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Geospatial Assessment of the Serra do Japi Preservation, Restoration, and Recovery Zone Conservation through NDVI-based spatiotemporal analysis, Jundiaí, São Paulo, Brazil

Avaliação geoespacial da conservação da Zona de Preservação, Restauração e Recuperação da Serra do Japi por meio de análise espaço-temporal baseada no NDVI, Jundiaí, São Paulo, Brasil

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Resumo: A preservação de áreas de alta diversidade biológica em regiões de rápida urbanização é uma preocupação global crescente. Nesse contexto, o presente estudo emprega técnicas de sensoriamento remoto para avaliar a efetividade de políticas públicas na Reserva da Serra do Japi, um raro remanescente de Mata Atlântica no estado de São Paulo, reconhecido por sua riqueza ecológica e alto endemismo de espécies. Por meio de imagens de satélite multitemporais, foram avaliadas as mudanças na cobertura vegetal entre 2013 e 2023, com o objetivo de determinar o impacto das políticas implementadas, em especial após a designação da área como patrimônio natural em 1983. Os resultados revelaram valores consistentemente elevados do Índice de Vegetação por Diferença Normalizada (NDVI) na Zona de Preservação, Restauração e Recuperação da Serra do Japi e na região de Jundiaí em seu entorno ao longo do período de dez anos, indicando uma cobertura vegetal preservada e estável. A análise de histogramas dos valores reclassificados de ΔNDVI mostrou que 94,5% dos pixels no interior da Zona da Serra do Japi não apresentaram variação significativa, enquanto 77,5% dos pixels na área urbana de Jundiaí permaneceram estáveis, indicando maior variabilidade da vegetação em regiões urbanizadas em comparação com a área protegida. Além disso, apenas 2% dos pixels na Serra do Japi indicaram possível perda de vegetação, proporção substancialmente inferior à observada na área urbana do município. Perdas localizadas de vegetação foram detectadas nas porções sul adjacentes à reserva, o que reforça a importância de esforços contínuos de monitoramento e restauração. O uso do sensoriamento remoto mostrou se uma ferramenta confiável e de baixo custo para detectar mudanças sutis espaciais e temporais na vegetação. Dessa forma, o fortalecimento dos marcos de conservação e a continuidade de programas de monitoramento de longo prazo são essenciais para prevenir futuras degradações e manter a resiliência ecológica da Reserva da Serra do Japi.
Palavras-chave: Sensoriamento remoto. NDVI. Conservação ambiental. Mata Atlântica. Serra do Japi.

Abstract: The preservation of biodiversity hotspots in rapidly urbanizing regions is an increasing global concern. In this context, the present study employs remote sensing techniques to evaluate the effectiveness of public policies in the Serra do Japi Reserve, a rare Atlantic Forest remnant in São Paulo State, renowned for its ecological richness and high species endemism. Using multitemporal satellite imagery, the study assessed changes in vegetation cover between 2013 and 2023 to determine the impact of implemented policies, particularly following the area's designation as a natural heritage site in 1983. The results revealed consistently high Normalized Difference Vegetation Index (NDVI) values within the Serra do Japi Preservation, Restoration, and Recovery Zone and the surrounding Jundiaí region over the ten-year period, indicating stable preserved vegetation cover. Histogram analysis of reclassified ΔNDVI values showed that 94.5% of pixels within the Serra do Japi Zone exhibited no significant change, while

77.5% of pixels in the urban area of Jundiaí remained stable, indicating greater vegetation variability in urbanized regions compared to the protected area. Additionally, only 2% of pixels within Serra do Japi indicated possible vegetation loss, a proportion notably lower than that observed in the municipality's urban area. Localized vegetation loss was detected in the southern areas adjacent to the reserve, underscoring the importance of continuous monitoring and restoration efforts. The use of remote sensing proved to be a reliable and cost-effective tool for detecting subtle spatial and temporal changes in vegetation. Therefore, reinforcing conservation frameworks and ensuring the continuation of long-term monitoring programs are essential to prevent future degradation and maintain the ecological resilience of the Serra do Japi Reserve.
Keywords: Remote sensing. NDVI. Environmental conservation. Atlantic Forest. Serra do Japi.

1 INTRODUCTION

Rapid urbanization has emerged as one of the primary drivers of native biome suppression worldwide, particularly in regions rich in biodiversity. The expansion of urban infrastructure and unregulated real estate development often fragments habitats and degrades ecosystems, leading to the irreversible loss of native vegetation (Seto et al., 2012; Stanimirova et al., 2023). In the Brazilian context, this scenario is especially critical in the Atlantic Forest biome, where remnants of native vegetation are under increasing pressure from expanding metropolitan areas, such as São Paulo. Urbanization frequently occurs without adequate environmental planning, compromising essential ecosystem services and increasing the vulnerability of remaining forest fragments. In this context, monitoring Land Use and Land Cover (LULC) change has become an important component of conservation planning, especially in areas where natural ecosystems are under growing and intense pressure (Liu et al., 2021; Vu & Bui, 2025). Recent studies have demonstrated that near-real-time monitoring of these changes is essential for detecting early signs of degradation and enabling timely policy interventions.

