforestation and degradation have recently exploded within protected areas, the amount of deforestation is small for the model resolution (e.g.: 0.09 Mha in 2021 [70]).

One of the most important input data for a model like GLOBIOM is the initial land cover/use map. In this study, we are using the Collection 4.1 of the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas), which has become a reference map for Brazil [28]. MapBiomas classes were mapped into GLOBIOM-Brazil classes for the year 2000 (see **Table S17**). In addition to MapBiomas data, statistics on crop area from the official yearly crop surveys (PAM/IBGE) [71] were also used because GLOBIOM-Brazil needs cropland information per crop type. Firstly, the crop areas from PAM/IBGE were allocated in each pixel, and the difference of this allocation to the "farming" class from MapBiomas was used to define the "pasture" class of GLOBIOM-Brazil. As a result, we have a consistent land cover/use initial map for Brazil based on MapBiomas collection 4.1.

Scenarios description

All scenarios are identical up to 2020 assuming different trajectories from 2021 onwards. Major differences among scenarios are related to the LULUCF and energy sectors. Our baseline (BASE) scenario tries to capture a weak environmental governance in Brazil. Regarding the LULUCF sector, under the BASE scenario there is an imperfect illegal deforestation control and no native vegetation restoration. As of September 2022, the Observatory of Restoration [72] accounted for only 0.08 Mha of native vegetation recovery due to restoration projects in the entire country, which supports our assumption on the absence of restoration under the BASE scenario. Regarding deforestation control, the BASE scenario projects, for example, annual deforestation rates of 1.06 Mha, on average, in the Brazilian Amazon between 2020 and 2030 (see **Table S3**), which is close to the latest estimates from PRODES (1.01 Mha in 2019, 1.08 Mha in 2020 and 1.3 Mha in 2021) [23]]. Conversely, our Forest Code (FC) scenario attempts to capture the full implementation of the key Brazil's Forest Code dispositions, including zero illegal deforestation, native vegetation restoration of environmental debts, environmental reserve quotas (CRA) and small farms amnesty.

Both BASE and the FC scenarios of this study are updates of the *IDCImperfect2* and the *FC* scenarios from Soterroni et al. [32]. The final native vegetation restoration target (approx. 13 Mha) is given by the total environmental debts of Legal Reserves (LR) and Areas of Permanent Preservation (APP) derived from the Rural Environmental Cadastre [73] with part of the LR debts compensated by the CRA mechanism [32]. Differently from the previous study [32], here (i) GLOBIOM-Brazil runs for 5-year time steps (instead of 10-year); (ii) double cropping system for soybeans and maize (no-till agriculture) is implemented into the model [33]; (iii) the Brazilian Soy Moratorium (a zero-deforestation agreement for soy) is effective from 2006 onwards regardless of the scenario [33]; (iv) the model version here uses the initial land use/cover map from MapBiomas Collection 4.1 [28]; and (v) the native vegetation restoration of the FC scenario follows the schedule defined in the National Plan for Restoration of Native Vegetation (PLANAVEG) [41], starting in 2021. According to PLANAVEG, restoration will start with 50 thousand hectares and will increase at a cumulative rate of 38.73% per year. Our FC+ scenario is built upon the FC but further eliminates legal deforestation and promotes approximately 35 Mha of native vegetation restoration from 2021 onwards. The FC+ restoration target is given by the FC target plus the amount of illegally deforested areas within small farms that received amnesty during the 2012 revision of the Forest Code (small farms amnesty) [73]. The LULUCF assumptions for the net zero scenarios BASENZ, FCNZ and FC+NZ follow the same assumptions from BASE, FC and FC+ scenarios, respectively. Agricultural practices follow the current trends regardless of the scenario, which include recovery of degraded pasture and expansion of non-till farming (double cropping soy-maize).

On the energy, IP and waste sectors, the assumptions were the same for the BASE, FC and FC+ scenarios. They comprise current energy policies, such as the current and contracted installed capacities for electric generation sources, refineries, distilleries, transmission and distribution assets of electric energy. It includes (i) the completion of the Angra 3 nuclear plant between 2025 and 2030, (ii) continuity of operation of the Jorge Lacerda coal-fired thermoelectric plant until 2040; (iii) the expansion of natural gas power plants; and (iv) implementation of mandatory blending of biodiesel at 20% (volumetric basis, B20) from 2028 onwards. These scenarios also account for international policies in place, such as the decarbonization goals of the International Maritime Organization (IMO) and the International Air Transport Association (IATA) with emission reduction targets of 50% in 2050, relative to 2008 and 2005 emissions, respectively. Carbon capture technologies are not considered under the BASE, FC and FC+ scenarios. Since there is no emission target, only the tendential technologies are chosen by the model. Conversely, for the BASE NZ, FCNZ and FC+NZ scenarios, the coal-fired and natural gas power plants from the previous scenarios are not forced into the model. Instead, it is allowed to use all its technological options, including CCS and BECCS, to reduce emissions and bridge the gap to net-zero GHG emissions in Brazil.

Validation of emissions for the historical period

Major historical trends of Brazilian land use, agricultural production and exports [32,33], and emissions from the agricultural and LULUCF sectors are captured by GLOBIOM-Brazil. According to the BASE scenario, from 2001 to 2015, Brazil's accumulated gross LULUCF emissions (16.44 gigatonnes of carbon dioxide equivalent ($GtCO_2e$)) are approximately 0.7% greater than the gross emissions from the Greenhouse Gas Emission and Removal Estimating System (SEEG) (16.55 $GtCO_2e$). They are also between the net (13.3 $GtCO_2e$) and the gross (21.5 $GtCO_2e$) emissions estimates from Brazil's 4th National Communication to the UNFCCC (4th NC) [40]. For the year 2015, the gross emissions from the LULUCF sector projected by the BASE scenario (0.98 $GtCO_2e$) are 14% greater than the gross LULUCF emissions from the 4th NC (0.86 $GtCO_2e$) and 21% greater than SEEG estimates (0.81 $GtCO_2e$) for the same year. Accumulated emissions from the agricultural sector as projected by GLOBIOM-Brazil under the BASE scenario amounts to 6.95 $GtCO_2e$ (GWP_{100};AR5) between 2001 and 2015, which are 8% smaller than the official estimates from the 4th NC (7.55 $GtCO_2e$) and 10% smaller than SEEG estimates (7.72 $GtCO_2e$) for the same period. When considering only emissions from enteric fermentation, GLOBIOM-Brazil estimates (5.28 $GtCO_2e$) are only 2% (5.38 $GtCO_2e$) and 1% (5.34 $GtCO_2e$) smaller than the 4th NC and SEEG estimates, respectively, for the period 2001-2015. For the year 2015, emissions from the agricultural sector (0.51 $GtCO_2e$) are 5% smaller than the official estimates from the 4th NC (0.54 $GtCO_2e$) and 7% smaller than SEEG estimates (0.55 $GtCO_2e$) for the same year. A comparison between the BASE scenario projections and official statistics for major indicators in land use, including agricultural area, production and exports can be found in **Figs. S10-S17**.

Energy, IP and waste emissions calculated by the BLUES model also reflect the major trends in Brazilian emissions. Within BLUES, the validation process comprises 2010, 2015 and 2020 projected emissions, and a linear interpolation between periods. Non-CO_2 emissions were converted to CO_2e by using GWP_{100} in AR5 IPCC. Accumulated total emissions for energy, IP and waste from 2010 to 2020 amounts to 6,822 million tonnes of carbon dioxide equivalent ($MtCO_2e$), or 2.9% greater than accumulated total emissions from SEEG (6,632 $MtCO_2e$). Emissions breakdown by sectors from 2010 to 2020 reveals a similar pattern. For the energy sector, accumulated emissions add up to 4,752 $MtCO_2e$, only 2,6% above SEEG emissions (4,631 $MtCO_2e$); IP emissions equal 1,116 $MtCO_2e$, or 1.6% greater than SEEG (1,098 $MtCO_2e$) and waste emissions total 953 $MtCO_2e$, or 5.7% greater than SEEG (902 $MtCO_2e$), for the same period. Looking specifically at 2015, total energy, IP and waste emissions totaled 670.6 $MtCO_2e$, or 4,6% greater than SEEG estimates (640.8 $MtCO_2e$). Energy emissions in 2015 were 477.3 $MtCO_2e$ according to BLUES, or 4.7% greater than SEEG (455.7 $MtCO_2e$). IP emissions from BLUES for 2015 were 104 $MtCO_2e$, or 1.9% greater than SEEG (102.1 $MtCO_2e$), whereas waste emissions were 89.3 $MtCO_2e$ in BLUES and 83.0 $MtCO_2e$ in SEEG, or 7.6% greater.

