BIOGEOGRAPHY: SCIENTIFIC PERSPECTIVES, CONSERVATION AND CLIMATE CHANGE

# Analysis of environmental changes in Brazil in the 21st cen-tury based on bioclimatic regimes: the case of the Amazon, the Cerrado and the Caatinga

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# Analysis of environmental changes in Brazil in the 21st cen-tury based on bioclimatic regimes: the case of the Amazon, the Cerrado and the Caatinga


## ABSTRACT

The objective of this work is to make a current environmental assessment of Brazil and its projection for 2070, with an emissions scenario that will continue to increase throughout the 21st century. Based on the maps of types of bioclimatic regimes in Brazil, its contemporary circumstances and its situation for an RCP 8.5 scenario for the year 2070 are established according to the CCSM4 climate change model of the Fifth Assessment Report of the IPCC in 2014. The current bioclimatic regimes were associated with the main eco-regions existing in Brazil: the Amazon, the Cerrado and the Caatinga. Using the Global Forest Wacht platform, the deforestation processes in this country and their causes are indicated, as well as the period of high intensity fires in September 2024. Finally, based on current biolimatic data, the changes in the Cerrado, the Catinga and the Amazon are shown.


**Keywords:** Bioclimatic regimes. Climatic change. Anthropization. Deforestation. Brasil.


# Análisis de los cambios ambientales en Brasil en el siglo XXI a partir de regímenes bioclimáticos: el caso de la Amazonía, el Cerrado y la Caatinga


## RESUMEN

El objetivo de este trabajo es hacer una valoración actual ambiental de Brasil y su proyección para 2070, con un escenario de emisiones que continué aumentando durante todo el siglo XXI. A partir de los mapas de tipos de regímenes bioclimáticos de Brasil se establece su situación actual y su situación para un escenario RCP 8.5 para el año 2070 según el modelo de cambio climático CCSM4 del Quinto Informe de Evaluación del IPCC en 2014. Se relacionan los regímenes bioclimáticos actuales con las principales ecorregiones existentes en Brasil: Amazonia, Cerrado y Caatinga. Con la plataforma *Global Forest Wacht* se muestran los procesos de deforestación en éste país y sus causas, así como el periodo de incendios de gran intensidad en septiembre 2024. Finalmente, a partir de los datos biolimáticos actuales se muestran los cambios en la Amazonia, el Cerrado y la Caatinga.


**Palabras clave:** Régimen bioclimático. Cambio climático. Antropización. Deforestación. Brasil.


# Análise das mudanças ambientais no Brasil no século XXI a partir de regimes bioclimáticos: o caso da Amazônia, do Cerrado e da Caatinga


## RESUMO

O objetivo da pesquisa é fazer uma avaliação dos problemas ambientais que estão ocorrendo atualmente no Brasil e a sua projeção para 2070, com um cenário de emissões que continuará aumentando ao longo do século XXI. A avaliação ocorreu com base em mapas dos tipos de regimes bioclimáticos atual do Brasil, e a sua situação em um cenário RCP 8.5 para o ano de 2070, segundo o modelo de mudanças climáticas CCSM4 do

Quinto Relatório de Avaliação do IPCC em 2014. Foram realizadas corelações entre os regimes bioclimáticos das principais ecorregiões existentes no Brasil: Amazônia, Cerrado e Caatinga. Com a plataforma Global Forest Wacht, foram apresentados os processos de desmatamento e suas causas, bem como o período de incêndios de alta intensidade em setembro de 2024. Por fim, com base em dados biolimáticos, foram apresentados as mudanças que ocorreram na Amazônia, no Cerrado e a Caatinga.
**Palavras-chave:** Regime bioclimático. Mudanças climáticas. Antropização. Desmatamento. Brasil.

## THE CURRENT BIOCLIMATIC REGIMES OF BRAZIL AND FOR THE RCP 8.5 SCENARIO FOR THE YEAR 2070

Brazil spans the eastern region of South America, covering a vast area of 8,515,770 km$^2$. This large expanse supports a wealth of biomes that stablishes Brazil as one of the most biodiverse countries globally, featuring the iconic Amazon rainforest—the most diverse ecosystem on Earth. Brazil is also home to other essential and emblematic biomes, including the Cerrado, the Caatinga, and Atlantic Forest. The country's long history, from colonization to the present day, has deeply impacted these ecosystems. Nonetheless, extensive natural territories remain, areas whose size and complexity mean we still have much to learn.

Brazil stands as a leader in environmental research, which has significantly advanced our understanding of these biomes. Foundational reference works like those by Toledo Rizzini (1997) and Ab'Saber (2003), along with more recent studies on individual biomes, such as the Amazon (Cochrane; Cochrane, 2012), Cerrado (Sano et al., 2008), Caatinga (Cardoso da Silva; Leal; Tabarelli, 2017; Leal; Tabarelli; Silva, 2003), and Atlantic Forest (Thomas, 2008), exemplify the breadth of this knowledge.

Today, the impacts of climate change bring an additional layer of uncertainty to these ecosystems, potentially intensifying the challenges posed by anthropogenic pressures and reshaping the trajectory of their future.

This study aims to examine the impacts of climate change on Brazil's natural environments and identify the stressors likely to exacerbate these effects in the future, using climate models and current deforestation data. To map Brazil's Types of Bioclimatic Regimes (TBR), we apply the analytical and cartographic methodology developed by Cámara, Díaz Del Olmo and Martínez Batlle (2020), which provides a multi-scalar and multi-temporal view of plant formations based on bioclimatic regimes.

The bioclimatic regime mapping was conducted using a complex raster map calculator in ArcGIS. In collaboration with the University of Zaragoza (Serrano-Notivoli; Longares; Cámara, 2022), we developed an R script that automates the process. This analysis uses the WorldClim global climate database (Hijmans et al., 2005; Fick; Hijmans, 2017), which interpolates data from 9,000 to 60,000 weather stations at a spatial resolution of 1 km$^2$ (Hijmans et al., 2005; Fick; Hijmans, 2017). For deforestation, fire data, and deforestation causes, we used the open-access Global Forest Watch platform (Hansen et al., 2013), which allows detailed studies down to country, state, and protected area levels.

The TBR methodology distinguishes 27 types of regimes, informed by Montero de Burgos and González (1974) bioclimatic diagrams and Thornthwaite and Mather (1955) and Thornthwaite, Mather and Carter (1957) water balances. The classification is based on bioclimatic principles from Schimper (1903), Warming (1909), and Huguet del Villar (1929), categorizing thermal conditions as follows:

- **Thermophylia:** Found in areas without thermal restrictions and with minimal annual temperature variability, typical of tropical climates.
- **Eurythermophylia:** Characterized by significant temperature variations across the year and within each month, without vegetative paralysis due to temperature. This is common in subtropical regions.
- **Cryophiylia:** Occurs in environments with short to moderate cold-induced vegetative dormancy (1-5 months), typical of deciduous forests in temperate climates.
- **Mesocryophylia:** Found in areas with prolonged cold dormancy (6-9 months), influencing plant distribution, with dominance by conifers or mixed forests. This regime is typical of subpolar regions.
- **Hypercryophylia:** Characterized by 10 to 12 months of thermal dormancy, which limits the growth of woody species, this regime is typical of tundra environments in polar regions.

