Spatial deforestation distribution in the Atlantic Forest biome based on the Brazilian PRODES System

Raquel Z. Molinez[1], Andrea F. Turíbio[1], Rodrigo S. do Carmo[1], Mariana M. S. Cursino[1], Luciana S. Soler[1], Silvana Amaral[1]

[1]Instituto Nacional de Pesquisas Espaciais – INPE São José dos Campos – SP – Brazil

{raquel_zozimo, turibiodea, rod19.silva, mariana.martins.sc, lusoler}@gmail.com, {silvana.amaral}@inpe.br

Abstract. *The Atlantic Forest (AF) is a biodiversity hotspot and the most deforested Brazilian biome. This work presents first the concepts of the Brazilian Satellite Monitoring Program, now extended to all Brazilian biomes including the AF (PRODES-MA). Then, an exploratory spatial analysis of the recent deforestation patterns is presented. According to PRODES-MA, out of the 1.032,69 km² deforestation increment in 2022, the majority (98%) stands for small areas (< 1,99km²) located in forest-type phytophysiognomies: Seasonal Semideciduous (27%), Dense Ombrophilous (19%) and Seasonal (14%). Deforestation is concentrated in four regions of federal states (Bahia, Minas Gerais, Paraná, and Santa Catarina), and clusters of municipalities presented a positive deforestation autocorrelation. Current AF deforestation is concentrated, and related to some municipalities' economic activities. Satellite monitoring systems, such as PRODES-MA, provide relevant data to assist AF conservation policies.*

1. Introduction

The Atlantic Forest (AF) is a biome of tropical and subtropical forests, originally covering nearly the entire Atlantic coast of South America, and stands for 15% of the Brazilian territory. Its vegetation encompasses several native phytophysiognomies: Dense Open and Mixed (also known as Araucaria) Ombrophilous and Seasonal Semideciduous and Deciduous, mangroves, sandbanks, high-altitude fields, swamps and forest enclaves in the Northeast [Ponzoni and Pessoa 2015]. AF is a global biodiversity hotspot, with a high level of endemism. At the same time, the AF is the only Brazilian biome with a non-dominant vegetation coverage. According to IBGE, in 2018, the remaining natural vegetation in the AF was 12,6% of its original area, which is a result of a historical human occupation process in the region that nowadays accommodates 72% of the Brazilian population including some resistant and diverse Indigenous Land and Quilombola Territories [IBGE 2020].

The Atlantic Forest is characterized by high levels of forest fragmentation that resulted from intensive deforestation activities throughout its colonization history. Such fragmentation issues are aggravated by the socio-economic context, the regional agricultural dynamics, and the high levels of urbanization [Fonseca 1985], [Ranta 1998]. Nowadays, the population residing in the AF domain faces landslides, floods, high temperatures, and other environmental risks all intensified by the removal of forest remnants. For the year 2022, PRODES accounts for 1.032,69 km² of deforestation [TerraBrasilis, 2023]. Consequently, there has been an economic downturn and a reduction in the quality of life [Gelain 2012], [Duarte 2017]. Despite the high rates of deforestation, there are still significant forest remnants in the AF that demand monitoring and preservation [Nascimento 2016].

The suppression of native vegetation in the Atlantic Forest occurs along the biome's gradient associated with various human processes and activities. Neighboring municipalities tend to exhibit similar deforestation behavior, implying spatial autocorrelation since the type of occupation or economic activity in one location can affect surrounding regions [Brown et al. 2016]. Recognizing deforestation spatial patterns provides fundamental information to enhance monitoring, as well as to formulate strategies for the restoration and preservation of its native vegetation.

Remote sensing is an efficient tool for diagnosing and monitoring the Atlantic Forest vegetation. Specifically, deforestation monitoring data, by providing continuous information, enables the identification of where, when, and how deforestation occurs. Additionally, remote sensing is one of the tools that allow us to assess the current state of forests, their changes over time, and the formulation of effective strategies for the conservation and restoration of the biome [Amaral et al. 2023], [Junior et al. 2006].

To obtain accurate information on deforestation in Brazil, develop carbon dioxide emissions strategies, and establish a system for observing and monitoring deforestation in Brazilian biomes, the Ministry of Environment (MMA) instituted the Environmental Monitoring Program of the Brazilian Biomes (PMABB) through Ordinance No. 365, dated November 27, 2015 [D. O. U. 2015]. This program extended the methodology developed and enhanced since 1988 by the PRODES-Amazonia project [INPE 2019] and PRODES-Cerrado [INPE 2018] to the other Brazilian biomes to mention: Atlantic Forest, Caatinga, Pampa, and Pantanal. The PMABB established a biennial inventory of deforestation maps from 2000 to 2016, and after 2017 up until 2022 such mapping became annual [INPE-Funcate 2019]. In addition to the historical series, the TerraBrasilis platform was developed to enable analysis, visualization, and access to PRODES results, and extensive geospatial data [Assis et al. 2019].

