

MONITORING ATLANTIC FOREST DEFORESTATION BY REMOTE SENSING SYSTEMS

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ABSTRACT

The Brazilian Atlantic Forest (MA) is a biodiversity hotspot, subject to historic and intense deforestation. Currently, three main monitoring systems based on satellite images monitor deforestation in the MA: The Atlas of forest remnants (SOS Mata Atlântica/INPE), MapBiomias, and PRODES-MA. To understand the contribution of each system and better interpret its results, this work presents their differences in concepts, methodologies, and characteristics. The Atlas has been fundamental for the definition of municipal and state public policies. MapBiomias highlights the main land cover conversions, and PRODES-MA is a reference for the national climate change policy. The methodological advances foreseen with the use of better-resolution images and semi-automatic detection techniques are also identified. Observing the nature, advantages, and limitations of each system enables us to identify the complementarity of the information to better communicate monitoring data and contribute to the prevention, control, and mitigation of deforestation in the Atlantic Forest.

Keywords - Atlantic Forest; deforestation; monitoring; remote sensing.

1. INTRODUCTION

The Brazilian Atlantic Forest (MA) is composed of a mosaic of forest and non-forest ecosystem remnants. It is a biodiversity hotspot containing 2420 vertebrate species and 20,000 plant species, with high levels of endemism and 1923 threatened species [1]. The MA occurs in 15% of the national territory, 17 states, and 3249 municipalities, and is the only Brazilian biome whose predominant cover class is not natural vegetation cover [2]. Also according to IBGE [2], in 2018, forest vegetation represented only 12.6% of its territory, and it was considered the biome with the highest population density, with 49.3% of Brazilian urban areas. There are about 145 million inhabitants or 72% of Brazil's population, and houses traditional communities, *quilombolas*, and indigenous peoples. Approximately 70% of the national GDP is produced in MA and at the same time, most of the springs and water sources that supply the large cities of the region are found in MA. These MA particularities are due to its history of occupation and urbanization from the coastal areas towards the interior, in the Brazilian territorial formation [2]

Since 1989, the SOS Mata Atlântica Foundation, in collaboration with the National Institute for Space Research - INPE, has monitored deforestation activities by publishing the Atlas of Forest Remnants in the Atlantic Forest. Currently, the MapBiomias and Prodes-MA projects, also

based on remote sensing data, have contributed to monitoring forest conversions in the MA. But what is the contribution of each system? How to interpret or communicate the different numbers and results for the MA?

In this context, this paper presents the main satellite monitoring systems of deforestation in the Atlantic Forest - Atlas of forest remnants from SOS Mata Atlântica/INPE, MapBiomias, and PRODES-MA. The objective is to discuss their characteristics and methodological and conceptual differences in the light of remote sensing, their products, and results, as well as prospects for methodological improvement.

2. MATERIAL AND METHODS

2.1. Study Area - the limits of the Atlantic Forest

The Atlantic Forest Biome (BMA) comprises 1,110,182 km² and it is an environmental complex that includes mountain ranges, plateaus, valleys, and plains throughout the Brazilian eastern Atlantic continental margin [3]. The BMA constitutes the great extra-Amazonian forest complex, formed by Ombrophylous Forests - Dense, Open, and Mixed; and Seasonal Forests - Semideciduous and Deciduous.

In 2006, the Federal Atlantic Forest Law (11.428/2006 and Decree 6.660/2008) was approved. This Law regulates the protection and use of the original configuration of native forest formations and their associated ecosystems in the MA. The Application Area of the Law corresponds to 1.309.736 km², and was delimited by IBGE [4], on the scale of 1:5.000.000. It comprises vegetation typologies that occur entirely in the BMA and also in the vegetation disjunctions in the Northeast or other regions, according to specific CONAMA, the Brazilian National Environment Council, resolutions for each state (Law 11.428 of 22.12.2006).

2.2. The Atlantic Forest monitoring systems

2.2.1. The Atlas of Forest Remnants of the Atlantic Forest

The Atlas of Forest Remnants of the Atlantic Forest [5] began in 1989. The first mapping was released in 1990, at the scale of 1:1,000,000, and by photointerpretation of Landsat images' color compositions. The methodology is based on the visual interpretation of Landsat images on screen, at a scale of 1:50,000. Deforestation areas smaller than 3 ha are not published, but considered as evidence and checked in the next

period. Images from the second semester are generally selected, with October as the reference month.