In terms of humidity, varying types of regimes emerge based on water limitations:

- **Ombrophylia:** Occurs in areas without annual water deficit, where monthly precipitation consistently exceeds 60 mm.
- **Mesophylia:** Experiences limited water availability, which may lead to periodic soil moisture deficit but without causing vegetative dormancy.
- **Tropophylia:** Defined by seasonal soil water deficits lasting 1 to 4 months, leading to temporary vegetative dormancy; forests in these regions typically include deciduous species adapted to water stress.
- **Xerophylia:** Conditions result in a longer vegetative dormancy of 5 to 8 months, favoring shrubs and succulents with thorny features.
- **Hyperxerophylia:** Characterized by severe water scarcity with 9 to 12 months of dormancy, resulting in sparse shrub vegetation, succulents, or even vegetation-free desert landscapes.

Figure 1 illustrates these findings in Brazil, showing 10 bioclimatic regimes out of a possible 27, highlighting the country's bioclimatic diversity. Present regimes include tropical ombrophyllo, mesophyllo, tropophyllo, xerophyllo, and ombro tropophyllo types across central and northern Brazil. In the south, subtropical euriytherm ombrophyllo, mesophyllo, and tropophyllo eregimes prevail, while cold temperate cryo ombrophyllo and cryo mesophyllo regimes appear in mountainous areas. Table 1 presents the relationship between these bioclimatic regimes, Köppen climate classifications, and corresponding ecoregions along with their representative plant formations.

For the 2070 climate change scenario, this study uses the Representative Concentration Pathway (RCP) of greenhouse gas concentrations from the IPCC's Fifth Assessment Report (Intergovernmental Panel on Climate Change, 2014). This approach incorporates radiative forcing alongside shared socio-economic pathways (see Table 2).

In May 2019, the $CO_2$ concentration recorded at Hawaii's Mauna Loa Observatory was 415.26 ppm. By 2023, it reached 419.68 ppm, and in August 2024, it was 422.99 ppm (National Oceanic & Atmospheric Administration, 2024). The annual average $CO_2$ growth rates at Mauna Loa from 2020 to 2024 were 2.28, 2.39, 1.81, and 3.36 ppm, respectively. If this trend continues at an average growth rate of 2.4 ppm/year, $CO_2$ levels could reach 533 ppm by 2070 and 605 ppm by 2100. With the historical growth rate accelerating—from




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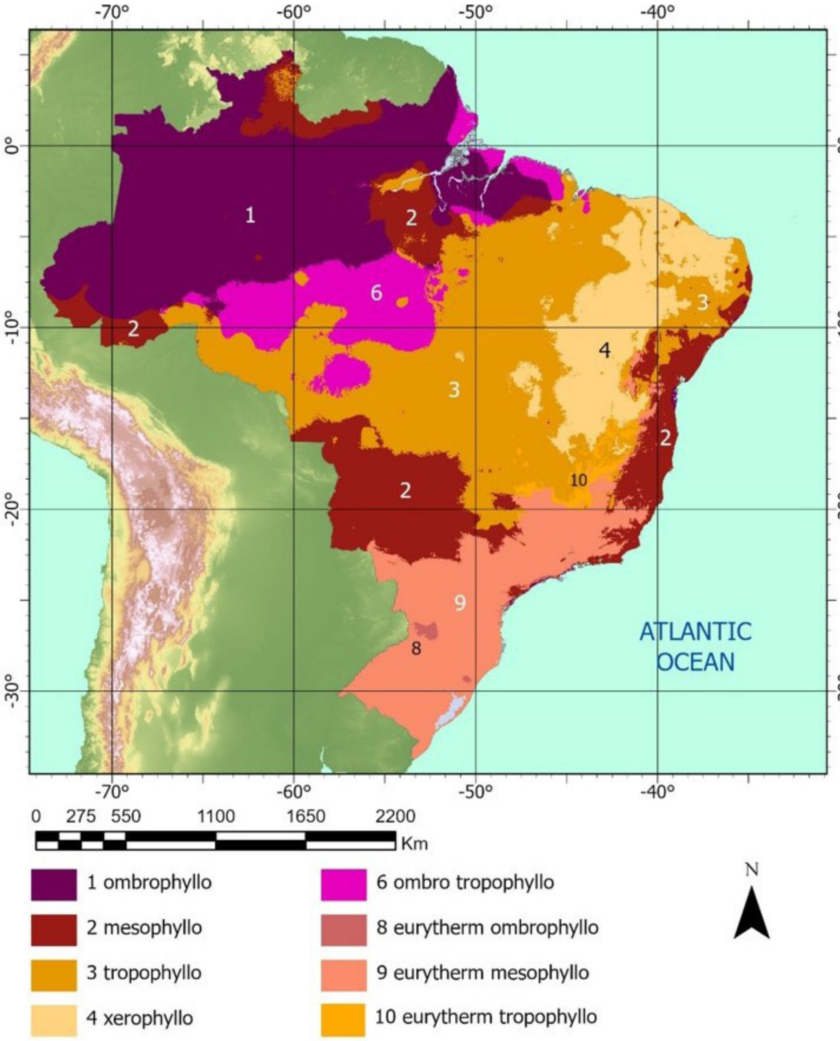


**Figure 1** – Bioclimatic regimes of Brazil today.
**Source:** own elaboration based on continuous database of climate data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

**Table 1** – Equivalence between the types of biclimatic regimes of Cámara, Díaz Del Olmo and Martínez Batlle (2020), the Köppen classification and the main ecoregions of Brazil.

| Bioclimatic regime | Köppen equivalence | Ecoregion | Plant formations |
|---|---|---|---|
| Ombrophyllo | Af, As | Tropical Moist Forests | Amazon forest<br>Northern Atlantic Mata |
| Ombro tropophyllo and ombro xerophyllo | Am | Tropical Moist Broadleaf Forests | Amazonian forests with semi-deciduous species |
| Mesophyllo | Aw | Tropical Moist Broadleaf Forests | Dry Atlantic forests<br>Tapajós-Xingu humid forests |
| Mesophyllo/ Tropophyllo | Aw | Tropical Grasslands, Savannas and Shrublands | Cerrado forest and savannas |
| Tropophyllo/ Xerophyllo | BSh | Deserts and Xeric Shrublands | Forests, savannahs and shrub formations of Caatinga |
| Eurytherm mesophyllo | Cfa | Tropical and Subtropical Moist Broadleaf Forests | Atlantic forest of the upper Paraná<br>Araucaria forests<br>Southern Atlantic Mata |

**Source:** Own elaboration based on information from the World Wildlife Fund for Nature (2024).

**Table 2** – Radiative forcing, radiative forcing trend and $CO_2$ concentration in ppm in 2100.

| | FR ($W/m^2$) | FR trend | $CO_2$ in 2100 in ppm |
|---|---|---|---|
| RCP 2.6 | 2.6 | decreasing in 2100 | 421 |
| RCP 4.5 | 4.5 | stable in 2100 | 538 |
| RCP 6.0 | 6.0 | growing | 670 |
| RCP 8.5 | 8.5 | growing | 936 |

**Source:** IPCC Fifth Report (Intergovernmental Panel on Climate Change, 2014).

0.94 ppm in 1959 to 3.36 ppm in 2024—the RCP 8.5 scenario may occur between 2070 and 2100 unless significant intervention is implemented.