Legal and illegal deforestation in Brazil

The Native Vegetation Protection Law (No. 12,651/2012), also known as Forest Code, is a legislation that regulates land use within private properties in Brazil. It obliges landowners to protect an amount of native vegetation within their farms. The law dates back to 1965 and was majorly revised in 2012. Although this revision promoted the reduction of environmental protection [74], the Forest Code still has the potential to reconcile agricultural growth and preservation in Brazil [32]. Nonetheless, the effective implementation of this crucial law remains a major challenge. The Forest Code defines areas of permanent preservation (APPs) and areas of legal reserves (LRs). The APPs are sensitive areas for preservation such as springs, mountain slopes, mangroves and riparian areas. The LRs are portions of land that must be set aside to promote biodiversity conservation and provision of ecosystem services. The size of legal reserves depends on the property area and the biome it is located in, ranging from 80% in the Amazon to 20% in the Atlantic Forest. Currently, the huge majority of deforestation in Brazil does not have authorised clearings and, consequently, is illegal [70]. Illegal deforestation is happening in undesignated public lands, conservation units, indigenous territories and, also, in private properties. Nonetheless, native vegetation within private properties beyond the LR requirements (also known as LR surpluses) can be legally deforested. The area of LR surpluses that can be legally converted is estimated at 103 Mha (at maximum) in Brazil [75]. Under our FC scenario, 33 Mha of Brazil's native vegetation are likely to be legally deforested between 2020 and 2050, with 48% of it located in the Cerrado biome, 26% in the Caatinga biome and 8% in the Amazon biome (see **Fig. S2b**).

Brazil's NDC

According to the United Nations Framework Convention on Climate Change (UNFCCC) submission records, Brazil's first ratified Nationally Determined Contributions (NDC) is from September 2016 [17], the first NDC update is from December 2020 [16], and the second NDC update is from March 2022 [21]. In its first updated NDC from December 2020, Brazil kept the same emissions reduction targets from its first ratified NDC — 37% by 2025 and 43% by 2030 — but revised the 2005 emissions reference levels from 2,133 to 2,837.96 $MtCO_2e$ (GWP_{100}; IPCC AR5) following the estimates presented in the 3rd Brazil's National Communication to UNFCCC from 2016 [55]. By adjusting the reference emissions levels without recalculating its emissions reduction goals accordingly, Brazil increased its emissions reduction targets in absolute values, from 1,343.79 $MtCO_2e$ (2025) and 1,215.81 $MtCO_2e$ (2030) to 1,787.91 $MtCO_2e$ (2025) and 1,617.64 $GtCO_2e$ (2030), respectively, which allows the country to release 33% more GHG emissions relative to the previous NDC (see **Table S1**). This increase in GHG emission budget is against the non-regression and progression principles of the Paris Agreement [10,11]. The first updated NDC omitted the goals of ending illegal deforestation and restoring 12 million hectares of forest by 2030 as well as other specific policy targets per sector (see the annex of the first NDC from September 2016 [17]). It also proposed to achieve economy-wide climate neutrality (net-zero GHG emissions) by 2060; however, this indicative target was conditioned on a down payment of US$ 10 billion per year by other countries. A group of young activists, supported by eight former Environmental Ministers, filed a lawsuit against the current Brazilian government seeking an annulment of this updated NDC.

During COP26, Brazil announced further changes to its climate plan [19,20], which were formally submitted to the UNFCCC after the event [21]. The second updated NDC includes a revision of its GHG emissions reduction target by 2030 relative to 2005 levels, from 43% to 50%, a commitment to eliminating illegal deforestation by 2028 (two years earlier than previous pledges), and the anticipation of an unconditional net-zero GHG emissions target in one decade, from 2060 to 2050. However, in absolute numbers, the latest 2030 target is still above the respective goal from the first NDC (see **Table S1**). Moreover, Brazil's net zero pledge lacks interim targets, details on reporting mechanisms and clarity on use of carbon offsets. During COP26, Brazil also signed the Glasgow Forest Pledge (Glasgow Leader's Declaration on Forests and Land use) committing to ending deforestation by 2030. Conversely, after COP26, the official monitoring system PRODES [23] released a 15-year high (13,038 km^2) deforestation rate in the Brazilian Amazon. In 2021, Brazil has also signed the Global Methane Pledge during COP26, but the latest NDC does not include efforts to reduce methane emissions and does not make clear commitments per sector. Although the latest NDC is ambiguous on net-zero CO_2 or net-zero GHG emissions, an official supporting letter submitted to the UNFCCC is clear on net-zero GHG emissions target [19]. The latest NDC also does not specify the emissions reference levels for 2005 in absolute numbers, but states "Brazil will adopt the latest national inventory report available" [21]. For this study we are using the 4th Brazil's National Communication to UNFCCC to define the 2005 emissions reference levels and the carbon removals from native forests.

Land use sector

According to our baseline (BASE) scenario, Brazil's gross emissions are projected to remain quite flat around 2,041 $MtCO_2e$, on average, from 2020 to 2050 (see **Fig. S1** and **Table S4**). Emissions from the agricultural and energy sectors are expected to increase by 39% and 15%, respectively, whilst emissions from the LULUCF sector are likely to decline by 39% during this period (see **Table S4**). Deforestation is expected to continue up to 2050 but at lower annual rates after 2030 (see **Table S3**). The accumulated deforestation is expected to amount to 64 Mha in Brazil, between 2020 and 2050, under the BASE scenario (see **Fig. S2a** and **Fig. S3a**). The projected rise in the GHG emissions from the agricultural sector will be mainly driven by cattle herd growth that is likely to increase by 37% through the same period (see **Fig. S4a**). Methane from enteric fermentation will be responsible for 76% of the emissions from this sector by 2050.

Figure S3 shows the evolution of major land use classes in Brazil as projected by the various scenarios. Note that FC and FCNZ, and FC+ and FC+NZ, are very similar regarding the land use sector with major differences observed in the evolution of planted forests (afforestation) (see **Fig. S3f**). Under the net zero scenarios FCNZ and FC+NZ, planted forests are higher when compared to FC and FC+, respectively, due to demand increase for BECCS from the energy sector (see **Methods**). By 2050, net native vegetation (losses and gains) in Brazil would amount to 467 Mha under the BASE, 511 Mha under FC/FCNZ, and 565 Mha under FC+/FC+NZ scenarios, with native vegetation restoration amounting to nearly 13 Mha under the FC/FCNZ and to approximately 35 Mha under the FC+/FC+NZ scenarios. Although cropland increases between 2020 and 2050 regardless of the scenario, by 2050 it would be reduced by 4% under the FC/FCNZ and by 12% under the FC+/FCNZ, relative to the BASE scenario. Pasture areas would decrease by around 10% under the FC/FCNZ and by around 27% under the FC+/FC+NZ, relative to BASE, in Brazil by 2050. Deforestation control and large-scale restoration would not prevent the production expansion of major commodities (soy and beef) during the next 30 years despite reductions when compared to the BASE scenario (see **Fig. S4**). By 2050, cattle herd and beef production would decrease by around 9% under the FC/FCNZ, and by around 18% under the FC+/FC+NZ scenarios relative to the BASE (see **Fig. S4a** and **S4b**). Cattle productivity increase would be required in order to prevent further production losses. Between 2020 and 2050, cattle productivity is expected to increase by around 37% under the FC/FCNZ and by 52% under the FC+/FC+NZ at national level (see **Fig. S5**). The Amazon biome would require a greater cattle ranching intensification up to 61% during the same period. The future soybean production would decrease by less than 10% by 2050 as projected by the various scenarios relative to the BASE (3% under FC/FCNZ and 9% under FC+/FC+NZ) (see **Fig. S4c**). It is worth mentioning we do not account for climate change impacts on agricultural production in this study. Recent studies have shown that, under climate change scenarios, agricultural losses would be significant, especially if weak deforestation control continues in Brazil [76,77].

Limitations

Several limitations are expected when projecting emissions for complex sectors such as LULUCF, agriculture, energy, waste and industrial processes, and are mainly related to input model parameters. The GLOBIOM-Brazil model, for example, considers key national input data such as initial land use/cover map from MapBiomas [28], carbon content map from Brazil's official communications to the UNFCCC [55] and internal transportation costs [32]. It also considers national production, consumption and exports of major commodities to calibrate the model. Although simplifications of reality, our models present a good match between projections and official statistics during the historical period (see **Validation**), which gives confidence in our future emissions projections for Brazil. One major limitation is related to net emissions estimates. To estimate net emissions we account for carbon removals by native forests following Brazil's communications to the UNFCCC. By using a conservative assumption of fixed carbon removals during the period 2020-2050, we might be underestimating the role of these removals in decreasing gross emissions over time. On the other hand, according to SEEG, from 2000 to 2020, around 65% of the annual carbon removals by native vegetation were from protected areas [24], which are mostly undisturbed primary forests. It is worth mentioning that removals from primary forests are widely debated, and various studies have indicated that those fluxes are overestimated or should be close to zero at a steady state level [78-83]. Additionally, illegal deforestation and illegal mining have recently exploded within protected areas that were supposed to be managed (or protected) to be aligned with the IPCC offsetting guidelines.

On the economic costs, our opportunity costs are considering only major commodities, which masks the costs of foregone production of other products. However, our costs are always relative to the baseline and it assumes the other commodities will have similar trends under different scenarios. We do not account for socio-economic issues that might affect restoration, however the areas restored within our model are environmental debts as defined by Brazil's Forest Code (i.e., illegally deforested areas in APPs and LRs) or are illegally deforested areas that recently received an amnesty by the government (small farms amnesty). In the agricultural sector, we did not consider all mitigation strategies comprehended in the Brazil's Low Carbon Agricultural program (ABC Plan) but afforestation and recovery of degraded pastures, which are expected to contribute to almost 60% of the total mitigation potential under the second phase of the plan (ABC+ Plan) [84]. Nonetheless, the expected mitigation potential of the ABC+ Plan (1,076 $MtCO_2e$ between 2020 and 2030 [84]) corresponds to almost two years of current (2020) emissions from the agricultural sector [24]. The current trends point to a limited contribution of the agricultural sector in decreasing emissions in Brazil. Moreover, the ABC/ABC+ plan falls short in its funding capacity. The 2023 Brazil's Agricultural Plan (Plano Safra) has less than 2% of all rural credits available for the ABC/ABC+ Plan. We expect that the additional mitigation potential from the agricultural sector not accounted for in our estimates will directly reduce the need of costly negative emissions technologies from the energy sector, especially in the FCNZ scenario.