To support conservation strategies in threatened landscapes, remote sensing has become an essential tool for detecting, quantifying, and monitoring changes in vegetation cover over time. Recent advances in spatial, temporal, and spectral resolution have enabled researchers to identify subtle patterns of vegetation degradation and recovery with unprecedented detail (Kooistra et al., 2024). This is particularly relevant in ecotones and urban-forest interfaces, where anthropogenic pressures cause rapid and often small-scale landscape alterations. Vegetation spectral indices, enhanced by integrating meteorological data and machine learning algorithms, for example, have significantly improved the ability to quantify ecosystem resilience (Sun et al., 2023). Moreover, the use of cloud-computing platforms and artificial intelligence has expanded access to satellite imagery, enabling real-time environmental monitoring at both local and global scales (Gorelick et al., 2017), (Shivaprakash et al., 2022). For example, multi-sensor approaches combined with deep learning models are now being employed to support conservation policies against anthropogenic threats (Pettorelli et al., 2024). In particular, Sentinel-2, MODIS, and Landsat based NDVI products have proven useful for tracking vegetation health across protected and buffer zones, providing tools to assess policy effectiveness over time. Collectively, these technological advances underscore the strategic value of remote sensing for evidence-based environmental management and conservation planning.

Considering these challenges, this study aims to assess the conservation effectiveness of the Serra do Japi region in the municipality of Jundiaí from 2013 to 2023, using remote sensing and geospatial analysis techniques. The research also seeks to evaluate the impact of environmental policies and the role of the Serra do Japi Foundation in preserving the area, identifying potential gaps and opportunities for improvement. Based on the findings, the study presents conclusions and recommendations to support future conservation and management strategies.

By integrating vegetation index time-series analysis, precipitation data, and burned-area records over a 10-year period, this study contributes to the growing body of research on spatiotemporal vegetation monitoring in protected peri-urban areas. Unlike broader-scale studies that focus on national or biome-wide trends (Cunha et al., 2019; Vancine et al., 2024), this research provides a localized and fine-grained evaluation of conservation effectiveness within a legally protected region under urban pressure. Additionally, this study applies NDVI differencing, cross-references fire data, and incorporates climatic variability, thereby offering a replicable framework for assessing ecological resilience in other urban-adjacent reserves within the Atlantic

Forest biome in São Paulo and other Brazilian states.

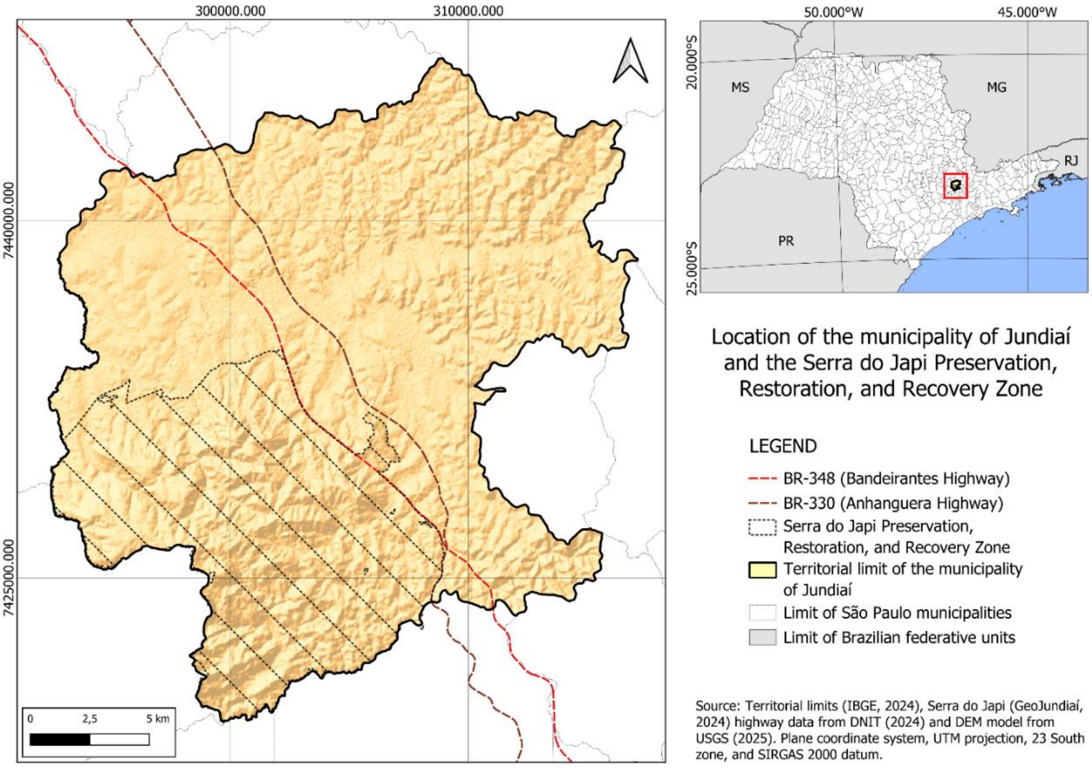
This article is an extended and revised version of a study previously presented at the XXV Brazilian Symposium on GeoInformatics (Perciani et al., 2025), which provided an initial geospatial assessment of the conservation status of Serra do Japi.