The climate model used for this study is the Community Climate System Model 4 (CCSM4), supported by the NSF and DOE. CCSM4 is a coupled climate model that simulates the Earth's climate system through five interconnected models of the atmosphere, ocean, land, land ice, and sea ice. These are coordinated by a central component, CAM, which enables comprehensive research into Earth's past, present, and future climate states.

The bioclimatic regime model results show a map (see Figure 2) indicating that tropical regimes could extend southward, reducing subtropical eurytherm areas by 561,363 km$^2$ (see Table 3). A significant decline is noted in ombrophilic areas (Amazon rainforest) by about 1.5 million km$^2$, and mesophyllo areas by 763,681 km$^2$, while the ombro tropophyllo regime (Köppen's Am) is projected to expand by 613,701 km$^2$. This regime describes humid forests with a water stress period of one to three months, encouraging semi-deciduous species and light-adaptive palms during the dry season. Aridity is also expected to increase, with expansions in tropophyllo (95,642 km$^2$), xerophyllo (1.8 million km$^2$), and hiperxerophyllo (Köppen BWh) regions, the latter appearing with an additional 22,380 km$^2$. These projections align with Beck et al. (2018) for the Köppen classification for the range 2070-2100 (see

**Table 3** – Variation in Km$^2$ extension between current bioclimatic regimes and the RCP 8.5 scenario for 2070.

| | current Km$^2$ | RCP 8.5 Km$^2$ | difference Km$^2$ |
|---|---|---|---|
| ombrophyllo | 2,165,396.08 | 695,513.38 | -1,469,882.69 |
| meosphyllo | 1,372,406.84 | 608,725.54 | -763,681.29 |
| tropophyllo | 2,385,938.13 | 2,481,580.78 | 95,642.64 |
| xerophyllo | 758,915.77 | 2,577,751.99 | 1,818,836.22 |
| hiperxerophyllo | 0.00 | 22,380.33 | 22,380.33 |
| Ombro tropophyllo | 691,026.41 | 1,304,728.06 | 613,701.65 |
| Ombro xerophyllo | 0.00 | 246,759.97 | 246,759.97 |
| Eurytherm ombrophyllo | 17,768.34 | 12,560.67 | -5,207.67 |
| Eurytherm mesophyllo | 1,037,904.25 | 558,628.01 | -479,276.23 |
| Eurytherm tropophyllo | 80,267.13 | 272.68 | -79,994.46 |
| Eurytherm xerophyllo | 2,093.31 | 0.00 | -2,093.31 |
| Cryo ombrophyllo | 59.57 | 0.00 | -59.57 |
| Cryo mesophyllo | 9.23 | 0.00 | -9.23 |

**Source:** Own elaboration based on continuous database of climatic data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

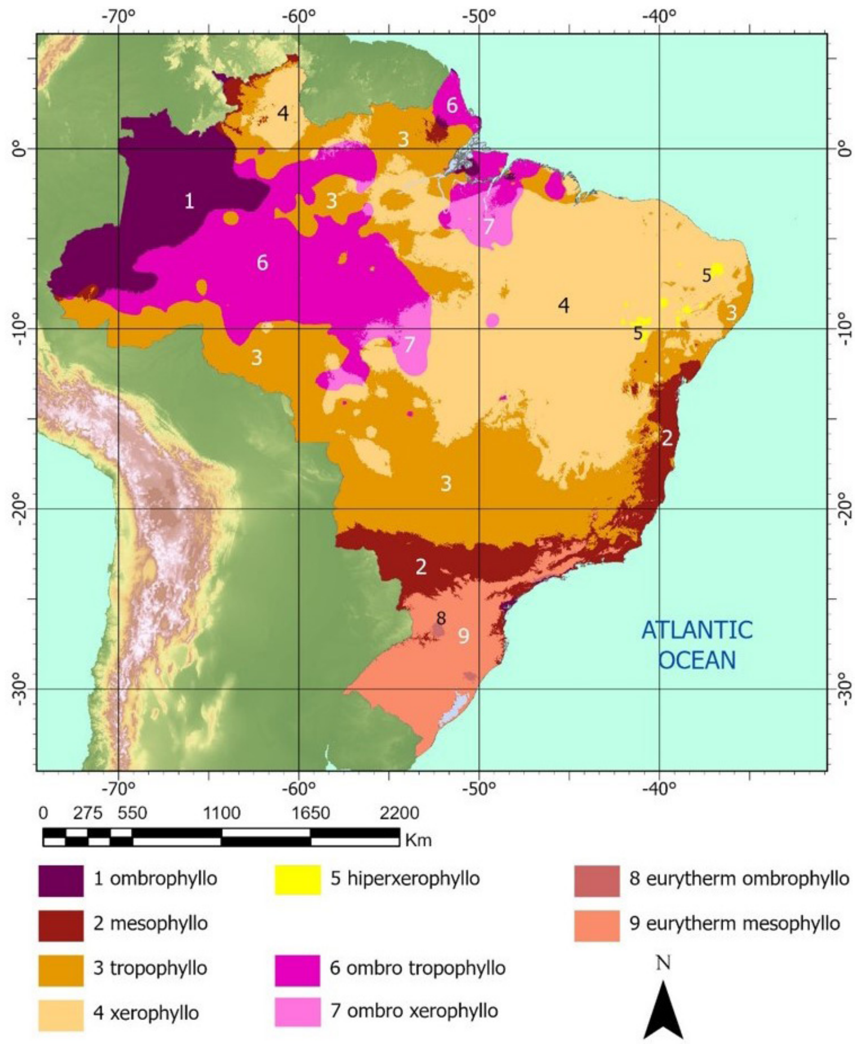


**Figure 2** – Bioclimatic regimes of Brazil for the RCP 8.5 scenario in 2070.
**Source:** own elaboration based on continuous database of climatic data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

Figure 3), in which the Af climate is restricted to the west as is the ombrophile, given the extension of the Am (ombrotropophyllo) where the very humid forests used to be. Also the extension of the Aw climate (tropophilic and xerophyllo) and the appearance of the BWh (hyperxerophyllo) in the northeast.

## DEFORESTATION IN BRAZIL AND KEY DRIVERS IN THE 21ST CENTURY

In 2010, Brazil had 492 million hectares of natural forest, representing 59% of its land area. Between 2001 and 2023, the country lost 31.1 million hectares of humid primary forest (ombrophyllo forest, Köppen Af), accounting for 45% of its total tree cover loss in this period. Overall, tree cover declined by 68.9 million hectares, equivalent to a 13% decrease since 2000 and resulting in 37.7 Gt of $CO_2$ emissions. In 2023 alone, Brazil lost 2.73 million hectares of tree cover, associated with 1.80 Gt of $CO_2$ emissions (Hansen et al., 2013) (see Figure 4).

