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# Transformation of Brazil's biomes: The dynamics and fate of agriculture and pasture expansion into native vegetation

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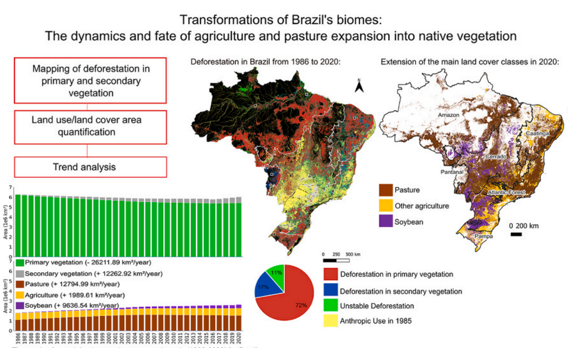
## HIGHLIGHTS

- We mapped the hotspots of LUCC's transition from forest to pasture to agriculture.
- Deforestation rates were predominant in primary (72 %) than secondary (17 %) forests.
- Soybean expansion drove the largest conversion from pasture to agriculture.
- Substantial vegetation regeneration rates are observed across different biomes.
- Overall, there are no substantial reductions in primary vegetation deforestation.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Land use and cover change (LUCC) in Brazil encompass a complex interplay of diverse factors across different biomes. Understanding these dynamics is crucial for informed decision-making and sustainable land management. In this study, we comprehensively analyzed LUCC patterns and drivers using 30 m resolution MapBiomas Collection 6.0 data (1985–2020). By mapping deforestation of primary and secondary natural vegetation, natural vegetation regeneration, and transitions between pasture, soybean, agriculture, and irrigation, we shed light on the intricate nature of LUCC in Brazil. Our findings highlight significant and increasing trends of deforestation in primary vegetation in the country. Simultaneously, the Atlantic Forest, Caatinga, Pampa, and other regions of the Cerrado have experienced intensification processes. Notably, the pasture area in Brazil reached its peak in 2006 and has since witnessed a gradual replacement by soybean and other crops. While pasture-driven deforestation persists in most biomes, the net pasture area has only increased in the Amazon and Pantanal, decreasing in other biomes due to the conversion of pasturelands to intensive cropping in other regions. Our analysis further reveals that primary and secondary vegetation deforestation accounts for a substantial portion of overall forest loss, with

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72 % and 17 %, respectively. Of the cleared areas, 48 % were in pasture, 9 % in soybean cultivation, and 16 % in other agricultural uses in 2020. Additionally, we observed a lower rate of deforestation in the Atlantic Forest, a biome that has been significantly influenced by anthropogenic activities since 1986. This holistic quantification of LUCC dynamics provides a solid foundation for understanding the impacts of these changes on local to continental-scale land-atmosphere interactions. By unraveling the complex nature of LUCC in Brazil, this study aims to contribute to the development of effective strategies for sustainable land management and decision-making processes.

## 1. Introduction

Tropical land-use and cover change (LUCC) substantially impact local to global ecosystem services, such as greenhouse gas emissions, soil fertility, biodiversity, water resources, and climate (Gibbs et al., 2010; Davidson et al., 2012; Dias et al., 2016; Souza et al., 2020; Borma et al., 2022; Caballero et al., 2022). Brazil, the fifth largest country by area (8,516,000 km$^2$), has diverse climates and ecosystems, which makes it one of the most biodiverse countries (Myers et al., 2000). Brazilian biomes, ranging from rainforests to grasslands, are crucial for regional and global carbon, energy, and hydrological cycles.

Due to its extensive biogeographic and ecosystems diversity, the drivers and nature of LUCC in Brazil are complex and vary across biomes, impacting long-term land use and land-atmosphere interactions differently from local to continental scales (Tilman et al., 2001; Lambin et al., 2003; Morton et al., 2006; Foley et al., 2011; Vergopolan and Fisher, 2016; Vieira et al., 2022). The LUCC includes *expansion*, *abandonment* with regrowth, and *intensification*. Expansion or extensification involves the conversion of non-agricultural lands, such as forests and natural grasslands, to pasture and cropland, commonly defined as deforestation. In our study, we refer to intensification as the conversion of land from low-intensity uses (such as grazing pasture) to higher-intensity uses (such as crop cultivation) (Phalan et al., 2014; Kreidenweis et al., 2018; Pretty et al., 2018; Benton and Harwatt, 2022).

Forest-to-pasture is the dominant LUCC transition in the Amazon frontier, while the southern Amazon and central Brazil regions are primarily characterized by soybean crop expansion mostly over pasture (Zalles et al., 2019; Silva Junior et al., 2021; Song et al., 2021; West et al., 2022). Wetland-grassland dynamics in the Pantanal are driven by interannual rainfall variability (Ivory et al., 2019). In contrast, natural vegetation cover has stabilized in settled areas like the coastal Atlantic Forest, but land use has intensified (Molin et al., 2017). The Atlantic Forest and Amazon also experience reforestation due to the abandonment of agriculture (Chazdon et al., 2020; Guimarães et al., 2022). A "forest transition" characterized by forest regrowth during rapid economic growth and urbanization after cropland abandonment has been observed in Brazil and other parts of Latin America (Mather and Needle, 1998). This is expected to continue with stable secondary forest regrowth increases, with the complex mosaic of LUCC impacting the land-atmosphere interactions (Moran et al., 2000).

However, the complex transitions and dynamics of LUCC in Brazil have yet to be fully documented, particularly how deforestation impacts land-atmosphere interactions, freshwater availability, and ecosystem health across diverse biomes. Existing literature has been limited in scope, focusing on site-specific locations (Santos and Naval, 2020; Bezerra et al., 2022) or specific biomes (Grecchi et al., 2014; Garcia and Ballester, 2016; da Silva and Bates, 2022;) or, when nationwide, analyzed the dynamics of only one land cover class (Parente et al., 2019; Zalles et al., 2019; Silva Junior et al., 2020; Souza et al., 2020), or lack the investigation of the land cover trajectories and dynamics (Souza et al., 2020). Globally, remote sensing data provides an opportunity to monitor at an unprecedented resolution the changes in land cover, deforestation rates, agriculture, and cropland expansion, among others (Sakai et al., 2004; Cunha et al., 2015; Dias et al., 2016; Oliveira et al., 2017; Levy et al., 2018; Op de Hipt et al., 2019; Rausch et al., 2019).

To improve our understanding of how LUCC overall Brazilian biomes, we introduce the first quantification and assessment of the LUCC transitions in Brazil at 30-m resolution and over the past 35 years using MapBiomas Collection 6.0 (1985–2020). To this end, we characterized the LUCC dynamics and identified key regions and processes driving intensification and extensification. Moreover, we specifically examined the deforestation of primary and secondary natural vegetation and their trends, as well as their transition into pasture, soybean, and other agricultural crops, providing insights into the spatial distribution of clearing activities. A trend analysis of deforestation and land use changes provides insights into which interactions drive the significant LUCC. By assessing the LUCC dynamics and transitions at 30-m resolution over the past 35 years, our study lays the foundation for a comprehensive understanding of the impacts and implications of diverse LUCC dynamics on local to continental-scale land-atmosphere interactions.

## 2. Material and methods

### 2.1. Land use and land cover data

We used annual land use and land cover maps from MapBiomas Collection 6 (MapBiomas, 2021) from 1985 to 2020 (Table SI1). This is a 30-m spatial resolution remote sensing product based on Landsat satellite processed in Google Earth Engine (GEE) (Gorelick et al., 2017). It uses automated classification algorithms that generate annual land use and land cover information about the Brazilian territory (Silva Junior et al., 2020; Souza et al., 2020; Rodrigues et al., 2022). The general reported accuracy of MapBiomas classification is 87.4 %, with 9.3 % allocation disagreement and 3.3 % area disagreement (MapBiomas, 2023).

### 2.2. Deforestation and regeneration maps

#### 2.2.1. Land-use/land cover maps

Classification errors in land use and land cover maps can complicate the analysis of time series data, which can erroneously overestimate the intensity of LUCC in a given pixel. Unrealistic transitions (e.g., pasture to forest in one year and then back to pasture in the next year) are often used to screen out classification errors, but overly strict algorithms may miss real critical transitions. To minimize classification errors, we generated three different maps of deforestation, each with a definition of "deforestation":

(i) Pixel was *Natural Vegetation* (NV) (forest, savanna, and grassland) at any year in the time series, even if for one year in the middle of the time series (ALL);
(ii) Pixel transitioned from NV at the beginning of the series to another cover (deforestation in primary vegetation) and remained an anthropic cover (PRIMARY); and
(iii) Pixels from primary and secondary vegetation were classified as anthropic at the beginning of the time series but became NV for at least four straight years and then transitioned back to non-forest (PRIMARY+SECONDARY).

The first map (ALL) was produced using MapBiomas data directly, without any pre-processing. Therefore, it included every pixel classified as NV (ID 3, 4, and 12 of MapBiomas classification – forest, savanna, and grassland) for any year in the time series and anthropic in a subsequent year. A visual analysis of the first deforestation map, considering the MapBiomas data without any correction, showed that there were significantly high rates of deforestation (and regeneration) in some specific parts of Brazil, especially in the Pantanal biome, some parts of the Cerrado, Atlantic Forest and the northernmost part of the Caatinga. To understand what was happening in these regions, we selected some pixels and analyzed MapBiomas classification over them, identifying that those pixels had multiple transitions over the years, in some cases going from forest (natural vegetation – NV) to pasture (anthropic) in one year, and then returning to forest in the next year, what could be considered an unrealistic transition (examples of the transitions are shown in Figure SI1). Therefore, we call those pixels with multiple transitions over the years as "unstable deforestation". As such, the ALL map likely overestimates deforestation.

In order to address these unrealistic transitions, we corrected the MapBiomas dataset in two different ways. First, to account for deforestation only in primary vegetation (PRIMARY), we corrected the MapBiomas dataset for unexpected land cover transitions from NV to anthropic. The algorithm checks if a transition from NV to anthropic cover is stable for more than two consecutive years: if a pixel was NV in one year, classified as anthropic in the next one or two years, and then returned NV, then the anthropic labels for that pixel are reclassified as NV.