The identification of deforested areas (or Decrement) is obtained by comparing the natural vegetation remnants from images of the previous period (or mask of natural areas). It is considered forest remnants: primary and secondary forests in initial, medium, and advanced stages of regeneration since they are areas of vegetation that have less anthropic interference and greater capacity to protect their original Atlantic Forest biodiversity.

The mapping considers the following classes: Forest Remnants; Deforestation (in Forest monitored by the Atlas); Forest *Restinga* Remnants; Forest *Restinga* Decrement; Mangrove Vegetation Remnants; Mangrove Vegetation Decrement; Non-forested Natural Areas: Pioneer Formations in Floodplains; Natural High-Altitude Fields; Vegetation Refuges; Dunes; Herbaceous *Restinga*; *Apicum*; Marshland and Humid Field.

As a tool for defining public policies, the mapping considers the limits of the Application Area of the MA Law, which were refined using the Brazilian vegetation map RADAM (1:1,000,000) as a reference. After delimitation, the deforestation polygons are confirmed on Landsat images from the historical series and high-resolution images (Google Earth). A second interpreter evaluates the identification and delimitation of all polygons.

The general release of the mapping occurs on May 27, the National Day of the Atlantic Forest. The files concerning the Atlas and the mapping are available for download (<https://www.sosma.org.br/iniciativas/atlas-da-mata-atlantica/>), and the remnants per municipalities can be viewed on "Aqui tem Mata" (<https://www.aquitemmata.org.br/#/>)

2.2.2. Mapbiomas – Atlantic Rainforest

In 2021, the MapBiomas project, in the scope of Collection 6, released the annual Mapping of Land Cover and Land Use in Brazil (1985-2020) - Atlantic Forest Highlights, from the annual land cover maps from 1985 to 2020 [6]. This work only discusses the results of Collection 6, since the MA deforestation data in Brazil in 2022 had not yet been compiled, when this article was written.

Using surface reflectance images from Landsat 5 (TM), 7 (ETM+), and 8 (OLI) sensors, the best pixels of the annual series are selected, obtaining the median for all bands to generate the annual mosaics. From April to September there is a lower probability of clouds, the period considered to select, by visual analysis, images with up to 50% cloud cover.

To enable the automatic digital classification procedure, performed entirely on the Google Earth Engine (GEE) platform, the processing is performed considering 30 homogeneous regions in the Atlantic Forest, and 10 land use and land cover classes. Forest formations are defined by: Natural forests (excluding planted forests) - areas larger than 0.5 ha, trees taller than 5 m, and tree cover variable according to each forest formation: canopy cover > 80% for Dense

Ombrophilous Forest and Mixed Ombrophilous Forest; and canopy cover > 60% for Open Ombrophilous Forest, Seasonal Deciduous Forest, and Seasonal Semideciduous Forest.

From Landsat images, 36 attributes (bands and indices) are extracted and selected by the feature importance analysis of the Random Forest classifier [7], considering all bands and 500 interactions. The classification is done per pixel, for each of the 30 regions, for each year, with the Random Forest algorithm. It uses for training those pixels that have not changed in the 35 years, considered "stable samples". The MapBiomas Collection 5 is used as a source of samples, with manually drawn polygons and complimentary samples. The number of samples for each class is defined for each region by visual analysis and by the classification accuracy of Collection 5. For all years the same subset of samples is used and training is performed on the same mosaic of the classified year.

After classification, several filtering is required: Time Range Filling Filter, Spatial Filter, Frequency Filter, Temporal Filter, Incident Filter, Wetland Filter (HAND), and the Wooded *Restinga* Classification. For validation, 14,487 independent points are used to calculate the accuracy measures. The results referring to deforestation are obtained from the analyses of the trajectories of the different classes of use and cover mapped over the period 1985 to 2020.

In 2022, with Collection 7, the "MapBiomas Atlantic Forest Trinational, Collection 1" was launched, which extends the monitoring to the entire extent of the Atlantic Forest domain in South America, including its extension in Argentina and Paraguay [8].

