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Historical and recent deforestation patterns in the Atlantic Forest from satellite monitoring system - PRODES

Padrões históricos e recentes de desmatamento na Mata Atlântica a partir do sistema de monitoramento por satélite - PRODES

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Abstract: The Atlantic Forest (AF) is a critical biodiversity hotspot and the second most deforested Brazilian biome proportional to its original area of natural vegetation. This work presents an exploratory spatial analysis of deforestation patterns from 1984 to 2022, using PRODES-MA data by the Brazilian Satellite Monitoring Program for the AF. During this period, 789600.587 km² of natural vegetation were deforested, being the majority (82%) of the 1309387 polygons with areas smaller than 0.199 km². A ranking of phytophysiognomies most affected by deforestation was provided based on the analysis of the following data: 2000 base map, historical series from 2004 to 2021, the 2022 deforestation map. The output shows that, Seasonal Semideciduous Forest accounted for 44%; 26%; and 28% respectively in 2000, within 2004 – 2021 and in 2022. Kernel density maps revealed deforestation concentration in 2022 in four regions: Bahia (BA), Minas Gerais (MG), Paraná (PR), and Santa Catarina (SC), mostly persistent throughout the historical series. Furthemore, spatial dependence analysis of deforestation by municipalities indicated positive autocorrelation and clusters consistent with density analysis. These regions with higher deforestation intensity are related to economic activities of some municipalities and their neighbors. Even though deforestation data from the PRODES-MA system are widely available, spatiotemporal analysis of its distribution highlighted priority areas useful for managing and planning conservation and recovery policies for AF.
Keywords: Spatial analysis. PRODES-MA methodology. Hotspot. Atlantic forest. Phytophysiognomy.

Resumo: A Mata Atlântica (MA) é o *hotspot* mais crítico de biodiversidade, sendo o segundo bioma brasileiro mais desmatado proporcionalmente à sua área original de vegetação natural. Este trabalho apresenta uma análise espacial exploratória dos padrões e tendências de desmatamento de 1984 a 2022, mapeados pelo Programa Brasileiro de Monitoramento por Satélite para a MA (PRODES-MA). Neste período foram desmatados 789.600,587 km² de vegetação natural, sendo a maioria (82%) dos 1.309.387 polígonos, com áreas inferiores a 0,199 km². As análises apresentaram um ranking de fitofisionomias mais atingidas pelos desmatamentos segundo os dados do mapa base de 2000; a série histórica de 2004 a 2021; e o último ano publicado em 2022. Os resultados mostraram que a Floresta Estacional Semidecídua representou 44 %; 26%; e 28% respectivamente em 2000, entre 2004 - 2021 e em 2022. Os mapas de densidade de kernel revelaram a concentração do desmatamento em 2022 em quatro regiões: Bahia (BA), Minas Gerais (MG), Paraná (PR) e Santa Catarina (SC), que foram, em sua maioria, persistentes na série histórica. Além disso, a análise de dependência espacial de desmatamento por municípios indicou autocorrelação positiva e agrupamentos, concordantes com a análise de densidade. Essas regiões de maior intensidade de desmatamento

relacionam-se às atividades econômicas de alguns municípios e seus vizinhos. Ainda que os dados de desmatamento do sistema PRODES-MA estejam disponíveis para amplo acesso, a análise espaço temporal de sua distribuição evidenciou áreas prioritárias úteis para a gestão e planejamento de políticas públicas de conservação e recuperação da MA.
Palavras-chave: Análise espacial. Metodologia PRODES-MA. Hotspot. Mata atlântica. Fitofisionomia.

1 INTRODUCTION

The Atlantic Forest (AF) is a morphoclimatic and phytogeographic domain, part of the tropical and subtropical humid broadleaf forest biome (OLSON et al., 2001). In Brazil, it extends along the coast, covering tropical and subtropical climates, in highly heterogeneous relief conditions, resulting in a high level of endemism and richness species. According to the Brazilian Institute of Geography and Statistics - IBGE (2020), its remaining natural vegetation cover has been reduced to 12% of its original area, which is highly fragmented as a result of a historical process of human occupation in the region. Not by chance, nowadays the original area of the AF is home for 72 % of the Brazilian population and concentrates the largest and most populated urban areas in the country. Such fragmentation issues are aggravated by the socioeconomic context, the regional agricultural dynamics, and the high levels of urbanization (FONSECA, 1985; RANTA et al., 1998).

This diverse mosaic of habitats within multiple types of land use makes the AF one of the most distinctive biogeographic units in the entire Neotropical Region (PRANCE, 1982). It was recognized as an important global biodiversity hotspot and one of the priorities for biodiversity conservation around the world (MYERS et al., 2000; MITTERMEIER et al., 2011).

In this context, the remaining forests in the AF require monitoring and preservation actions as high rates of deforestation have threatened what is left of them (NASCIMENTO; SANTOS; GOUVEIA, 2016). According to National Institute for Space Research - INPE´s official deforestation data (PRODES-MA), in the last three years a total loss of 2750.350 km² of native vegetation in the biome was identified (2020-2022) (TERRABRASILIS, 2024). Remote sensing data, allows detecting where, when, and how deforestation occurs, based on continuous and synoptic land cover information. Then, possible to assess the current coverage status of forests, and their changes along the time, supporting the formulation of more effective conservation and restoration strategies (AMARAL; CURSINO; ALMEIDA, 2023; MESQUITA JÚNIOR et al., 2007).

To address the National Climate Change Policy with accurate information on deforestation in Brazil and to establish a monitoring deforestation system to all Brazilian Biomes, the Ministry of Environment (MMA) instituted the Environmental Monitoring Program of the Brazilian Biomes (PMABB) (Ordinance nº. 365, 11/27/2015) (BRASIL, 2015). This program allowed INPE to extend the methodology developed first to the Deforestation Monitoring Program by Satellites – PRODES to Amazonia and Cerrado biomes (INPE, 2018; INPE, 2019) to the further Brazilian biomes: Atlantic Forest, Caatinga, Pampa and Pantanal. The PRODES Brazil established a biennial inventory of deforestation maps from 2000 to 2016, and annual from 2017 until 2022 (INPE; FUNCATE, 2019). Historical databases of deforestation increments to all Brazilian biomes are public and can be accessed in TerraBrasilis platform that was developed to enable analysis, visualization and consultation (ASSIS et al., 2019). Since 2023, the PRODES Atlantic Forest project (PRODES-MA) has been continued by INPE's team as part of the Monitoring Program by Satellites of the Brazilian Biomes (BiomasBR) initiative.