The lack of solution (infeasibility) under the BASE NZ scenario also points to our limitation in estimating the missing gap to net-zero GHG emissions under this scenario. Some sensitivity analysis on economic and population growth, and behavioural changes would lead to a different energy demand scenario. Additionally, studies including faster deployment of specific technologies would result in an earlier market penetration. These analyses could be used to both calculate impacts on the system cost and show what would be necessary to provide a feasible BASE NZ scenario. It would probably require a degrowth economy, or it could be even more costly than the FCNZ and FC+NZ scenarios.

Supplementary Tables

Table S1: NDC targets in $MtCO_2e$ using GWP_{100} in IPCC AR5.

NDC submission	2005 emissions level	NDC Target			Source
		2025 (37%)	2030 (43%)	2030 (50%)	
1st NDC (2015)	2,133.00	1,343.79	1,215.81	-	2nd National Communication [85]
1st Updated NDC (Dec. 2020)	2,837.96	1,787.91	1,617.64	-	3rd National Communication [55]
2nd Updated NDC (Apr. 2022)	2,562.28	1,614.24	1,460.50	1,281.14	4th National Communication [40]
1st Updated NDC relative to 1st NDC	704.96 (+33%)	444.12 (+33%)	401.83 (+33%)	-	-
2nd Updated NDC relative to 1st NDC	429.28 (+20%)	270.45 (20%)	244.69 (+20%)	65.33 (+5%)	-

*NC = National Communication.

Table S2: Brazil's official estimates regarding CO_2 removals from the LULUCF sector. Official net emissions for the reference year 2005 are also indicated. Values are in $MtCO_2e$ using GWP_{100} in IPCC AR5 (or in SAR when indicated). Abbreviation: NC = National Communication to the UNFCCC.

Official Estimates (publication year)	Net emissions in 2005	CO_2 removals (last available year/period)	GHG Emissions Inventory (publication year)
1st Estimate (2013) [86]	2,032.26 (SAR)	-317.17 (2010)	2nd Inventory (2010) [85]
2nd Estimate (2014) [87]	2,042.99 (SAR)	-317.24 (2012)	2nd Inventory (2010) [85]
3rd Estimate (2016) [88]	2,735.89 (SAR)	-774.72 (2014)	3rd Inventory (2016) [55]
4th Estimate (2017) [89]	2,738.00 (SAR)	-774.71 (2015)	3rd Inventory (2016) [55]
5th Estimate (2020) [90]	2,448.93	-655.92 (2016)	3rd Inventory (2016) [55]
3rd NC (2016) [55]	2,837.96	-747.90 (2002-2010)	3rd Inventory (2016) [55]
4th NC (2020) [40]	2,562.28	-521.83 (2010-2016)	4th Inventory (2020) [40]

Table S3: Accumulated native vegetation loss in Brazil and major biomes, from 2020 to 2030 (one decade), from 2030 to 2050 (two decades) and from 2020 to 2050 (three decades) as projected by the various scenarios. Brackets show the average annual deforestation rates per period. The FC+ and FC+NZ scenarios do not project any deforestation between 2020 and 2050. Values are in million hectares (Mha).

Scenarios	2020-2030		2030-2050		2020-2050	
	BASE	FC or FCNZ	BASE	FC or FCNZ	BASE	FC or FCNZ
Brazil	29.17 (2.92)	16.1 (1.61)	34.83 (1.74)	16.86 (0.84)	64.0 (2.13)	33.01 (1.10)
Amazon	10.59 (1.06)	2.10 (0.21)	13.67 (0.69)	0.70 (0.03)	24.26 (0.81)	2.80 (0.09)
Cerrado	12.88 (1.29)	7.81 (0.78)	12.30 (0.62)	8.04 (0.40)	25.18 (0.84)	15.85 (0.53)

Table S4: Emissions for all sectors as projected by the BASE scenario. Estimates for the LULUCF and Agricultural sectors are from GLOBIOM-Brazil, and estimates for the Energy, Industrial Processes (IP) and Waste sectors are from BLUES. C removals are derived from the latest Brazil's emissions inventory [40]. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Positive emissions	LULUCF	786.42	870.31	793.26	643.36	586	547.43	502.56
	Agriculture	556.27	603.01	652.9	686.49	719.37	753.31	772.61
	Energy	384.30	386.87	408.05	439.56	458.41	454.23	442.59
	IP	96.43	110.61	122.33	124.42	147.34	159.0	170.57
	Waste	89.81	109.97	123.06	129.76	144.35	153.49	158.60
Negative emissions	C removals	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83
	Afforestation	-53.96	-59.13	-59.96	-63.93	-54.04	-53.21	-53.24
	Restoration	0	0	0	0	0	0	0
Gross emissions		1913.23	2080.77	2099.60	2023.59	2055.47	2067.46	2046.93
Net emissions		1337.44	1499.81	1517.81	1437.83	1479.6	1492.42	1471.86

Table S5: Emissions for all sectors as projected by the FC scenario. Estimates for the LULUCF and Agricultural sectors are from GLOBIOM-Brazil, and estimates for the Energy, Industrial Processes (IP) and Waste sectors are from BLUES. C removals are derived from the latest Brazil's emissions inventory [40]. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Positive emissions	LULUCF	786.42	367.32	337.99	235.16	163.99	150.64	116.86
	Agriculture	556.27	594.76	639.17	656.19	678.60	699.16	709.99
	Energy	384.30	386.87	408.05	439.56	458.41	454.23	442.59
	IP	96.43	110.61	122.33	124.42	147.34	159.0	170.57
	Waste	89.81	109.97	123.06	129.76	144.35	153.49	158.60
Negative emissions	C removals	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83
	Afforestation	-53.96	-58.35	-58.84	-60.02	-54.89	-57.27	-56.92
	Restoration	0	-5.42	-36.16	-138.85	-118.36	-105.72	-98.04
Gross emissions		1913.23	1569.53	1630.60	1585.09	1592.69	1616.52	1598.61
Net emissions		1337.44	983.93	1013.77	864.39	897.61	931.70	921.82

Table S6: Emissions for all sectors as projected by the FC+ scenario. Estimates for the LULUCF and Agricultural sectors are from GLOBIOM-Brazil, and estimates for the Energy, Industrial Processes (IP) and Waste sectors are from BLUES. C removals are derived from the latest Brazil's emissions inventory [40]. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	2020	2025	2030	2035	2040	2045	2050
Positive emissions	LULUCF	786.42	46.81	88.50	66.03	57.62	37.78	39.92
	Agriculture	556.27	585.29	624.82	632.19	626.78	641.44	643.00
	Energy	384.30	386.87	408.05	439.56	458.41	454.23	442.59
	IP	96.43	110.61	122.33	124.42	147.34	159.0	170.57
	Waste	89.81	109.97	123.06	129.76	144.35	153.49	158.60
Negative emissions	C removals	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83
	Afforestation	-53.96	-61.56	-61.80	-63.90	-55.74	-55.12	-56.98
	Restoration	0	-4.74	-33.65	-187.78	-359.64	-289.80	-261.97
Gross emissions		1913.23	1239.55	1366.76	1391.96	1434.50	1445.94	1454.68
Net emissions		1337.44	651.41	749.48	618.45	497.29	579.19	613.90

Table S7: Emissions for all sectors as projected by the FCNZ scenario. Estimates for the LULUCF and Agricultural sectors are from GLOBIOM-Brazil, and estimates for the Energy, Industrial Processes (IP) and Waste sectors are from BLUES. C removals are derived from the latest Brazil's emissions inventory [40]. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Positive emissions	LULUCF	786.42	367.32	337.99	235.16	164.00	159.25	103.72
	Agriculture	556.27	594.76	639.17	656.19	678.37	697.84	706.07
	Energy	384.30	395.17	420.94	438.91	377.64	286.94	228.84
	IP	96.43	110.60	121.17	121.16	117.53	109.89	115.38
	Waste	89.81	109.77	119.08	115.67	87.53	67.64	69.78
Negative emissions	C removals	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83
	Afforestation	-53.96	-58.35	-58.84	-60.02	-71.04	-131.37	-230.68
	Restoration	0	-5.42	-36.16	-138.85	-118.36	-105.72	-98.04
	Energy	0	-0.46	-1.61	-13.55	-73.23	-242.16	-372.93
Gross emissions		1913.23	1577.62	1638.35	1567.09	1425.07	1321.56	1223.79
Net emissions		1337.44	991.56	1019.91	832.84	640.61	320.48	0.31

Table S8: Emissions for all sectors as projected by the FC+NZ scenario. Estimates for the LULUCF and Agricultural sectors are from GLOBIOM-Brazil, and estimates for the Energy, Industrial Processes (IP) and Waste sectors are from BLUES. C removals are derived from the latest Brazil's emissions inventory [40]. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	2020	2025	2030	2035	2040	2045	2050
Positive emissions	LULUCF	786.42	46.81	88.50	66.03	56.52	39.09	36.01
	Agriculture	556.27	585.29	624.82	632.19	626.75	639.95	637.34
	Energy	384.3	397.21	422.98	462.24	466.68	384.33	290.50
	IP	96.43	110.6	121.2	121.2	127.0	123.6	115.4
	Waste	89.81	110.0	120.5	117.2	115.1	110.8	71.3
Negative emissions	C removals	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83	-521.83
	Afforestation	-53.96	-61.56	-61.80	-63.90	-67.80	-79.50	-158.24
	Restoration	0	-4.74	-33.65	-187.78	-359.28	-285.52	-266.41
	Energy	0	-0.49	-0.87	-5.56	-12.82	-90.58	-203.92
Gross emissions		1913.23	1249.91	1378.00	1398.86	1392.05	1297.77	1150.55
Net emissions		1337.44	661.29	759.85	619.79	430.32	320.34	0.15

Table S9: Brazil's cumulative GHG emissions per sector as projected by the various scenarios during the period 2020-2050. Values are in $MtCO_2e$ using GWP_{100} in AR5.