Secondly, we defined deforestation in secondary vegetation as areas that were non-NV in 1985 but that, at some point in the time series, were classified as NV. Some pixels were only classified as NV for one or two years, then returned to their previous use. We assumed that to be a misclassification of the original MapBiomas dataset and reclassified pixels where NV cover lasted at least four years. If a pixel was anthropic in one year and then classified as NV in the next three years and then reverted to anthropic use, all years in that sub-sequence for that pixel are reclassified as anthropic, not being considered regenerated (Figure SI1). The algorithm includes both secondary and primary deforestation after 1985. To account for only secondary vegetation, we subtracted it from the PRIMARY dataset for each year of the time series to generate the SECONDARY time series (accounting for only secondary vegetation). Suppose a pixel experienced both primary and secondary deforestation. In that case, it is classified as PRIMARY, so we are potentially underestimating the amount of secondary clearing if it occurs in an area cleared after 1985.

### 2.2.2. Mapping deforestation and regeneration

This study defines deforestation as the transition of NV (i.e., forest, savanna, or grassland) to anthropic land use (i.e., pasture, agriculture, urban, plantation forestry). Regeneration is defined as the conversion of anthropic land use to NV. Deforestation and regeneration were annually mapped following the methodology developed by Souza et al. (2020), using three different LUCC maps and a surface water extent map as input data. (Fig. 1).

A water mask using maximum water surface extent data (1984–2020) developed by (Pekel et al., 2016) was used to avoid the inclusion of false detection of NV within wetland areas in the MapBiomas products (Silva Junior et al., 2020). In the one biome with extensive wetlands (Pantanal), we did not use the water mask and included wetlands in the analysis.

For each input layer (ALL, PRIMARY, and SECONDARY), we mapped the annual increments of deforestation and regeneration. Binary maps for each class were created, classifying each pixel in NV (value 1) and anthropic cover (value 0). Each pixel classified as 0 in a given year and 1 in the previous year was mapped as deforested in the given year. Because the dynamics of grassland and wetland in the Pantanal can overestimate deforestation/reforestation rates, we applied a mask with the median extent area of the wetland area for the Pantanal from 1986 to 2020.

Deforestation was mapped by combining the annual increments for each year. For each year, we summed the increments maps from the prior years. The sum of these maps results in pixels with values greater than 1, so to create annual binary maps of deforestation extent, the maps were reclassified for each year by assigning a value of 1 to pixels with values between 2 and 33 and pixels with a value 0 were kept unchanged (Silva Junior et al., 2020). A total of 35 (1986 to 2020) maps were obtained for deforestation and regeneration, where the changes have a value of 1 and stable pixels or other transitions a value of 0.

When comparing the three deforestation maps generated from the different datasets (ALL, PRIMARY, and SECONDARY), the difference between the ALL and the other datasets shows that some pixels had multiple transitions from NV to non-NV and back. While some of this may be classification errors, there may also be areas where multiple transitions occur. We call these pixels "unstable deforestation". We compared the deforestation area from the datasets we used (ALL and PRIMARY+SECONDARY), with PRODES data, which is a project that monitors clear-cut deforestation using satellites, estimating annual rates based on the deforestation increments identified in each satellite image (Assis et al., 2019) (Figure SI2). The MapBiomas dataset corrected for unrealistic transitions shows the lower rates of deforested areas, except for the Pantanal Biome. Amazon, Caatinga and Pampa biomes show similar areas between datasets. Deforested areas for the Cerrado and Atlantic Forest from PRODES are higher than when calculating using MapBiomas data.

## 2.3. Other land-use and land-cover classes

MapBiomas provides maps of irrigated areas, including center pivot irrigation systems, irrigated rice, and other irrigation systems in some municipalities in the Brazilian semi-arid region (Rudorff et al., 2021). The total amount of irrigated area by biome was computed for each year.

We used the corrected maps (unexpected transitions) to create masks for the analysis of LUCC. We used the PRIMARY+SECONDARY dataset as a mask for each year in the time series. For natural classes (forest, savanna, and grassland), we applied an anthropic mask, defined as pasture, soybean, and other agricultural uses (Table SI1). We applied an NV mask for anthropic classes (pasture, agriculture, and soybean), defined as all NV pixels in the screened dataset. No mask was applied for the wetland and irrigation classes. We performed a separate analysis to capture wetland-grassland dynamics in the Pantanal. The grassland class was separated from the NV class, and wetlands were included in the analysis.

We calculated the total area of each land cover class for each biome and the transitions from one class to another for the years between 1986 to 2003 and 2003 to 2020. A trend analysis of the annual area of each class was carried out for deforestation of primary vegetation (PRIMARY) and secondary vegetation (SECONDARY) using the Mann-Kendall (M-K) Test (Mann, 1945; Kendall, 1975). To understand trends in different periods, we ran the test for 1986–2020, 1986–2000, 2001–2020, 2001–2010, and 2011–2020. We also generated trend maps for deforestation in primary and secondary vegetation, by calculating the change in deforested area at each 10 km × 10 km cell in Brazil.

Distinct from previous studies in the literature (Zalles et al., 2019; Silva Junior et al., 2020; Souza et al., 2020; Sales et al., 2022), our research takes a unique approach to address critical aspects. Firstly, we meticulously correct land use classifications to account for unrealistic transitions, ensuring the accuracy and reliability of our results. Secondly, we comprehensively map and analyze trends in deforestation of both primary and secondary forests across all biomes in Brazil. This expansive scope allows us to capture the full extent of land use change dynamics in the country. As a result of these methodological advancements, our findings substantially diverge from those of previous studies, providing a precise and comprehensive understanding of the complex patterns and drivers of land use change in Brazil.

## 3. Results

### 3.1. Deforestation patterns in Brazil

Clearing of NV occurred in all biomes of Brazil from 1985 to 2020 (Fig. 2), which was mainly replaced by pasture (48 %), soybean (9 %), and other agriculture (16 %) (Fig. 4a). Most of the deforestation in the country since 1985 occurred in primary vegetation (72 %), 17 % in secondary vegetation, and 11 % in areas classified as "unstable deforestation." The rate of primary vegetation loss in the country was 26,212 km$^2$ year$^{-1}$ (0.4 % year$^{-1}$) (Fig. 4b), with an increase in the pastureland of 12,795 km$^2$ year$^{-1}$, soybean area by 9637 km$^2$ year$^{-1}$ and other agriculture by 1990 km$^2$ year$^{-1}$ (Fig. 4b).

On the border with the Cerrado biome, the southern Amazon is the most affected by post-1985 deforestation (Fig. 2 and Figure SI3), where NV is primarily replaced by pasture (69 % of the deforested area in the Amazon was replaced by pasture, and 44 % in the Cerrado). In the Atlantic Forest, most deforestation occurred before 1985 (Fig. 2 and Figure SI3), though deforestation of primary vegetation is still observed in the northmost and southernmost parts. In the Caatinga biome, primary vegetation's deforestation rates were 4338.1 km$^2$ year$^{-1}$ and regeneration of 2958.90 km$^2$ year$^{-1}$ (Fig. 3), with frequent deforestation in secondary vegetation (1530.9 km$^2$ year$^{-1}$; blue pixels in Fig. 2). Most of southern Cerrado exhibited anthropic use in 1985 (33 % of the biome area), but high rates of primary deforestation persist (10,192.6 km$^2$ year$^{-1}$ during 1985–2020), with little secondary vegetation regrowth (2093.04 km$^2$ year$^{-1}$). For the Pampa biome in southern Brazil, deforestation occurred in 14 % of the area (1193.4 km$^2$ year$^{-1}$ in primary NV and 566.8 km$^2$ year$^{-1}$ in secondary NV). In the Pantanal, however, the secondary vegetation's deforestation rate (646.73 km$^2$ year$^{-1}$) is likely due to the grassland/wetland dynamics. By 2020, 25 % of the cleared area in Brazil experienced secondary NV regrowth.

Deforestation in primary vegetation showed positive trends from 1986 to 2020 over the entire country (Fig. 7a). Hotspots of primary deforestation are in the Amazon biome with the Cerrado border, in Pará, Mato Grosso, and Rondônia States. There is also a hotspot of primary deforestation in the western part of Bahia State, in the Cerrado biome. Although at lower rates than primary vegetation, deforestation of secondary vegetation also showed positive and substantial trends in most of the country (Fig. 7b). Some decreasing trends can be observed in some areas of the Caatinga, Pantanal, and Amazon (Pará, Maranhão, and Tocantins borders).

Regeneration accounts for a significant area of NV in 2020 in all biomes (Fig. 3). Notably, the Caatinga, Atlantic Forest, and Pantanal biomes exhibit substantial regeneration. In the Caatinga, regenerated areas constitute a significant proportion of the NV regions, primarily on the northeastern border with the Atlantic Forest, encompassing the coastal area of Rio Grande do Norte State. Additionally, significant NV regeneration occurs in the central region of the Caatinga, corresponding to the interior of Ceará State (Figure SI4).

The Atlantic Forest shows prominent NV regeneration along its borders with the Cerrado and Caatinga biomes, particularly in Minas Gerais and Bahia. The Pantanal also displays high rates of NV regeneration, particularly in proximity to wetland areas. In the Pampa biome, notable regeneration can be observed around Patos Lagoon. Riparian areas in the Amazon exhibit significantly high rates of NV regeneration. Although there are positive trends of secondary regeneration (12,262.93 km$^2$ year$^{-1}$) (Fig. 4b), deforestation has also been increasing (8552.76 km$^2$ year$^{-1}$; Figure SI5), resulting in net forest loss in all biomes (Table SI2 and Figure SI5).

