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# FOREST COVER STABILITY AND SPATIAL HETEROGENEITY ACROSS MUNICIPALITIES IN THE ATLANTIC FOREST (2000–2024)

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**Recebido em: 15/01/2026 – Aprovado em: 02/03/2026 – Publicado em: 30/03/2026**
**DOI: 10.18677/EnciBio_2026A4**

## 1 ABSTRACT

Recent assessments indicate stability in forest cover in the Atlantic Forest over recent decades, supporting an optimistic narrative of forest recovery. However, analyses based on aggregated metrics may obscure territorial inequalities and persistent degradation processes at local scales. The central hypothesis of this study is that apparent biome-scale forest-cover stability masks spatially heterogeneous patterns of forest loss and gain across municipalities. The objective was to assess the spatial distribution of forest cover and its relative changes between 2000 and 2024 at the municipal scale, identifying regional asymmetries and limitations of interpretations based on aggregated indicators. We used annual land-use and land-cover data from MapBiomas Collection 10, with 30 m spatial resolution, considering native forest formations within the Atlantic Forest biome. Analyses were conducted for 2,661 municipalities after applying minimum thresholds for intersected area and initial forest cover. Metrics included forest-cover proportion and Relative Forest-Cover Change (RFC), evaluated using descriptive statistics and spatial analyses. Results show that although total forest cover across the biome remained close to 23% during the study period, approximately 70% of municipalities retain less than 30% forest cover. Diffuse and low-magnitude forest gains coexist with spatially concentrated losses, particularly in the Northeast and eastern Minas Gerais. We conclude that forest-cover stability at aggregated scales does not represent homogeneous recovery, highlighting the need for spatially explicit analyses to support more targeted conservation and restoration strategies.

**KEYWORDS:** Land-use dynamics, Remote sensing, MapBiomas dataset, Tropical forests.

# ESTABILIDADE DA COBERTURA FLORESTAL E HETEROGENEIDADE ESPACIAL ENTRE MUNICÍPIOS NA FLORESTA ATLÂNTICA (2000–2024)

## 2 RESUMO

Avaliações recentes indicam estabilidade da cobertura florestal na Mata Atlântica nas últimas décadas, sustentando uma narrativa otimista de recuperação florestal. No entanto, análises baseadas em métricas agregadas podem ocultar desigualdades territoriais e processos persistentes de degradação em escalas locais. A hipótese central deste estudo é que a aparente estabilidade da cobertura florestal no nível do bioma mascara padrões espacialmente heterogêneos de perda e ganho florestal entre municípios. O objetivo foi avaliar a distribuição espacial da cobertura florestal e suas mudanças relativas entre 2000 e 2024, em escala municipal, identificando assimetrias regionais e limites da interpretação baseada em métricas agregadas. Foram utilizados dados anuais de uso e cobertura da terra da Coleção 10 do MapBiomas, com resolução espacial de 30 m, considerando formações florestais nativas da Mata Atlântica. A análise foi conduzida para 2.661 municípios, após aplicação de filtros mínimos de área e cobertura florestal inicial. As métricas analisadas incluíram proporção de cobertura florestal e Mudança Relativa da Cobertura Florestal (RFC), avaliadas por meio de estatísticas descritivas e análises espaciais. Os resultados indicam que, embora a cobertura florestal total do bioma tenha permanecido próxima a 23% no período analisado, cerca de 70% dos municípios apresentam menos de 30% de cobertura florestal. Observou-se coexistência de ganhos florestais difusos e de baixa magnitude com perdas espacialmente concentradas, especialmente em regiões do Nordeste e leste de Minas Gerais. Conclui-se que a estabilidade da cobertura florestal em escala agregada não representa recuperação homogênea, evidenciando a necessidade de análises espacialmente explícitas para subsidiar políticas de conservação e restauração mais direcionadas.

**PALAVRAS-CHAVE:** Cobertura florestal, Sensoriamento remoto, Heterogeneidade espacial, Florestas tropicais.

## 3 INTRODUCTION

Tropical forests have experienced intense loss and fragmentation over recent decades, resulting in profound impacts on biodiversity, ecological processes, and the provision of ecosystem services (ARROYO-RODRÍGUEZ *et al.*, 2017; HANSEN *et al.*, 2020). In regions with a long history of human occupation, such as eastern South America, forest conversion associated with agricultural expansion, urbanization, and infrastructure development has shaped highly anthropized landscapes characterized by fragmented mosaics and strong edge dominance. In this context, recent forest-cover dynamics have been widely investigated using remote sensing data, revealing signals of deforestation slowdown and, in some cases, stability or net gains in forest area at regional scales (LIRA *et al.*, 2012; CROUZEILLES *et al.*, 2020; BICUDO DA SILVA *et al.*, 2023).

The Brazilian Atlantic Forest represents one of the most emblematic examples of this process. Recognized as a global biodiversity hotspot, the biome currently retains between 11% and 25% of its original forest cover, mostly distributed in small and isolated fragments, often smaller than 50 ha (JOLY *et al.*, 2014; DIAS *et al.*, 2023; RESENDE *et al.*, 2024). Despite this high degree of fragmentation, recent studies based on land-use and land-cover time series have pointed to an apparent stabilization of total forest area since the early 2000s, frequently interpreted as evidence of a forest transition or recovery associated with natural regeneration in abandoned or low-agricultural-suitability areas (REZENDE *et al.*, 2015; SCHWEIZER *et al.*, 2022; COSTA *et al.*, 2024).