The significant loss of 5,378,844 hectares in 2016 is notable (see Figure 5), primarily driven by deforestation in the Amazon region, as illustrated in Figure 6.

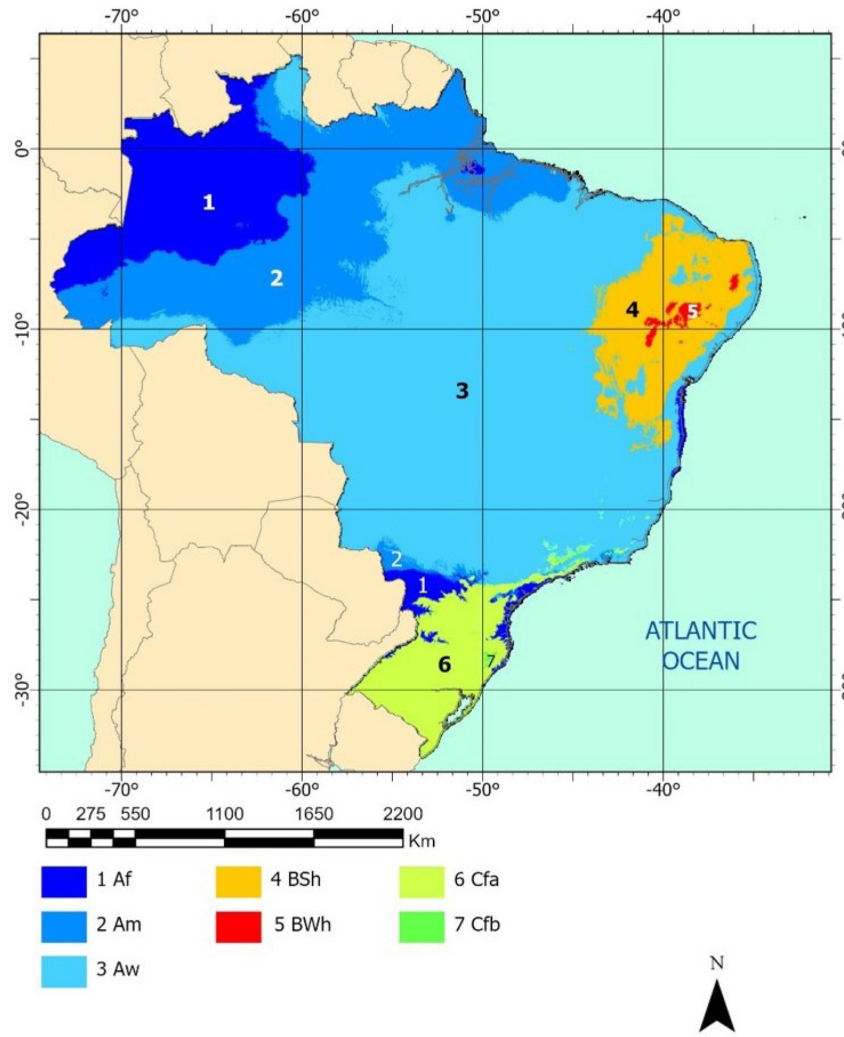


**Figure 3** – Köppen-Geiger Climate Classification Scenario for Brazil (2071-2100).
**Source:** Beck et al. (2018).

Figures 5 and 6 indicate a total deforestation loss of 68 million hectares across Brazil during the 21st century, with 6.31% of this occurring in the state of Amazonas. Notably, only in 2016, 5 million hectares were lost, 10% of which were within Amazonas.

Analyzing the drivers of these losses, the Global Forest Watch platform identifies five main factors. Among these, three are particularly significant: deforestation for commodity cultivation, deforestation due to shifting agriculture, and forestry (replacing natural forests with tree plantations). Urbanization and forest fires, while contributing less in terms of total area, are also relevant factors (see Figure 7).

If the causes of deforestation are analyzed by type of land use, specifically for staple crop cultivation, forestry, and shifting agriculture, data from the past 23 years of the 21st century (see Figure 8) indicates that staple crop cultivation has the largest impact, accounting for 42.8 million hectares of deforested land. Shifting agriculture follows, with 16.7 million hectares, and forestry at 7 million hectares. Additional causes, though smaller in extent, have irreversible effects (Figure 9); for instance, urban expansion covers 53,000 hectares, and natural fires account for 156,000 hectares, which are considered alongside provoked fires discussed further below.

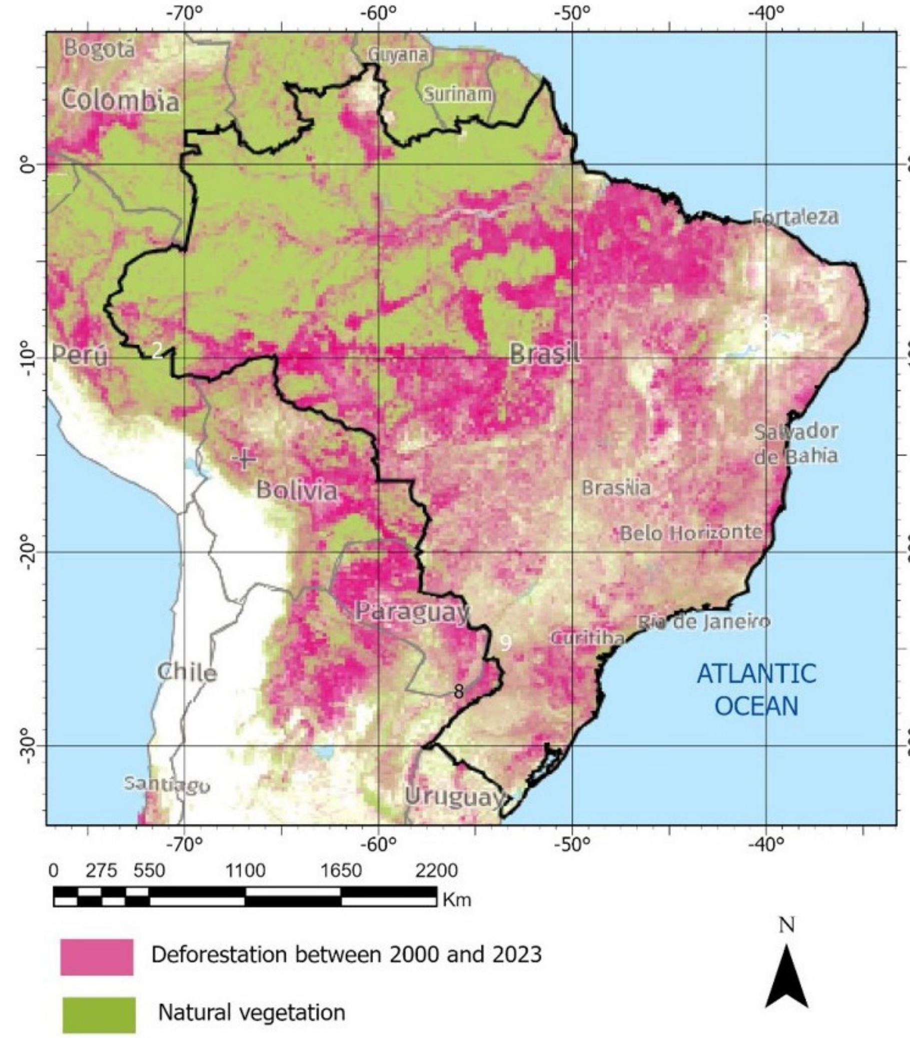


**Figure 4** – Loss of forest mass in Brazil between 2000 and 2023.
**Source:** Hansen et al. (2013). Accessed via Global Forest Watch (2024).