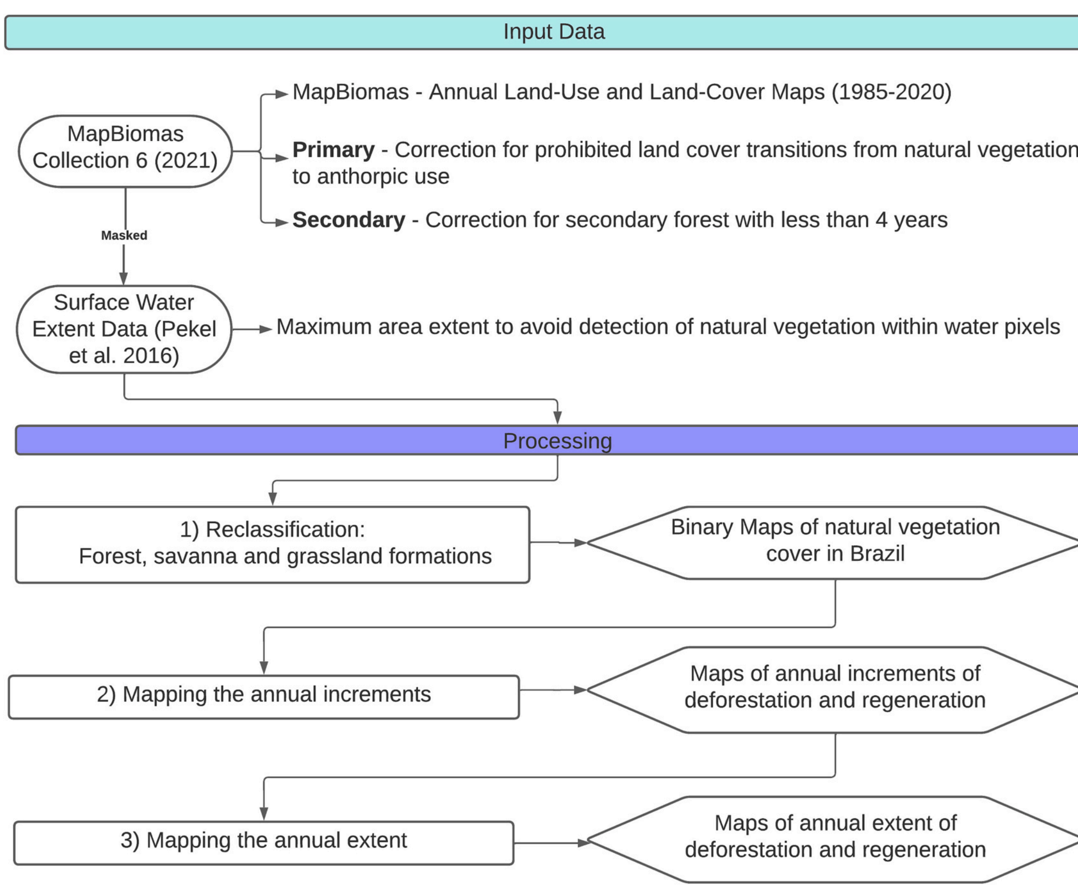


**Fig. 1.** Workflow with the steps for generating deforestation and reforestation maps.

### 3.2. Land-use and land-cover dynamics

The area of primary vegetation decreased by 13 % (819,058.4 $km^2$, an area loss of approximately 3.5 times the state of Rondônia) (Fig. 4b), and the area of anthropic (pasture+soybean+other agriculture) cover increased by 31 % (821,263.5 $km^2$) (Fig. 5) in all biomes from 1985 to 2020. Irrigation (Figure SI6) currently represents a minor land use across the country, occupying a relatively small area compared to the total extent of each biome. However, it is important to note that there is a significant potential for expansion, and this trend is already underway. According to the Irrigation Atlas by ANA (National Water Agency, ANA, 2021), there are expectations of doubling the irrigated area in the next 15 years, which could have impacts on the country's water resources and potentially exacerbate conflicts over water usage. Irrigation also occurs in a few areas in the Cerrado (representing 12,345 $km^2$, 0.4 % of the biome area, mainly related to center pivot irrigation) and the semi-arid Caatinga (2555,8 $km^2$, 0.2 % of the biome area).

Extensification is significant in the country, with the continued clearing of primary vegetation, especially in the agricultural frontier (in the Amazon and Cerrado biomes). Increasing trends of primary and secondary deforestation can be observed over the entire country reaching up to 20 and 10 $km^2$ per year in a 10x10km area, respectively (Fig. 7, Fig. 8). Intensification, especially from pasture to cropland (soybean and other crops), occurred mainly in the Atlantic Forest, Cerrado, and Pampa (Fig. 6). We did not quantify intensification within a given crop, such as shifts from single to double cropping, observed in soybean areas in the Cerrado, where a second drop of corn or cotton follows the soybean (Neill et al., 2017). Such double cropping accounted for nearly 50 % of the total soybean area in Mato Grosso by 2011 (Spera et al., 2014).

Our analysis reveals that the expansion of new pasture areas has undergone a significant shift from the Atlantic Forest biome to the Cerrado biome over the past few decades. In particular, the conversion of older pastures in the Atlantic Forest, especially in the western region of Parana state, was replaced by soybean crops (Fig. 5, Figure SI9). This transition suggests a trend towards intensification and the replacement of traditional pasture-based systems with more intensive agricultural practices. Moreover, at the interface of the Cerrado and Atlantic Forest biomes, specifically between Sao Paulo and Minas Gerais, our findings indicate that old pastures have been progressively replaced by other crops.

Furthermore, the establishment of pasture in deforested areas has primarily advanced along the borders of the Cerrado and Amazon biomes (Fig. 5 and Figure SI9). Notably, the MATOPIBA region, encompassing parts of the states of Maranhão, Tocantins, Piauí, and Bahia, as well as Mato Grosso and Rondônia states, exhibits significant expansion of new pasture areas, signifying the ongoing transformation of these regions.

#### 3.2.1. Amazon

In the Amazon, soybean expansion started in the early 2000s, mostly in pasture and NV areas, but still covered a small percentage of land cover in 2020 (Fig. 6 and Figure SI3). Forest and savanna decreased from 92 % to 82 %, and pasture area increased from 4 % to 14 % from 1985 to 2020 (Fig. 6), also showing significant positive trends (12, 685.25 $km^2$ $year^{-1}$, Fig. 8). Moreover, significant positive trends for deforestation in

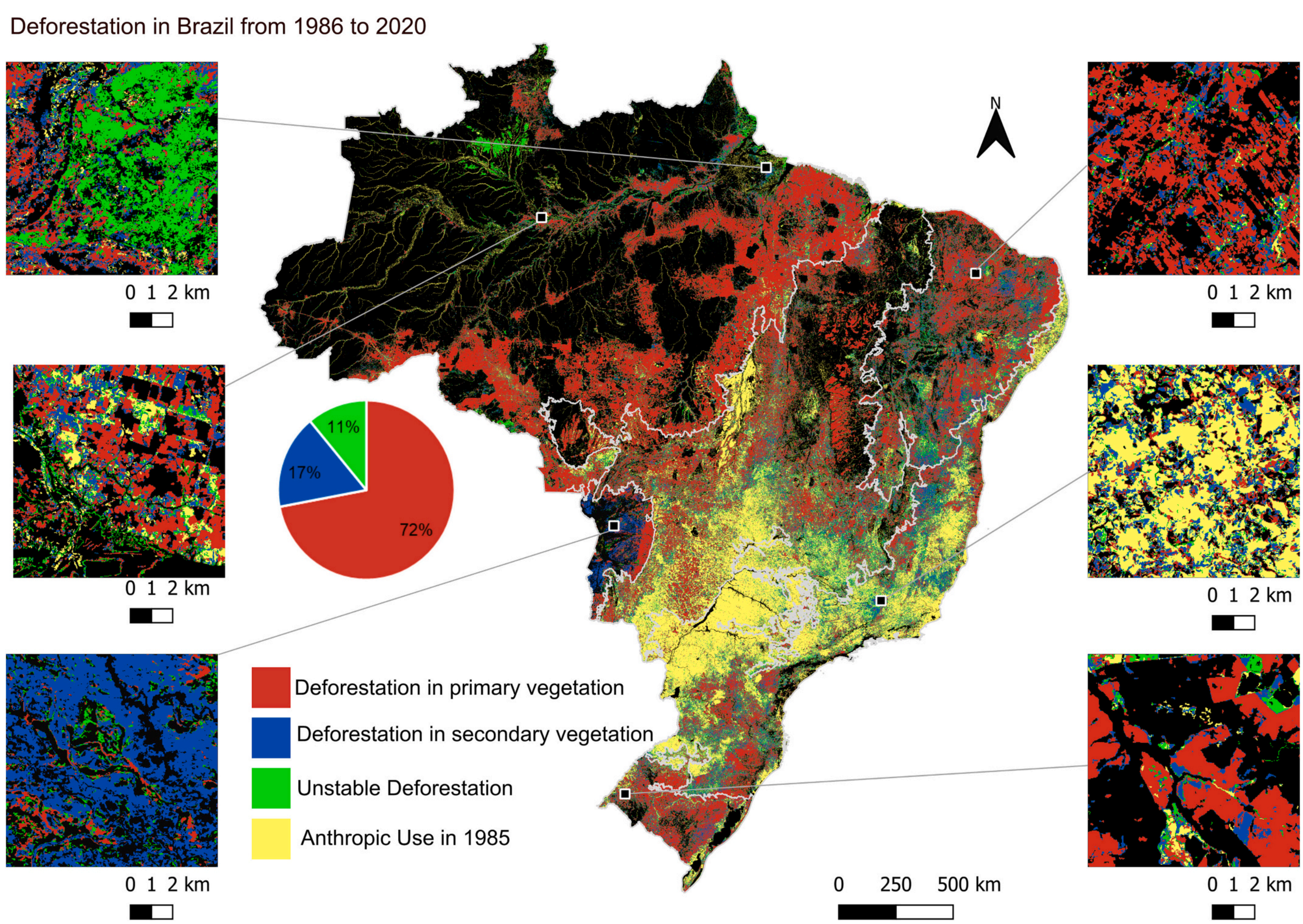


**Fig. 2.** Primary, secondary, and unstable deforestation and areas already in Brazil's anthropic land use in 1985.

primary (+17,825.13 km$^2$ year$^{-1}$ for 1986–2020) and secondary forests (+1779.58 km$^2$ year$^{-1}$ for 1986–2020), regeneration (+3490.15 km$^2$ year$^{-1}$ for 1986–2020), pasture (+12,685.25 km$^2$ year$^{-1}$ for 1986–2020), soybean (+1483.18 km$^2$ year$^{-1}$ for 1986–2020), agriculture (+413.99 km$^2$ year$^{-1}$ for 1986–2020) in all periods tested (1986–2020; 1986–2000; 2001–2020; 2001–2020; 2011–2020) can be observed in the biome (Fig. 8).