The PRODES-MA provides consistent deforestation baseline data from 2000 whose construction adopted satellite images dating back to 1984. However, in order to understand deforestation dynamics more in-depth analyses are required rather than solely annual deforestation area estimates and visualization of respective maps. The key challenge is to build a temporal analysis of the spatial distribution and behavior of deforestation patterns. Therefore enabling the discernment of trends and identification of significant changes among regions, localities and adjacent patterns. Neighboring municipalities tend to exhibit similar deforestation behaviors, implying spatial autocorrelation, as the type of occupation or economic activity in one locality can affect neighboring regions (BROWN; BROWN; BROWN, 2016). Thus, an analysis of the

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historical series of PRODES-MA (2000 to 2021) in comparison with recent occurrences (2022) can provide a broader understanding of deforestation in the AF. Considering that historical and consistent data are available from PRODES-MA, to better understand the deforestation in the AF, we question:

a) what are the main characteristics of deforestation in the AF regarding the distribution and location of deforested areas? Where are the biome's deforestation hotspots? Which phytophysiognomies are mostly affected by deforestation?;

b) considering the municipal context, are there significant spatial patterns of deforestation occurrence in the AF? In this case, what is the nature of deforestation clustering in the territory?

To answer the proposed questions, we first explain the PRODES deforestation data, then, we explore the deforestation spatial distribution over twenty years (2000 to 2021) and estimate the intensity of deforestation in the different phytophysiognomies in the AF. Finally, we detail the recent (2022) deforestation spatial patterns and autocorrelation. This work highlights PRODES-MA's potential to generate valuable information for conservation strategies. Also, by identifying the most affected areas and highlighting deforestation patterns, we provide useful information to indicate priority areas for monitoring, protection and restoration, contributing to improving monitoring, as well as planning strategies for the restoration and preservation of native vegetation in the AF.

This paper is an extended version of Molinez et al. (2023), presented in XVII Brazilian Symposium on GeoInformatics (GEOINFO 2023).

2 METHODOLOGY

Deforestation data from PRODES-MA was accessed from TerraBrasilis, pre-processed, and analyzed in terms of size, distribution, phytophysiognomy, and spatial dependence. Deforestation polygons were analyzed considering their number and area frequency. The spatial distribution was first discussed based on maps of deforestation density distribution (Kernel density), and the assessment of deforestation patterns was observed considering their phytophysiognomies, and spatial correlation analyses (Moran's Index). The analyses of the number and area of polygons, the incidence of deforestation on phytophysiognomies, and the Kernel density map were carried out considering three time periods: the 2000 map, which consolidates all deforestation recorded from 1985 to 2000; the historical series available from 2004 to 2021; and the most recent data released, referring to 2022. The spatial autocorrelation analysis was performed using the most recent PRODES-MA 2022 deforestation data.

2.1 The PRODES-MA deforestation mapping

In PRODES, deforestation corresponds to the removal of the original vegetation cover, whether forest or non-forest physiognomies in the AF, regardless of the class of use or cover that followed the deforestation. Mapping is based solely on the evident removal of native vegetation (INPE; FUNCATE, 2019). The classes and criteria mapping are described in an Interpretation Key, which guides the deforestation classification. Mapping protocols and procedures follow consolidated methods from PRODES Amazonia (INPE, 2018) and PRODES Cerrado (INPE, 2019).

Annually, deforestation areas larger than 1 hectare (ha) are identified through visual interpretation of satellite images, at 1:75000 scale. The current spectral pattern of native vegetation is compared with the pattern of the previous year's image, which may vary according to the type of soil, phytophysiognomy types, climate, and historical context in the different sub-regions of the biome. The suppression of native vegetation has been mapped based on Landsat series images (30 m), composition R5G6B4 up to 2022. In 2023 mapping, PRODES-MA used MSI/Sentinel-2 images (20 m) and band composition R8G11B4. Once deforestation is mapped, this area will not be observed again in subsequent years. Deforestation limits, obtained year by year, will compose what is called the "deforestation mask" for mapping the following year. This "mask" contains the accumulated boundaries of all previously deforestation-mapped areas. Therefore, agreeing with PRODES methodology, PRODES-MA does not detect deforestation in secondary forest areas (INPE; FUNCATE, 2019).

Deforestation interpretation and mapping are supported by the TerraAmazon software system, which systematizes and manages geographic databases, and the results are then made available on the web portal

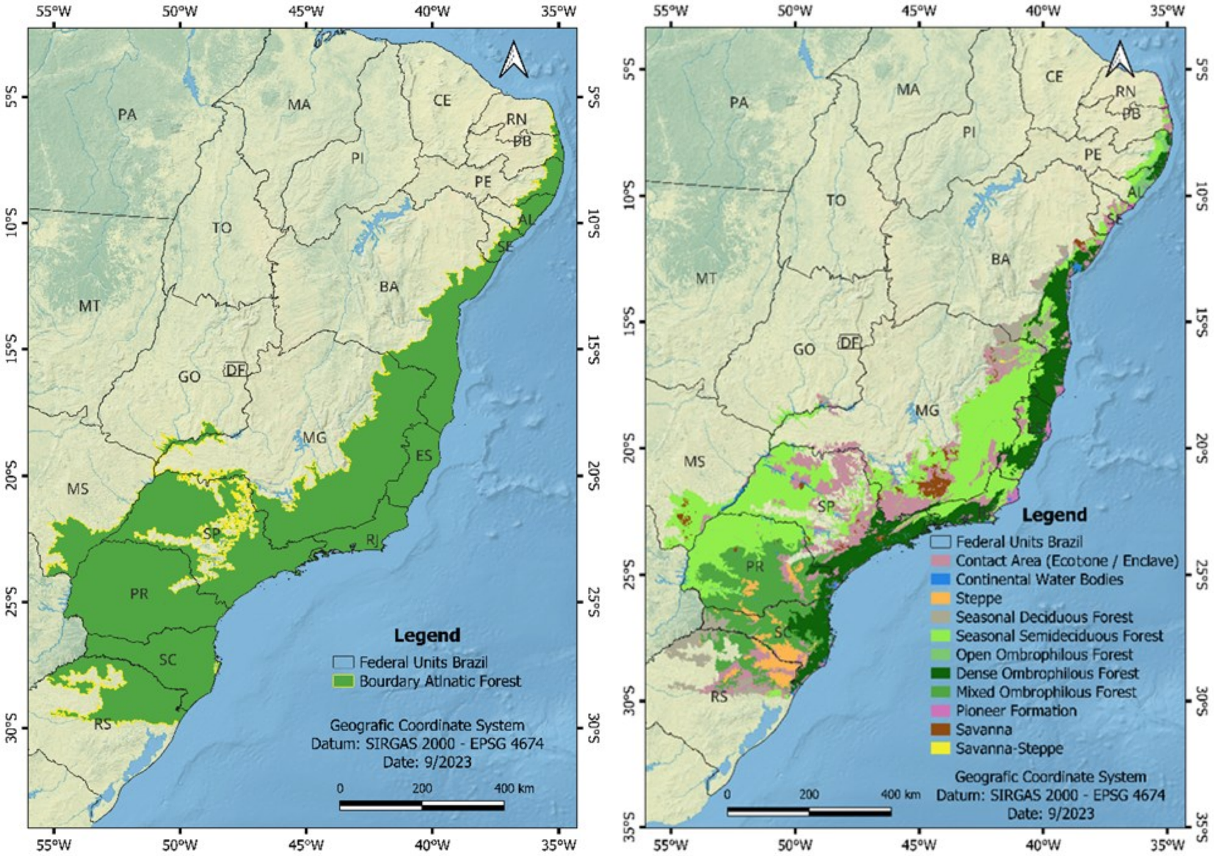
TerraBrasilis (TERRABRASILIS, 2024).