	Source	BASE	FC	FC+	FCNZ	FC+NZ
LULUCF (net)		2,342	-13,039	-21,436	-14,383	-22,141
Positive		19,715	6,860	1,683	6,837	1,665
Negative		-17,373	-19,899	-23,119	-21,220	-23,806
C removals		-15,655	-15,655	-15,655	-15,655	-15,655
Restoration		0	-2,513	-5,688	-2,513	-5,687
Afforestation		-1,718	-1,731	-1,776	-3,052	-2,464
Agriculture		20,938	19,889	18,768	19,862	18,732
Energy (net)		12,949	12,949	12,949	7,222	10,549
Positive		12,949	12,949	12,949	10,742	12,120
Negative		0	0	0	-3,520	-1,571
Industrial processes		4,171	4,171	4,171	3,479	3,595
Waste		4,096	4,096	4,096	2,847	3,225
GHG Emissions (total)	Positive	61,869	47,965	41,667	43,767	39,337
	Negative	-17,373	-19,899	-23,119	-24,740	-25,377
	Net	44,496	28,066	18,548	19,027	13,960

Table S10: Additional cumulative and annualised costs as projected by the FCNZ and FC+NZ scenarios relative to BASE between 2020 and 2050. Values are in billion $US\$_{2019}$ (US$1 = R$4.03) and adjusted to present values for the analysed period using a discount rate of 5%. Restoration costs are mean values among different techniques and restoration scenarios from PLANAVEG.

Sector	Cumulative investments		Annualised investments	
	FCNZ	FC+NZ	FCNZ	FC+NZ
Energy	223.84	94.78	14.6	6.2
Land use	17.85	49.05	1.16	3.19
Opportunity costs	9.25	29.23	0.60	1.90
Restoration costs	8.60	19.82	0.56	1.29

Table S11: CO_2 and non-CO_2 emissions calculated in GLOBIOM-Brazil.

Sector	Source	GHG	Reference	Tier
LULUCF	Native vegetation conversion and deforestation	CO_2	Carbon in above and below ground living biomass downscaled at 0.5 degree from 3rd Emissions Inventory Biomass Map [55]	2
	Carbon uptake*	CO_2	Growth curves for Brazil's six biomes as described in Soterroni et al. [32] and based on [54,68,91]	2
	Other land conversion	CO_2	Ruesch and Gibbs (2008) [92]	1
Crops	Synthetic fertilisers	N_2O	EPIC [64] runs output/IFA + IPCC EF	1
	Organic fertilisers	N_2O	RUMINANT model [65]	2
	Rice methane	CH_4	Average value per hectare from FAO	1
Livestock	Enteric fermentation	CH_4	RUMINANT model [65]	3
	Manure management	N_2O CH_4	RUMINANT model [65]	2
	Manure dropped/applied to pastures/cropland	N_2O	RUMINANT model [65]	2

* Emissions considered only in the scenarios with native vegetation restoration.

Table S12: Average restoration costs of different techniques per biome as defined in [58]. Total planting costs are given by the simple average between seedling and direct planting costs. For Cerrado, the final costs are 30% from forest and 70% from savanna restoration costs. Values are in US$$_{2019}$ per hectare (US$ 1.00 = R$4.03).

Years	Total planting (seedling and direct planting)	Enrichment planting	Assisted Natural regeneration	Natural regeneration
Amazon	1,361.92	981.97	461.77	50.49
Cerrado	2,652.81	370.80	427.80	50.49
Atlantic Forest	2,189.77	1,178.58	115.81	52.10
Caatinga, Pantanal and Pampa	2,125.66	821.12	358.30	50.89

Table S13: Average restoration costs of different techniques weighted by PLANAVEG scenarios (high, moderate, low and very low) [41] based on average costs from [58]. For Cerrado, the final costs are 30% from forest and 70% from savanna restoration costs. 'Mean' column represents the mean values over all scenarios. Values are in US$$_{2019}$ per hectare (US$ 1.00 = R$4.03).

Years	High	Moderate	Low	Very Low	Mean
Amazon	840.48	776.48	712.47	648.47	744.48
Cerrado	1,421.41	1,196.06	970.71	745.36	1,083.39
Atlantic Forest	1,239.95	1,085.7	931.44	777.18	1,008.57
Caatinga, Pantanal and Pampa	1196.04	1042.44	888.85	735.25	965.65

Table S14: Native vegetation restoration increment per biome as projected by the FCNZ scenario following the PLANAVEG schedule from 2021 onwards. Values are in million hectares (Mha).

Years	Amazon	Cerrado	Caatinga	Atlantic Forest	Pantanal	Pampa	Brazil
2021-2025	0.10	0.12	0.11	0.21	0	0	0.54
2026-2030	0.30	1.14	0.61	0.95	0.02	0.09	3.11
2031-2035	2.28	1.86	0.23	3.72	0.04	0.36	8.49
2036-2040	0.20	0.04	0	0.06	0	0	0.30
2041-2045	0.13	0.02	0	0.15	0	0	0.30
2046-2050	0.01	0.01	0	0.03	0	0	0.05
2021-2050	3.02	0.95	3.19	5.12	0.06	0.45	12.79

Table S15: Native vegetation restoration increment per biome as projected by the FC+NZ scenario following the PLANAVEG schedule from 2021 onwards. Values are in million hectares (Mha).

Years	Amazon	Cerrado	Caatinga	Atlantic Forest	Pantanal	Pampa	Brazil
2021-2025	0.10	0.13	0.12	0.18	0	0	0.53
2026-2030	0.16	1.38	0.63	0.78	0.01	0.02	2.98
2031-2035	1.35	4.40	1.36	7.24	0.02	0.15	14.52
2036-2040	6.30	2.49	0.09	4.78	0.08	0.88	14.62
2041-2045	0.60	0.13	0	0.09	0	0.03	0.85
2046-2050	0.58	0.09	0	0.61	0	0	1.28
2021-2050	9.09	8.62	2.20	5.12	0.06	0.45	34.78

Table S16: Short description of GLOBIOM-Brazil land use classes.

Land use classes	**Description**
Native vegetation (unmanaged)	Unmanaged forests and native vegetation ranging from rainforest in the north to natural grassland in the south.
Planted forest	Short-rotation plantations such as pinus and eucalyptus.
Managed forest	Forests that are exploited in a sustainable way.
Pasture	Areas used for livestock ranching.
Cropland	Planted areas regarding the 18 GLOBIOM crops: barley, dry beans, cassava, chickpeas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, sorghum, soya, sugarcane, sunflower, sweet potatoes, wheat, and oil palm.
Non-productive land	Mosaic of natural vegetation and areas previously converted from agriculture but not currently under production.
Other agricultural land	Planted areas regarding the crops not modelled by GLOBIOM-Brazil such as coffee, cocoa and orange.
Wetland	Areas with permanent water cover, or areas that are regularly flooded.
Not related lands	Bare areas, water bodies, snow and ice.
Restoration	Native vegetation restoration due to obligatory environmental debts payment (APP and LR) of the Forest Code.

Table S17: Mapping between MapBiomas and GLOBIOM-Brazil land cover classes.

MapBiomas classes (Collection 4.1)	**GLOBIOM-Brasil land cover/use classes**
1. Forest	
1.1 *Natural Forest*	Native Vegetation
1.2 *Planted Forest*	Planted Forest
2. Non Forest Natural Formation	
2.1 *Wetland*	Native Vegetation
2.2 *Grassland*	Native Vegetation
2.3 *Salt Flat*	Native Vegetation
2.4 *Rocky Outcrop*	Not related lands
2.5 *Other Non Forest Natural Formation*	Native Vegetation
3. Farming	Cropland, Other agricultural land and Pasture
4. Non vegetated area	
4.1 *Beach and Dune*	Not related land
4.2 *Urban Infrastructure*	Not related land
4.3 *Mining*	Not related land
4.4 *Other Non vegetated Area*	Non-productive land
5. Water	Wetlands
6. Non Observed	Not related land
7. Non identified	Not related land