Continuing the PMABB initiative, INPE presented the PRODES Mata Atlântica Project (PRODES-MA) - a satellite-based deforestation monitoring system for the Atlantic Forest, mapping annual deforestation increments starting from 2023. The project employs images from the MSI/Sentinel-2 satellite, with superior spatial and temporal resolution compared to the Landsat satellite images utilized in the PMABB program.

In this context, given the deforestation data of the Atlantic Forest available and the recent deforestation processes within the biome, this article raises the following questions:

1) What concept is used, or what constitutes deforestation for the PRODES-MA system? How are polygons mapped by this concept detected, considering the adopted methodology?

2) What are the primary characteristics of deforestation in the Atlantic Forest regarding the distribution and location of deforested areas? Where are the biome's deforestation hotspots? Which phytophysiognomies are mostly affected by deforestation?

3) Within the municipal context, are there significant spatial patterns of deforestation occurrence in the Atlantic Forest, and of what nature are they?

This study presents initial exploratory analyses of PRODES-MA deforestation data. To answer the proposed questions, we explain the concept of deforestation and then characterize the main deforestation spatial patterns and autocorrelation. This work contributes to the presentation of PRODES-MA, highlighting its potential to generate valuable information for conservation strategies. By identifying the most affected areas and highlighting deforestation patterns, priority areas for monitoring, protection, and restoration are pointed out.

2. Atlantic Forest PRODES Monitoring System

Continuing the historical series and monitoring of PMABB, INPE integrated the Atlantic Forest biome into the PRODES project, monitoring the annual deforestation rate. We refer to the deforestation data generated at PMABB and produced from 2023 onward as PRODES Mata Atlântica project (PRODES-MA). Annually, deforestation data is mapped through visual interpretation, at a 1:75.000 scale, for areas larger than 1 ha (hectare), using satellite images. Up to 2022, the mapping relied on OLI/Landsat series images (30 m) with an R5G6B4 composition. For 2023, INPE implemented mapping using MSI/Sentinel-2 images (20 m), and R8G11B4 band composition.

In PRODES-MA, deforestation refers to areas where native vegetation of the Atlantic Forest has been suppressed. This includes both forested and non-forested physiognomies. Deforestation is identified by comparing the current spectral pattern of native vegetation with the pattern from the previous year's image. The detection does not involve identifying the specific land use or coverage to which the cleared native vegetation areas were converted. Mapping is carried out solely for the evident removal of native vegetation [INPE-Funcate 2019]. Once mapped as deforestation, the area will not be observed in subsequent years, and its limits will be included in the "deforestation mask" for the following years. This "mask" refers to the accumulated boundaries of all previously mapped areas. Therefore, PRODES-MA does not observe deforestation in secondary forest areas, following PRODES methodology.

The detection of deforestation by visual interpretation is based on the spectral and contextual distinction of targets, which can vary according to the type of soil, phytophysiognomy, climate, and historical context, in different sub-regions of the biome. The classes and criteria for the mapping are outlined in an Interpretation Key, which guides the deforestation classification. The Mapping Protocol and procedures were built upon methods consolidated in PRODES Amazonia [INPE 2019] and PRODES Cerrado [INPE 2019]. Interpretation is facilitated by the TerraAmazon [INPE and Funcate 2023] software system, which systematizes and manages the geographic database and the results are made available to TerraBrasilis.

3. Methodology

Deforestation data from PRODES-MA 2022 was accessed from TerraBrasilis, pre-processed, and analyzed in terms of size, distribution, phytophysiognomy, and spatial dependence. Specifically, deforestation polygons were analyzed considering their distribution of area frequency (Histogram); the distribution was discussed based on a deforestation density distribution map (Kernel density); and the assessment of deforestation patterns was observed considering their phytophysiognomies, and spatial correlation analyses (Moran's Index).

The study area corresponds to the Atlantic Forest biome, whose geographical boundaries were defined by the Instituto Brasileiro de Geografia e Estatística (IBGE) in 2019 at a 1:250.000 scale (Figure 1-A). With 1.110.182 km², the biome is found in 3.082 municipalities of 17 federative units (Alagoas-AL, Bahia-BA, Ceará-CE, Espírito Santo-

ES, Piauí-PI, Goiás-GO, Mato Grosso do Sul-MS, Minas Gerais-MG, Rio de Janeira-RJ, São Paulo-SP, Paraíba- PB, Pernambuco-PE, Paraná-PR, Santa Catarina-SC, Sergipe-SE, Rios Grande do Norte-RN e Rio Grande do Sul-RS). Due to its latitudinal extent, the Atlantic Forest 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).