2.2 Study area

The study area corresponds to the AF biome, whose geographical boundaries were defined by the Brazilian Institute of Geography and Statistics - IBGE in 2019 at 1:250000 scale (Figure 1-A). With 1110182 km², the AF biome comprises 3082 municipalities of 15 federative units: Alagoas (AL), Bahia (BA), Espírito Santo (ES), Goiás (GO), Mato Grosso do Sul (MS), Minas Gerais (MG), Rio de Janeiro (RJ), São Paulo (SP), Paraíba (PB), Pernambuco (PE), Paraná (PR), Santa Catarina (SC), Sergipe (SE), Rio Grande do Norte (RN), and Rio Grande do Sul (RS). Due to its latitudinal extent, the AF exhibits a diversity gradient of phytophysiognomies (IBGE, 2012), reflecting the environmental complexity of soil categories, terrain, forested and non-forested formations, and associated ecosystems (Figure 1-B).

Seasonal Deciduous and Semideciduous Forests are further inland, subject to two distinct climatic periods that cause leaf fall in the dry season, however, in the Semideciduous Forest, the loss of leaves is less pronounced. Open Ombrophylous Forest, predominant near the northeastern coast, has lower tree density and may have a drier season, while Dense Ombrophilous has a high density of trees, with humidity maintained by regular rain throughout the year. The Mixed Ombrophilous Forest, or "araucaria forest", is a transition between the previous two, presenting intermediate density and moderate variation in rainfall, being a typical vegetation of the Southern Plateau region, with floristic disjunctions in refuges in the Serras do Mar and Mantiqueira (IBGE, 2012).

Figure 1 – A) Atlantic Forest Biom’s limit in Brazil; B) Phytophysiognomies of the Atlantic Forest Biome.



Elaboration: The authors (2023).

The AF also has Pioneer Formation phytophysiognomies, which are coastal areas composed of sandy soil, sparse vegetation, and patches of Savanna, characterized by the shared dominance of tree and herbaceous species. Savanna-Steppe grassland plant typologies with a thorny woody layer, do not show clear tree dominance, while the phytophysiognomy of the Steppe region is characterized by continuous herbaceous vegetation, extending from the Cerrado region to the broad South American pampas. Finally, in the AF biome, there, there are also areas of ecotones resulting from contact between two or more border phytophysiognomies

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(IBGE, 2012).

2.3 Data and methods

The main database for this study is the deforestation vectors of the AF, which includes the following vector classes: 1) cumulative deforestation, comprising the complete mapping of native vegetation loss up to 2000; 2) annual increment – polygons depicting annual native vegetation loss mapped from 2004 to 2022; 3) cloud and unobserved areas, which include polygons of cloud, cloud shadow, and terrain shadow; 4) hydrography; 5) residual. Residual class in PRODES corresponds to areas where deforestation occurred in any previous year but was not mapped at that date due to identification challenges. For this study, we only used the cumulative deforestation layers (2000) and the annual increment layer (from 2004 to 2022).

Due to spatial clipping for publication based on state boundaries and scene origin, the deforestation polygons in TerraBrasilis might exhibit areas of less than 1 ha. In this study, polygons smaller than 1 ha (the project's minimum area) were excluded to avoid bias in the analysis of polygon areas. These geometries, which are less than 1 ha in size, collectively sum up to 14 km², constituting less than 0.002% of the total deforested area in the historical series (789600.587 km²).

The limit of the biome (IBGE, 2019) was prepared and used to cut out the vegetation map with the phytophysiognomies classes (IBGE, 2021), and the political division limits, which contain the municipal boundaries and federal units (IBGE, 2022). To analyze deforestation within the phytophysiognomies, the first level of IBGE legend (legend_1) was utilized, with the classes: Open Ombrophilous Forest; Dense Ombrophilous Forest; Mixed Ombrophilous Forest; Seasonal Deciduous Forest; Seasonal Semideciduous Forest; Savanna; Savanna-Steppe; Steppe; Pioneer Formation; Contact Areas and Continental Water Bodies (Figure 1-B).

Deforestation vector data from 2000 to 2022, a total of 1309387 deforestation polygons, were used in the analysis of the general deforestation patterns. Basic statistics of the polygons were calculated, as well as their intersection area to the phytophysiognomies of the AF. The general deforestation distribution was analyzed based on hotspot maps, calculated based on the center of mass of the deforestation polygon centroids. For Kernel density maps, the area of each deforestation polygon was attributed as the weight of its respective centroid, the operating radius was 100000 m, and the pixel size was 100 m.

For spatial correlation analysis, initially, 2022 deforestation areas were computed for each of the 3082 municipalities within the AF biome. Then, in the spatial analysis, we estimated Moran's Index, which correlated each municipality's deforestation vectors with the average deforestation area of neighboring municipalities' polygons. We utilized a first-order Queen Contiguity spatial weight matrix.

Data preprocessing, phytophysiognomies deforestation statistics, and Kernel density result maps were processed using RStudio and QGIS software. Spatial correlation analyses were performed using GeoDa software.