Supplementary Figures

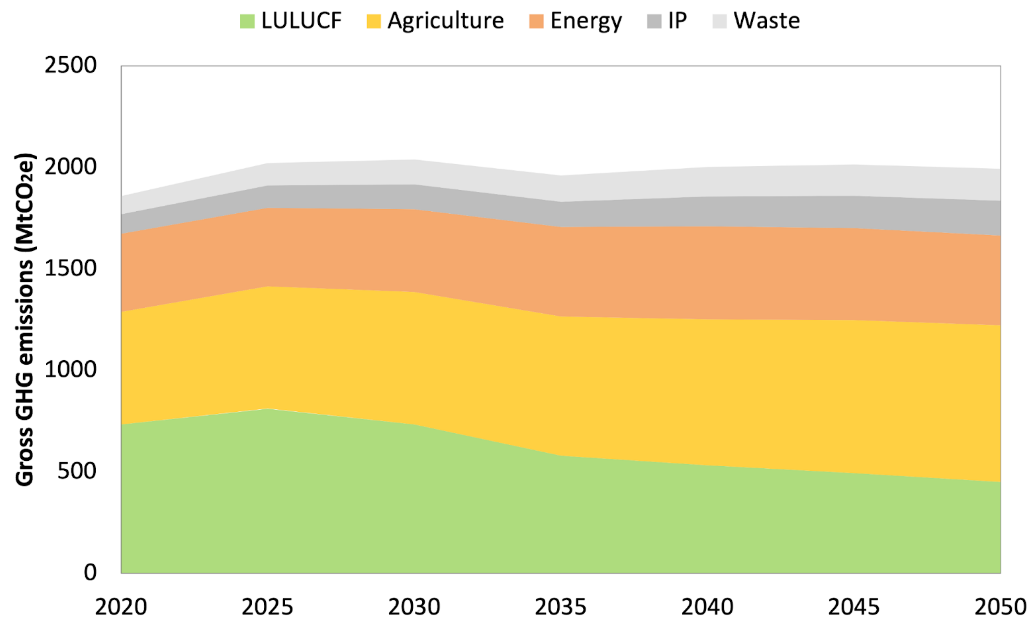

Figure S1: Brazil's future gross emissions (period 2020-2050) for all sectors as projected by the BASE scenario. Values are in million tonnes of carbon dioxide equivalent ($MtCO_2e$) using GWP_{100} and IPCC AR5.

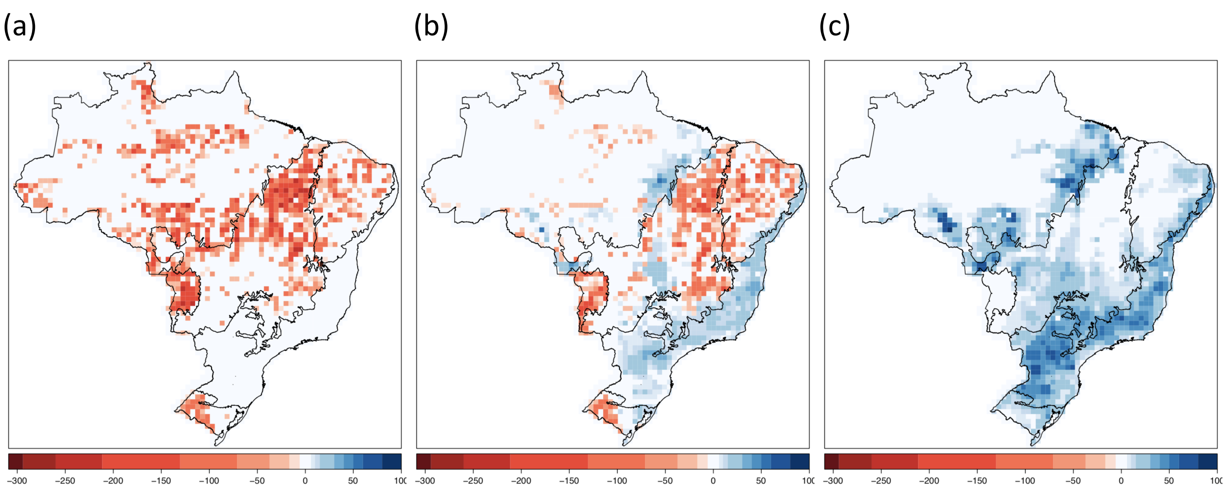

Figure S2: Spatial distribution of cumulative native vegetation loss or deforestation (red) and cumulative native vegetation restoration (blue) as projected by the scenarios (a) BASE, (b) FCNZ, and (c) FC+NZ, between 2020 and 2050. Colour bar values are expressed in thousands of hectares per cell.

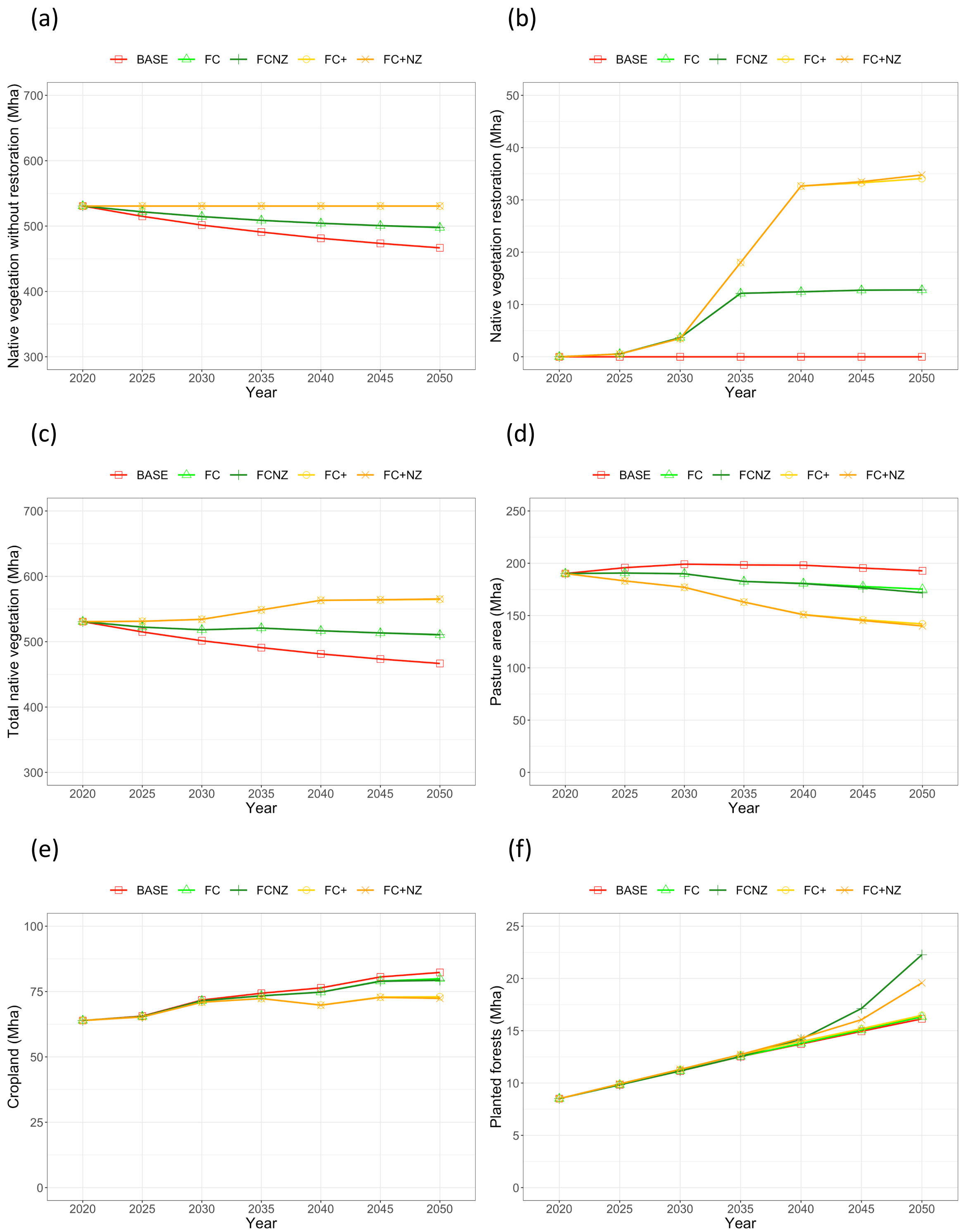

Figure S3: Evolution of major land-use classes at national level including (a) Native Vegetation without restoration, (b) Restoration, (c) Total Native Vegetation, (d) Pasture, (e) Cropland and (f) Planted Forest (or afforestation) as projected by the scenarios BASE, FC, FCNZ, FC+ and FC+NZ, between 2020 and 2050. Values are in million hectares (Mha).