However, interpretations based on aggregated forest-area metrics have important limitations. Assessments conducted at biome or national scales tend to mask territorial inequalities, concealing the coexistence of contrasting processes of forest loss and gain across different regional and local contexts (ROSA *et al.*, 2021;

PIFFER *et al.*, 2022). In highly fragmented landscapes, small-magnitude forest gains may stabilize total forest area without substantially altering landscape structure, while concentrated losses in specific regions may be diluted in aggregated analyses. Thus, forest-cover stability does not necessarily imply homogeneous ecological recovery or a reduction in landscape vulnerability.

Recent studies in the Atlantic Forest have emphasized that contemporary forest dynamics are strongly spatially heterogeneous, reflecting historical land-use legacies, socioeconomic differences, regional governance patterns, and biophysical constraints (ROSA *et al.*, 2021; DIAS *et al.*, 2023; BROGGIO *et al.*, 2024; VANCINE *et al.*, 2024). While parts of the South and Southeast show signs of diffuse forest regeneration, regions of the Northeast and eastern Minas Gerais continue to experience persistent losses or stagnation trajectories at very low levels of forest cover. In this context, municipal-scale analyses play a central role, as they capture local land-use decisions and reveal spatial patterns that are obscured in more aggregated assessments (VELASCO *et al.*, 2020; PIFFER *et al.*, 2022). In addition, evidence that vegetation structure modulates local thermal conditions and environmental quality supports the interpretation of heterogeneous landscape responses across human-modified territories (SANTOS *et al.,* 2024).

Despite advances in long-term land-cover monitoring, few studies have systematically assessed how biome-scale forest-cover stability emerges from highly unequal municipal trajectories over extended temporal windows. In particular, it remains poorly explored to what extent the stability observed at the biome scale results from the aggregation of deeply unequal local trajectories, and how these territorial asymmetries constrain the interpretation of forest-cover stability as an indicator of ecological recovery.

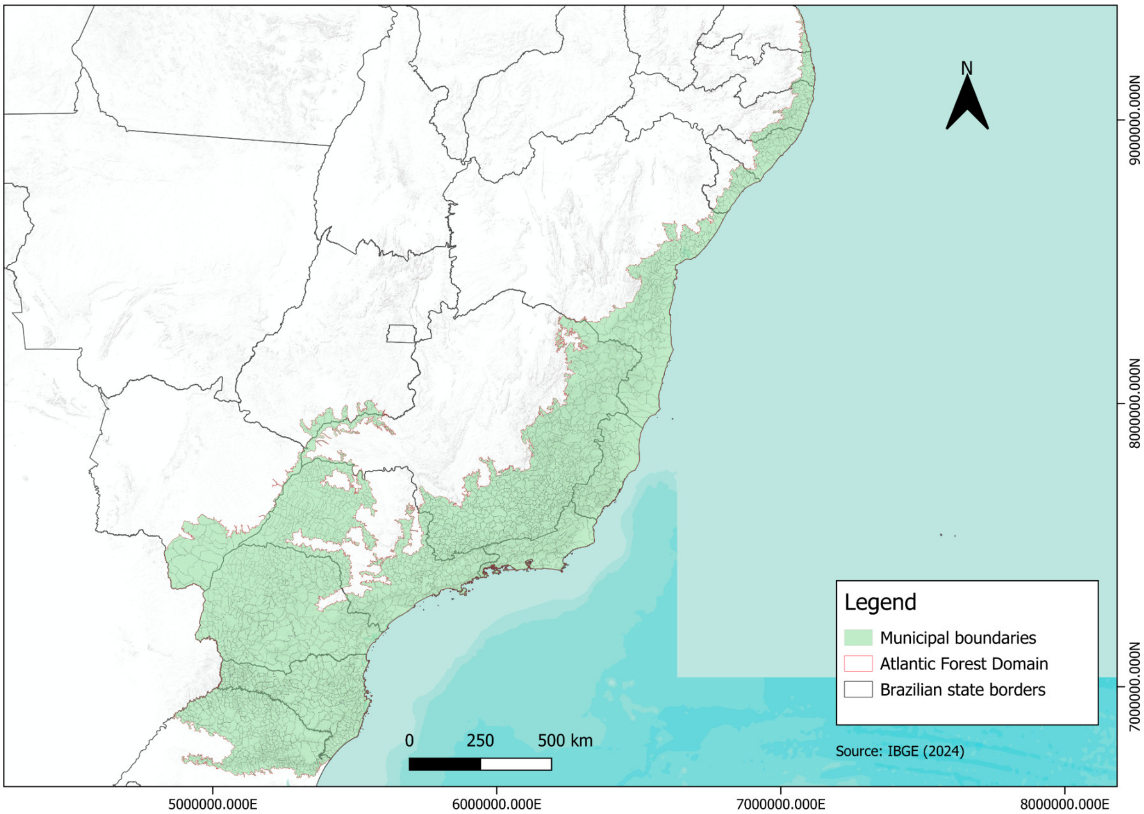
In this context, this study is based on the hypothesis that the apparent stability of forest cover observed at the Atlantic Forest biome scale between 2000 and 2024 masks structurally persistent patterns of forest scarcity and uneven recovery across municipalities. Specifically, biome-scale stability may result from the aggregation of highly contrasting local trajectories, characterized by diffuse, low-magnitude forest gains and spatially concentrated losses. Thus, this study aims to assess the spatial distribution of forest cover and its relative change at the municipal scale, explicitly examining whether aggregated stability reflects homogeneous ecological recovery or conceals deep territorial asymmetries that limit the interpretation of forest-cover stability as an indicator of landscape recovery.