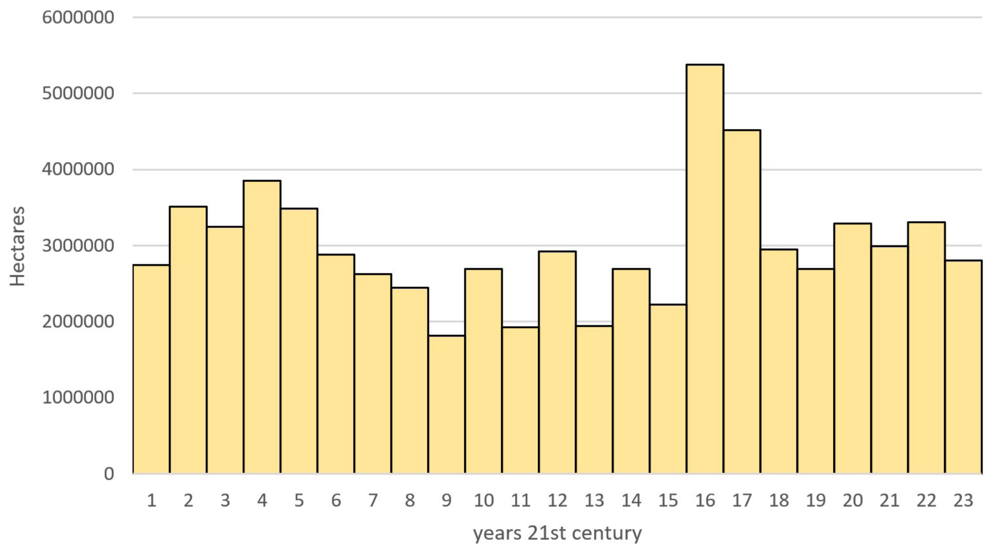


**Figure 5** – Loss of tree cover in Brazil in the 21st century.
**Source:** Global Forest Change 2000-2022 Data Download (Hansen et al., 2013).

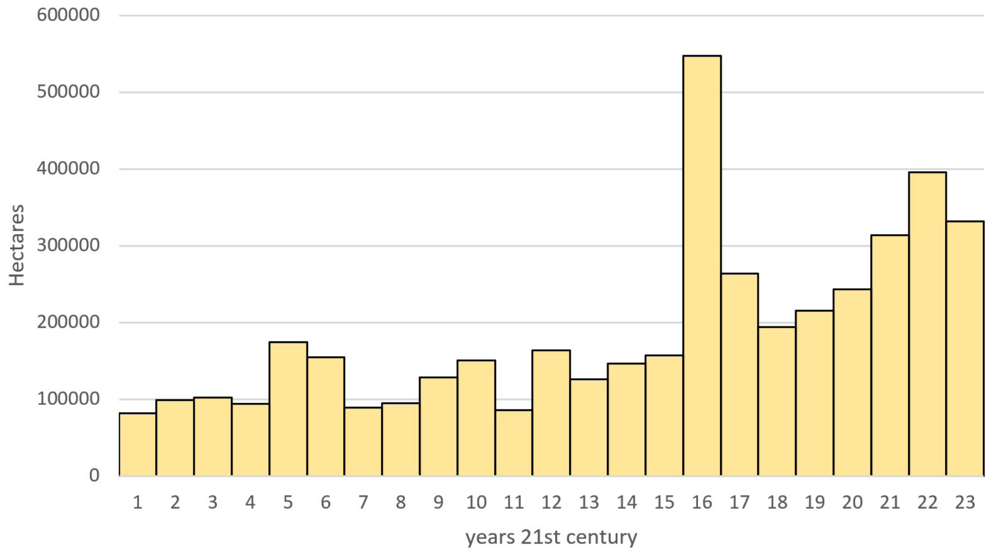


**Figure 6** – Loss of tree cover in the Amazon in the 21st century.
**Source:** Global Forest Change 2000-2022 Data Download (Hansen et al., 2013).