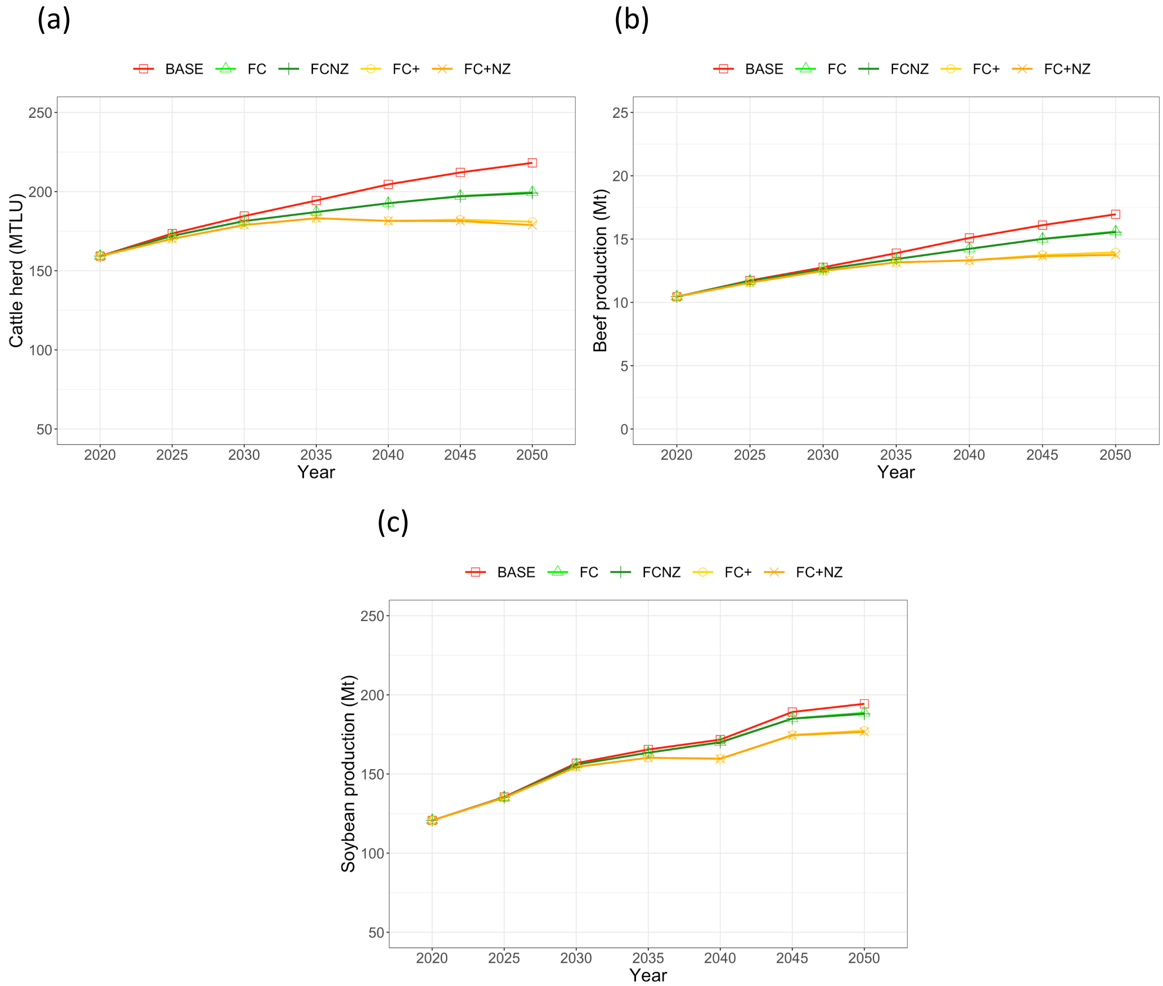

Figure S4: Evolution of (a) cattle herd, (b) beef production and (c) soy production, between 2020 and 2050, as projected by the various scenarios. Soy and beef production values are in million tonnes (Mt). Cattle herd values are in million tropical livestock units (MTLU) [1 TLU corresponds to 0.7 bovine].

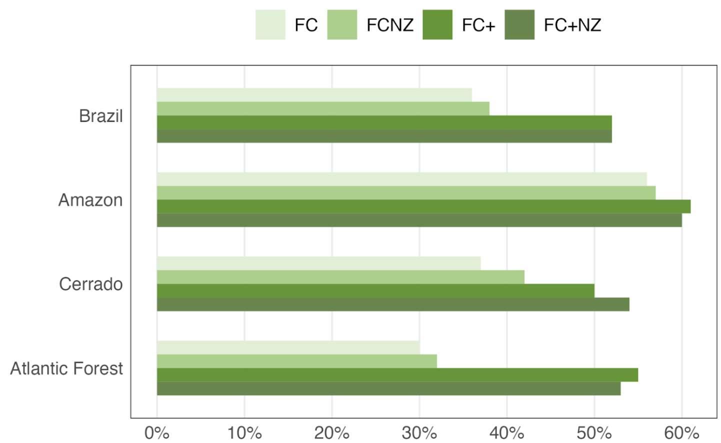

Figure S5: Cattle herd intensification between 2020 and 2050 as projected by the FC, FCNZ, FC+ and FC+NZ scenarios in Brazil and major biomes.

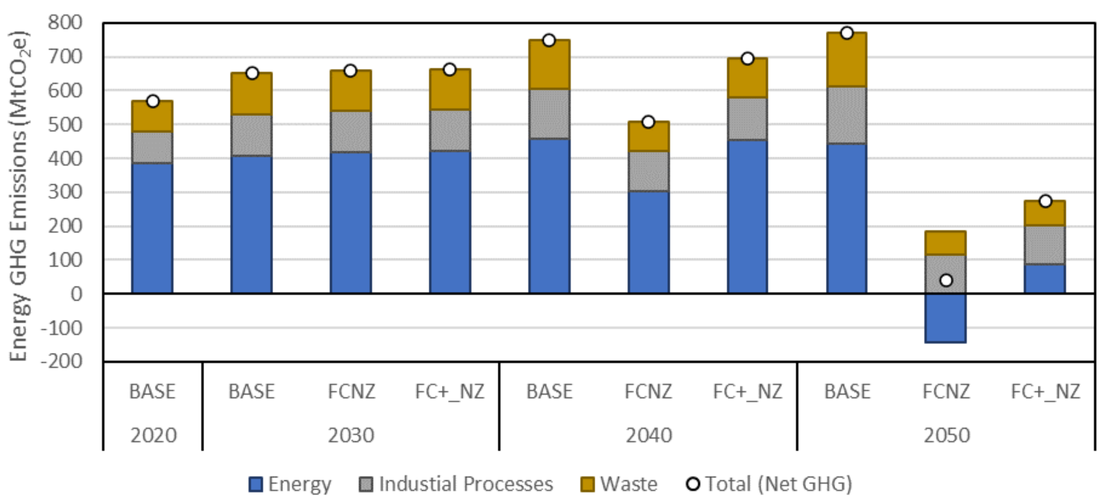

Figure S6: GHG emissions for energy, industrial processes and waste for the BASE, FCNZ and FC+NZ scenarios, in million tonnes of CO_2 equivalent ($MtCO_2e$), during the period 2020-2050.

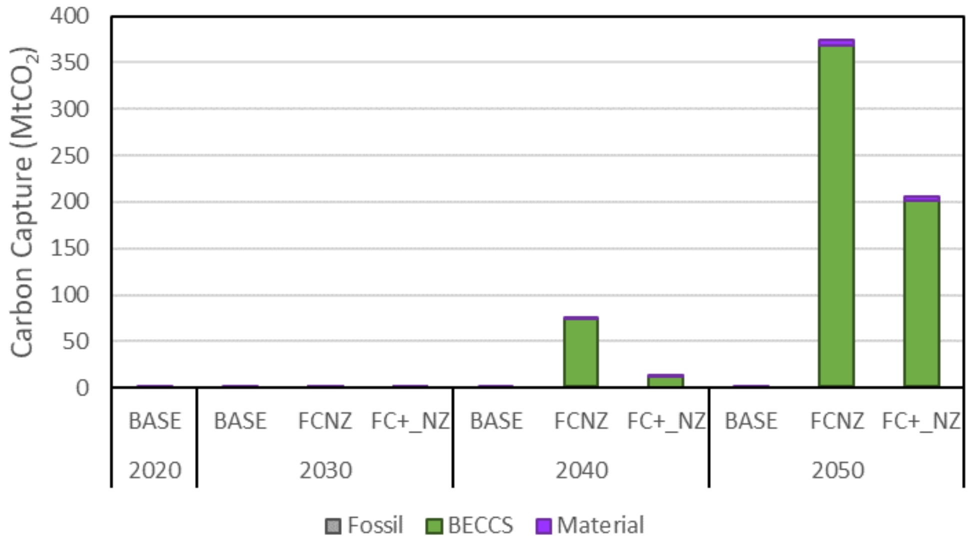

Figure S7: Carbon captured by fossil sources, bioenergy and materials for the BASE, FCNZ and FC+NZ scenarios, in million tonnes of CO_2 equivalent ($MtCO_2e$), during the period 2020-2050. Bioenergy with carbon capture and storage (BECCS) would mostly come from the production of cellulosic biofuels, such as green kerosene and green diesel, in both FCNZ and FC+NZ scenarios, and also from electricity generation with sugarcane bagasse. Within the energy sector, from 65% (FC+NZ) to 80% (FCNZ) of emissions reductions are due the deployment and use of BECCS.

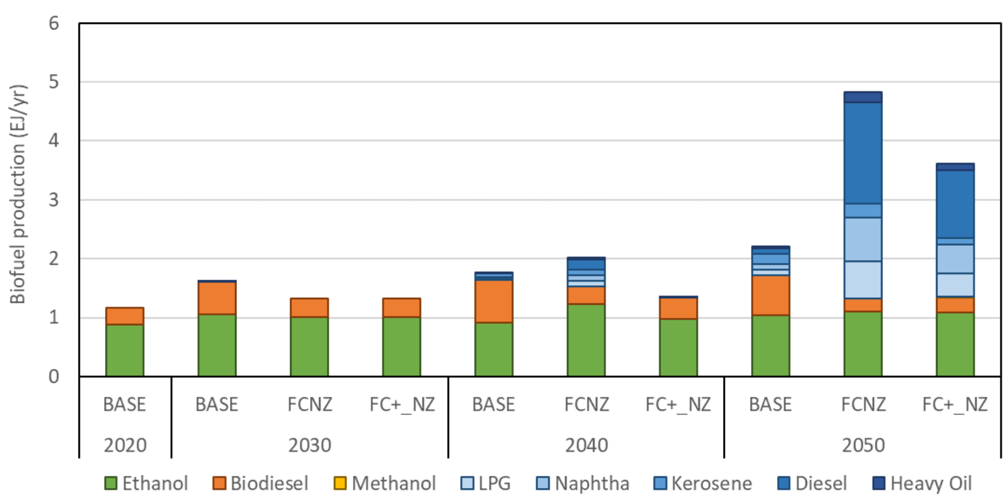

Figure S8: Biofuel production (period 2020-2050) per type for BASE, FCNZ and FC+NZ scenarios, in PJ/year. In blue, the participation of cellulosic biofuels and feedstock increases to mainly decarbonize the transport sector. They can be used as drop-in fuels at cars, buses, aeroplanes and ships. Green naphtha can be used to decarbonize the petrochemical industry.