# 4 MATERIALS AND METHODS

## 1.1 Study area

The study covers the Brazilian Atlantic Forest biome, a highly fragmented tropical forest domain extending along the eastern portion of Brazil (Figure 1). The Atlantic Forest spans a wide latitudinal, altitudinal, and climatic gradient, hosting a mosaic of phytophysiognomies, including dense and mixed ombrophilous forests with Araucaria, semideciduous and deciduous seasonal forests, alluvial forests, mangroves, and restinga formations along coastal plains (VITÓRIA *et al.*, 2019; GRELLE *et al.*, 2021; MASSANTE; GASTAUER, 2023; GUIMARÃES *et al.*, 2024).

**FIGURE 1:** Spatial Distribution of the Atlantic Forest Biome and Analyzed Municipalities in Brazil




Source: Authors (2026)

These formations exhibit strong variation in climate, soils, and hydrological regimes, which is reflected in high functional and phylogenetic heterogeneity of tree communities (VITÓRIA *et al.*, 2019; MININI *et al.*, 2022; MASSANTE; GASTAUER, 2023). This climatic variability is coherent with evidence from tropical conditions in Brazil showing that temperature regimes and environmental context are key factors shaping system responses in field studies (ANTUNES *et al.,* 2022).

## Forest cover data

Forest-cover data were obtained from MapBiomas Collection 10, a nationally consistent annual land-use and land-cover dataset for Brazil that provides annual information on land-cover dynamics, from which forest-cover estimates were extracted for the period analyzed. MapBiomas is based primarily on Landsat satellite imagery, with a spatial resolution of 30 m, and applies a standardized classification framework that integrates machine-learning algorithms, extensive training datasets, and expert-based validation. This approach ensures temporal comparability across years and has been widely adopted in studies assessing long-term land-cover dynamics and forest change in Brazil (DE ARAÚJO MOTA *et al.,* 2023).

For the purposes of this study, forest cover was defined as native woody vegetation within the Atlantic Forest biome. We included the MapBiomas classes corresponding to Forest Formation, Mangrove, and Floodable Forest, which together represent the dominant forest physiognomies of the biome. These classes were aggregated to generate a single forest-cover layer for each year, allowing a consistent assessment of total forest extent through time.

All raster datasets were spatially clipped using the official Atlantic Forest domain boundary provided by the Brazilian Institute of Geography and Statistics (IBGE), ensuring that only pixels located within the biome were included in the analysis. Raster layers were reprojected to a common coordinate reference system and checked for spatial alignment to guarantee consistency across years. This preprocessing ensured that observed temporal changes reflected land-cover dynamics rather than artefacts of projection or spatial mismatch.

Although MapBiomas provides a consistent and widely validated time series, classification uncertainties at 30 m resolution may affect local estimates, particularly in highly fragmented landscapes. However, the use of long-term trends and municipal-scale aggregation helps reduce the influence of year-specific classification noise on the interpretation of forest-cover dynamics.

**Forest cover metrics**

Forest-cover metrics were calculated at the municipal scale, which represents a key administrative unit for land-use governance and environmental management in Brazil. Municipal boundaries were obtained from the IBGE cartographic base (2022, scale 1:250,000), and analyses were restricted to the portion of each municipality located within the Atlantic Forest domain.

For each municipality i and year t, the total forest area (km²) was calculated according to Author (year), as shown in Equation 1.

$$FA_{i,t} = \sum_{p=1}^{n} A\,p \quad (1)$$

where $A_p$ represents the area of each forest pixel p within municipality i at time t, and n is the total number of forest pixels.

The proportion of forest cover was then calculated according to Equation 2.

$$FC_{i,t} = \frac{FA_{i,t}}{TA_i} x\ 100 \quad (2)$$

where $TA_i$ is the total area of the municipality i located within the Atlantic Forest domain.

Forest-cover metrics were extracted for the baseline year (2000) and the most recent year of the series (2024), allowing the characterization of both current forest extent and long-term trajectories.

**Relative forest change**

To assess forest-cover dynamics over the study period, we calculated Relative Forest Change (RFC), defined as the proportional change in forest cover between 2000 and 2024 relative to the baseline year, as described in Equation 3.

$$RFC_i = \frac{FC_{i,2024} - FC_{i,2000}}{FC_{i,2000}} \quad (3)$$

where $FC_{i,2000}$ and $FC_{i,2024}$ represent the proportion of forest cover in municipality in 2000 and 2024, respectively.

Negative RFC values indicate proportional forest gains, while positive values indicate proportional forest losses. Expressing change relative to baseline forest cover allows comparison among municipalities with contrasting historical forest extents and highlights spatial heterogeneity in forest trajectories across the biome.
Because RFC is expressed relative to baseline forest cover, proportional gains may be inflated in municipalities with very low forest cover in 2000. Therefore, RFC is interpreted in this study as an indicator of trajectory direction and relative change intensity, rather than as a direct measure of ecological recovery.

In addition to municipal-scale analyses, forest-cover metrics were aggregated by Brazilian macro-regions (Northeast, Southeast, South, and Center-West) to examine broader regional patterns of forest stability, loss, and recovery.

**Data filtering and analytical consistency**

To enhance analytical robustness and minimize distortions associated with extremely small spatial units or near-zero baselines, two filters were applied prior to analysis. First, municipalities with less than 10 km² of territory within the Atlantic Forest domain were excluded. Small intersected areas are highly sensitive to classification uncertainty at 30 m resolution and may inflate proportional metrics.
Second, municipalities with less than 5% forest cover in 2000 were excluded, as minimal baseline values can generate inflated RFC estimates in response to small absolute changes. These thresholds ensure that proportional metrics reflect meaningful forest dynamics rather than numerical artefacts.