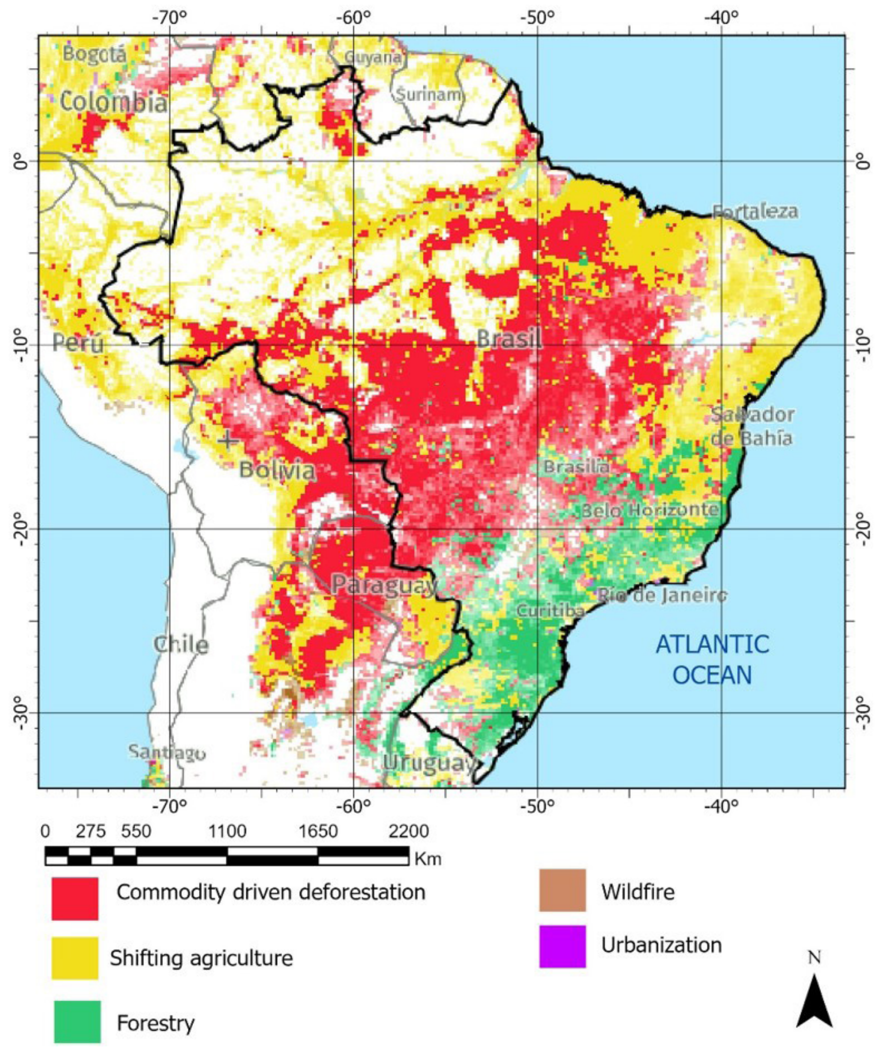


**Figure 7** – Map of main causes of deforestation in Brazil during the 21st century.
**Source:** Curtis et al. (2018).

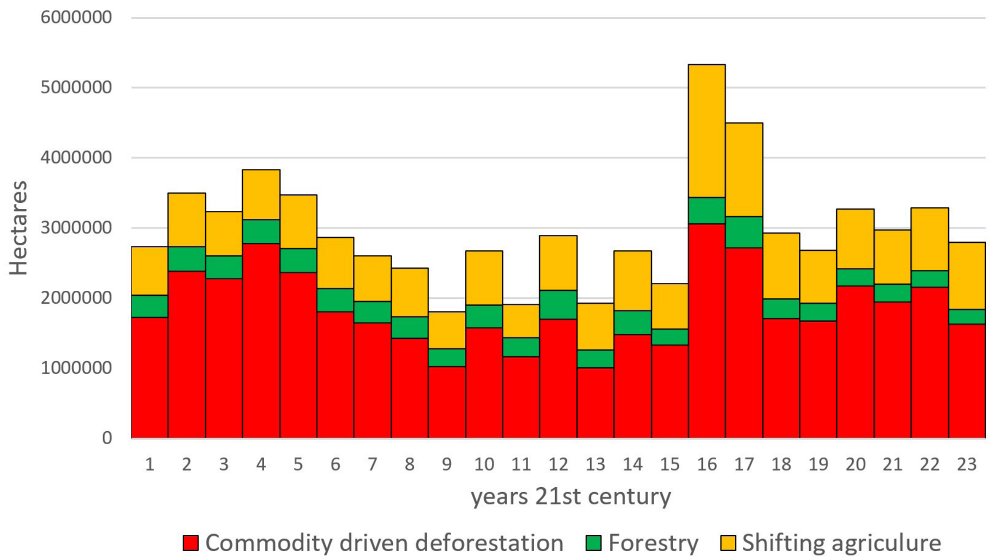


**Figure 8** – Largest causes of deforestation in Brazil in the 21st century.
**Source:** Curtis et al. (2018).

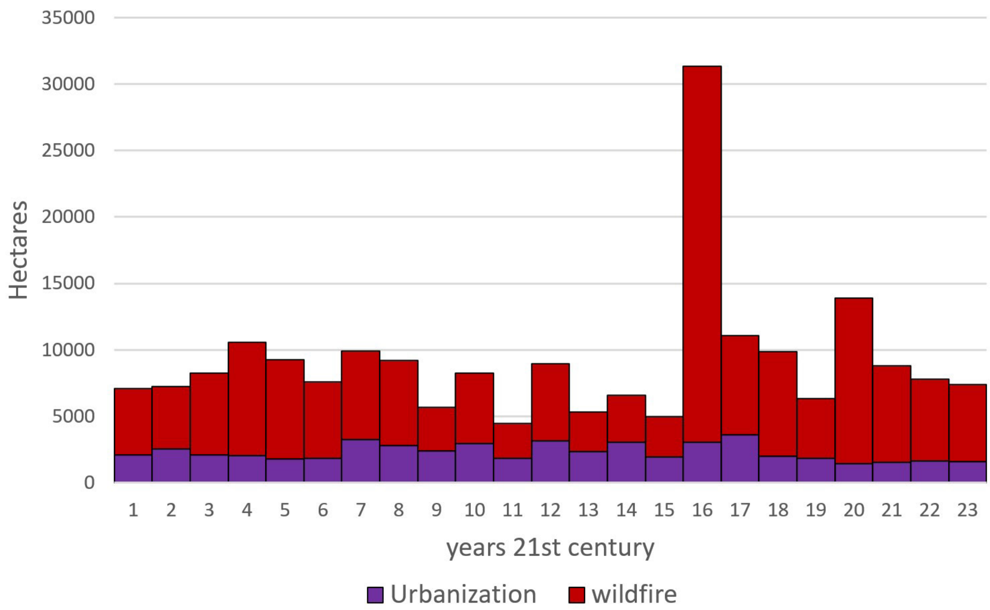


**Figure 9** – Largest causes of deforestation in Brazil in the 21st century.
**Source:** Curtis et al. (2018).

The loss of tree cover in Brazil due to fires from 2000 to 2023 (Figure 10) reached 10.6 million hectares (representing 15% of total tree cover loss), adding to the 58.4 million hectares attributed to other causes. During this period, 2016 saw the greatest annual loss due to fires, with 2.38 million hectares affected, constituting 44% of that year's total tree cover loss.

One of the most intense moments has taken place between August 25 and September 25, 2024 (Figura 11). This data was derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m thermal anomalies (NASA/NOAA satellites), which complement the Moderate Resolution Imaging Spectroradiometer (MODIS) for fire detection. For this period,


**Figure 10** – Intensity of tree cover loss due to fires between 2000 and 2023. Darker, greater intensity of loss.
**Source:** Tyukavina et al. (2022).

maps revealed a concentration of fires in central Brazil, particularly in the Mato Grosso and the Cerrado regions rather than the Amazon, as illustrated in Figure 10, covering data from the past 23 years. This map also shows a clear progression of deforestation along the Amazon River, from downstream to upstream.

## OBSERVED CHANGES IN BIOCLIMATIC REGIMES IN THE CAATINGA, CERRADO, AND AMAZON

After presenting the impacts of climate change and anthropogenic deforestation, this section focuses on climate change-driven environmental changes in three significant Brazilian biomes: the Amazon, the Cerrado, and the Caatinga, each exhibiting a spectrum from hyperhumid to arid conditions.