3 RESULTS

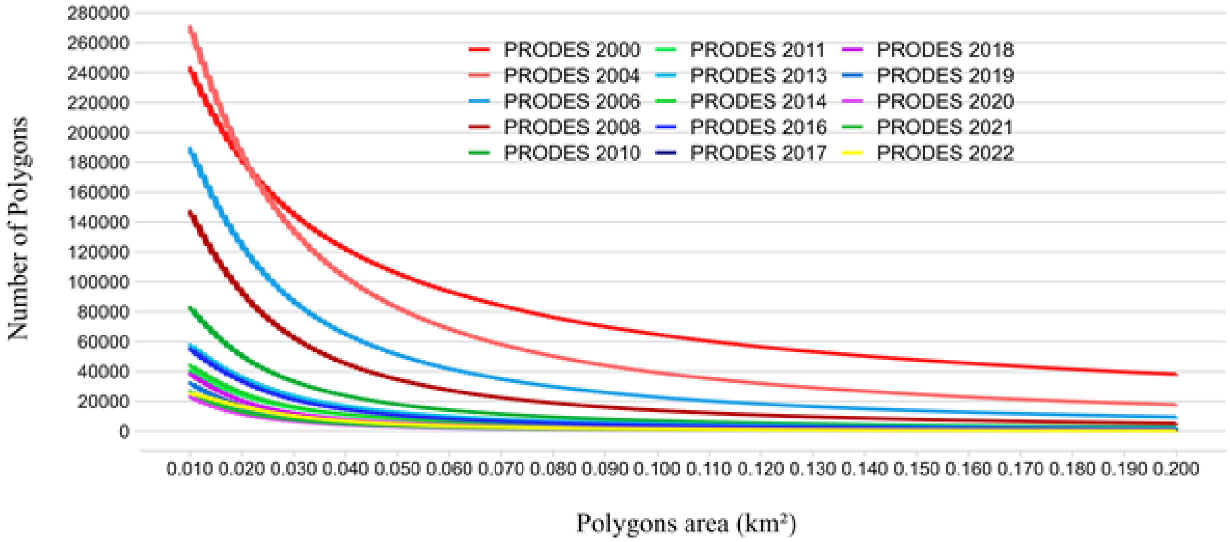
3.1 Deforestation area characteristics

For this study, a total of 789586.167 km² of deforested area was considered. This total includes deforestation recorded on the 2000 base map and the removal of polygons smaller than 1 ha. From 2001 to 2022, as reported by TerraBrasilis, the PRODES-MA historical series mapped 62686.43 km² of consolidated deforestation increase in the AF biome. Similarly, in this study, a total of 61647.665 km² was considered for the historical series from 2001 to 2021 and 1032.610 km² in the year 2022.

The size distribution of deforestation polygons from PRODES-MA presented a wide area range. The smallest area was the minimum mapping area (0.010 km²). The largest deforestation polygon has 17692.203 km² in the map base (2000), 68.400 km² in the historical series (2004 to 2021), and 3.827 km² for the most recent PRODES-MA deforestation data (2022). However, the majority of deforestation polygons (82%) lie within 0.010 km² and 0.199 km². Larger deforestation polygons (> 0.199 km²) account for a smaller proportion (18%) of the database. The predominance of small polygons and the size distribution of the majority

(82%) of deforestation polygons PRODES 2000 to 2022 are presented in Figure 2, and Table 1 illustrates their basic statistics (mean, median area, first quartile above and third quartile below). The statistical results of deforestation increments show a considerable decrease in their statistical values from 2000 to 2004 and a gradual decline from 2004 until the beginning of their stabilization in 2011. It is also possible to observe an upward trend from 2020.

Figure 2 – Size distribution of deforestation polygons (km²) for PRODES 2000 to 2022, considering 82% of polygons analyzed.



Elaboration: The authors (2024).

Table 1 – PRODES MA - deforestation polygon size (km²) statistics - Median; First Quartile and Third Quartile for every year of the historical series. (*) 2000 - cumulative deforestation area from 1985 to 2000.

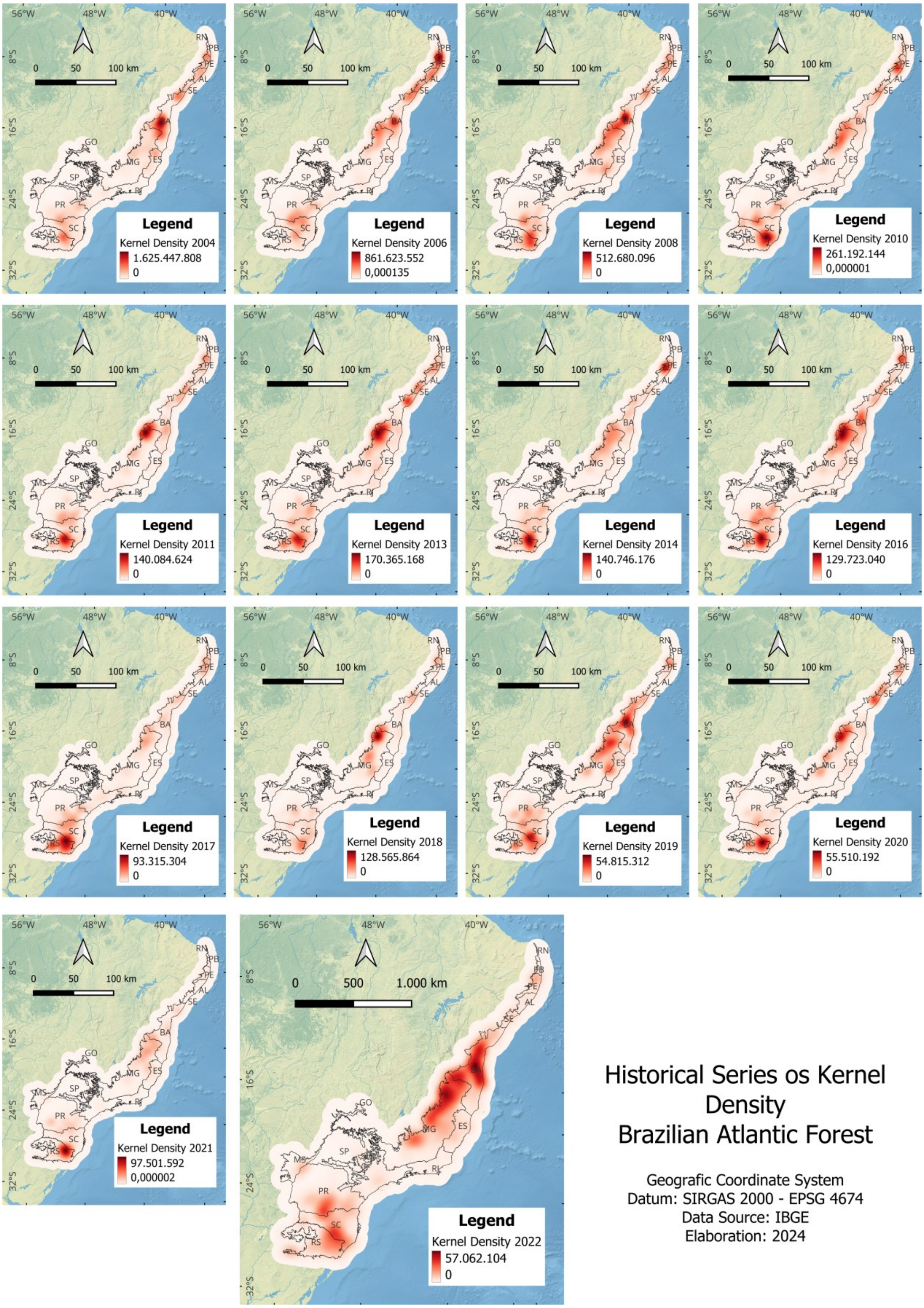
PRODES Year	Total area mapped	Mean	Median	First Quartile	Third Quartile
2000*	726905.890	2.987	0.040	0.020	0.108
2004	22501.561	0.083	0.030	0.017	0.061
2006	12767.483	0.067	0.027	0.017	0.054
2008	8008.178	0.054	0.026	0.016	0.047
2010	4004.359	0.049	0.024	0.016	0.045
2011	1879.737	0.046	0.024	0.015	0.043
2013	2855.139	0.049	0.025	0.016	0.045
2014	1887.281	0.043	0.023	0.015	0.041
2016	2414.412	0.044	0.024	0.016	0.042
2017	1165.924	0.036	0.021	0.014	0.034
2018	1344.194	0.035	0.021	0.014	0.035
2019	1067.100	0.033	0.020	0.014	0.033
2020	789.579	0.034	0.020	0.014	0.033
2021	926.716	0.035	0.020	0.014	0.033
2022	1032.610	0.041	0.025	0.017	0.042