### 3.2.2. Cerrado

The Cerrado had more than half (~54 %) of its NV cleared and approximately 46 % replaced by pasture, soybean, and other agricultural uses by 2020 (Fig. 6). Pasture, soybean, and other agriculture are the anthropic uses in the biome (Fig. 5). In the early 2000s pasture shifted towards other uses, mainly soybean and other agriculture (Fig. 5). In 2020 soybean represented 9 % of the area of the biome (Fig. 6).

Pasture in the Cerrado was converted mainly to soybean fields and other agriculture in the early 2000s (Fig. 5). Negative trends in the pasture area occurred from 2001 to 2020 (−4198.89 km$^2$ year$^{-1}$), with positive trends for soybean in the same period (7527.95 km$^2$ year$^{-1}$; Fig. 8). Soybean accounted for 9 % of the Cerrado by 2020 (Fig. 6). Positive and statistically significant trends were detected in the Cerrado for deforestation in primary and secondary NV, reforestation, soybean, and irrigation (Fig. 8). The pasture area reached a peak in 2005 and showed positive trends over the whole period (1986–2020, +1674.37 km$^2$ year$^{-1}$) and early period (1986–2000, +9602.63 km$^2$ year$^{-1}$), but negative trends in the recent 10 (−4198.89 km$^2$ year$^{-1}$) and 20-year (−4198.89 km$^2$ year$^{-1}$) periods (2001–2020 and 2011–2020), and no trends in 2001–2010. Agriculture in the Cerrado showed no trends in 1986–2020 and 1986–2000, and positive trends after 2001 (2001−2020,2001−2010,2011−2020).

### 3.2.3. Atlantic Forest

For the Atlantic Forest biome, most deforestation occurred before 1985 (Fig. 2 and Figure SI3). though deforestation of primary forests can still be observed in the northmost and southernmost parts. Deforestation in primary (+2618.48 km$^2$ year$^{-1}$ for 1986–2020) and secondary forests (+1700.68 km$^2$ year$^{-1}$ for 1986–2020), reforestation (+2646.71 km$^2$ year$^{-1}$ for 1986–2020) showed significant positive trends in all periods (Fig. 8). Pasture, soybean, and other agriculture are the anthropic uses in the biome, with pasture area decreasing (−4296.30 km$^2$ year$^{-1}$) and being replaced by soybean (+2264.62 km$^2$ year$^{-1}$) and other agriculture uses (+1520.95 km$^2$ year$^{-1}$) through agricultural intensification (Fig. 5 and Fig. 6).

### 3.2.4. Pampa

The Pampa also showed intensification, where other agricultural uses shifted to soybean (Fig. 5). Grassland decreased from 53 % in 1986 to 37 % in 2020, replaced mainly by other agriculture and soybean (Fig. 5). Deforestation occurred in 14 % of the biome area. Predominant land uses in this biome are other agricultural uses, especially rice, and soybean, which increased from 6 % in 1986 to 21 % in 2020 (Fig. 6). Irrigated areas are very significant in this biome and increased from 1985 to 2020 (Fig. 5).

Positive trends for primary (+1193.4 km$^2$ year$^{-1}$ for 1986–2020) and secondary deforestation (+566.8 km$^2$ year$^{-1}$ for 1986–2020), and

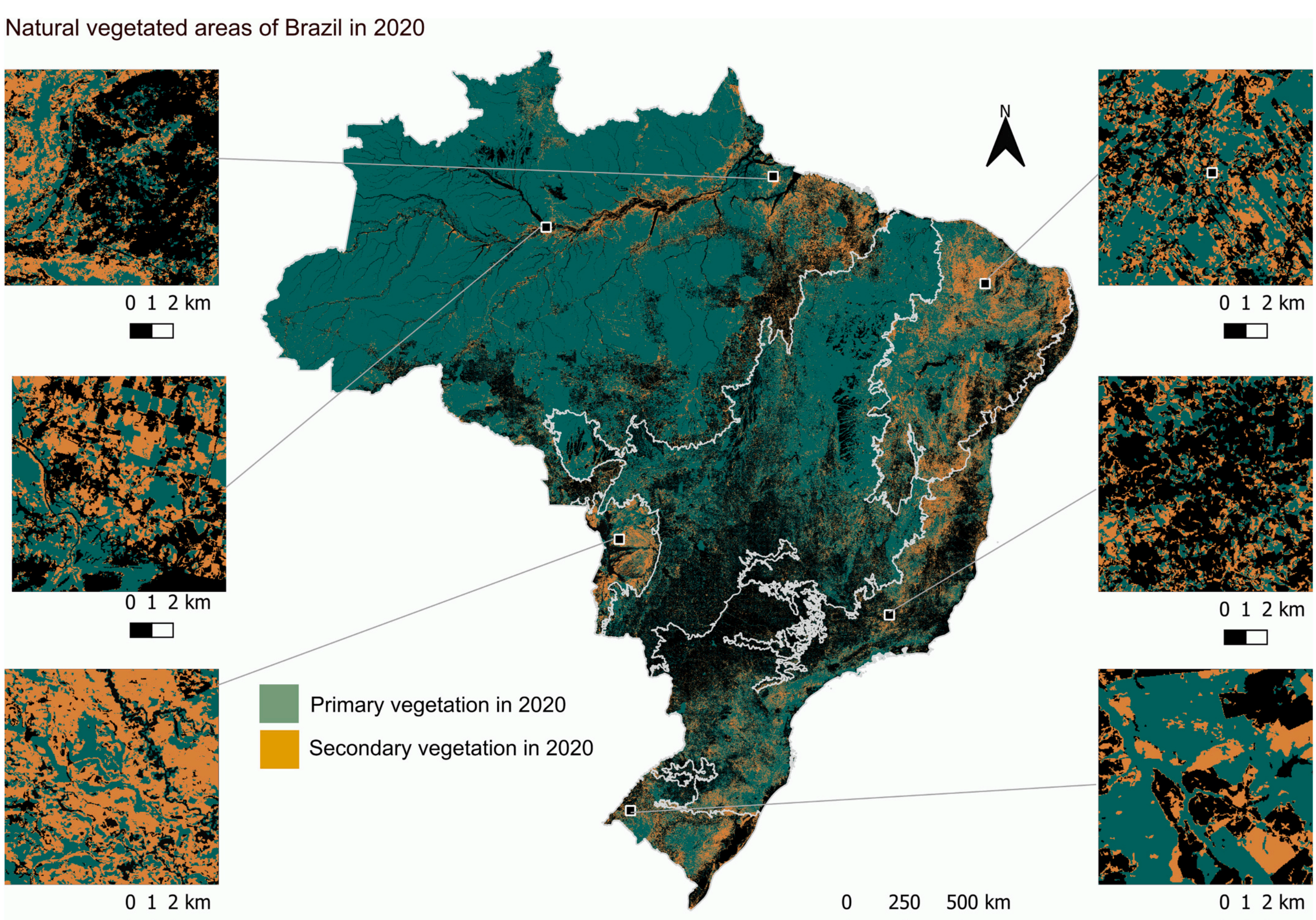


**Fig. 3.** Naturally vegetated areas of Brazil in 2020.

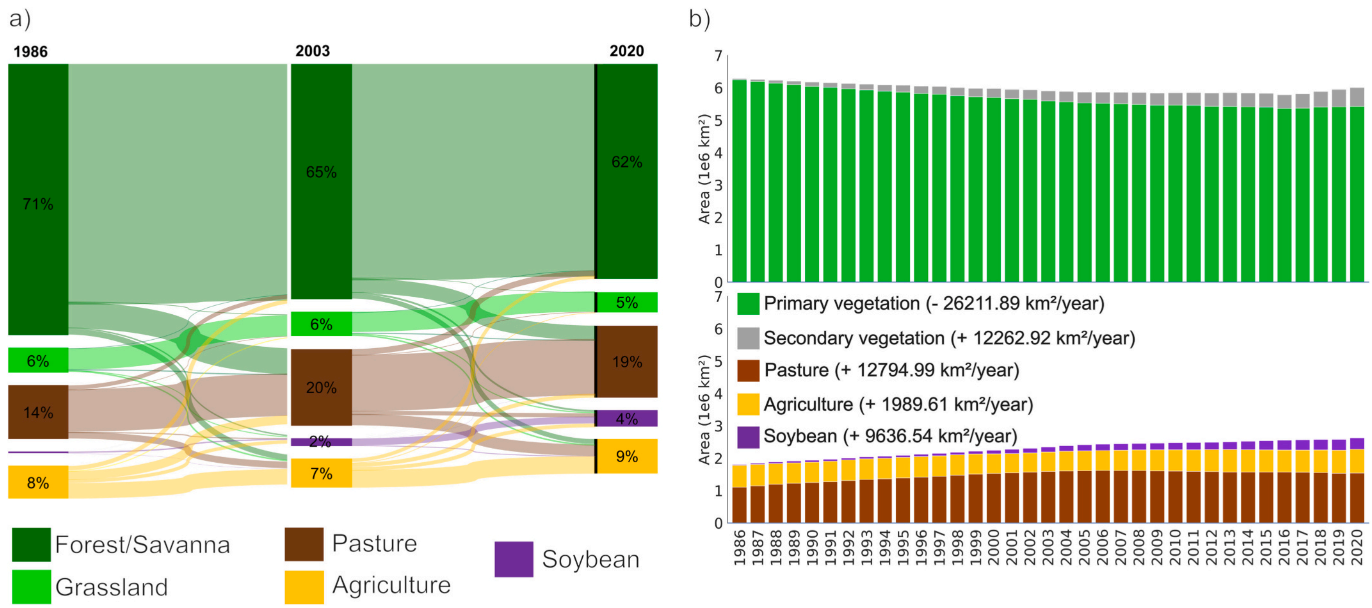


**Fig. 4.** Transitions of LUCC in all of Brazil. a) Sankey diagram showing the transitions of each LUCC from 1986 to 2003 and 2003 to 2020; b) time series of each land cover class area with respective annual trends from 1986 to 2020.