2.2.3. PRODES-MA - INPE

The Project "Environmental Monitoring of Brazilian Biomes by Satellites: Atlantic Forest, Caatinga, Pampa and Pantanal" of INPE [9] was designed to meet the National REDD+ strategy, a mechanism for payments for avoided emissions of Greenhouse Gases (GHG) by reducing deforestation and forest degradation, to consolidate efforts to meet the goals set out in the National Policy on Climate Change (PNMC). To meet the national REDD+ strategy, the Ministry of Environment (MMA) published Ordinance 365/2015, which established the Biomes Environmental Monitoring Program (PMABB). Among PMABB objectives is the construction of a historical series of deforestation maps for the Atlantic Forest, Caatinga, Pampa, and Pantanal biomes, and the annual monitoring of deforestation in these Biomes from 2017 to 2021.

The mapping of deforestation in the Atlantic Forest biome follows the methodology developed and used in the PRODES-Amazon [10] and PRODES-Cerrado [11] projects: visual analysis at scale 1:75,000; manual vectorization of deforestation polygons, larger than 1ha in the case of the Atlantic Forest; in medium spatial resolution images, mainly from Landsat satellites.

For the MA, the Base Map for 2016 was initially produced, from color composition - RGB564 (OLI/Landsat8), with contrast enhancement by histogram manipulation, and segmentation by Region Growth (Similarity: 50 and Area (pixels): 20). An interpreter analyzed and edited all segments for further classification. The mapping of the biennial historical followed the legend defined for the Base Map, updating the polygons by visual interpretation, considering the classes: deforestation (agricultural areas, pasture or fallow, mining, burn scar, urban area, reforestation), hydrography (reservoir, water) and unobserved (cloud, cloud shadow, relief shadow). The classes: non-vegetated natural areas, floodable areas, natural forest or pioneer formations, araucaria forests, and natural grassland formations are not mapped. The mappings and their statistics will be released on the TerraBrasilis platform (<http://terrabrasilis.dpi.inpe.br/>), together with data from the other Brazilian Biomes.

3. RESULTS AND DISCUSSION

The diversity of phytophysionomies and the latitudinal gradient of the MA ensure high biodiversity and at the same time impose challenges for its mapping and monitoring by remote sensing. The spectral patterns of the different phytophysionomies make it difficult to define unique and uniform deforestation detection/classification methods. The selection of cloud-free images depends on climatic conditions, which in turn vary with a latitudinal gradient and local geographic and geomorphological conditions.

Although they are all based on Landsat images, the conception, definition of legends and the objective of the systems differ (Table 1). For the Atlas, the identification and accounting of deforestation in a consistent historical series has been a fundamental instrument for actions with municipal and state governments to control deforestation and encourage restoration projects of the MA [12].

MapBiomias proposes to map land use and land cover, and deforestation is, at first, a byproduct of the analyses of trajectories of its classes. With the expansion of mapping to the entire MA domain in Latin America, the scope for monitoring is broadened, attracting international attention to the Atlantic Forest deforestation.

| Characteristics | SOS MA | MapBiomias | PRODES_MA |
|--------------------------|---|---|---|
| Mapped Area | MA Law Limit | MA Law Limit and Biome | MA Biome |
| Mapping object | Preserved forest remnants | Land Use and Cover, any forest cover | Native vegetation (forest, shrub, grassland, etc.) |
| Minimum area | > 3 ha | > 0.5 ha | > 1 ha |
| Image | Landsat / Sentinel | Landsat | Landsat |
| Resolution | 30 - 10 m | 30 m | 30 m |
| Scale | 1:50.000 on screen | n.a. | 1:75.000 on screen |
| Historical Series | 1989 - 2021 | 1985-2020 | 2016 - Base 2004-2018 - biannual > 2019 - annual |
| Methodology | on-screen visual interpretation | Random Forest Classification | on-screen visual interpretation |
| Data Access | https://www.sosma.org.br/iniciativas/atlas-da-mata-atlantica/ | https://plataforma.brasilmapbiomias.org | http://terrabrasilis.dpi.inpe.br/downloads/ |
| Legend | Forest Decrement, Land Cover classes | Classes of Land Use and Land Cover | Deforestation |

Table 1. General characteristics of the Atlantic Forest monitoring systems

Regarding PRODES-MA, the deforestation mapping generated corresponds to the official monitoring results, together with the deforestation rates of the other Brazilian Biomes, as established in PMABB and the national REDD+ strategy [13].

3.1. How much Atlantic Forest is left

Answering how much of the original Atlantic Forest remains requires an answer that is neither simple nor unique. Rezende et al (2018), with RapidEye (5m) images from 2013, mapped 32 million ha of native vegetation in the MA domain in Brazil, which would correspond to 28% of the Biome [14].