Elaboration: The authors (2024)

3.2 Deforestation distribution over time, space, and phytophysiognomic types

The Kernel density distribution maps for PRODES 2000 to 2022 deforestation polygons are presented in Figure 3. In 2000, the density of deforestation polygons was spread out along the biome due to the characteristic of this data as a single consolidated vector of analyses of the suppression of native vegetation since 1984. From 2004 until 2022, generally, there were two of the most frequent general hotspot areas – in Bahia/Minas Gerais (BA/MG), and Santa Catarina/Rio Grande do Sul (SC/RS). In the Northeast Region, there were hotspots in Pernambuco (PE) in the years 2006, 2014, and 2016. By analyzing in detail the PRODES 2022 deforestation hotspot map, four deforestation regions are evident: 1) southeastern Bahia (BA); 2) north of Minas Gerais (MG); 3) Rio Grande do Sul/ Santa Catarina (RS/SC); and 4) south of Paraná (PR). Visual comparing these hotspots at previous density distribution years, we noticed that: 1) BA hotspot was intense from 2004 to 2008, and it came up again in 2019 and 2022; 2) MG hotspot first appeared in 2006, showed low intensity until 2010, and high intensity in 2011, 2013, 2016, 2018, and 2020; 3) RS/SC hotspot although it was less intense in 2022, it has been present since 2004, with less relevance only in 2018; 4) The PR hotspot is a recent focus, intense only in 2022.

Figure 3 – Kernel density distribution maps showing deforestation hotspots in the Atlantic Forest biome from PRODES-MA 2004 to 2022.



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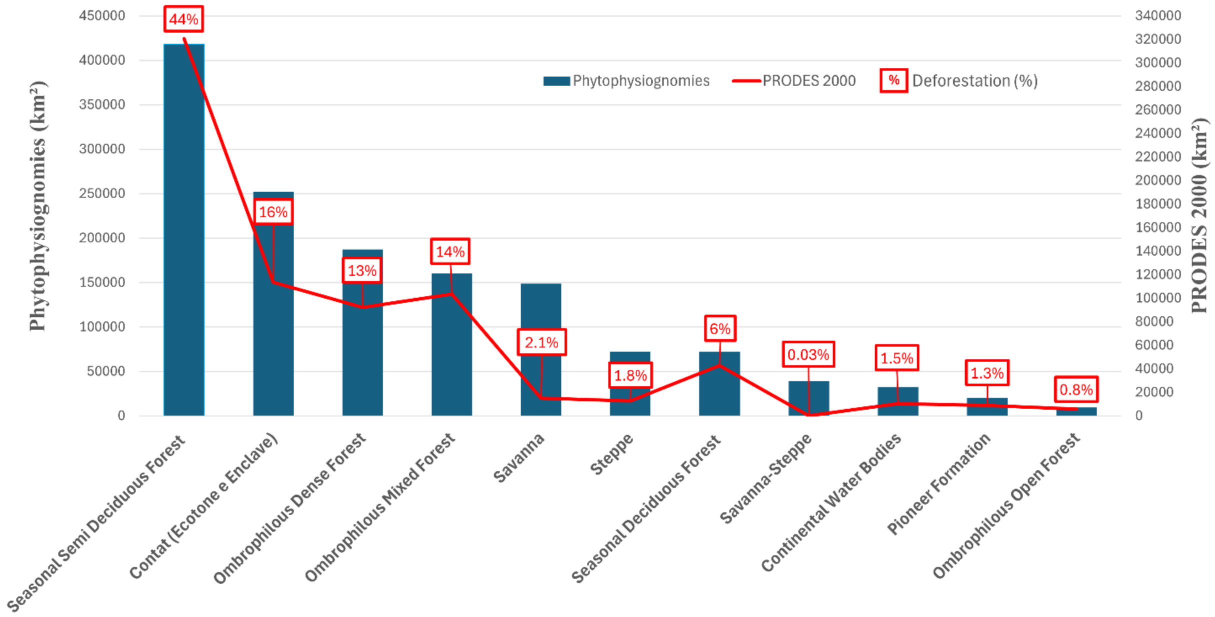
Considering the distribution of the PRODES-MA base map (2000) within the AF biome, the most affected phytophysiognomy was the Seasonal Semideciduous Forest, accounting for 44% of the deforestation (Figure 4). It is followed by the Contact Areas (16%), and in third place, the Mixed Ombrophilous Forests (14%). The least affected phytophysiognomies by deforestation in 2000 were: Savanna-Steppe (0.03%), followed by Open Ombrophilous Forest (0.8%), and Pioneer Formation (1.3%).

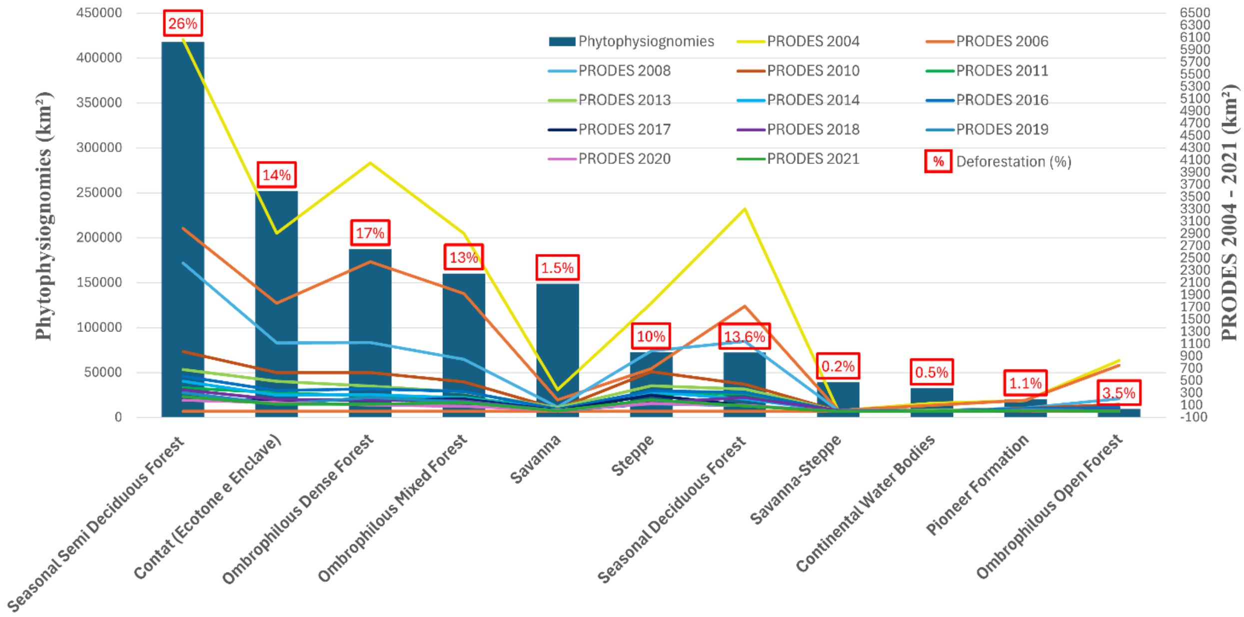
Figure 4 – Total area (km²) of each phytophysiognomy type in the Atlantic Forest in 2021, and deforestation PRODES 2000 areas (km²).