2 STUDY AREA CHARACTERIZATION

Serra do Japi is a rare remnant of the Atlantic Forest in São Paulo State (Figure 1), encompassing the Serra do Japi Municipal Biological Reserve. It is located between the coordinates 23°12'/23°21' South and 46°30'/47°05' West, within the geomorphological province of the Atlantic Plateau (Ross & Moroz, 1996). This region is critically important for the conservation of the Atlantic Forest biome, as only 7.9% of its original forest cover remains. The richness of its biodiversity is directly linked to the diverse climatic conditions of Serra do Japi, situated in an ecotonal region (Ab'Sáber, 1979), a transition area between the Ombrophylous Forests of Serra do Mar and the Semideciduous Forests (Hasi et al., 1978). Climatic studies have identified a pronounced seasonal climate characterized by a hot, rainy season and a dry, cold season (Pinto, 1992). Consequently, variations in altitude, temperature, humidity, and soil within Serra do Japi confer unique biodiversity to this region (Ab'Sáber, 1992). Recognized by UNESCO as an integral part of the "Atlantic Forest Biosphere Reserve", it remains one of the last large, continuous forest areas still preserved (Jesus, 2004).

The topography of Serra do Japi plays a decisive role in limiting human occupation and serves as a natural constraint on anthropogenic pressure (Ab'Sáber, 1992). With altitudes ranging from approximately 700 to over 1,200 meters and a rugged relief characterized by steep slopes and dense forest cover, the region presents natural barriers that restrict urban expansion and intensive land use. This geomorphological complexity contributes to the preservation of its ecological integrity by making large-scale infrastructure development both technically challenging and economically unviable. Furthermore, this natural protection is reinforced by its legal designation as a conservation unit, which imposes additional restrictions on land use and promotes long-term environmental safeguarding. Together, these physical and legal factors help maintain Serra do Japi as one of the most well-preserved remnants of the Atlantic Forest in the state of São Paulo, despite its proximity to highly urbanized areas.

Figure 1 – Serra do Japi Preservation, Restoration, and Recovery Zone, Jundiaí municipality.



Source: Authors (2025).

Throughout its history, the region has faced numerous threats to its environmental integrity, despite significant achievements in conservation. Notably, Resolution No. 11/1983, issued by the Council for the Defense of Historical, Archaeological, Artistic, and Tourist Heritage (CONDEPHAAT), recognized Serra do Japi as a heritage site of environmental, historical, and cultural importance. This resolution imposed restrictions on land use and urban expansion to ensure its preservation. Subsequently, São Paulo State Law No. 12,233/2006 officially established the Serra do Japi Biological Reserve in Jundiaí, further strengthening the legal protection and management of the area (Ballerini & Galhardi, 2014).

The areas listed in the resolution are located near the Anhanguera and Bandeirantes highways. This proximity, combined with the region's economic and industrial potential, encourages the emergence of irregular subdivisions and increases pressure from the real estate sector, thereby posing risks to the Serra. Additionally, the area is constantly threatened by fires, exacerbated by deforestation resulting from irregular land occupation. The presence of private properties in the Serra leads owners to subdivide the land for real estate development, complicating efforts to monitor land use across different jurisdictions (Scarabello, 2009).

The Serra do Japi Foundation was established in 2015 as a significant milestone in the conservation efforts of this region, supporting CONDEPHAAT Resolution No. 11. Since its inception, the foundation has played a crucial role in implementing conservation policies and promoting environmental awareness. Its creation marked a renewed commitment to protecting the heritage of Serra do Japi, emphasizing the urgent need for coordinated actions to ensure its ecological sustainability. This region plays a vital role in providing ecosystem services, such as supporting, provisioning, regulatory, and cultural services, that are essential for society's survival and the improvement of human well-being. Notably, Serra do Japi contains springs that supply water to Jundiaí and other municipalities in São Paulo, benefiting entire cities (Almeida, 2007). Given this context, the importance of public policies aimed at preserving and sustainably managing Serra do Japi becomes evident, particularly considering that the area is located in a rapidly urbanizing region between the municipalities of São Paulo, Jundiaí, and Campinas, which substantially increases its risk of destruction (Cardoso-Leite et al., 2005).

3 METHODOLOGY

To evaluate vegetation dynamics and conservation effectiveness in the Serra do Japi region, a methodological approach based on remote sensing and geoprocessing techniques was employed. This approach facilitates the detection of spatial and temporal patterns in land cover, thereby supporting informed decision-making for environmental conservation. The methodology builds upon the framework proposed by Ponzoni et al. (2012), which focuses on using spectral data to describe, monitor, and analyze vegetation through quantitative indices and image interpretation supported by Geographic Information Systems (GIS). For improved organization and clarity, this section is structured to comprehensively describe the datasets employed, including their sources, temporal coverage, and spatial resolution, as well as the procedures applied during data processing.