Similar precautions regarding small spatial units and baseline effects in proportional landscape metrics are widely discussed in the landscape ecology and remote sensing literature (TUMER *et al.*, 2001; OLOFSSON *et al.*, 2014).

After applying both criteria, 2,661 municipalities were retained for analysis, ensuring analytical consistency while preserving broad spatial representativeness.

**Analytical approach**

The analytical approach is primarily descriptive and exploratory, aiming to characterize spatial heterogeneity and long-term trajectories rather than to establish causal relationships.

Forest cover and change were evaluated using descriptive and spatially explicit analyses. The distributions of forest cover ($FC_{i,2000,2024}$) and relative forest change were examined using histograms and summary statistics to characterize central tendencies, dispersion, and skewness.

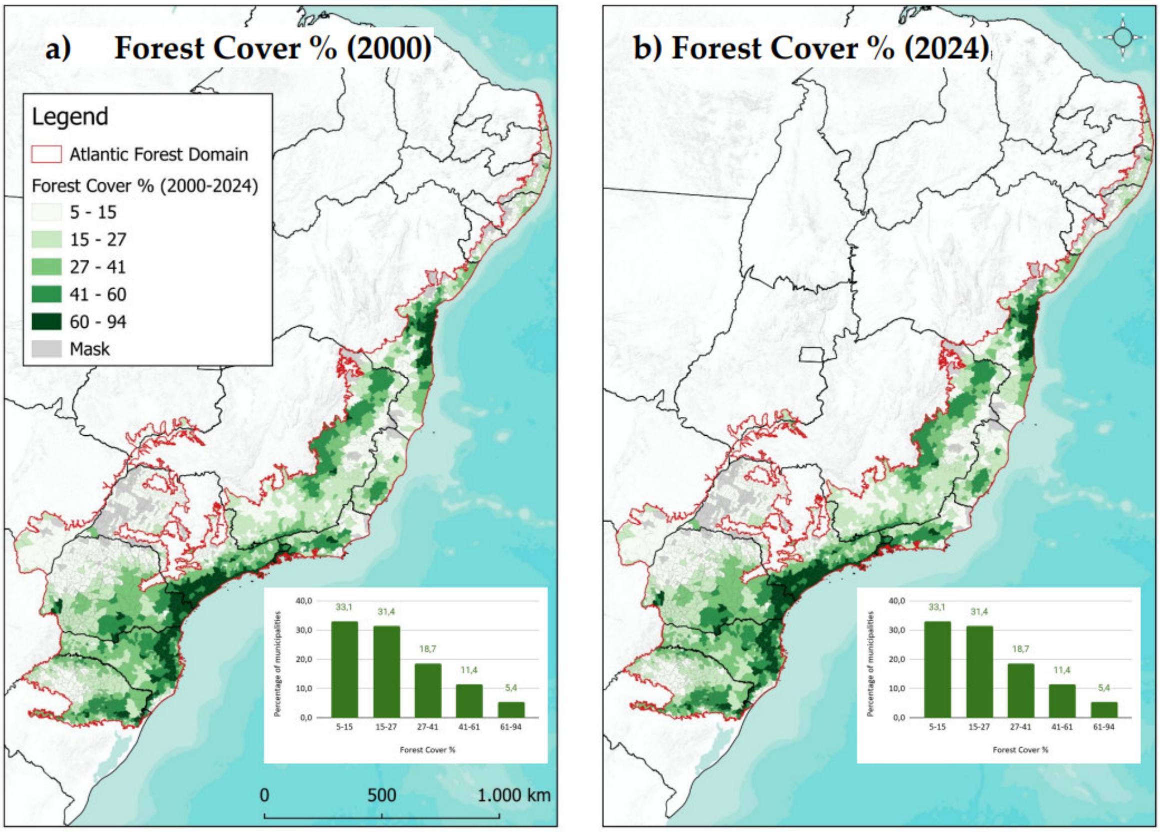
Regional contrasts were explored through boxplots and tabular summaries, enabling comparison of forest-cover distributions and change trajectories among Brazilian macro-regions. Spatial patterns of forest cover in 2024 and RFC between 2000 and 2024 were visualized using thematic maps at the municipal scale, allowing identification of clusters of persistent low forest cover, diffuse regeneration, and continued forest loss.

All statistical analyses were descriptive and exploratory. Forest-cover proportion and Relative Forest Change (RFC) were summarized using descriptive statistics to characterize central tendency and dispersion. The distributions of both variables were examined using histograms, allowing visualization of their frequency distributions and skewness patterns. Regional differences among Brazilian macro-regions (Northeast, Southeast, South, and Center-West) were explored through boxplots and tabular summaries to compare forest-cover distributions and change trajectories across regions. The relationship between RFC and forest cover was examined through graphical analysis to identify proportional change patterns associated with different baseline forest-cover levels. Spatial patterns of forest cover (2024) and RFC (2000–2024) were analyzed through thematic maps at the municipal scale. Because the analytical approach of this study is descriptive and exploratory, no inferential statistical tests were performed and no significance level was adopted. All spatial analyses and visualizations were conducted in QGIS to ensure transparency and reproducibility of the analytical workflow.

## RESULTS AND DISCUSSIONS

At the biome scale, the comparison between the baseline year (2000) and the most recent year (2024) indicates that total forest cover remained close to 23%, indicating limited net change between these two points in time when assessed at an aggregated spatial scale (Figure 2). This pattern is consistent with previous assessments based on long-term land-use and land-cover time series, which report a historical slowdown in deforestation and a recent stabilization of forest area in the Atlantic Forest (LIRA *et al.*, 2012; CROUZEILLES *et al.*, 2020; BICUDO DA SILVA *et al.*, 2023).