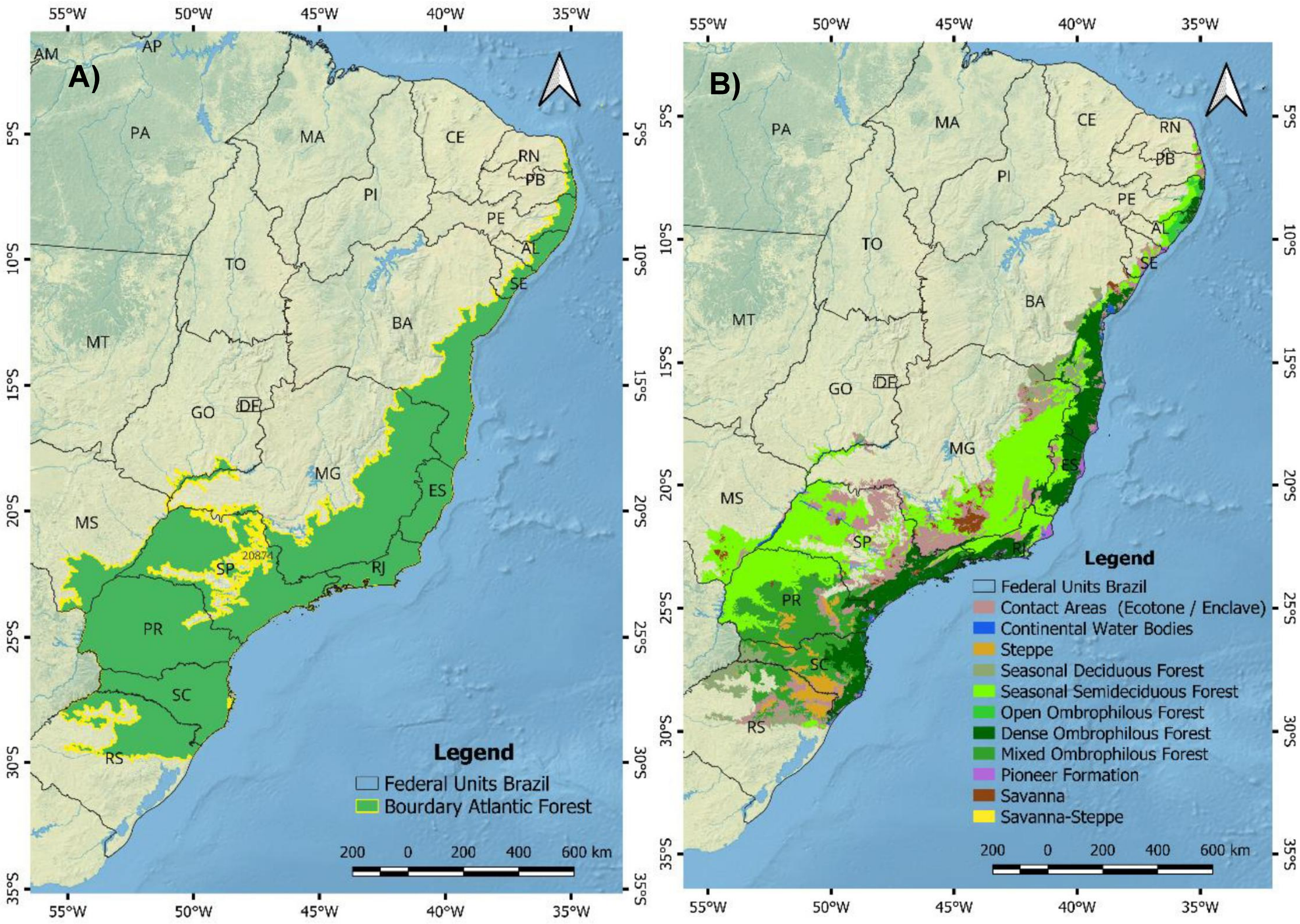

Figure 1. A) Atlantic Forest Biome´s limit in Brazil; B) Phytophysiognomies of the Atlantic Forest Biome.

The main database for this study is the deforestation vectors of the Atlantic Forest, generated by PRODES-MA and published on the TerraBrasilis portal, within a single geopackage file. This file includes the following vectors: 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 2000 to 2022; 3) *cloud* - 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 accessed the annual increment layer and selected only deforestation polygons for the year 2022.