Elaboration: The authors (2023).

To the historical series (Figure 5), from 2004 to 2021 the most affected photophysiognomies type by deforestation were Seasonal Semideciduous Forests (26% of deforestation area), followed by Dense Ombrophilous Forests (17%) and Contact Areas (14%). The least affected phytophysiognomies by deforestation from 2004 to 2021 were: Savanna-Steppe (0.2%), followed by Pioneer Formation (1.1%), and Savanna (1.5%) (Figure 5).

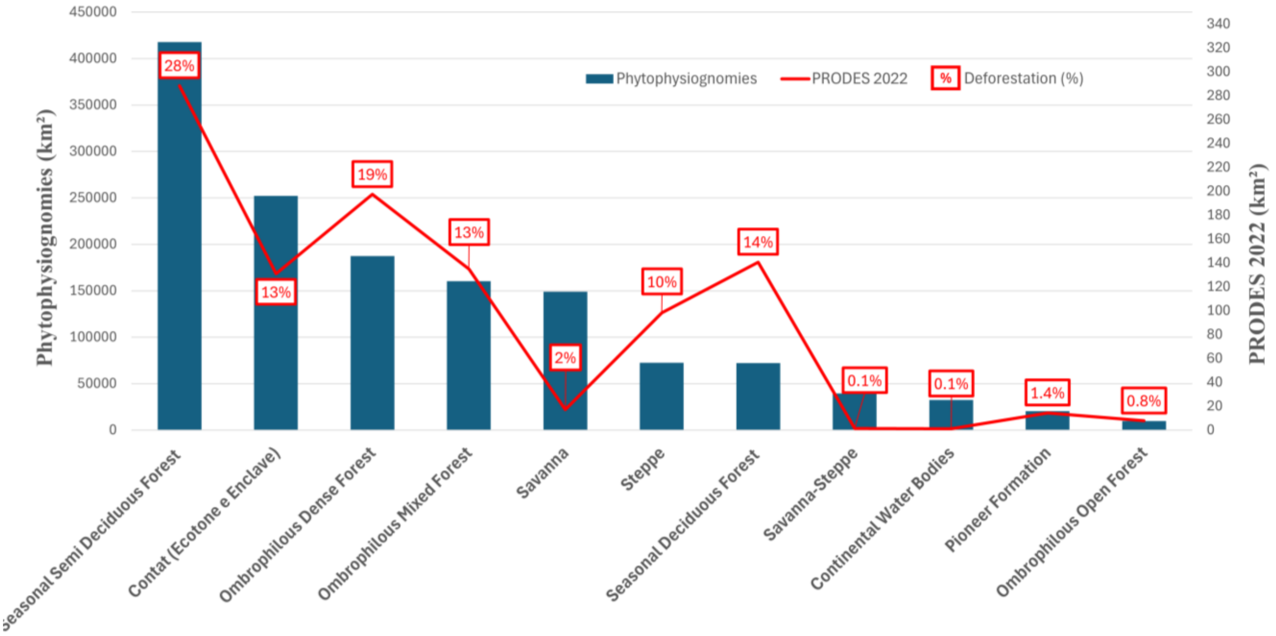
Figure 5 – Total area (km²) of each phytophysiognomy type in the Atlantic Forest in 2021, and deforestation PRODES 2004 - 2021 areas (km²).



Elaboration: The authors (2023).

Most of the deforestation mapped by PRODES 2022 within the AF biome (28% of the year's deforestation area) occurred over Seasonal Semideciduous Forests (Figure 6), followed by Dense Ombrophilous Forests (19%) and Seasonal Deciduous Forests (14%). The least affected phytophysiognomies by deforestation in 2022 were: the Savanna-Steppe (0.1%), followed by the Open Ombrophilous Forest (0.8%), and Savanna (1.4%).

Figure 6 – Total area (km²) of each phytophysiognomy type in the Atlantic Forest in 2021, and deforestation PRODES 2022 areas (km²).



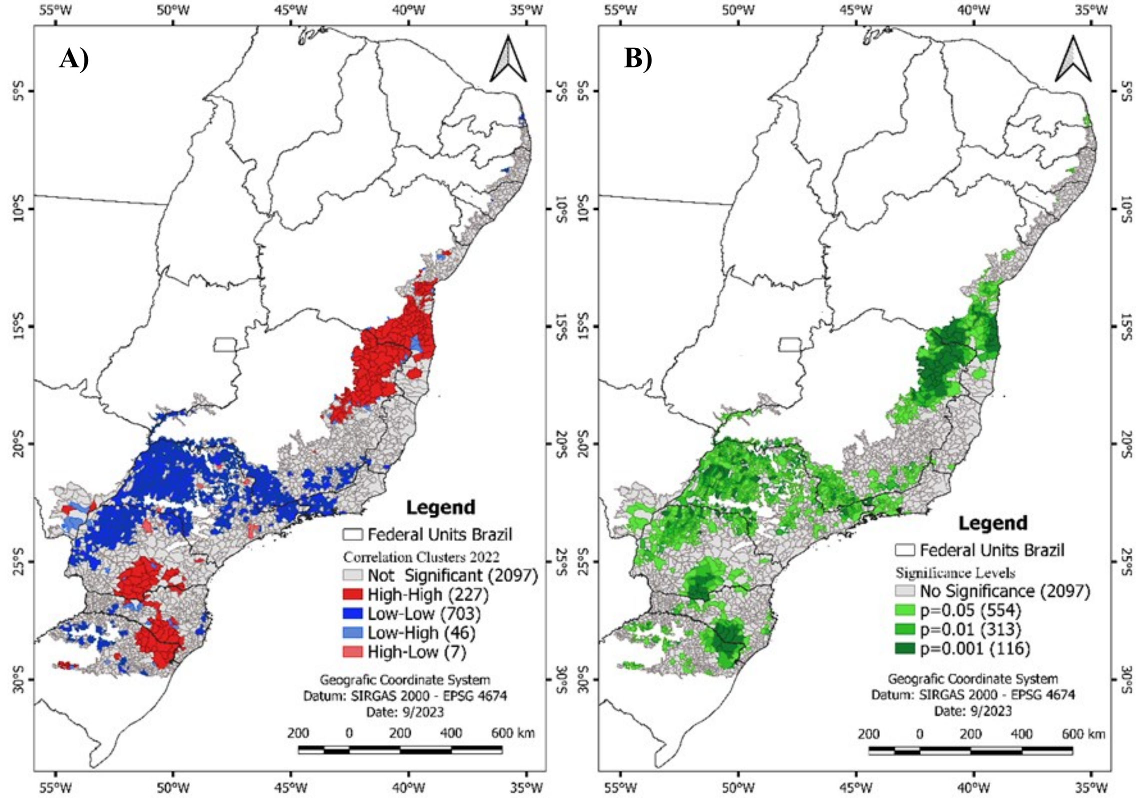
Elaboration: The authors (2023).