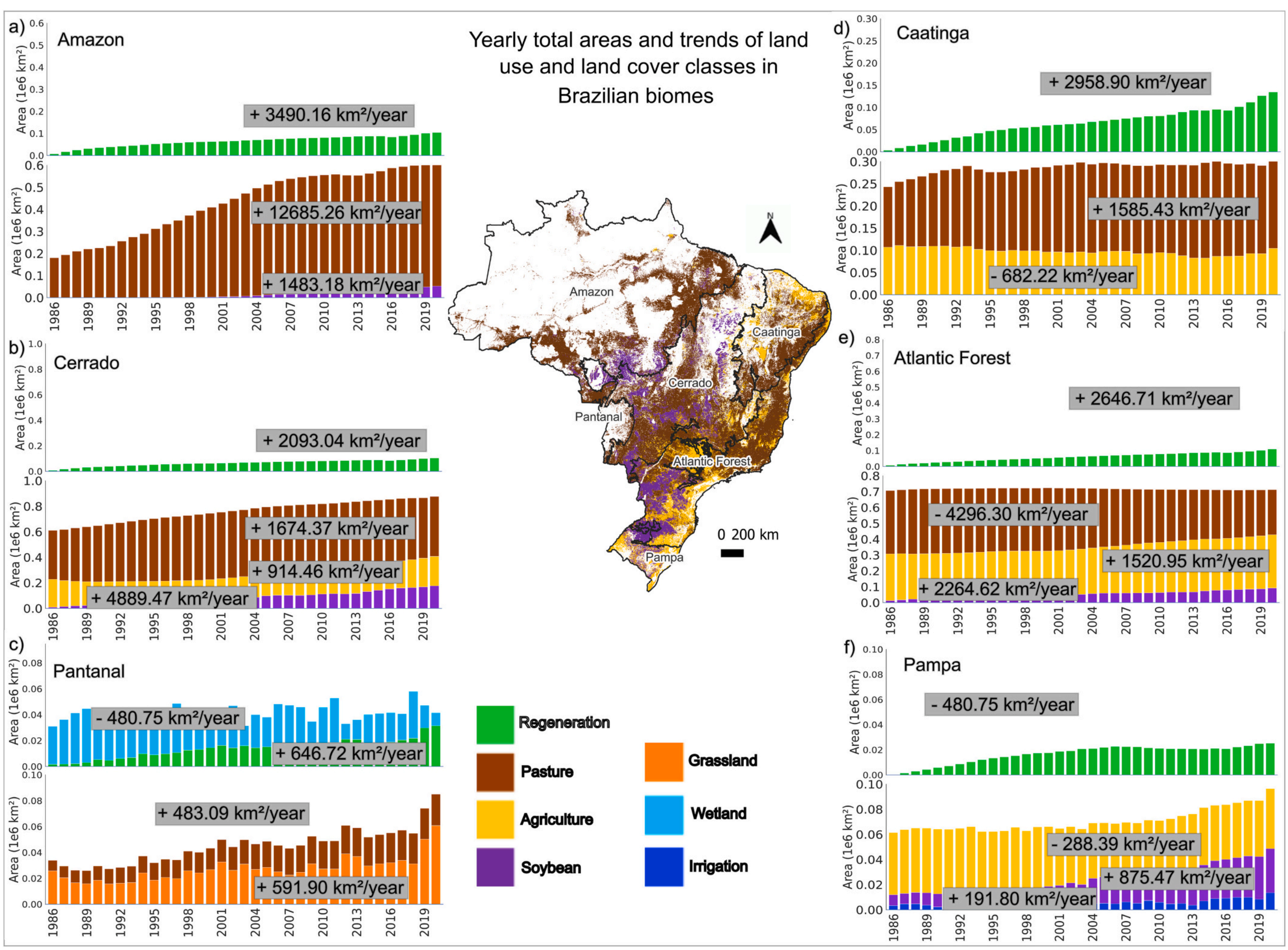


**Fig. 5.** The dynamics of the land cover classes for each biome in Brazil (panels a–f). Each panel shows the time series of each land cover class area and trends (1986–2020). The plots do not include land classes representing less than 5 % of the biome area.

soybean (+875 $km^2$ $year^{-1}$ for 1986–2020), were found for all periods, as well as for regeneration (+654.41 $km^2$ $year^{-1}$ for 1986–2020), except for the 2001–2010 time period where no trends were detected. Agriculture showed negative trends in 1986–2020 (−288.39 $km^2$ $year^{-1}$), 1986–2000 (−187.37 $km^2$ $year^{-1}$), and 2001–2010 (−531.51 $km^2$ $year^{-1}$), and no trends in 2001–2020 and 2011–2020. For irrigation, positive trends were found in all periods (+191.8 $km^2$ $year^{-1}$ for 1986–2020) except 1986–2000 where no trends were detected.

#### 3.2.5. Caatinga

In the Caatinga, conversion of NV to pasture and other agricultural uses was the most common land cover transition (Fig. 4 and Figure SI3, Fig. 5). The biome has also had significant regeneration (16 % of the total area and 7 % of the cleared area), with positive trends (2958.90 $km^2$ $year^{-1}$; Fig. 7). From 2003 to 2020, the percentage of natural vegetation in the biome was stable, as regrowth balanced new deforestation (Fig. 5). NV decreased from 1986 to 2003, transitioning to pasture and other crop uses (Fig. 6). From 2003 to 2020, the proportion of NV converting to other uses was less than from 1986 to 2003, with some pasture areas being replaced by agriculture.

Mann Kendall trend analysis (Fig. 7, Fig. 8) showed positive trends in deforestation in primary NV (Fig. 7, Fig. 8, +4338.1 $km^2$ $year^{-1}$ for 1986–2020) and reforestation (Fig. 8, +2958.9 $km^2$ $year^{-1}$ for 1986–2020) for all periods. Deforestation in secondary NV also showed positive trends (+1530.9 $km^2$ $year^{-1}$ for 1986–2020), except for 2011–2020, where no trends were detected (+376.17 $km^2$ $year^{-1}$). Trends were positive for pasture in the whole period (1986–2020, +1585.42 $km^2$ $year^{-1}$), the early period (1986–2000, + 3422.28 $km^2$ $year^{-1}$), and the recent 20-year period (2001–2020, +344.43 $km^2$ $year^{-1}$), but no trends for 2001–2010 and 2011–2020. For soybean, the Caatinga showed positive trends in 1986–2020, 1986–2000, and 2001–2020, negative trends in 2001–2010, and no trends in 2011–2020. Agriculture showed negative trends in 1986–2020 and 1986–2000, and no trends in 2001–2020, 2001–2010, and 2011–2020.

#### 3.2.6. Pantanal

The Pantanal has a specific dynamic: seasonal flooding impacts the land cover. The borders with the Amazon and Cerrado biomes are the most affected by deforestation. Pasture is the most significant land use class, increasing yearly from 1985 to 2020 (+483.1 $km^2$ $year^{-1}$) (Fig. 5). The wetland and grassland areas fluctuate seasonally and annually. In dry seasons and years, dried wetlands are classified as grasslands (Fig. 5) and revert to wetlands during wet periods, so the total area in grassland + wetland stays relatively constant. From 1985 to 2020, the area of grasslands increased (591.89 $km^2$ $year^{-1}$) with a decrease in wetlands (−480.75 $km^2$ $year^{-1}$) (Fig. 5 and Fig. 8).

Moreover, positive trends in all periods were detected for deforestation in primary forests (+861.37 $km^2$ $year^{-1}$ for 1986–2020) and pastures (+483.1 $km^2$ $year^{-1}$). Deforestation in secondary NV showed positive trends for all periods (+514.5 $km^2$ $year^{-1}$ for 1986–2020), except for 2011–2020 (+113.75 $km^2$ $year^{-1}$, no trend detected). The same is true for regeneration (+646.73 $km^2$ $year^{-1}$ for 1986–2020), except no trends were detected in 2001–2010 (+79.76 $km^2$ $year^{-1}$). Soybean showed positive trends in 1986–2020 and 1986–2020, and no trends for 2001–2020, 2001–2010, and 2011–2020. Irrigation showed negative trends in 1986–2020 and 2001–2020, and no trends for 1986–2000, 2001–2010, and 2011–2020. Wetlands showed negative trends for the 1986–2020 and 1986–2000 time periods, and no trends for 2001–2020, 2001–2010, and 2011–2020.

## 4. Discussion

Drivers for LULCC are non-linear, complex, and change with socioeconomic conditions, and transitions among different land cover are dynamic and often not stable (Lambin and Meyfroidt, 2010). Therefore, it is important to gain a better understanding of where and when LULCC occurs. LULCC's negative outcomes may result from the depletion of resources in key ecosystem goods and services due to severe degradation from past land-use practices (Lambin and Meyfroidt, 2010). Moreover, LULCC can be caused by socioeconomic changes and technological innovations that often occur independently of ecosystems and follow their dynamics. These changes are exogenous: they can be driven by urbanization, economic development, or globalization, but still affect land management and land use (Lambin and Meyfroidt, 2010).