Due to spatial clipping for publication based on state boundaries and scene origin, the deforestation polygons in TerraBrasilis might exhibit areas under 1 ha. In this study, polygons smaller than 1 ha (the project's minimum area) were excluded to avoid bias in the area analysis. These geometries, which are less than 1 ha in size, collectively sum up to 15 km², constituting less than 0,002% of the total deforested area in the historical series (790.008,151 km²).

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

Deforestation vector data for 2022 composed of a total of 25.380 deforestation polygons, were used in the analysis of the current general deforestation patterns. Basic statistics of the polygons were calculated, as well as their intersection area to the phytophysiognomies of the Atlantic Forest. The general deforestation distribution was analyzed based on a hotspot map, calculated from the center of mass of the deforestation polygon centroids. For this Kernel density map, the area of each deforestation polygon was attributed as the weight of its respective centroid, the operating radius was 100.000 m, and the pixel size was 100 m.

For spatial correlation analysis, initially, 2022 deforestation areas were computed for each of the 3.082 municipalities within the AF biome. Then, we conducted spatial analysis by calculating 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 results map were processed in QGIS software. Spatial correlation analyses were performed using GeoDa software.

4. Results

4.1. Deforestation area characteristics

In 2022, as reported by TerraBrasilis, PRODES-MA mapped 1.032,69 km² of consolidated deforestation increment within the biome. For this study, a total of 1.032,610 km² of deforested area was considered after removing polygons smaller than 1 ha. The geometries of deforestation within the AF biome for the year 2022 exhibit polygon areas ranging from 0,010 km² (minimum area) to 3,827 km² (largest observed area). However, the majority of deforestation polygons (98%) fall within the range of 0,010 km² to 0,199 km², with larger deforestation polygons accounting for a smaller proportion (2%) of the database. The graphs (Figure 2-A, Figure 2-B) depict the predominant distribution of 2022 deforestation polygons (98%) and illustrate an average area of 0,041 km² and a median of 0,025 km², with the first quartile above 0,017 km² and the third quartile below 0,042 km².