The methodological procedures employed in this study began with the acquisition of satellite images from the Landsat-8 OLI sensor, provided by the USGS, for the years 2013 and 2023, covering the study area. Subsequently, the NDVI vegetation index and false-color composites were generated in QGIS. Concurrently, average NDVI and total annual precipitation data for the period 2013-2023 were obtained from the Climate Engine platform. Additionally, fire occurrence data for the same period were extracted using MapBiomas Fire Collection 3.0. All these data were analyzed and compared to evaluate spatiotemporal patterns and potential correlations in vegetation dynamics and environmental conservation in the Serra do Japi region. Finally, a histogram of reclassified pixels was constructed to quantify potential vegetation gains and losses based on the comparison of NDVI data from 2013 and 2023.

3.1 Data used

To conduct this study, the territorial boundaries of Jundiaí and the Serra do Japi area within the

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municipality were utilized, as provided by the Brazilian Institute of Geography and Statistics (IBGE) and the GeoJundiaí platform, respectively. These boundaries were used to delineate the analysis area and to extract georeferenced data for satellite image processing and NDVI calculation. Since Climate Engine only permits data retrieval within limits defined by a vector spatial information layer (polygon), the average annual NDVI and total yearly precipitation from 2013 to 2023 were obtained for the specified territorial limits of the Jundiaí municipality and the Serra do Japi Preservation, Restoration, and Recovery Zone. Under these conditions, the average NDVI was derived from Landsat-8 data at 30-meter resolution for each year in the analysis period. Simultaneously, the total annual precipitation in millimeters was obtained for each year from the Climate Hazards Group InfraRed Precipitation (CHIRPS) database, which has a 4.8-kilometer spatial resolution and daily data collection.

Additionally, data from the MapBiomas Fire Collection 3.0 regarding accumulated burned areas over the past decade (2013–2023) were also acquired (MapBiomas, 2024). It is important to highlight that meteorological precipitation data were included to account for potential seasonal effects on NDVI changes throughout the study period. All collected data were tabulated and subsequently visualized in graphs, developed in Python on Google Colab, which facilitates data manipulation and graphical representation via specific libraries. Furthermore, a percentage-based histogram of the reclassified pixels was created in Python using VS Code. To ensure transparency and reproducibility, the source code used in the analysis is available at https://github.com/BrunoPerciani/serra-do-japi. The characteristics of the datasets used in this study, including their sources, resolutions, and temporal coverage, are summarized in Table 1.

Table 1 – Description of geospatial and meteorological data used in the study.

Data type	Source	Time span	Spatial resolution	Temporal resolution	Format / Access
NDVI	Landsat-8 (USGS Earth Explorer)	2013–2023	30 m	Annual (dry season images)	GeoTIFF / EarthExplorer
Precipitation	CHIRPS	2013–2023	~ 4.8 km	Daily (aggregated annually)	NetCDF / Climate Engine
Fire occurrence	MapBiomas Fire Collection 3.0	2013–2023	30 m	Annual (burned area mapping)	Raster / MapBiomas Platform
Administrative boundaries	IBGE	—	Vector (polygon)	Static	Shapefile / IBGE
Serra do Japi Preservation, Restoration, and Recovery Zone boundaries	GeoJundiaí	—	Vector (polygon)	Static	Shapefile / GeoJundiaí

Source: Authors (2025).

3.2 Methods

On this basis, a mixed research methodology was adopted, combining quantitative analysis, such as the calculation of spectral indices from satellite data, with meteorological data. This approach aligns with the study by Matas-Granados et al. (2022), who used NDVI time series from Landsat and Sentinel-2 imagery, combined with climatic data, to monitor vegetation dynamics and assess the long-term effectiveness of conservation efforts in protected forest areas across subtropical regions.

Under these conditions, as demonstrated by Rodrigues et al. (2019), QGIS software was employed to process and analyze geospatial data. The methodology involved acquiring Landsat 8 satellite images and calculating vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). It is important to clarify that the Landsat-8 Level 2 satellite images used in this study were obtained from the USGS Earth Explorer platform and already included surface reflectance products with atmospheric correction. This processing level was deliberately chosen to minimize the effects of atmospheric scattering and absorption, thereby improving spectral analysis accuracy. Subsequently, the analyses compared seasonal variations and correlated the data with predominant agricultural activities, generating thematic maps that represented vegetation changes over time. In the present study, the same methodology was applied to create thematic maps of Serra do Japi. The satellite images were obtained from the Landsat-8 satellite via the EarthExplorer platform, provided by the United States Geological Survey (USGS). This approach provided spatial and temporal coverage spanning 10 years (2013-2023). The image acquisition process was conducted directly through the USGS website to map various LULC classes, including urban areas and dense vegetation.

To conduct this study and achieve the proposed objectives, a methodological approach was adopted that integrated geospatial data acquisition and processing, NDVI analysis, and meteorological data. According to Mutanga et al. (2023), although NDVI remains one of the most widely used vegetation indices in environmental monitoring, it tends to saturate in high-biomass areas, reducing its sensitivity in dense canopies. Furthermore, NDVI performance can be affected by atmospheric interference and sensor differences, which may limit its reliability for long-term comparative studies.