**FIGURE 2:** Spatial Distribution of Municipal Forest Cover across the Atlantic Forest Biome in 2000 and 2024



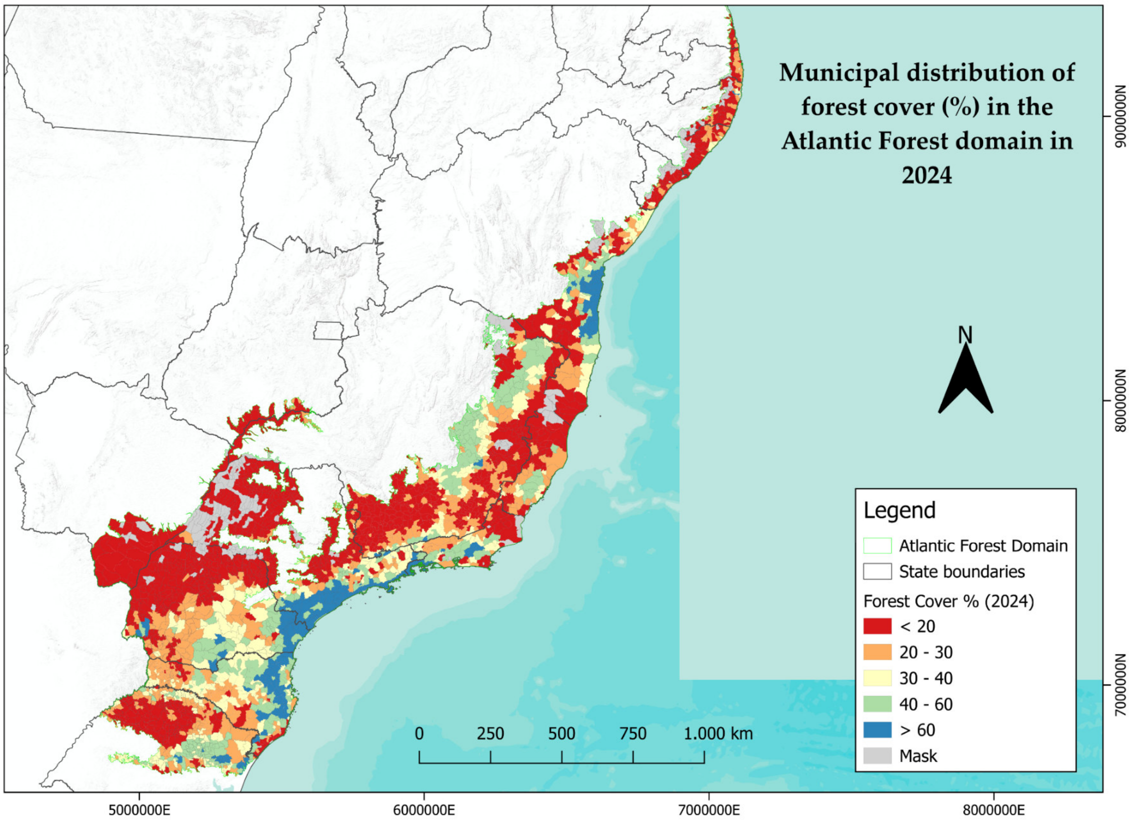

Source: Authors (2026)

However, this aggregated stability emerges from the balance between contrasting and spatially uneven processes of forest gain and loss occurring simultaneously across the biome. Regional forest-cover trajectories frequently represent the net outcome of these opposing processes, where deforestation and forest regeneration coexist across landscapes and collectively determine observed net forest change (CHZDON, 2016). As a result, although total forest area remains relatively constant, this metric fails to capture the diversity of local trajectories and the spatial distribution of forest cover, reinforcing that analyses based solely on aggregated indicators may lead to overly optimistic interpretations of the biome's forest condition.

The spatial distribution of forest cover in 2024 reveals strong heterogeneity at the municipal scale, contrasting with the more aggregated pattern observed at the biome scale (Figure 3). Approximately 70% of the municipalities analyzed exhibit less than 30% forest cover (Figure 4), indicating the predominance of highly fragmented, structurally impoverished landscapes dominated by small patches, extensive edge effects, and the absence of core areas, as previously described for the Atlantic Forest and other Brazilian contexts (PARRAS *et al.*, 2020; DIAS *et al.*, 2023; BROGGIO *et al.*, 2024).

Municipalities with higher proportions of forest cover are relatively rare and are spatially concentrated in areas of rugged terrain, protected zones, and coastal mountain systems such as the Serra do Mar, as well as in portions of southern Brazil, where conservation units and topographic constraints have contributed to limiting deforestation and the intensification of fragmentation (SOUZA *et al.*, 2025; SILVA *et al.*, 2021). These local patterns are consistent with analyses showing that, even when total forest cover is stable or moderately high, the landscape tends to be composed of numerous small and isolated fragments, with high edge density and a pronounced loss of functional connectivity (FERNANDES; BATISTA, 2020; SIQUEIRA *et al.*, 2021; DIAS *et al.*, 2023).