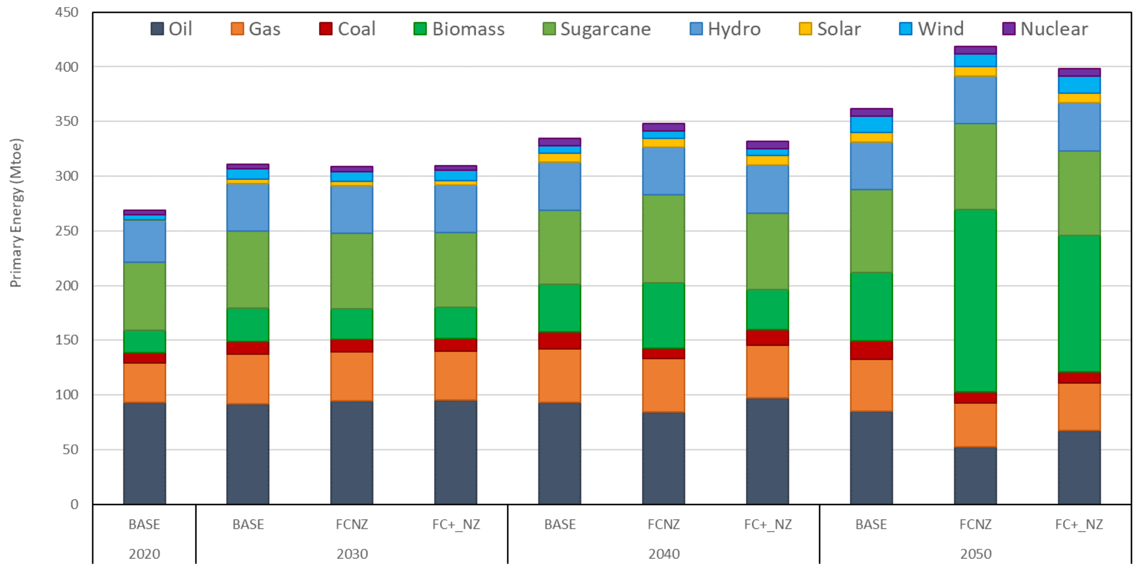

Figure S9: Primary energy per source for the BASE, FCNZ and FC+NZ scenarios, in million tonnes of equivalent oil (Mtoe), during the period 2020-2050. Biomass increase is justified due to its use in the production of cellulosic biofuels and in the electric generation.

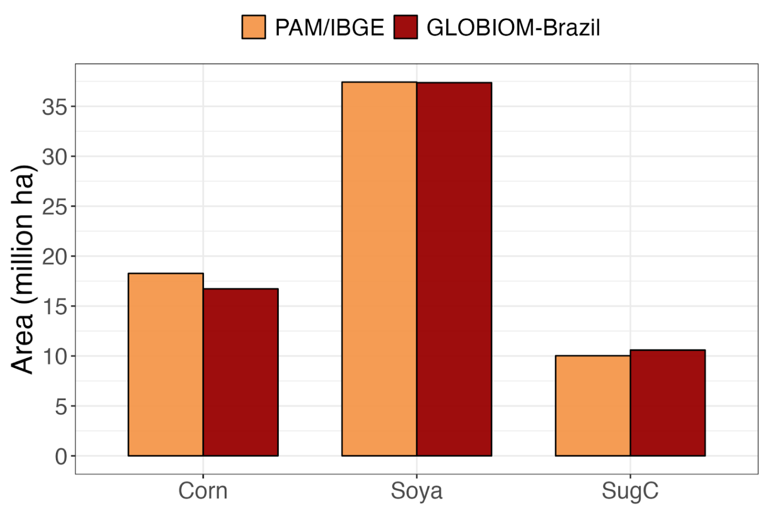

Figure S10: Comparison of major crop areas between GLOBIOM-Brazil (BASE scenario) and PAM/IBGE for the year 2020. PAM/IBGE numbers are 2019-2021 average [71].

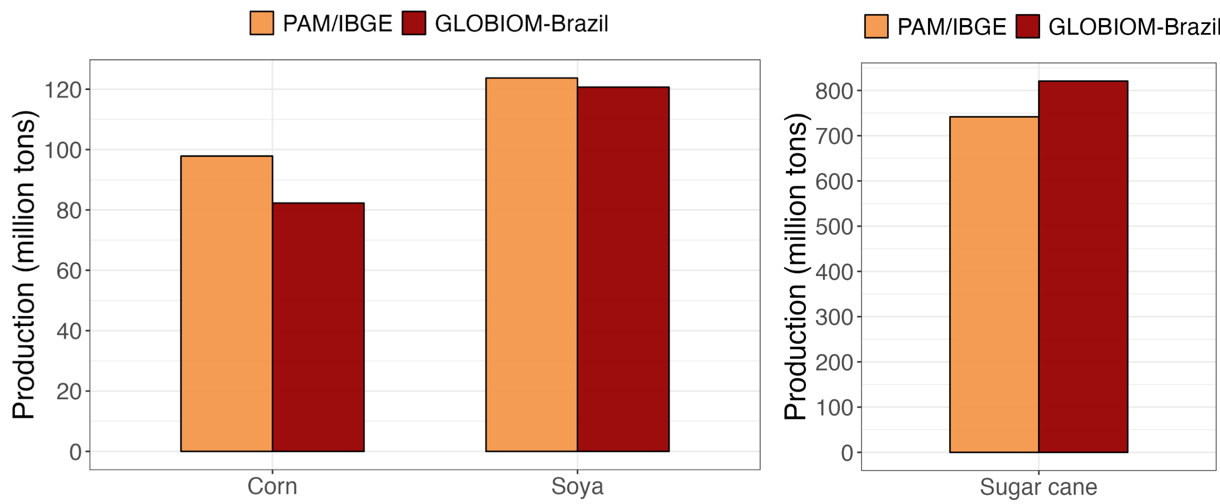

Figure S11: Comparison of production of major crops between GLOBIOM-Brazil (BASE scenario) and PAM/IBGE for the year 2020. PAM/IBGE numbers are 2019-2021 average [71].

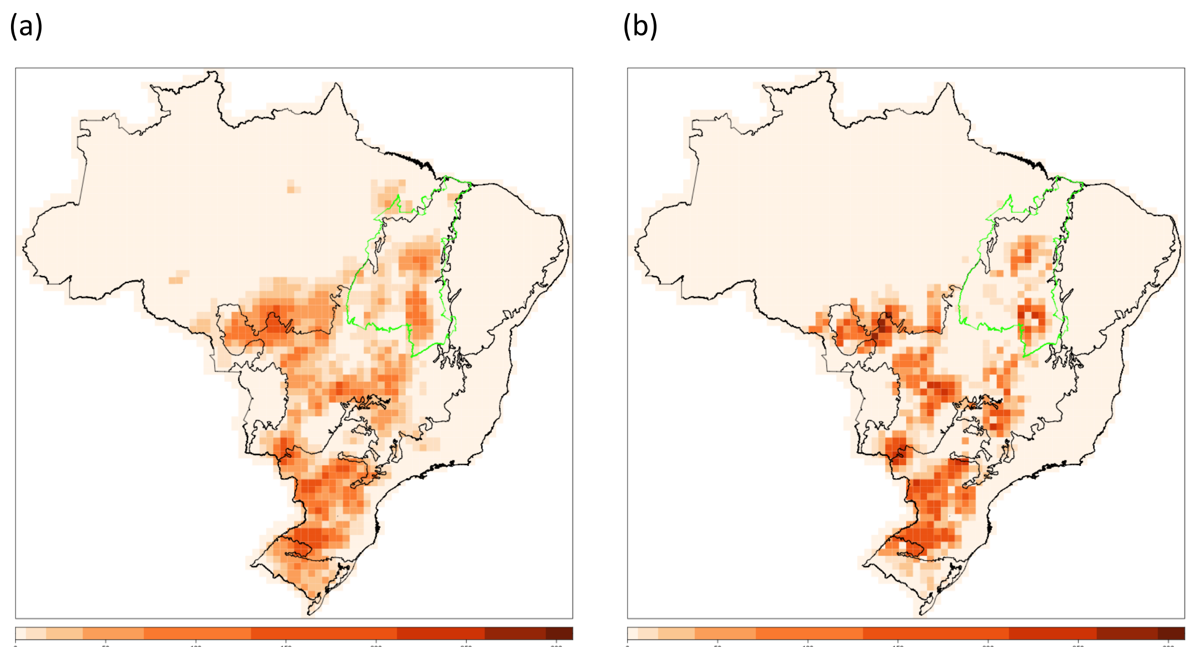

Figure S12: Spatial distribution of Brazil's soybean area in 2020 according to (a) PAM/IBGE, and (b) GLOBIOM-Brazil (BASE scenario). The Matopiba region is indicated in green. Colour bar values are expressed in thousands of hectares per cell.