According to Eastman et al. (2013), some of the main NDVI applications used in this study include detecting environmental changes by identifying areas affected by deforestation, fires, or drought, as well as analyzing seasonality to examine vegetative growth patterns over time. It is important to acknowledge that NDVI has limitations due to atmospheric influences, as clouds and aerosols can affect data quality (León-Tavares et al., 2021). Furthermore, to create the false-color composition, which also served as a tool for comparing regions during the study periods, a combination of bands 5 (near-infrared: 0.845 – 0.885 µm), 6 (short-wave infrared: 1.560 – 1.660 µm), and 4 (red: 0.630 – 0.680 µm) was used to facilitate analysis of the region's vegetation cover. This technique was also employed by Dan et al. (2016), who used composites to support their analysis of mangrove forests in the Mahakam Delta, Indonesia, and to compare the results.

Additionally, to complement the analysis of geoprocessed satellite images, the Climate Engine platform was used. According to Huntington et al. (2017), this cloud computing platform enables the visualization and processing of climate and remote sensing data. Its primary advantage is the ability to process large volumes of data without requiring local infrastructure, thereby facilitating environmental monitoring and the analysis of natural processes. Furthermore, the platform supports detailed analyses, including the creation of maps, time series, and graphs, all accessible through a web interface. This provides users, from researchers to government agencies, with easy and flexible access to data, supporting informed decision-making for monitoring droughts, ecological stress, and the impacts of extreme weather events.

Moreover, the georeferenced fire data were used to complement the analysis of Serra do Japi, enabling the identification and quantification of areas affected by wildfires during the study period, and integrating this information allowed for an assessment of the relationship between LULC dynamics and fire occurrence, contributing to a broader understanding of environmental impacts and the state of vegetation conservation in the region. To quantify potential vegetation losses and gains over the study period, we applied a straightforward image-differencing approach by subtracting the 2013 NDVI raster from the 2023 NDVI raster (ΔNDVI = NDVI {2023} – NDVI {2013}), a widely used change-detection technique in remote sensing (Lu et al., 2004). The resulting ΔNDVI raster was then reclassified into three conservative classes: possible vegetation loss (−2 to −0.125), no significant change (−0.125 to 0.125), and possible vegetation gain (0.125 to 2). Next, the ΔNDVI was masked to two analysis units: (i) the Serra do Japi Preservation, Restoration, and Recovery Zone, and (ii) the urban portion of Jundiaí (municipal area excluding the protected zone). For summary statistics and plotting, we extracted one point per pixel from each masked raster and exported the attribute table to CSV format. The overall workflow was documented in a process flowchart. Following this methodology, a temporal analysis of the study area was conducted, and the proposed objectives were achieved through comparison of the results. This detailed approach ensured greater precision in interpreting the observed changes over time.