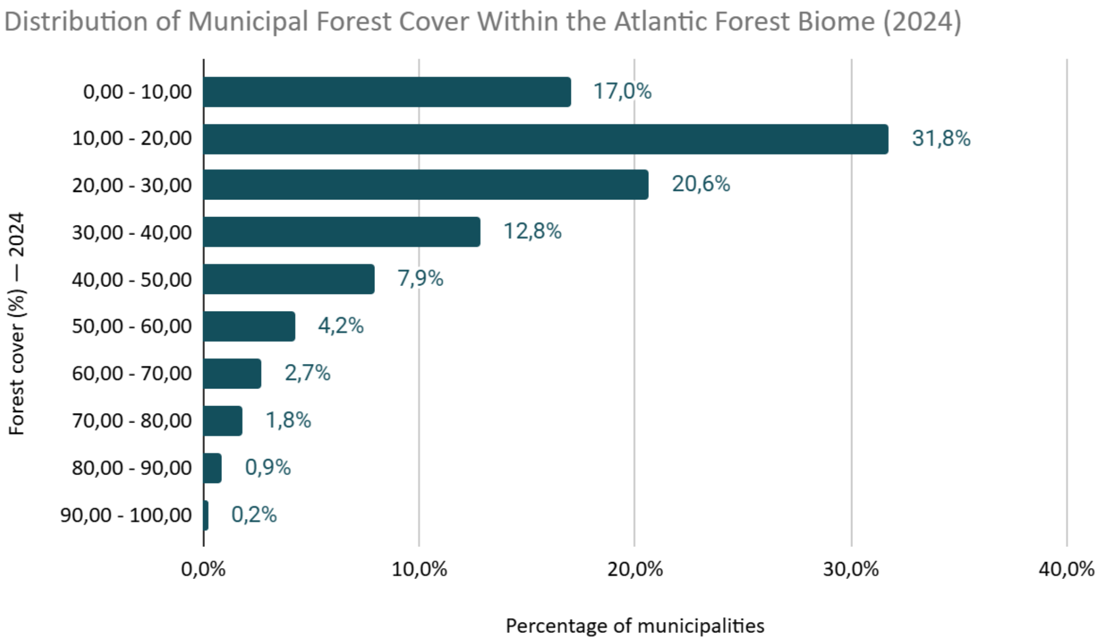
**FIGURE 3.** Municipal distribution of forest cover (%) in the Atlantic Forest biome in 2024. Most municipalities retain low forest cover, while higher values are spatially concentrated in mountainous and protected regions.




Source: Authors (2026)

The scarcity of municipalities with intermediate forest cover values indicates a polarized spatial distribution, in which contexts of high forest conservation coexist with extensive areas of chronic degradation, with few municipalities occupying intermediate conditions. This pattern is consistent with studies highlighting the persistence of historical land use legacies in the Atlantic Forest, where conversion processes that occurred decades ago continue to shape present-day landscape configuration and forest scarcity (ROSA *et al.*, 2021; DIAS *et al.*, 2023; BROGGIO *et al.*, 2024).

**FIGURE 4:** Distribution of Municipal Forest Cover Percentages across the Atlantic Forest Biome in 2024



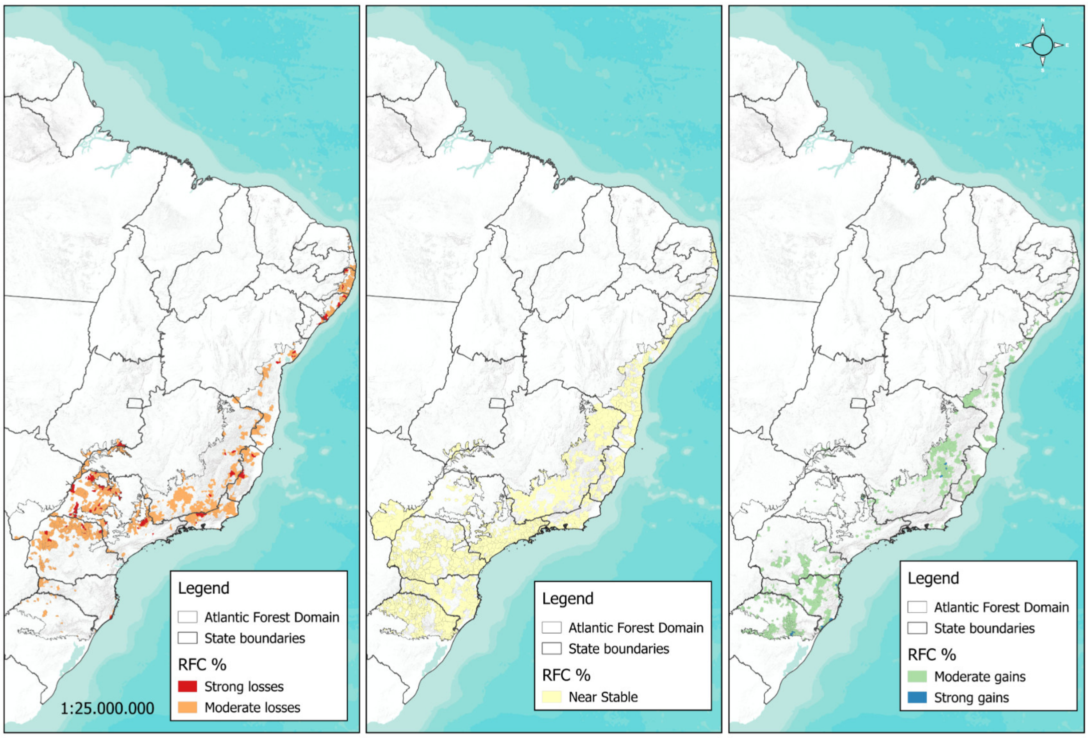

Source: Authors (2026)

From an ecological perspective, the predominance of municipalities with low forest-cover percentages is likely to impose strong constraints on landscape connectivity and on the maintenance of ecological processes in the Atlantic Forest, as many species and ecosystem functions depend on a sufficient amount of habitat at the landscape scale (BOESING *et al.*, 2018; ARROYO-RODRÍGUEZ *et al.*, 2020; FARIA *et al.*, 2023). Even in the absence of explicit metrics of fragment size or connectivity, the low forest-cover levels observed indicate that large portions of the biome are probably below critical habitat and biodiversity thresholds (approximately 20–40% forest cover), ranges within which studies have reported sharp collapses in taxonomic, functional, and phylogenetic diversity, biomass, and ecological functions in fragmented tropical landscapes (ROCHA-SANTOS *et al.*, 2017; BOESING *et al.*, 2018; FARIA *et al.*, 2023).