Roads are a proximate cause of deforestation in tropical forests, such as the Amazon and the Cerrado (Aldrich et al., 2007; Barber et al., 2014; Botelho et al., 2022). Our deforestation maps (Figure SI3) show this pattern, where primary deforestation occurs around federal roads, especially in the Amazon. The rapidly growing network of illegal or unofficial roads also impacts deforestation rates (Barber et al., 2014). Roads in the Amazon already cross or are less than 10 km away from 41 % of the forest area, with 67 % in private properties and settlements and 33 % in public lands (Botelho et al., 2022).

Parente et al. (2019) mapped Brazil's spatial-temporal dynamics (1985–2017) of pasture areas. Pasture expansion occurred mainly in the Amazon and Cerrado during the first half of the study period (between 1985 and 2002), followed by intensification and transitions to other agriculture in the final years of the time series. We observe the same pattern in our study (Fig. 4b), with increasing pasture areas until 2006 and a shift towards increasing areas of soybean and other agriculture, both from pasture areas and forests. In our study, the pasture area peaked in the middle of the study period (the mid-2000s) in the Caatinga and Cerrado. From the trend analysis (Fig. 7), we can see that pasture trends are positive and higher (+9602.63 $km^2$ $year^{-1}$) for the 1986–2000 period in the Cerrado, while for the 2011–2020 period, the trend shows decreasing pasture areas over the biome (−4198.89 $km^2$ $year^{-1}$). In the Caatinga, higher positive trends are shown in the 1986–2000 period (+3422.28 $km^2$ $year^{-1}$). In contrast, pasture decreased over the entire period (−4296.29 $km^2$ $year^{-1}$) in the Atlantic Forest, with the highest decreasing trend over the 2001–2010 period (−7231.83 $km^2$ $year^{-1}$).

In the Amazon, our estimates show that 69 % of the deforested area in 2020 was pasture in the biome, similar to West et al. (2022), which showed that pasture expansion is responsible for approximately 80 % of deforestation. Maciel et al. (2020) found that pasture has been an essential driver of deforestation in Mato Grosso State, where the conversion of NV to pasture (2001–2017) was predominant, which compares well with our results (Fig. 6).

Pasture areas have decreased in the Atlantic Forest since 2003, replaced by soybean and other agricultural uses (Fig. 6). The region is responsible for producing 50 % of sugarcane in Brazil (included in the other agriculture class in this study) and leads the production of other crops, such as peanuts, cotton, rice, coffee, beans, oranges, cassava, and soy (Bezerra, 2021). The Atlantic Forest has historically experienced the most extensive LUCC. It is one of the most threatened ecosystems on Earth, with less than 7 % of its original forest remaining intact in several fragments (Brannstrom and Oliveira, 2000; Morellato and Haddad, 2000; Webb et al., 2005). Rosa et al. (2021) have shown that areas of native forest cover loss in the Atlantic Forest were recently occupied mostly by pasturelands (36 %), a mosaic of agro-pastoral land uses (26 %), croplands (19 %), and monoculture tree plantations (16 %).

Until the 1970s, the Cerrado biome was considered unsuitable for agriculture due to its soil properties (Grecchi et al., 2013). Technological advances and urban and road infrastructure development in previously isolated areas allowed pasture and agriculture expansion (Ferreira et al., 2013; Parente et al., 2019; Rudke et al., 2022). Beuchle et al. (2015) also showed that over 50 % of Cerrado's NV was converted to cropland and pasture between 1990 and 2010, similar to our estimate (46 %).

Crop cultivation in Brazil is driven by domestic and international demand, an important economic driver of LUCC (van der Hilst et al., 2018; Pendrill et al., 2019; Rudke et al., 2022). According to Song et al. (2021), in South America, 9 % of forest loss was converted to soybean by

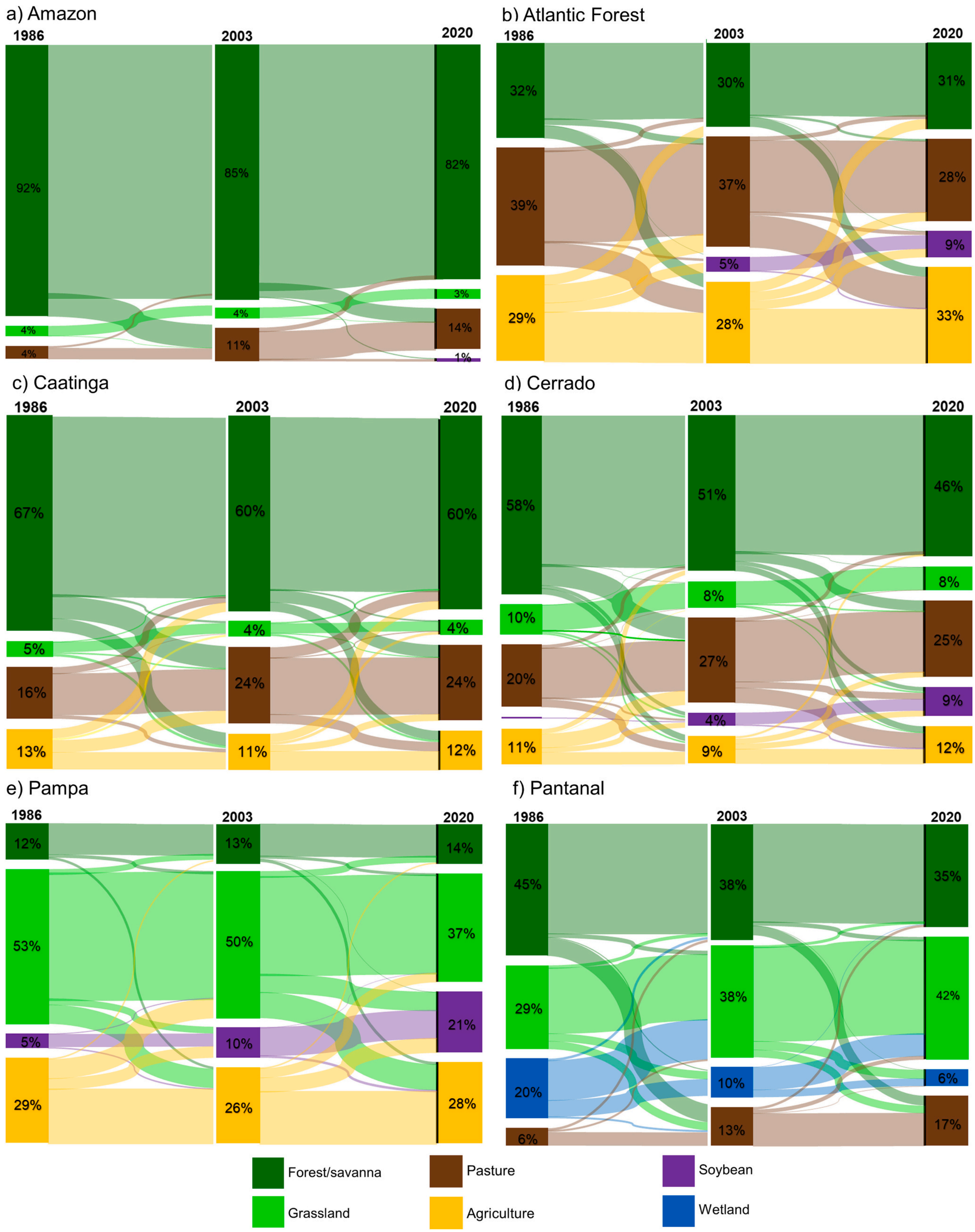


**Fig. 6.** Transitions of LUCC in each of Brazil's biomes. Each panel (a-f) shows the Sankey diagram of land cover classes transitions from 1986 to 2003 and 2020 for the most significant classes in each biome (forest, grassland, pasture, soybean, agriculture, and wetland – for the Pantanal biome).

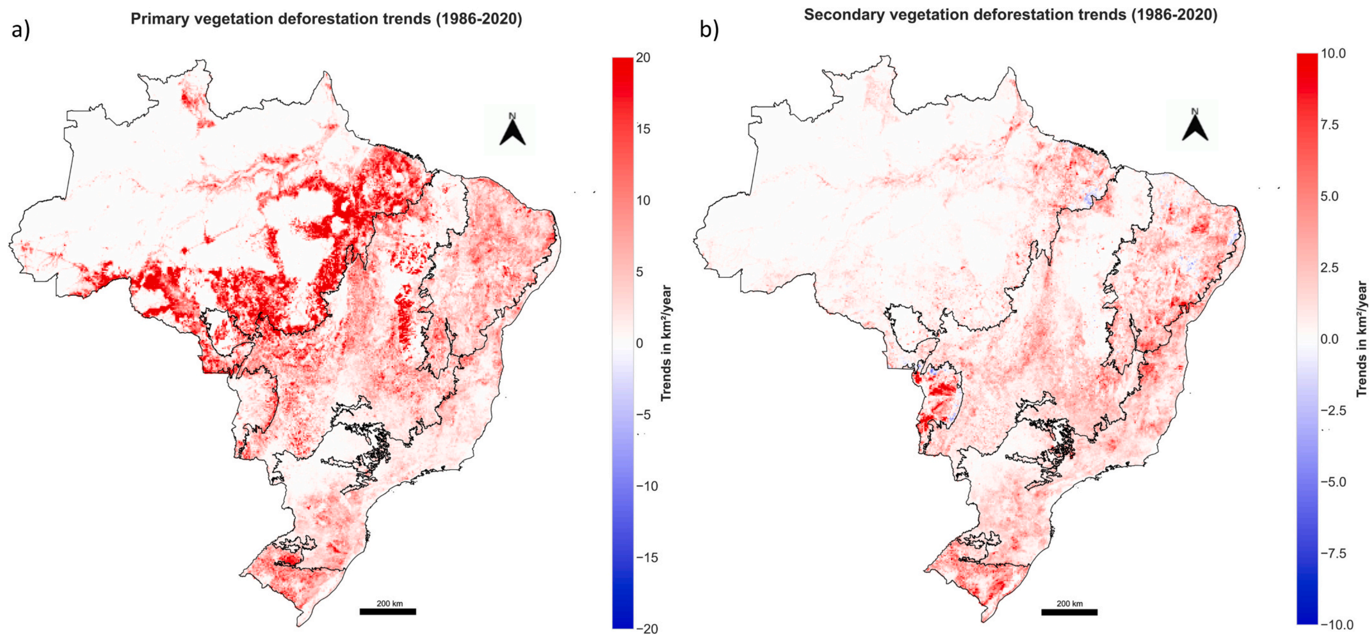


**Fig. 7.** Trend analysis maps in a 10 km × 10 km grid for (a) deforestation in primary vegetation and (b) deforestation in secondary vegetation. Colors indicate deforestation trends in $km^2$ $year^{-1}$, where red tones represent increasing trends and blue tones decrease trends.