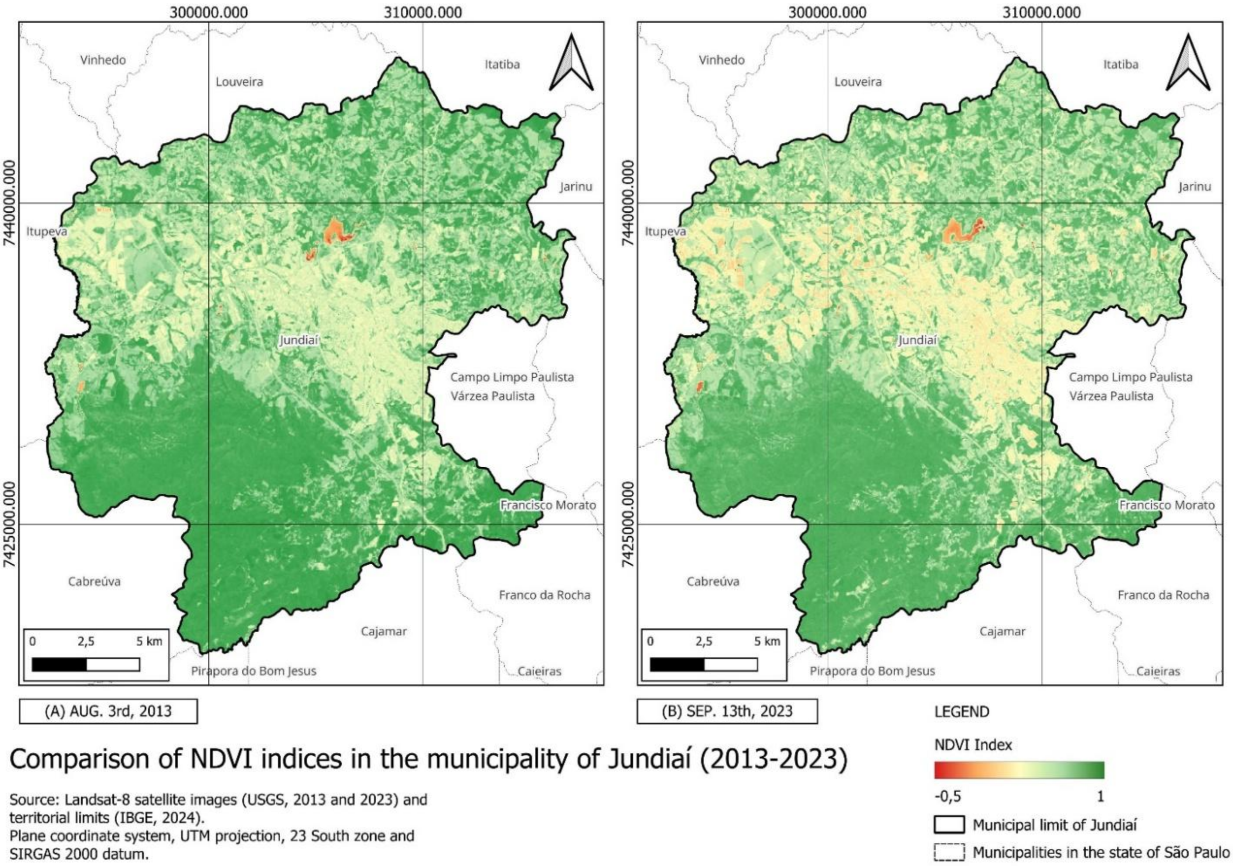
4 RESULTS AND DISCUSSION

Figures 2 and 3 present the NDVI and false-color composition of the study region. Figure 4 illustrates the differences in the NDVI within the municipality of Jundiaí between 2013 and 2023, highlighting areas of potential vegetation loss and deforestation in red. Additionally, Figure 5 shows the average annual NDVI and precipitation for both Jundiaí and Serra do Japi. A detailed analysis of these results reveals a complex scenario regarding the conservation of vegetation cover in the Serra do Japi Preservation, Restoration, and Recovery Zone. Notably, exhibited minimal variation in NDVI throughout the study period (Figure 5), with a sample standard deviation of 0.01. In contrast, Jundiaí maintained a relatively stable NDVI, with a sample standard deviation of 0.02, slightly higher than that of the Serra region.

4.1 Vegetation dynamics and localized losses

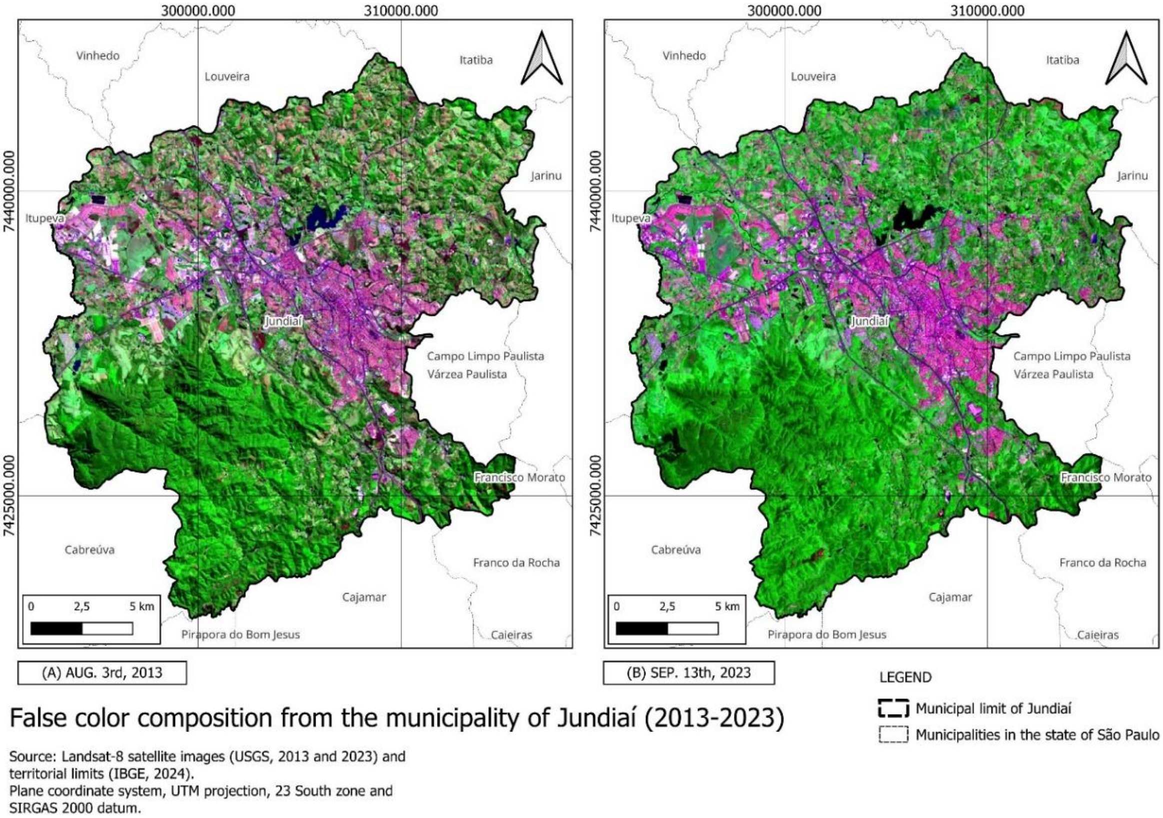
The NDVI (Figure 2) and false-color composition (Figure 3) facilitated the comparison and identification of changes in vegetation cover patterns within the study area over the years analyzed. The color composition highlights areas without vegetation cover in hot pink. Although the Serra do Japi Biological Reserve did not experience significant changes between 2013 and 2023, a small area of native vegetation loss was detected in the Serra do Japi Preservation, Restoration, and Recovery Zone, located in the southern region of Jundiaí near the neighborhoods of Santa Gertrudes. These results correspond with observed local dynamics: these areas experience intense urban pressure, real estate development for gated communities, and proximity to major state highways. In many cases, native forest patches are cleared and replaced by eucalyptus plantations, an exotic species within the Atlantic Forest biome. This pattern reflects documented LULC changes in the urban fringes around São Paulo, which impact biodiversity and alter hydrological and soil regimes (Couto et al., 2011; Inkotte et al., 2024).