3.3 Spatial autocorrelation analysis of deforestation

The Moran's Index correlation for deforestation PRODES 2022 by municipality resulted in the Moran Global Index of 0.542, indicating a general positive spatial autocorrelation. Deforestation in this year presented spatial dependence, discarding randomness. The Moran scatterplot map illustrates the relationships between neighbors (Figure 7-A). For the High-High ratio (positive correlations), 227 municipalities were identified, predominantly in the southern regions of the states of Santa Catarina (SC) and Paraná (PR), north and northeast of Minas Gerais (MG), and southeast of Bahia (BA). For the Low-Low correlations (positive correlations), 703 municipalities prevailed, mainly in the northwest of the states of São Paulo (SP) and Paraná (PR) and south of Bahia (BA). In 2097 municipalities had no significant correlation. Inverse correlations, Low-High (negative correlations), appeared in 46 municipalities, while inverse High-Low correlations (negative) were observed in 7 municipalities (Figure 7-A).

Considering only results with statistical significance, 554 municipalities had p-value=0.05, 313 municipalities had p-value=0.01, and 116 municipalities had p-value=0.001 (Figure 7-B). This gradation refers to the risk associated with rejecting the null hypothesis of Moran's Index (which assumes spatial data independence) at 5%, 1%, or 0.1% of the time. Hence, the calculated value of p-value=0.001 (0.1%) means a higher level of confidence in the analysis results. Municipalities with p=0.001 significance exhibited a greater number of High-High correlations due to their strong spatial correlation of deforestation rates with neighboring municipalities in 2022. The p=0.001 significance level also displayed a higher incidence of Low-Low correlations, albeit in a smaller number, indicating spatial correlation in the low deforestation rates between municipalities for 2022.

Figure 7 – A) Moran's Index correlation clusters for 2022 deforestation by MA municipalities; B) Significance levels of correlation by municipality.



Elaboration: The authors (2023).

4 DISCUSSION

After analyzing 243375 deforestation polygons for the year 2000, 1040632 polygons between 2004 and 2021, and 25380 polygons for 2022, four main spatial and geographical characteristics of deforestation in the Atlantic Rainforest are revealed: 1) most of the deforestation polygons, from 2000 to 2022, are close to the minimum mapped area (1 ha); 2) the 2022 deforestation hotspots are concentrated in southeastern Bahia (BA), northern and northeastern Minas Gerais (MG), southern Santa Catarina (SC), and southern Paraná (PR). These hotspots patterns repeated in most years of the historical series (2000 to 2021) with an addition in the northeast region (Pernambuco (PE)) that appears in some years; 3) the most affected phytophysiognomy by deforestation in the historical series from 2000 to 2021 was Seasonal Semideciduous Forests, which continues to be the most affected in 2022; 4) Moran's Index revealed a global spatial dependence of deforestation among municipalities, with significant dependency areas coinciding with hotspots deforestation on the density map.

Considering the methodology and concepts adopted at PRODES-MA, during visual interpretation at the 1:75000 scale, polygons of 1 ha appear to be small areas. However, when they are observed integrated with adjacent polygons mapped in previous years, they indicate large deforested areas. The fact that the sizes of most deforestation polygons (82%) ranged from 0.010 km² to 0.199 km² can reflect a pattern explained by environmental laws and regulations that may have inhibited larger deforestation polygons in the biome (DORTZBACH et al., 2021; MELLO-THÉRY, 2019).

The Atlantic Forest Law (2006) regulates the conservation, protection, regeneration, and use of the biome, restricting permission to clear primary and secondary forests to just a few specific situations (BRASIL, 2006). Another significant legal framework that may have limited the suppression of native vegetation beyond the areas found in PRODES-MA is the Forest Code. It establishes norms and guidelines for forest preservation, land use, and regulation of water resources (BRASIL, 2012; DORTZBACH et al., 2021). Recently, the presence of payment for ecosystem services (Law 2012, Revised in 2021) has contributed to the increase in planted forest cover in the AF and the reduction of native vegetation loss (BRASIL, 2021; RUGGIERO et al.,

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2019).

Statistics on the size of deforestation polygons show a considerable decrease in their values from 2000 to 2004. This is justified first because the 2000 base map compiled all deforestation areas that occurred within the limits of the AF from 1984 to 2000, incorporating the deforestation rates analyzed over 16 years. Then, the 2004 mapping includes deforestation areas that occurred from 2000 to 2004 (INPE; FUNCATE, 2019). Subsequently, there was another gradual decline in deforestation statistics from 2004 to 2006, until they began to stabilize in 2011, reflecting the trends in data on deforestation published in the Atlantic Forest Atlas in the same period (FUNDAÇÃO SOS MATA ATLÂNTICA, 2022). These figures may reflect the influence of the aforementioned laws on the protection and conservation of the biome.

According to Moran's Index results, three clusters comprising 227 municipalities with the highest concentration of 2022 deforestation were identified, namely, the southeastern part of Bahia (BA); the northern and northeastern regions of Minas Gerais (MG); and the southern regions of Paraná (PR) and Santa Catarina (SC). All four regions have high soil organic carbon stocks (GOMES et al., 2019). Considering that our results are based on native vegetation or old-growth vegetation, despite having a lower carbon sequestration rate than second-growth forests, they present higher above-ground and soil carbon stocks (HEINRICH et al., 2021; BRANCALION, 2020). Thus, vegetation loss in these areas could increase CO2 emissions and, in turn, raise air temperature (LUYSSAERT, 2008; GEORGE et al., 2007). Furthermore, since the region for the cluster in BA and MG has poor stability and resilience, deforestation can have short and long-term consequences (MAURE et al., 2022). The short-term effect is related to the emission of CO2 due to forest loss per se. The long-term one is related to the region's inability to allow forests to regrow to their full potential, which could possibly mean that a second-growth forest will not sequester as much carbon from the atmosphere and will not stock as much carbon in its biomass and on the ground.