Evidence from the Atlantic Forest shows that reductions in forest cover and connectivity are associated with functional losses in tree and mammal communities, the simplification of seed dispersal and pollination networks, and declines in forest bird diversity, reinforcing that many municipalities with low forest cover tend to operate below levels compatible with the long-term persistence of biodiversity and ecological functioning (ROCHA-SANTOS *et al.*, 2017; FERREIRA *et al.*, 2020; FARIA *et al.*, 2023).

The analysis of Relative Forest Cover Change (RFC) between 2000 and 2024 reveals the coexistence of contrasting trajectories among Atlantic Forest municipalities. While many municipalities experienced limited proportional change over the period considered, the spatial patterns of RFC indicate the simultaneous occurrence of forest gains and losses across distinct portions of the biome, highlighting strong spatial heterogeneity in recent forest cover dynamics (Figure 5).

**FIGURE 5.** Spatial patterns of relative forest-cover change (RFC) between 2000 and 2024 across Atlantic Forest municipalities: (A) municipalities experiencing forest loss, (B) municipalities with relatively stable forest cover, and (C) municipalities exhibiting forest gains. Gains are spatially diffuse, whereas losses are more geographically concentrated.

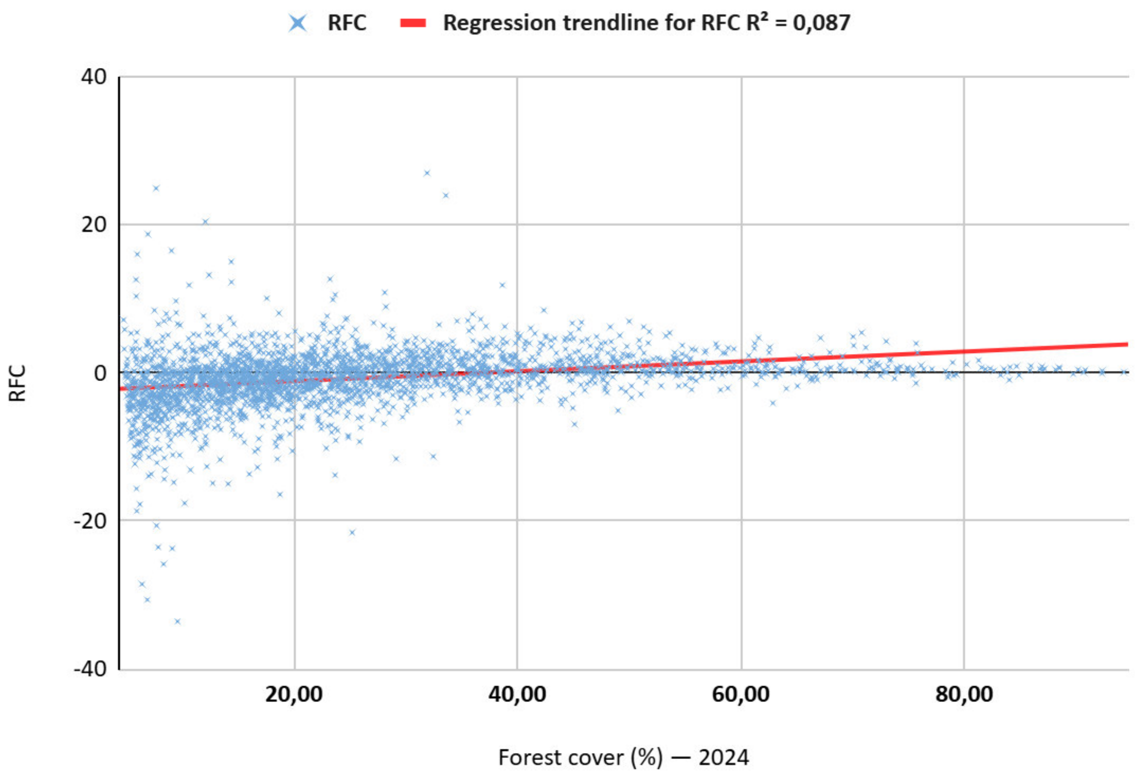



Source: Authors (2026)

Spatially, forest gains tend to be diffuse and of low magnitude, distributed across a relatively large number of municipalities, particularly in the South and Southeast regions. In contrast, more intense forest losses are less frequent but spatially concentrated, occurring mainly in parts of the Northeast and eastern Minas Gerais, regions historically subject to persistent land-use pressures and socioeconomic constraints.

The relationship between RFC and forest cover in 2024 further indicates that large proportional gains are predominantly concentrated in municipalities that currently retain low levels of forest cover (Figure 6). In these contexts, small absolute increases in forest area translate into substantial proportional gains, without representing a meaningful improvement in the structural condition of the landscape. This pattern reinforces the need for caution when interpreting proportional change metrics as indicators of ecological recovery, particularly in historically forest-scarce and highly fragmented municipalities.