Figure 2 – Comparison of NDVI in the area between 2013 (A) and 2023 (B).



Source: Authors (2024).

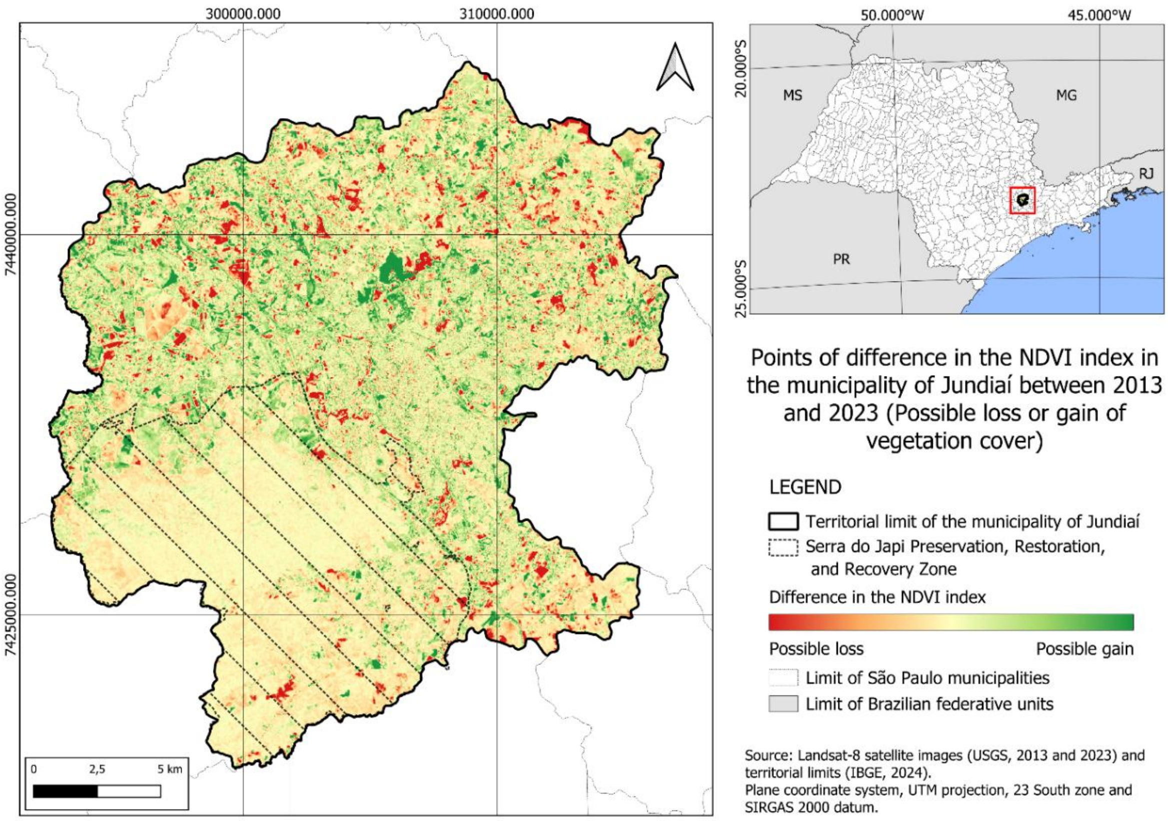
Figure 3 – Comparison of false color composition (7-5-3) between 2013 (A) and 2023 (B).



Source: Authors (2024).

Regions experiencing vegetation loss are highlighted in red in Figure 4, where the NDVI difference between 2013 and 2023 was calculated to emphasize these changes spatially.

Figure 4 – Subtraction between the NDVI of 2013 and 2023.