Due to severe negative consequences of deforestation, it is essential to understand its main drivers. In this regard, a large-scale analysis, encompassing natural areas in Latin America, 369 scientific articles published between 1990 and 2014 revealed primary factors directly linked to deforestation increase, in order of significance: agricultural expansion, livestock farming, infrastructure, and roads, with population pressure also considered a significant indirect factor (ARMENTERAS et al., 2017). A 1% rise in population density has been linked to a 0.2% increase in the likelihood of deforestation in Paraná (PR) between 2000 and 2020 (MOHEBALIAN et al., 2022). Similarly, in the northernmost region of Minas Gerais between 2000 and 2015, a positive relationship was observed between population growth and deforestation. Additionally, livestock farming and land cultivation emerged as significant factors (DUPIN et al., 2018). An important environmental characteristic that might be associated with the three deforestation clusters is the soil concentration of organic matter, which depends on the type of geological rock formation (VEIGA et al., 2008). According to recent soil maps, most of these areas have soils with high concentration of clay and water that allows more humidity and nutrient retention, hence favoring the success of agriculture activities (EMBRAPA, 2022).

In addition to the mentioned factors, the commercial exploitation of wood was also identified as relevant in explaining deforestation, particularly in Seasonal Semideciduous Forest areas (VILLELA et al., 2006). Among the most exploited species in this phytophysiognomy are Ivorywood (*Balfourodendron riedelianum*) and Canjarana (*Cabralea canjerana*), as well as Jequitibá species that can occur in both Seasonal Semideciduous and Dense Ombrophilous Forests (CARVALHO, 1998). These forests respectively rank first and third in the deforestation outcomes by phytophysiognomy in this study.

Two clusters comprising 703 municipalities with high correlation involving lower deforestation concentration in the year 2022 (Low-Low) were identified. In these regions, the predominant phytophysiognomies are Seasonal Semideciduous Forests and Contact Areas, respectively. However, the Low-Low correlation does not necessarily indicate a low degree of degradation of these phytophysiognomies. The Seasonal Semideciduous Forests have the largest deforested area among the phytophysiognomies most degraded, according to our results. Moreover, one of the strongest inducers of anthropic action in AF was closely associated with land appropriation, which marks the extensive occupation of some regions of the biome, including the Low-Low correlation regions, since before the PMABB historical series (MELLO-THÉRY, 2019).

The low correlation results among municipalities Low-High and High-Low refer to a smaller number of municipalities in the analysis (53). In the High-Low, the analyzed municipalities exhibit more deforestation than the average of neighboring municipalities, potentially indicating that such municipalities have not yet influenced the others. In Low-High cases, the analyzed municipalities experience less deforestation compared to the average of their neighbors, similarly suggesting that they have not yet been influenced by the others (ANSELIN, 1995). Reverse analysis cases often indicate areas with possible transitional pattern trends. High-Low cases may suggest the onset of a deforestation process in the central region, while Low-High cases could indicate the depletion of natural areas due to intense deforestation in previous years.

Considering that the areas identified as deforestation hotspots in the historical series and in the last year (2022) coincide with significant High-High autocorrelation among municipalities, neighboring municipalities likely engage in similar economic activities throughout much of the historical series and also in recent years (TRIGUEIRO; NABOUT; TESSAROLO, 2020). Depending on the region's economic activities, there can be a generation or alteration of other factors that intensify deforestation, such as the construction of highways and roads, product prices, agricultural input availability, and rural credit (MARGULIS, 2003; FEARNSIDE, 2005). In some AF regions, situated in the northeast of Minas Gerais (MG), rural credit has shown a positive association with deforestation, meaning that higher rural credit leads to greater native vegetation suppression. Conversely, in the southeast of Bahia (BA), there was an inverse relationship between agricultural credit and deforestation (GUIMARÃES et al., 2023). Thus, despite deforestation clusters being linked to distinct economic activities, municipalities within each cluster should exhibit similarities in both their economic activities and their secondary effects that amplify deforestation. Therefore, an in-depth study of each cluster separately is suggested.

5 CONCLUSION

This work first elucidates the concept and methodology employed by PRODES Atlantic Forest to enable its use in spatial geographic analyses. Deforestation of the Atlantic Forest according to PRODES-MA on the 2000 map base was around 726905.890 km², 61647.665 km² for the historical series from 2004 to 2021 and for 2022 (the last year) was 1032.690 km². Deforestation in the AF occurs mostly through the removal of small areas of native vegetation and was concentrated in the Semideciduous Seasonal Forest regions as follows: 44% of deforestation until 2000; 26% of deforestation between the years 2004 and 2021; and 28% of deforestation in the year 2022. Secondly, the phytophysiognomies of Contact Areas represented 16% until the year 2000; in Dense Ombrophylous Forests it was 17% from 2004 to 2021; and in Dense Ombrophylous Forests, it was 19% in 2022. In third place, with 14%, were Mixed Ombrophylous Forests until the year 2000; Contact Areas with 14% in the years 2004 to 2021; and Seasonal Deciduous Forests with 14% in 2022. The prevalence of deforestation areas close to 1 ha, and the decrease in deforestation area statistics close to 2006 and 2011, reinforces the importance of the PRODES-MA methodology in monitoring the Atlantic Forest biome for compliance with environmental preservation and conservation laws. A smaller cartographic scale for visual interpretation, or satellite images with a spatial resolution greater than 30 meters, would not have identified most of the deforestation mapped.

Spatial PRODES-MA deforestation patterns in the Atlantic Forest were evident, including current clusters of municipalities exhibiting positive autocorrelation (High-High and Low-Low) for deforestation. In general, the 2022 deforestation hotspots coincided with clusters of municipalities showing significant positive High-High autocorrelation, primarily associated with forest phytophysiognomies. This concentration may be linked to population growth, the economic activities of municipalities, and the demand for raw materials and anthropogenic space generated by these activities.

The historical and current PRODES Mata Atlantica deforestation data are available for consultation, visualization, and download on the TerraBrasilis platform. Deforestation in the AF occurs in small areas (close to 1 ha), which makes it difficult to visualize at the biome scale. However, when analyzing the spatial distribution, we emphasize areas with the highest intensity of vegetation removal. Deforestation from 1985 to 2022 has occurred in favored regions and at different intensities. Thus, the spatial analysis presented in this paper highlighted critical and priority areas for deforestation control strategies. This information can contribute to the planning of monitoring and command-and-control policies for the Atlantic Forest biome's remaining

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natural vegetation.

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Authors Contribution

Conceptualization, R.Z.M. and S.A.; methodology, R.Z.M. and S.A.; software, R.Z.M. and R.S.C.; validation, R.Z.M., S.A. and L.S.; formal analysis, R.Z.M. and R.S.C.; investigation, R.Z.M.; data curation, R.Z.M.; writing-original draft preparation, All authors.; writing-review and editing, All authors.; visualization, R.Z.M., S.A. and L.S.; supervision, S.A.; project administration, S.A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors have no conflicts of interest to declare. The funders did not interfere in the development of the study, in the analysis or interpretation of the data, in the writing manuscript, or in the decision to publish the results.

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