In the Amazon (refer to Figure 12 and Table 4), a marked decline is observed in the hyperhumid forest (ombrophyllo forest, Köppen Af), with an estimated loss of 1,315,379.17 km$^2$. Meanwhile, semi-deciduous and palm-dominated forests (ombro tropophyllo, Köppen Am) are expanding, covering 695,381.66 km$^2$. Aridification is also apparent along the eastern and


**Figure 11** – Concentration of fires between the months of August and September 2024 (Hansen et al., 2013).

**Table 4** – Changes in the extent of bioclimatic regimes between the current situation and the climate change scenario for RCP 8.5 for the year 2017 in the Amazon.

| | current Km² | RCP 8.5 Km² | difference Km² |
|---|---|---|---|
| ombrophyllo | 1,997,846.94 | 813,430.00 | -1,315,379.17 |
| mesophyllo | 337,674.85 | 41,810.00 | -302,596.26 |
| tropophyllo | 270,474.30 | 1,062,877.00 | 621,279.50 |
| xerophyllo | 0.00 | 291,887.00 | 244,893.19 |
| Ombro tropophyllo | 435,833.65 | 1,348,290.00 | 695,381.66 |
| Ombro xerophyllo | 0.00 | 66,476.00 | 55,773.36 |
| Euryterm ombrophyllo | 17.62 | 0.00 | -17. 62 |

**Source:** Own elaboration.

northern edges of the Amazon, where tropophyllo (621,279.50 km$^2$) and xeric bioclimatic regimes (244,893.19 km$^2$) are increasing, extending toward the Cerrado (savannas and forests) and the shrubby Caatinga. These findings can be compared with Beck et al. (2018) in Figure 3, highlighting significant environmental changes and posing risks of considerable biodiversity loss in both flora and fauna.

In the Cerrado region, environmental shifts are especially significant in the north and southwest. In the north, there has been a transition from a tropophyllo regime characterized by Köppen Aw-type forests and savannas, resulting in a loss of 329,544.94 km², to a xeric Köppen BSh-type regime with shrub formations more typical of the Caatinga biome, expanding by 774,411.26 km². In the southern areas, the subtropical euryterm meophyllo regime in mountainous regions is being replaced by a tropical mesophyllo and tropohyllo regime, which represents a substantial change in the local biocenosis and could lead to species substitutions. In the southwestern area of the Cerrado, cloud forest formations, primarily Cerrado forests, have retreated by 264,261.51 km², being replaced by a tropophyllo regime more typical of dry tropical forests and savannas (see Figure 13 and Table 5).

In the Caatinga, the most significant change is the near-total loss of the mesophyllo regime in mountainous regions, retreating by 62,674.14 km² and giving way to the tropophyllo regime. This

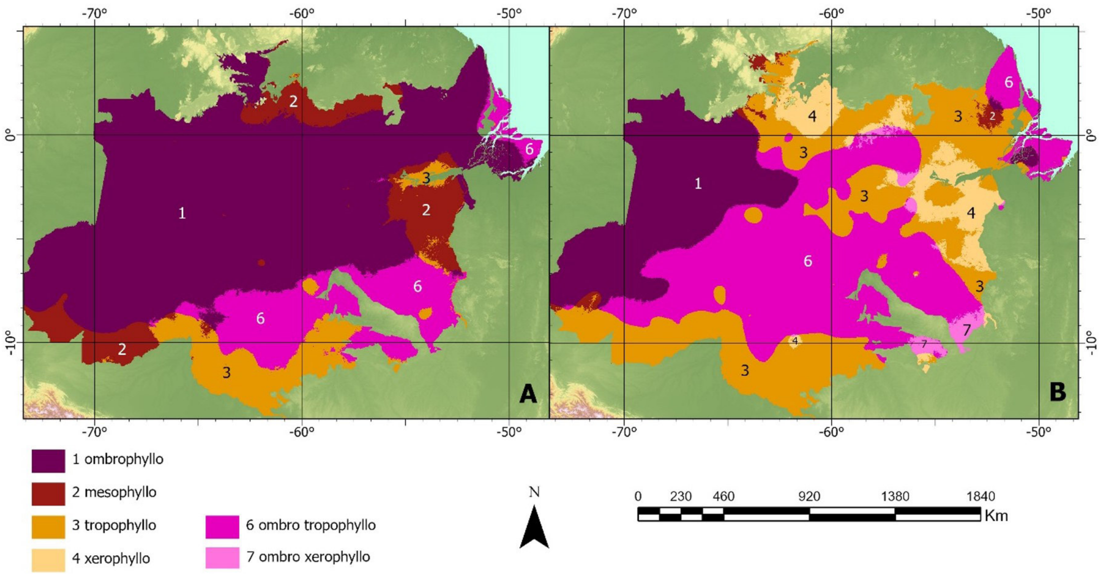


**Figure 12** – Current bioclimatic regimes (A) and bioclimatic regimes for the RCP 8.5 climate change scenario for the year 2070 (B) for the Amazon.
**Source:** own elaboration based on a continuous base of climatic data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

**Table 5** – Changes in the extent of bioclimatic regimes between the current situation and the climate change scenario for RCP 8.5 for the year 2017 in the Cerrado.

| | current Km² | RCP 8.5 Km² | difference Km² |
|---|---|---|---|
| mesophyllo | 369,918.46 | 105,656.95 | -264,261.51 |
| tropophyllo | 1,175,692.38 | 846,147.44 | -329,544.94 |
| xerophyllo | 172,323.89 | 946,735.15 | 774,411.26 |
| Ombro tropophyllo | 29,646.90 | 12,442.37 | -17,204.53 |
| Ombro xerophyllo | 0.00 | 12,648.76 | 12,648.76 |
| Euryterm mesophyllo | 130,868.06 | 6,808.49 | -124,059.57 |
| Euryterm tropophyllo | 52,143.01 | 160.25 | -51,982.76 |
| Euryterm xerophyllo | 6.71 | 0.00 | -6.71 |

**Source:** Own elaboration.

shift results in the replacement of semi-deciduous forests by dry tropical forests and savannas. On the surface of the eastern Brazilian shield, the tropophyllo bioclimatic regime also declines, losing 100,560.02 km$^2$ to an expanding xerophyllo regime. This transition replaces the subhumid Caatinga's dry forests and savannas with thorny shrublands characteristic of the arid Caatinga.

In areas currently dominated by the dry Caatinga (xerophyllo regime), a further shift is underway towards a hyperxerophyllo bioclimatic regime (Köppen BWh), leading to desert-like plant formations. These changes align with Köppen's projected climate map for the 2070-2100 scenario (see Figure 3). Additionally, the subtropical eurytherm regimes in mountainous areas are disappearing and being replaced by the tropophyllo regime (see Figure 14 and Table 6).