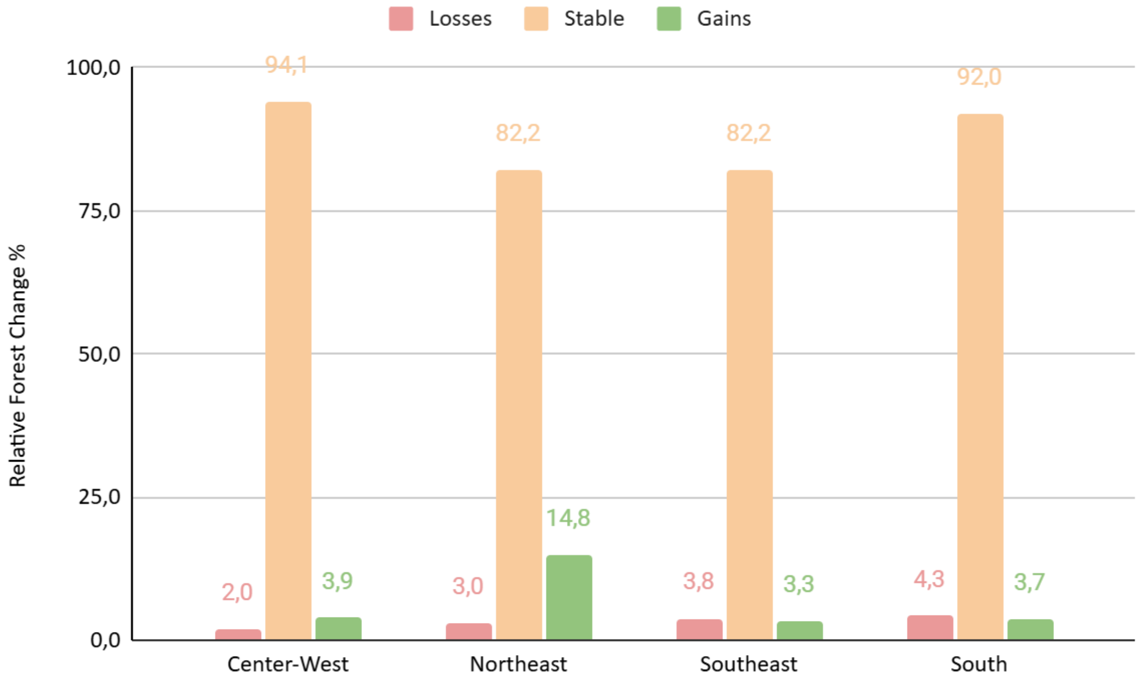
**FIGURE 6.** Relationship between relative forest change (RFC) and baseline forest cover in 2000. Large proportional gains are concentrated in municipalities with very low initial forest cover.




Source: Authors (2026)

The aggregation of results by Brazilian macro-regions highlights marked contrasts in forest-cover change trajectories across the Atlantic Forest. The South and Southeast regions exhibit a higher proportion of municipalities classified as experiencing moderate forest gains, reflecting more favorable trajectories of diffuse regeneration (Figure 7). Nevertheless, these regions also display substantial internal variability, with the coexistence of municipalities retaining relatively high forest cover and others remaining under conditions of chronic degradation.

**FIGURE 7.** Regional composition of forest-cover change trajectories between 2000 and 2024, expressed as the proportion of municipalities experiencing forest loss, relative stability, or forest gain. Regional contrasts reveal divergent recovery and degradation patterns across the Atlantic Forest.




Source: Authors (2026)

In contrast, the Northeast presents a higher frequency of municipalities characterized by persistent forest losses or relative stability at very low forest-cover levels, indicating structural constraints to recovery. Similar patterns are observed in eastern Minas Gerais and in the Central-West portion of the Atlantic Forest domain, where low forest cover and limited evidence of recovery prevail over the period analyzed. These regional contrasts reflect long-standing differences in land-use history, intensity of anthropogenic pressure, institutional capacity, and environmental governance, underscoring the relevance of the municipal scale for understanding contemporary forest dynamics.

Taken together, these results demonstrate that forest-cover stability at the biome scale does not correspond to homogeneous recovery across the Atlantic Forest. The maintenance of total forest area is largely sustained by diffuse, low-magnitude gains that compensate for spatially concentrated losses, without substantially altering the pervasive condition of forest scarcity affecting a large share of municipalities. Consequently, the observed stability represents a fragile balance between opposing processes rather than a consistent transition toward structural landscape recovery.

These findings reinforce limitations previously identified in the literature regarding the use of aggregated forest-area metrics as indicators of success in conservation and restoration initiatives (ROSA *et al.*, 2021; PIFFER *et al.*, 2022). In highly fragmented biomes such as the Atlantic Forest, interpreting forest-cover stability requires explicit consideration of spatial distribution, local contexts, and historical land-use legacies. Municipal-scale analyses therefore provide a more appropriate basis for identifying priority areas for conservation and restoration and for guiding territorially differentiated public policies.

## CONCLUSIONS

This study shows that the apparent stability of forest cover in the Atlantic Forest between 2000 and 2024 does not reflect homogeneous ecological recovery. Municipal-scale analyses reveal pronounced spatial heterogeneity, with the predominance of low forest-cover levels and the coexistence of diffuse, low-magnitude gains and spatially concentrated losses. Consequently, aggregated metrics mask persistent territorial inequalities and provide a limited representation of forest dynamics in highly fragmented landscapes.

By adopting a municipal-scale perspective, this study offers a more accurate basis for interpreting forest-cover dynamics and for supporting conservation and restoration strategies that explicitly consider local contexts and historical land-use legacies. These findings highlight the need for territorially differentiated approaches to guide effective and equitable forest conservation policies in the Atlantic Forest.

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