2016, of which soybean as a direct driver accounted for 5 %, and soybean as a latent driver accounted for 4 %. The high exportation prices led soy cultivation to expand rapidly in Brazil's Midwest and northern Cerrado (Castro, 2014; Spera et al., 2016). New agricultural frontiers in the Cerrado have been created, for instance, in southeastern Goiás State, the central region of Mato Grosso State, and the MATOPIBA region, a continuous zone formed by the states of Maranhão, Tocantins, Piauí, and Bahia (Santos and Naval, 2020). Soy has not expanded into the Caatinga region, possibly due to low rainfall availability and lack of irrigation infrastructure. At the cost of its NV, Brazil is now the world's largest exporter of soybeans (Santos and Naval, 2020).

The Caatinga is the only uniquely Brazilian biome, one of the world's most populated and biologically diverse semi-arid regions. However, it is considered one of the least known biomes in Brazil, despite its significant LUCC and unsustainable use of land resources (Santos et al., 2011; Beuchle et al., 2015,). The Caatinga semi-arid climate and heterogeneous vegetation cover consist of scrubland and seasonally dry forest (Leal et al., 2005; Santos et al., 2011).

Compared with different biomes, irrigation is more significant in Pampa, where lowlands have been used for irrigated rice production for over a century (Giacomeli et al., 2022). Annually, 1 million ha are cultivated with flooded rice (Giacomeli et al., 2022). The recent boom in soybean production shifted these wetlands to rainfed soybean, and approximately 33 % of the lowlands have been rotated with other grain crops (Theisen et al., 2017; Giacomeli et al., 2022). Expanding irrigated agriculture in Brazil, particularly in the Cerrado and Amazon regions, can significantly increase agricultural production (Lathuillière et al., 2016; ANA, 2021). However, this expansion may also lead to conflicts over water use. While the current percentage of irrigated areas in these biomes or the total Brazilian area remains relatively small, there are projections for significant and accelerated growth of these areas in the coming decades (Lathuillière et al., 2016; Multsch et al., 2020).

Zalles et al. (2019) showed an increase in cropland extent in all Brazilian territory from 2000 (26.0 Mha) to 2014 (46.1 Mha). The MATOPIBA region more than doubled in cropland extent. The states of Goiás, Minas Gerais, and São Paulo each experienced more than 50 % increase in croplands, with 79 % on pasture, and 20 % from the conversion of natural vegetation (Zalles et al., 2019) We report a similar pattern in our study, with increasing soybean and other crops replacing pasture areas. Spatiotemporal dynamics of cropland expansion reflect market conditions, land use policies, and other factors (Zalles et al., 2019).

Much has been discussed about forest preservation in protected areas in Brazil. Deforestation is typically lower in protected areas than in unprotected lands (Nolte et al., 2013; Pierri Daunt and Sanna Freire Silva, 2019; Folharini et al., 2022). Although much more present in the Amazon biome, we can see the importance of protected areas in preventing deforestation in all of Brazil (Figure SI7 and Figure SI8), with a clear pattern of deforestation around but not in conservation units. Qin et al. (2023) showed that Protected Areas (PAs) increased by 52 % in forested areas in the Brazilian Legal Amazon between 2000 and 2021, accounting for only 5 % of net forest loss and 12 % of total forest loss. They also showed that total forest loss in PAs subject to "strict conservation" decreased by 48 % in the years after establishment, compared with an 11 % decline in protected areas subject to "sustainable use." In the Atlantic Forest biome, Pierri Daunt and Sanna Freire Silva (2019) showed that ~95 % of the state parks in the state of São Paulo are still covered by mature forest (84.3 %). These show the importance of protected areas and how legislation towards conservation is an effective tool to ensure forest preservation and regeneration.

Past clearing of NV and subsequent abandonment is essential in regeneration dynamics, especially in the Amazon and the Caatinga. Guimarães et al. (2022) analyzed the agricultural potential of 72,000 $km^2$ mapped in 2019, where the secondary vegetation is six years old or older, demonstrating that 73 % of this area is classified as having "low agricultural suitability," abandoned, and undergoing regeneration. Under the right conditions, natural regeneration can restore these areas to the forest. These naturally regenerating forests sustain biodiversity, provide a wide range of ecosystem goods and services, and support rural economies and livelihoods (Chazdon et al., 2020).

LUCC transitions in Brazil are complex and ongoing, and extensive literature has described the multifaceted deforestation processes in the country (Grecchi et al., 2013, 2014; Beuchle et al., 2015; Garcia and Ballester, 2016; Zalles et al., 2019; Zalles et al., 2021; Alencar et al., 2020; Song et al., 2021; da Silva and Bates, 2022; Lapola et al., 1979). Efforts have been made to mitigate deforestation and promote regeneration; however, primary vegetation cover has experienced significant declines, primarily due to pasture expansion. The high rates of

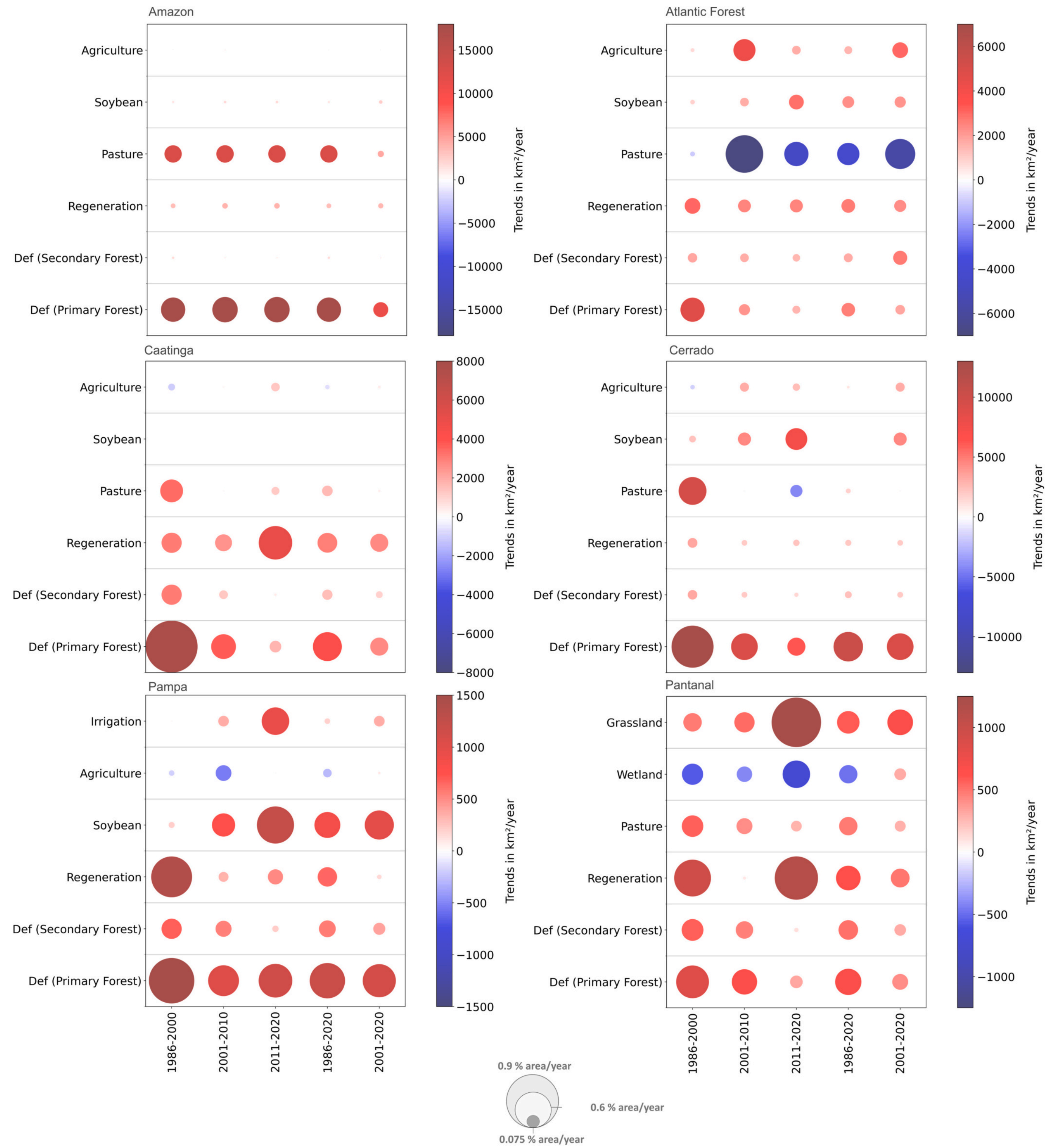


**Fig. 8.** Summary of trend analysis of the different land cover types for Brazilian biomes (panels a-f). Each panel shows the Mann-Kendall trend test results for significant land cover classes in each biome. Colors indicate the trends in $km^2$ $year^{-1}$, where red tones represent increasing trends and blue tones decrease trends. Circle sizes show the intensity of LUCC trends as the percentage of the area (land cover class area concerning the biome area) per year.

deforestation in secondary vegetation in the Pantanal and Pampa may be due to the inclusion of the grassland class. Notably, the southern Amazon region has been heavily impacted by deforestation since 1985, with the conversion of primary forests into pasturelands. Our analysis reveals that pasture extensification in the Amazon has been concentrated on the borders of Conservation Units (Figure SI9). While some instances of pasture expansion can be observed within certain protected areas, such as the *Ilha do Bananal* in the Cerrado biome (State of Tocantins), *Triunfo do Xingu* in Pará State (Amazon biome), and *Reentrâncias Maranhenses* in Maranhão (located on the Amazon and Cerrado borders), the impact is particularly prominent along the borders of these areas. However, rates of secondary regeneration also increased. This observation highlights the importance of examining the relationship between protected area boundaries and LUCC dynamics, specifically in terms of regeneration and intensification processes.