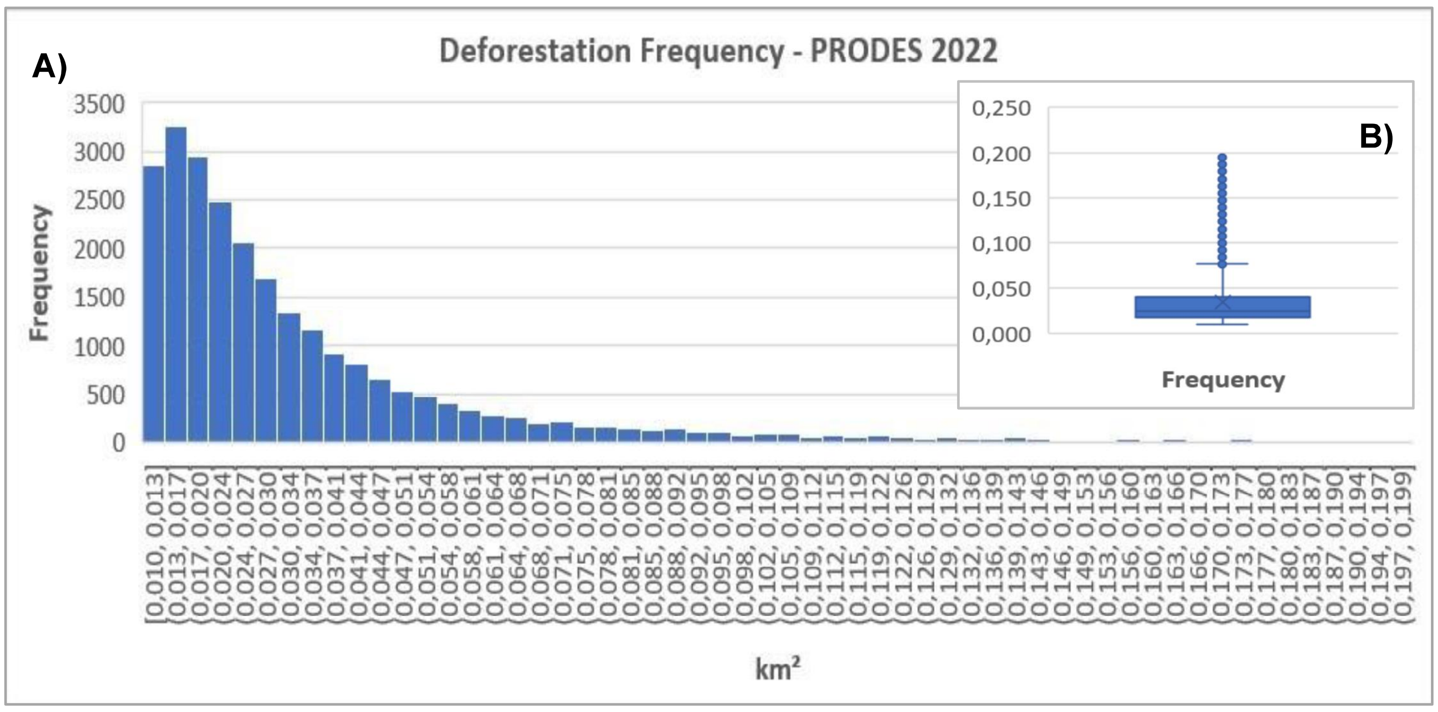

Figure 2. A) Distribution of deforestation polygons in km² for 2022 considering 98% of polygons analyzed; B) Statistic of deforestation polygons (98%).

4.2. Hotspot analysis and affected phytophysiognomies

The Kernel density distribution map revealed the deforestation hotspots (Figure 3) highlighting the concentration of deforestation in four main regions: 1) southeastern Bahia; 2) northern and northeastern Minas Gerais; 3) southern Paraná; and 4) southern Santa Catarina.

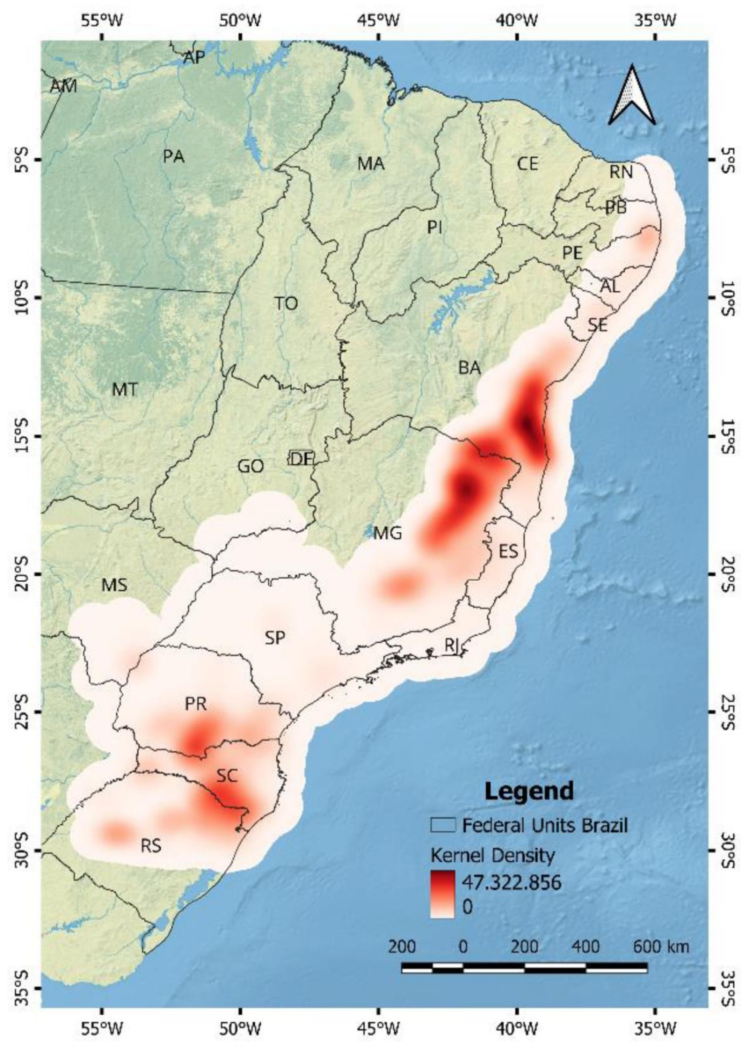

Figure 3. Deforestation hotspots of 2022 considering the distribution of point density and polygon area.

Considering the distribution of 2022 PRODES-MA within the AF biome, the most affected phytophysiognomies was the Semideciduous Seasonal Forest, accounting for 27% of the deforestation (Figure 4). It is followed by the Dense Ombrophilous Forest, comprising 19% of the year's deforestation, and in third place, the Deciduous Seasonal Forests with 14% of the year's deforestation. The least affected phytophysiognomies by deforestation in 2022 were: Savanna-Steppe (0,1%), followed by Open Ombrophilous Forest (0,8%), and Savanna (1,4%).