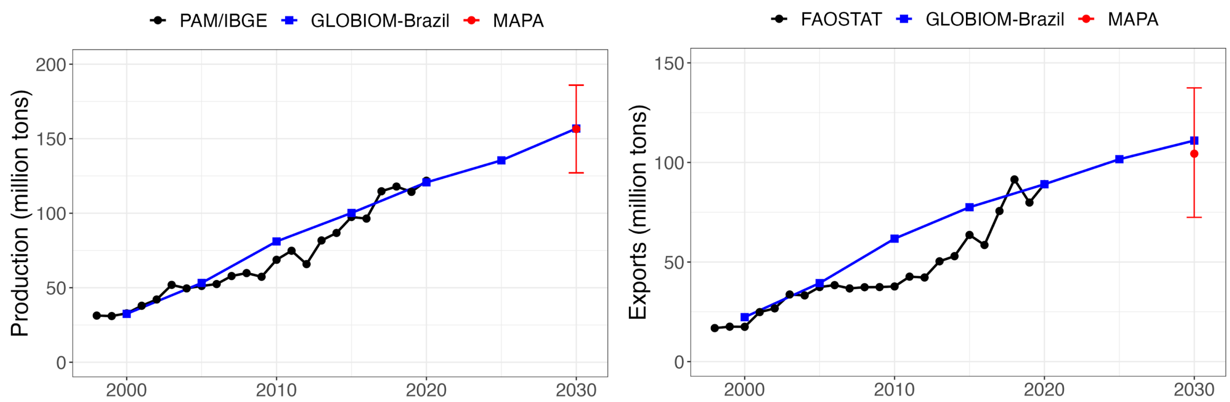

Figure S13: Evolution of soybean (a) production and (b) exports as projected by GLOBIOM-Brazil (BASE scenario), from 2000 to 2030. Official estimates from PAM/IBGE are indicated in black and projections from MAPA [93] (minimum, mean and maximum) are indicated in red.

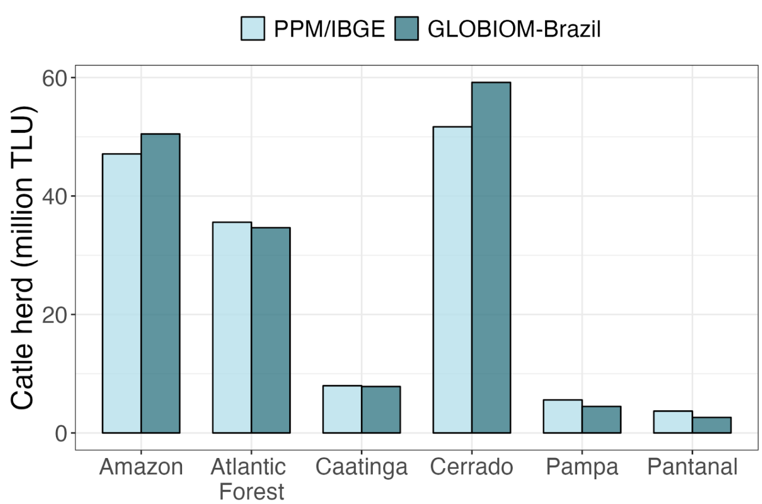

Figure S14: Comparison of cattle herd in million tropical livestock unit (MTLU) per biome between GLOBIOM-Brazil (BASE scenario) and PPM/IBGE for the year 2020 [1 TLU corresponds to 0.7 bovine]. PPM/IBGE numbers are 2019-2020 average [67].

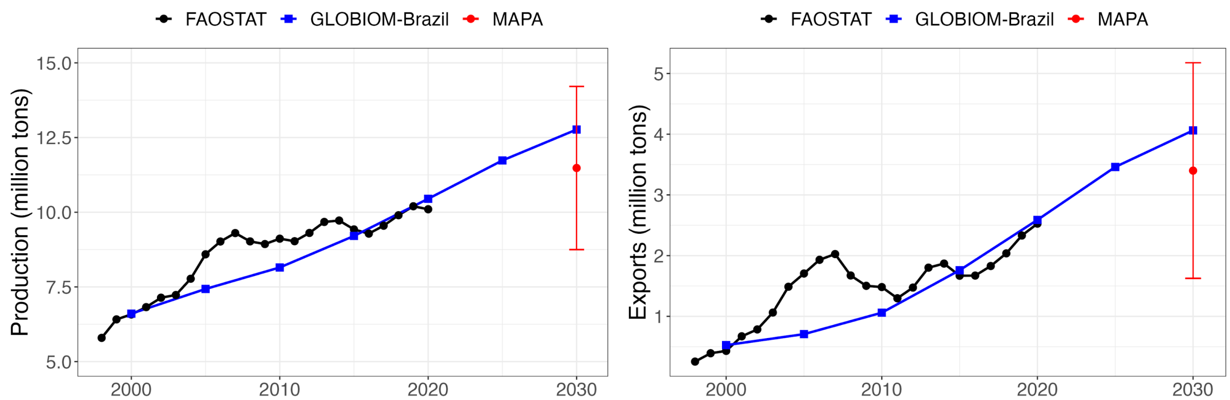

Figure S15: Evolution of beef (a) production and (b) exports as projected by the GLOBIOM-Brazil (BASE scenario), from 2000 to 2030. Official estimates from FAO are indicated in black and projections from MAPA [93] (minimum, mean and maximum) are indicated in red.

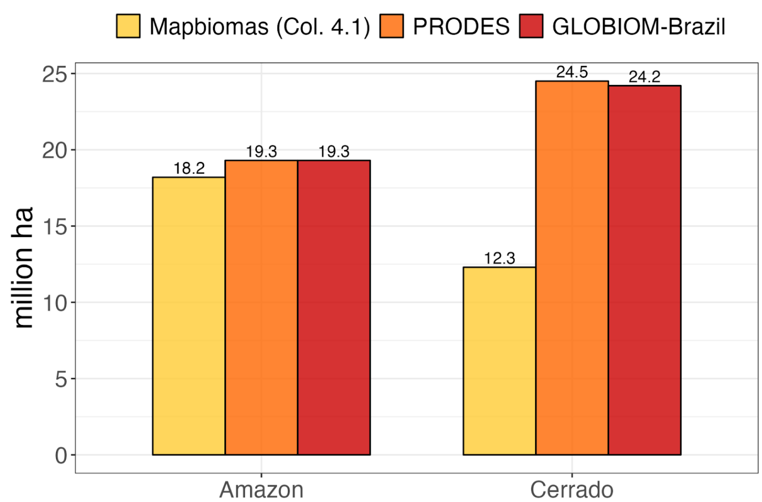

Figure S16: Comparison of accumulated deforestation and native vegetation loss in (a) Amazon and (b) Cerrado biomes, from 2001 to 2015, as projected by GLOBIOM-Brazil (BASE scenario) and PRODES and MapBiomas. Note that projected Cerrado deforestation is between PRODES Cerrado [94] and MapBiomas [28] estimates.

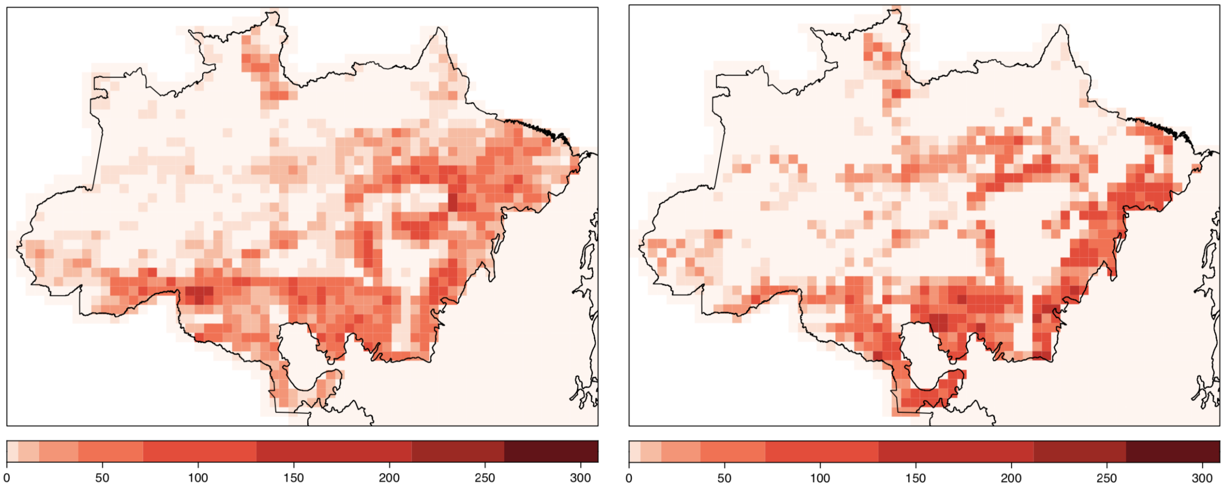

Figure S17: Spatial distribution of accumulated deforestation in the Brazilian Amazon from 2001 to 2020, as estimated by PRODES/INPE (left) and as projected by GLOBIOM-Brazil (BASE scenario) (right). Colour bar values are expressed in thousands of hectares per cell.

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