Results also show substantial reforestation in the Caatinga due to permanent abandonment and the evolution of agriculture by secondary vegetation. If managed properly, these areas can naturally regenerate into forests, supporting biodiversity, providing ecosystem services, such as carbon sequestration and watershed protection, and benefiting rural communities (Koch and Kaplan, 2022; Maeda et al., 2023). As expected by forest transition theory, it has not been widespread. The forest transition in Brazil requires a multi-faceted approach that addresses the underlying economic and social drivers of deforestation while promoting sustainable land use practices.

### 4.1. Uncertainties and limitations

In terms of data quality and limitations, there are some factors to consider regarding the use of remote sensing data for LUCC analysis. Although remote sensing data can provide valuable insights into LUCC, there are limitations to the accuracy and resolution of these data (Congalton et al., 2014; Verburg et al., 2011). In this study, we used annual land-use and land-cover maps from MapBiomas Collection 6. While the general reported accuracy of MapBiomas classification is 87.4 %, there are still potential limitations (Sales et al., 2022). Despite the high overall accuracy of MapBiomas classification, there are still misclassification errors that can affect the accuracy, such as difficulty to distinguish certain land cover types from others, for instance, in the Cerrado, due to the complexity of natural vegetation gradients, distinguishing anthropogenic land-use classes from natural cover is not always straightforward (Alencar et al., 2020). Seasonal variations, different vegetation strata, and deciduousness during the dry season also pose challenges for remote sensing-based change detection (Alencar et al., 2020). Additionally, classification errors in land-use and land-cover maps can complicate the analysis of time series data, which can erroneously overestimate the intensity of LUCC in a given pixel. To minimize these, we generated three different maps, each with a different definition of "deforestation". However, it's important to note that some of these maps may still overestimate or underestimate deforestation, especially in areas where there are unrealistic transitions or unexpected land-cover transitions, for instance in the northwest of the Amazon biome (between Roraima and Amazonas States), north of Caatinga biome, and some areas between the Cerrado and Atlantic Forest transition, at Minas Gerais State (green areas in Fig. 2).

While our study sheds light on some drivers and patterns of LUCC in Brazil, there are limitations to our understanding of these processes. Results showed significant deforestation in the Amazon, Pantanal, and Cerrado biomes, as well as intensification of land use in other biomes such as the Atlantic Forest and Caatinga, however, it is important to investigate other factors that contribute to these changes that were not accounted for in our study. Therefore, it is important to acknowledge potential uncertainties in the drivers of LUCC and their implications for our study's conclusions. Nonetheless, our study provides a valuable foundation for understanding the dynamics of LUCC in the different Brazilian biomes, which is crucial for informed decision-making and sustainable land management in Brazil.

Intensification of land use from pasture to cropland, particularly soybean, and other crops, was observed mainly in the Atlantic Forest, Cerrado, and Pampa biomes. This shift in land use is often driven by economic factors, such as the demand for food and biofuels, and can have significant environmental consequences. In addition, monoculture systems such as soybean cultivation can reduce biodiversity and ecosystem resilience. Despite these challenges, intensification can also have benefits such as increasing agricultural productivity and reducing the need for new land conversion (Cohn et al., 2014; Bowman et al., 2012; Garcia et al., 2017; Latawiec et al., 2014). However, our analysis did not capture intensification within a specific crop, such as shifts from single to double cropping observed in soybean areas of the Cerrado, where a second crop of corn or cotton follows the soybean (Neill et al., 2017). This highlights the need for future research to further explore the specific impacts of different crops on LUCC, including potential trade-offs and synergies between different land uses. Understanding these interactions could provide valuable insights into the ecological consequences of intensification.

### 4.2. Implications for management

Primary vegetation in most of Brazil's biomes is still being cleared at high rates (+38,212.13 $km^2$ $year^{-1}$ in all territory), especially in the Amazon and Cerrado borders, highlighting the urgent need for sustainable land management practices to mitigate the negative impacts of land-use change. Reforestation efforts, such as planting native trees and restoring degraded areas to their natural state, can be effective in combating deforestation. However, it is essential to promote policies that prevent the deforestation of secondary vegetation, which we show is happening significantly in all biomes and is currently not protected by national policies aimed at curbing deforestation (Heinrich et al., 2021). Heinrich et al. (2021) showed that maintaining the 2017 secondary forest area in the Amazon had the potential to contribute ~5.5 % to Brazil's 2030 net emissions reduction target. Implementing legal mechanisms to protect and expand secondary forests whilst supporting old-growth conservation is, therefore, key to realizing their potential as a nature-based climate solution.

Additionally, implementing sustainable farming practices can help reduce environmental impacts. Alternative agricultural systems can better sustain ecosystem diversity and function (Maeda et al., 2023). As such, agroforestry practices can promote biodiversity by integrating plant and animal life to improve natural conditions (Maeda et al., 2023). Promoting these sustainable practices may significantly benefit the environment and local communities, through ecosystem services maintenance, soil fertility, and improving food security. In addition, the implementation of legal mechanisms to motivate sustainable land use practices can help ensure that this approach can be more comprehensive and can contribute to long-term solutions for conservation.

Policies and regulations can be extremely important to reduce the rate of deforestation and promote sustainable land management (OECD, 2020). Increasing the enforcement of existing regulations that limit deforestation, such as the Forest Code, and reinforcing penalties for illegal deforestation is crucial for the preservation and maintenance of Brazil's biodiversity. Moreover, provide incentives to farmers to adopt sustainable land use practices, and invest in reforestation efforts, such as payments for ecosystem services. These policy interventions could help create a regulatory environment that encourages sustainable land management practices and promotes the preservation of Brazil's biomes.

On the other hand, the expansion of soybean and other crops in the country has significantly increased agricultural productivity, contributing to its position as a leading global agricultural exporter. However, this expansion has also led to challenges such as deforestation itself, soil degradation, and the loss of biodiversity (Henders et al., 2015) due to the clearing of natural vegetation. Furthermore, it is also important to consider the impact of irrigation on water resources and ecosystems (Lathuillière et al., 2016; Multsch et al., 2020). While irrigation has enabled increased crop yields and boosted agricultural production, it also leads to water depletion and can have negative impacts on downstream water users and aquatic ecosystems (Multsch et al., 2020). Effective policies and regulations are needed to balance the benefits of agricultural expansion with the need to protect natural resources and promote sustainable land management practices.

## 5. Conclusions

This study analyzed deforestation dynamics in the Brazilian biomes, including deforestation of primary and secondary vegetation, regeneration, and changes within anthropic land covers. Deforestation in primary vegetation showed positive trends (+38,212.13 $km^2 year^{-1}$)

between 1986 and 2020. Pastures expanded in the Amazon, Cerrado, and Pantanal. However, pastures peaked in the early 2000s in the Caatinga and Cerrado, with constant declines in the Atlantic Forest due to replacement by soybean and other agriculture. We found evidence of agricultural intensification across Brazil: soybean area increased in most biomes, except in the Pantanal, where grasslands and pastures have replaced drying wetlands. Agriculture in the Pampa biome remained approximately stable, but the soybean area increased. In the Atlantic Forest, natural vegetation remained relatively constant, pasture decreased, and agriculture and soybean increased, especially after 2003. We find limited evidence of a “forest transition” to net reforestation: all biomes had net clearing of primary and secondary deforestation since 1985, where NV was replaced mainly by pasture, soybean, and other agriculture.

In a previous study, we conducted a systematic review (Caballero et al., 2022), analyzing and demonstrating the significant impacts that LUCC has had on surface-atmosphere interactions in the six biomes of Brazil. Most studies were of the Amazon and Cerrado biomes, with few in the Atlantic Forest, one in Caatinga, and none in the Pampa. We found that the consequences of both intensification and extensification on the ecosystem and land-atmosphere functions have yet to be comprehensively documented for all biomes. Overall, LUCC in Brazil can have significant impacts on land-atmosphere interactions and the services that ecosystems provide. While this study provides the LUCC quantification and understanding foundation, future research will quantify how land-atmosphere interactions have changed during land cover change across Brazilian biomes.

## CRediT author contribution statement

**C.B.C.:** Conceptualization, Data Curation, Formal Analysis, Validation, Visualization, Writing – First Redaction, Writing – Review and Editing. **T.W.B.:** Formal Analysis, Validation, Visualization, Writing – First Redaction, Writing – Review and Editing. **N.V.:** Formal Analysis, Validation, Visualization, Writing – Review and Editing. **T.A.P.W:** Formal Analysis, Writing – Review and Editing. **A.R.:** Conceptualization, Data Curation, Formal Analysis, Visualization, Writing – Review and Editing. All authors discussed the results and commented on the manuscript.

## Declaration of competing interest

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

## Data availability

MapBiomas data is freely available at https://plataforma.brasil.mapbiomas.org/. The assets generated for deforestation and regeneration can be accessed in Google Earth Engine via:-

Deforestation in primary vegetation: users/cassiacaballero/deforestation/def_PRIMARY-

Deforestation in secondary vegetation: projects/et-brasil/assets/cassia/def_SECONDARY

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166323.

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