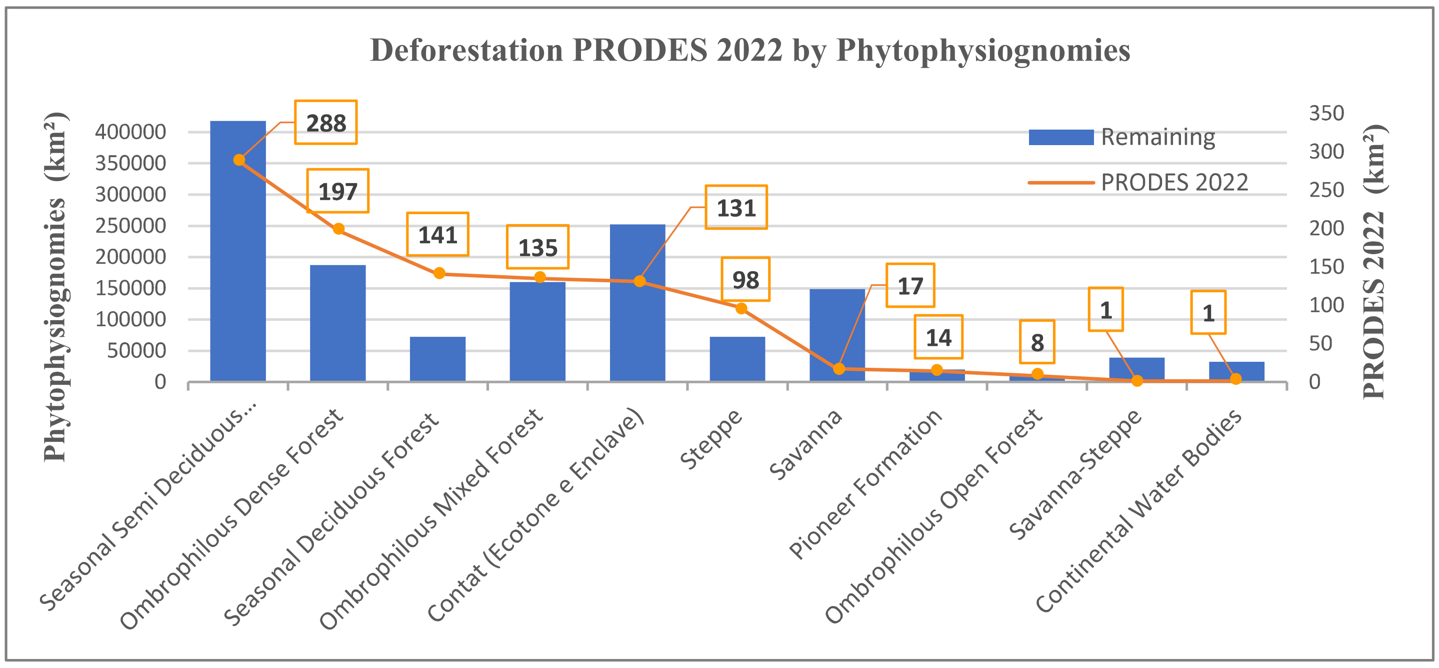

Figure 4. The total area of each phytophysiognomy domain in the Atlantic Forest in 2021 and distribution of PRODES 2022 deforestation areas (km^2).

4.3. Spatial autocorrelation analysis of deforestation

The Moran Global Index correlation resulted in 0,542, indicating a general positive spatial autocorrelation. Deforestation presented spatial dependence, discarding randomness. The Moran scatterplot map illustrates the relationships between neighbors (Figura 5-A). For the High-High ratio (positive correlations), 227 municipalities were identified, predominantly in the southern regions of the states of SC and PR, north and northeast of MG and southeast of BA. For the Low-Low correlations (positive correlations), 703 municipalities prevailed, mainly in the northwest of the states of SP and PR and south of MG. In 2.097 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 5-A).

For municipalities with High-High correlation, Steppe, Contact Areas, Mixed and Dense Ombrophilous Forests, and Deciduous and Semideciduous Seasonal Forests are predominant. In municipalities with Low-Low correlation patterns, Semideciduous Seasonal Forests and Contact Areas predominate.

For 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 5-B). This gradation refers to the risk associated with rejecting the null hypothesis of Moran's Index (which assumes spatial data independence) 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.