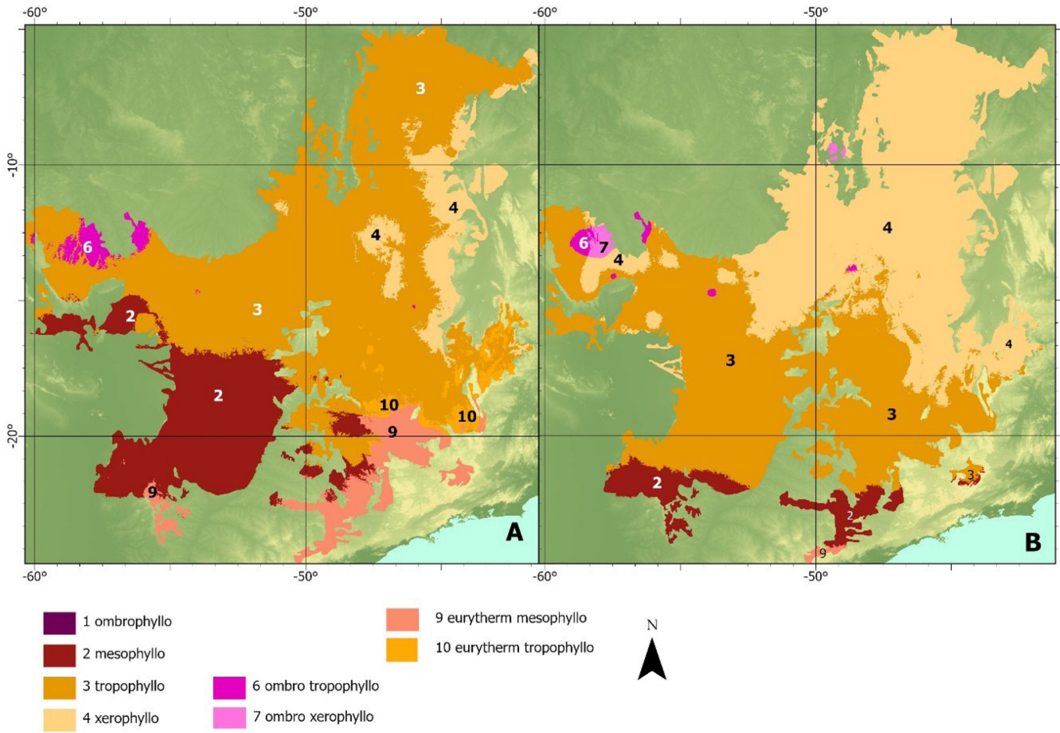


**Figure 13** – Current bioclimatic regimes (A) and bioclimatic regimes for the RCP 8.5 climate change scenario for the year 2070 (B) for the Cerrado.
**Source:** own elaboration based on a continuous base of climatic data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

**Table 6** – Changes in the extent of bioclimatic regimes between the current situation and the climate change scenario for RCP 8.5 for the year 2017 in Caatinga.

| | **actual Km$^2$** | **RCP 8.5 Km$^2$** | **diferencia Km$^2$** |
|---|---|---|---|
| mesophyllo | 68,354.17 | 5,680.03 | -62,674.14 |
| tropophyllo | 205,905.70 | 105,345.68 | -100,560.02 |
| xerophyllo | 549,904.93 | 706,010.11 | 156,105.18 |
| hiperxerophyllo | 0.00 | 22,380.33 | 22,380.33 |
| Euryterm mesophyllo | 11,007.68 | 18.46 | -10,989.22 |
| Euryterm tropophyllo | 3,444.10 | 0.00 | -3,444.10 |
| Euryterm xerophyllo | 839.00 | 0.00 | -839.00 |

**Source:** Own elaboration.

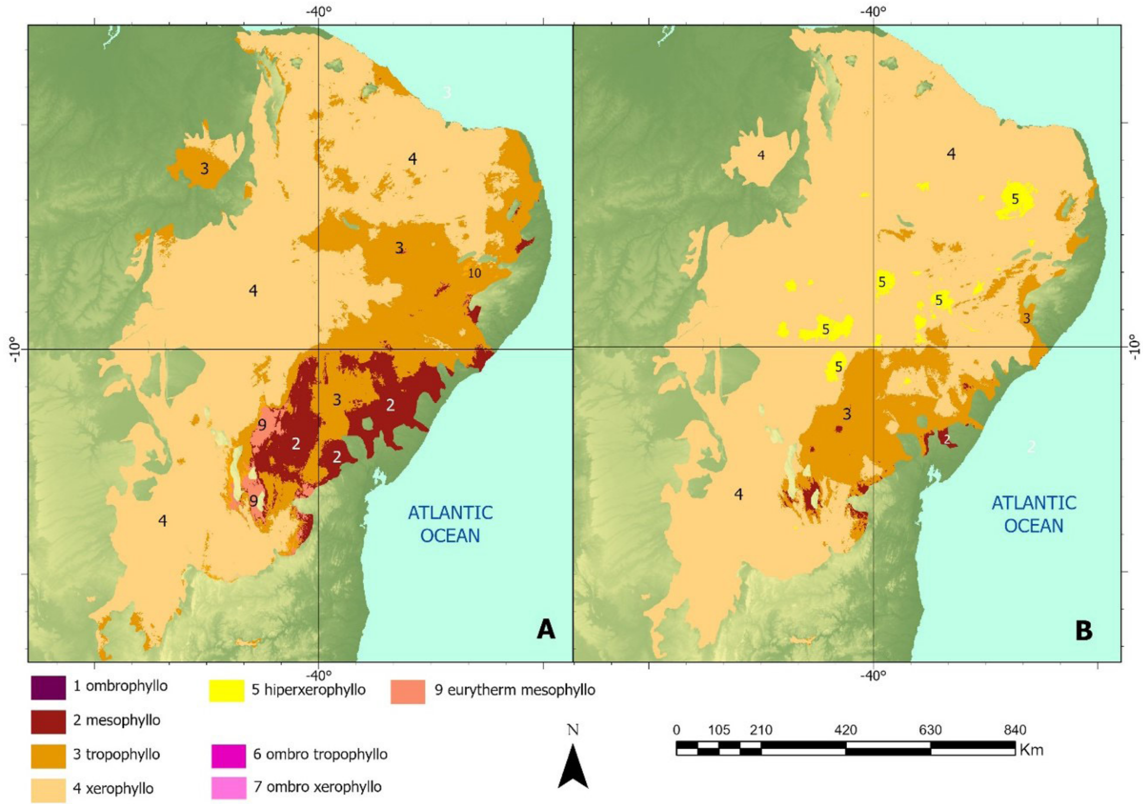


**Figure 14** – Current bioclimatic regimes (A) and bioclimatic regimes for the RCP 8.5 climate change scenario for the year 2070 (B) for Caatinga.
**Source:** own elaboration based on a continuous base of climatic data from Wordclim (Hijmans et al., 2005; Fick; Hijmans, 2017).

## CONCLUSIONS

Environmental changes in Brazil's forests throughout the 21st century, the primary focus of this study, have led to significant forest loss, totaling 68.9 million hectares of tree cover, of which 31.1 million hectares were primary humid forest. Critical years in this process, such as 2016, reflect the dominant impact of deforestation for staple crop production and shifting agriculture, primarily driven by the expansion of the agricultural frontier. This expansion has frequently involved direct clearing and burning of natural forests.

In addition to these anthropogenic pressures, climate change linked to global warming has intensified aridification, promoting an expansion of sub-arid and arid bioclimatic regimes by approximately 1.9 million hectares. This shift includes tropophyllo and xerophyllo bioclimatic zones, especially prominent in the Cerrado and Caatinga, but also evident in the Amazon, where 1.4 million hectares of very humid ombrophyllo forest have been lost. This work details these changes for the Amazon, Cerrado, and Caatinga biomes.

The Amazon is an internationally recognized ecological asset, and the Cerrado and Caatinga, while lesser-known, are experiencing a profound decline and remain vital national resources for Brazil. Beyond addressing climate change, urgent measures are required to halt agricultural frontier expansion; otherwise, projected bioclimatic impacts for the 2070 climate scenario could bring even more severe consequences.

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