According to the MA Atlas, in 2013 there were 18.3 million ha of native forests (more than 3ha and better-preserved forest) or 14% of the MA Law application area. By 2020, this area reduced to 16.2 million ha or 12.4% of the MA Law area [5].

For MapBiomias, in 2020, 31% of the MA Biome was covered by native vegetation (including savanna, grasslands, and floodplains), with 29% covered by forest formations (Forested Forest, Savanna, Mangrove and *Restinga*); and 25.8% of the Law Enforcement area covered by forest.

In other words, estimates may vary considering the geographic boundary of the MA (Biome or MA Law Enforcement Area), the definition of forest/legend, the resolution of the images, and the classification procedures adopted.

3.2. Deforestation of the Atlantic Forest

According to the historical series of the Atlas (Figure 1), the intense reduction in the early 2000s was followed by a period of a slight decrease in deforestation figures[5]. However, in 2021 the deforestation intensified again, with 21,642 ha, or an increase of 66% compared to 2019-2020, and 90% higher than the lowest value (11,399 ha) of the historical series, in 2017-2018. Also according to the Atlas, five states hold 89% of deforestation: Minas Gerais (9,209 ha), Bahia (4,968 ha), Paraná (3,299 ha), Mato Grosso do Sul (1,008 ha), and Santa Catarina (750 ha). São Paulo, Rio de Janeiro, Sergipe, and Pernambuco, which had deforestation close to zero, had an increase. Alagoas, Ceará, Paraíba, and Rio Grande do Norte had deforestation of less than 50 ha, but the cloud cover does not guarantee that they are with zero deforestation.

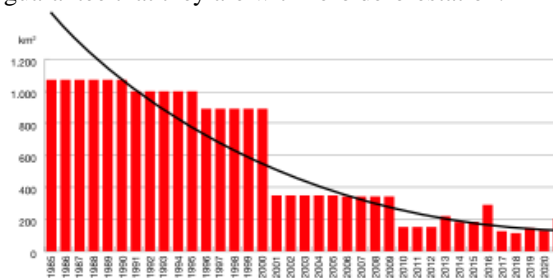


Figure 1. Deforestation rate and historical trend - Atlantic Forest Remnants Atlas (2022)

MapBiomias reported a total loss of 31.2% of primary vegetation from 1987 to 2019 or 10 million ha. For 2020, it indicated a loss of more than 30,000 ha of mature forest. The project does not disclose explicit deforestation data, but since it monitors land use and cover, it discusses the forest conversion by each period. The data from PRODES-MA have not yet been released, but will be available for consultation and access on the TerraBrasilis platform by the end of 2022.

3.3. New technologies in monitoring systems

With new sensors and free and better-resolution images, monitoring systems are being improved. The Atlas 2020-2021 was made with Copernicus MSI/Sentinel 2 (10m) images, providing greater detail of deforestation limits. Tests indicated a maximum increase of 7% in the estimate of deforested areas [5].

PRODES-MA team is researching improvements to detect deforestation over Sentinel-2 mosaics from Brazil Data Cube [15], using algorithms such as the Satellite Image Time Series - SITS [16] and supervised convolutional neural networks [17] for semi-automatic detection of deforestation. There are also other monitoring initiatives such as the Deforestation Alert System of the Atlantic Forest (SAD). Developed by SOS Mata Atlântica, Arcplan, and MapBiomias, SAD monitors monthly evidence of deforestation considering areas larger than 0.3 ha, with automatic classification of Sentinel-2 images (<https://www.sosma.org.br/iniciativas/alertas/>).

4. CONCLUDING REMARKS

This article describes methodologies and definitions for understanding the utility and relevance of the main systematic monitoring systems of the Atlantic Forest. The Atlas of Forest Remnants of SOS-Mata Atlântica/INPE, which monitors only forest remnants of more than 3ha, has been the main instrument for demanding municipal, state, and federal public policies to control deforestation. MapBiomias, due to its comprehensiveness and territorial reach has provided land use and cover data that shows the forest conversions in MA. The PRODES-MA system will provide complementary information for monitoring the Brazilian Biomes supporting policies for environmental compensation. This highlights the complementary nature of the different systems.

The availability of images with better spatial and temporal resolutions, and algorithms for automatic detection are driving the improvement of the systems. Recognizing the complementarity of the systems is central, not only for research development but especially for communicating the results for conservation strategies.

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