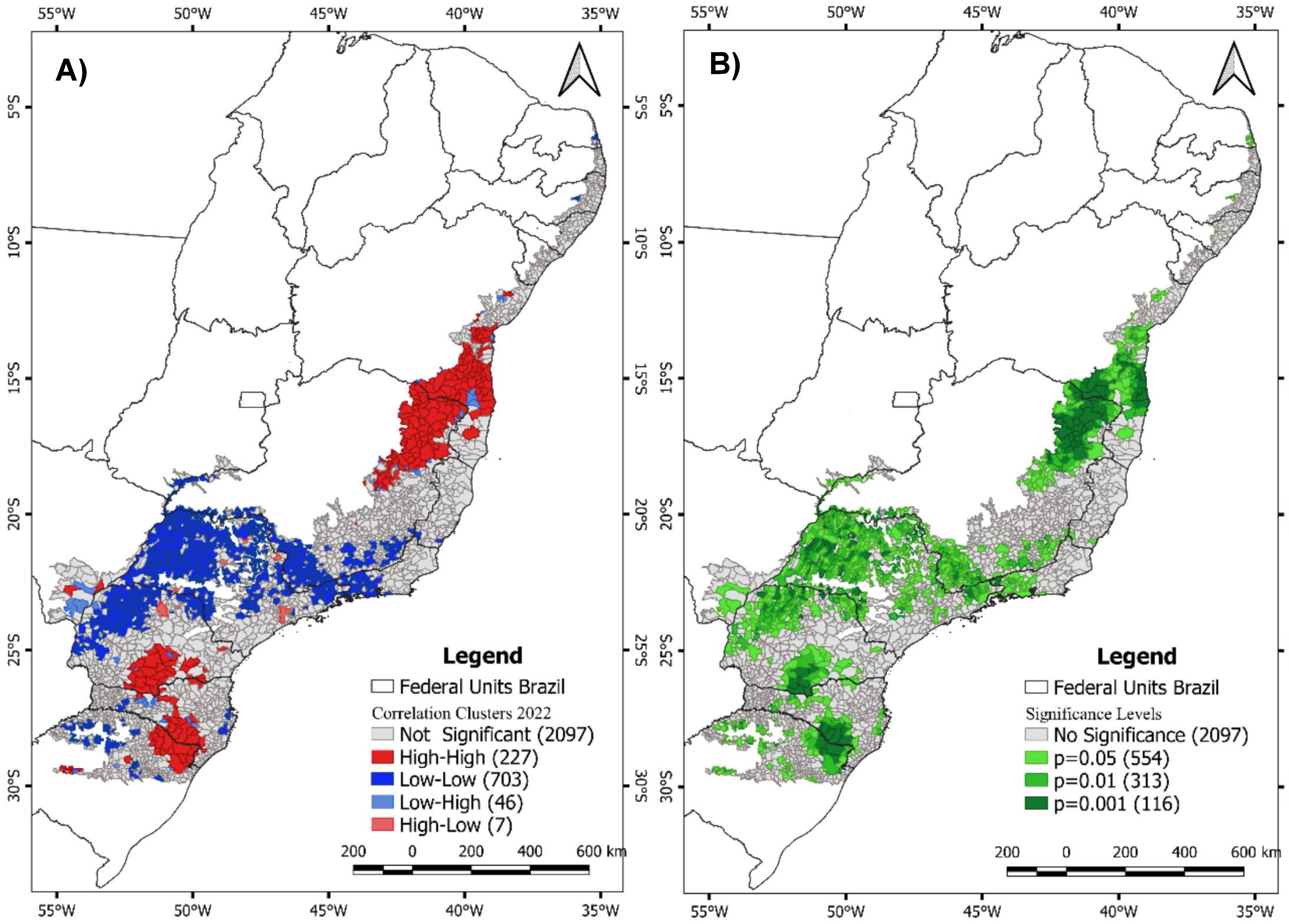

Figure 5. A) Moran Index correlation clusters for 2022 deforestation by MA municipalities.; B) Significance levels of correlation by municipality.

5. Discussion

Our analysis, involving 25.380 deforestation polygons mapped for the year 2022, unveiled three key findings directly tied to the PRODES methodology: 1) the substantial portion of 2022 deforestation polygons closely approximate the minimum mappable area (1 ha); 2) the 2022 deforestation hotspots are concentrated in northern and northeastern Minas Gerais, southeastern Bahia, southern Paraná, and southern Santa Catarina, corresponding to the Steppe, Contact Areas, regions of Mixed Ombrophilous Forest, Dense Ombrophilous Forest, and Seasonal Semideciduous and Deciduous Forest phytophysiognomies; 3) Moran's Index revealed a global spatial dependence of deforestation among municipalities, with significant dependency areas coinciding with hotspots deforestation.

Considering the methodology and concepts adopted by PRODES-MA, during the visual interpretation at a scale of 1:75.000, polygons of 1 ha are interpreted and detected which may appear to correspond to small areas. However, when added to adjacent polygons mapped in previous years, they indicate significant deforested areas. Therefore, can be seen the importance of these parameters 's concepts on methodology.

The fact that most deforestation polygons in 2022 (98%) correspond to areas ranging from 0,010 km^2 to 0,199 km^2 may be associated with environmental laws and regulations that may have inhibited deforestation beyond these area limits in the biome.

The Atlantic Forest Law (2006) rules the conservation, protection, regeneration, and use of the biome, restricting permission to clear primary and secondary forests to just a few specific situations [Atlantic Forest Law 2006]. Another significant legal framework is the Forest Code, which establishes norms and guidelines for forest preservation, land use, and regulation of water resources, which may have limited the suppression of native vegetation [Forest Code 2012]. Recently, the presence of payment for ecosystem services [Law 14.119 2012, Revised in 2021] has contributed to the increase in planted forest cover in the AF and the reduction of native vegetation loss [Ruggiero 2019].

According to Moran's Index results, three clusters comprising 227 municipalities with the highest concentration of 2022 deforestation were identified, namely, the northern and northeastern regions of Minas Gerais; the southeastern part of Bahia; and the southern regions of Paraná and Santa Catarina. In these areas, the predominant affected phytophysiognomies included Steppe, Contact Areas, Dense Ombrophilous Forest, and Seasonal Semideciduous Forest. These clusters may be linked to various drivers of different intensities, as indicated by underlying forces and proximate causes such as changes in GDP, population density, and agricultural activities, among others. At a large-scale analysis encompassing natural areas of Latin America, 369 scientific articles published between 1990 and 2014 were examined, revealing three 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 2017]. Studies conducted in the Atlantic Forest in the state of Paraná (PR) indicated that a 1% increase in GDP is associated with a 0,9% higher likelihood of deforestation between 2000 and 2020. Additionally, each 1% rise in population density was linked to a 0,2% increase in deforestation likelihood in the same state and timeframe [Mohebalian 2022].

Similarly, in the northernmost region of Minas Gerais between 2000 and 2015, a positive relationship was observed between GDP and population growth with deforestation increment. Additionally, livestock farming and land cultivation emerged as significant factors [Dupin 2016]. 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 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. These municipalities are primarily located in the regions between the northwest of Paraná (PR) and the southwest of São Paulo and between the southeast of São Paulo (SP) and the south of Minas Gerais (MG). In these regions, the predominant phytophysiognomies are Seasonal Semideciduous Forest and Contact Areas, respectively. However, the Low-Low correlation does not necessarily indicate a low degree of degradation of these phytophysiognomies. The Seasonal Semideciduous Forest has the largest deforested area among the phytophysiognomies, and Contact Areas rank fifth among the most degraded.

The low correlation results among municipalities (Low-High and High-Low) relate to a smaller number of municipalities in the analysis (53). In the High-Low, the analyzed municipality exhibits more deforestation than the average of neighboring municipalities, potentially indicating that such municipality has not yet influenced the others. In Low-High cases, the analyzed municipality experiences less deforestation compared to the average of its neighbors, similarly suggesting that it has not yet been influenced by the others [Anselin 1995]. Reverse analysis cases often indicate areas with possible transition 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 coincide with significant High-High autocorrelation among municipalities, neighboring municipalities likely engage in similar economic activities [Trigueiro 2020]. Depending on the region's economic activities, there can be the 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 [Margulism 2002], [Fearnsidef 2020], [Ferreira 2005]. In some Atlantic Forest regions, situated in the northeast of Minas Gerais, rural credit showed a positive association with deforestation, meaning that higher rural credit led to greater native vegetation suppression. Conversely, in the southeast of Bahia, there was an inverse relationship between agricultural credit and deforestation [Guimarães 2023]. Thus, despite deforestation clusters being linked to distinct economic activities, municipalities within each cluster should exhibit similarities in both economic activities and their secondary effects that amplify deforestation.

6. Conclusion

This work elucidates the concept and methodology employed by PRODES Atlantic Forest to facilitate its use in spatial geographic analyses. Deforestation in the Atlantic Forest, according to PRODES-MA 2022, while significant for the entire biome (1.032,69 km²), primarily occurs through the removal of small areas of native vegetation and is predominantly associated with forest phytophysiognomies: Seasonal Semideciduous Forest (27%), Dense Ombrophilous Forest (19%), and Seasonal Forests (14%). The prevalence of deforestation areas close to 1 ha reinforces the importance of the PRODES-MA methodology in monitoring the Atlantic Forest biome. If a larger cartographic scale were adopted for visual interpretation or if satellite images had a spatial resolution of more than 30 m, it would not be possible to identify the substantial portion of deforested areas.

Using PRODES-MA 2022 data, current spatial deforestation patterns in the Atlantic Forest were identified, including 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 the population growth, the economic activities of municipalities, and the demand for raw materials and anthropized space generated by these activities.

Therefore, considering the Brazilian Atlantic Forest biome, with only 12,6% of its natural vegetation preserved, accommodating 72% of Brazil's population, the deforestation process is still active and intense over specific areas. Data from PRODES-MA makes it possible to monitor and study the ongoing deforestation process.

7. Acknowledgments

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