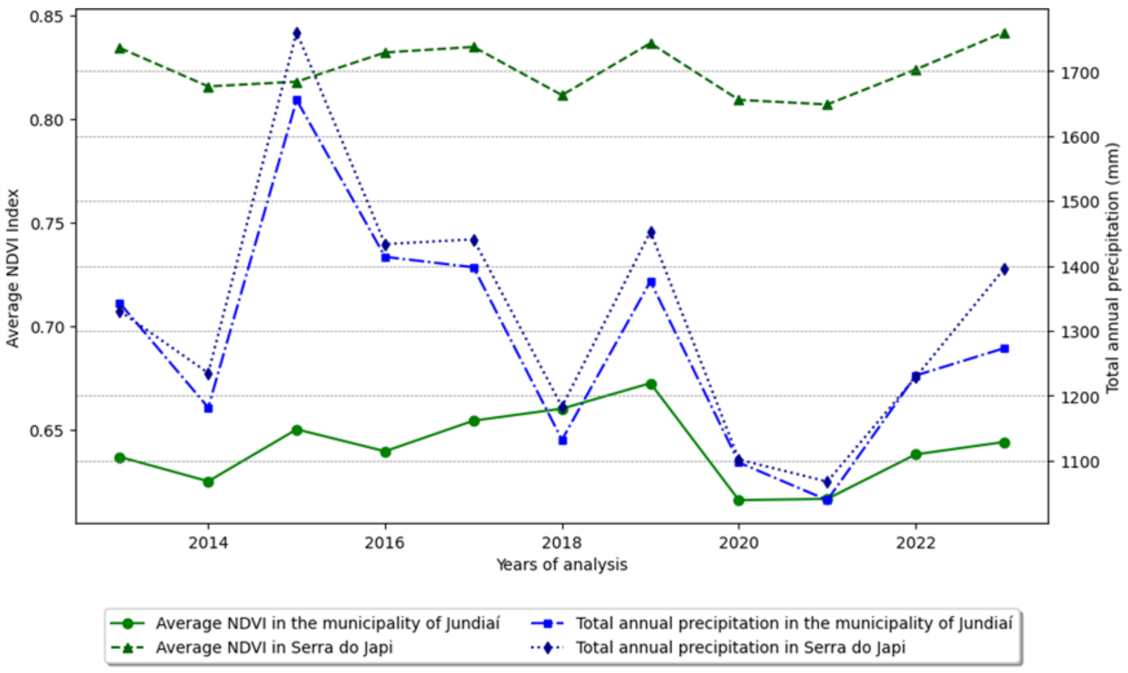
Source: Authors (2025).

4.2 Precipitation variability, NDVI resilience, and seasonality

Furthermore, the total annual precipitation in the study region did not cause significant changes in average yearly NDVI values (Figure 5). Even during the prolonged drought in Southeast Brazil between 2014 and 2017, recognized as one of the most severe in over a century, the NDVI remained relatively stable, indicating vegetation resilience under extreme dry conditions. Remote sensing studies support this observation, showing that although precipitation anomalies were significant, vegetation indices such as NDVI did not decline proportionally in protected areas (Gomes et al., 2017). Additionally, broader assessments covering the period from 2011 to 2019 indicate that, despite frequent severe drought events throughout Brazil, the Atlantic Forest biome maintained a relative moisture balance, with no significant long-term decline in vegetation greenness (Cunha et al., 2019).

It is important to emphasize that the observed oscillation trends in NDVI values do not necessarily reflect actual changes in vegetation. Instead, these fluctuations may result from limitations in the images data and atmospheric conditions. Such minor variations could fall within the natural variability of the vegetation, particularly given the complexity of the Serra do Japi ecosystem and the environmental factors influencing vegetation cover over time, such as precipitation. Notably, the years 2020 and 2021 recorded the lowest NDVI values in Serra do Japi, coinciding with the years of lowest precipitation. This pattern is consistent with NDVI's known responsiveness to environmental and meteorological factors affecting vegetation health, as described by Ponzoni et al. (2012). In this study, an annual approach to temporal analysis was employed to mitigate the effects of seasonality, as specific cycles, such as prolonged droughts or heavy rainfall, can temporarily impact vegetation health and cause pronounced seasonal variations. Nevertheless, the stability observed in the average annual NDVI suggests that the region’s vegetation is resilient to typical climate fluctuations, maintaining a balanced dynamic over time. This finding is supported by the study of Ferreira et al. (2019) in the Itapemirim River basin, where the authors noted that seasonality significantly influences NDVI variation, primarily due to climatic differences throughout the year, including periods of drought and heavy rainfall. To address this, Ferreira et al. (2019) used an annual NDVI time series derived from 16-day MODIS images, enabling analysis of average trends and vegetation persistence over a 15-year period. By focusing on annual maximum value composites, their approach minimized the effects of seasonal fluctuations, ensuring that short-term oscillations did not obscure the identification of long-term trends in vegetation resilience.

Figure 5 – Comparison of the average NDVI and total annual precipitation in the Jundiaí municipality and Serra do Japi between 2013 and 2023.



Source: Authors (2024).

4.3 Ecosystem services, municipal NDVI, and orographic context

No significant variations in NDVI were observed during the study period for either Serra do Japi or Jundiaí. It is important to note that the vector spatial information layer for the municipality of Jundiaí includes Serra do Japi, which likely influenced this result positively. The high and stable average NDVI of the Serra do Japi contributed to the municipality's overall average NDVI, encompassing even the most urbanized areas of the city. This finding is noteworthy, as Serra do Japi provides essential ecosystem services to the city's residents (Ballerini & Galhardi, 2014) and contributes to the increase in the city's average annual NDVI.

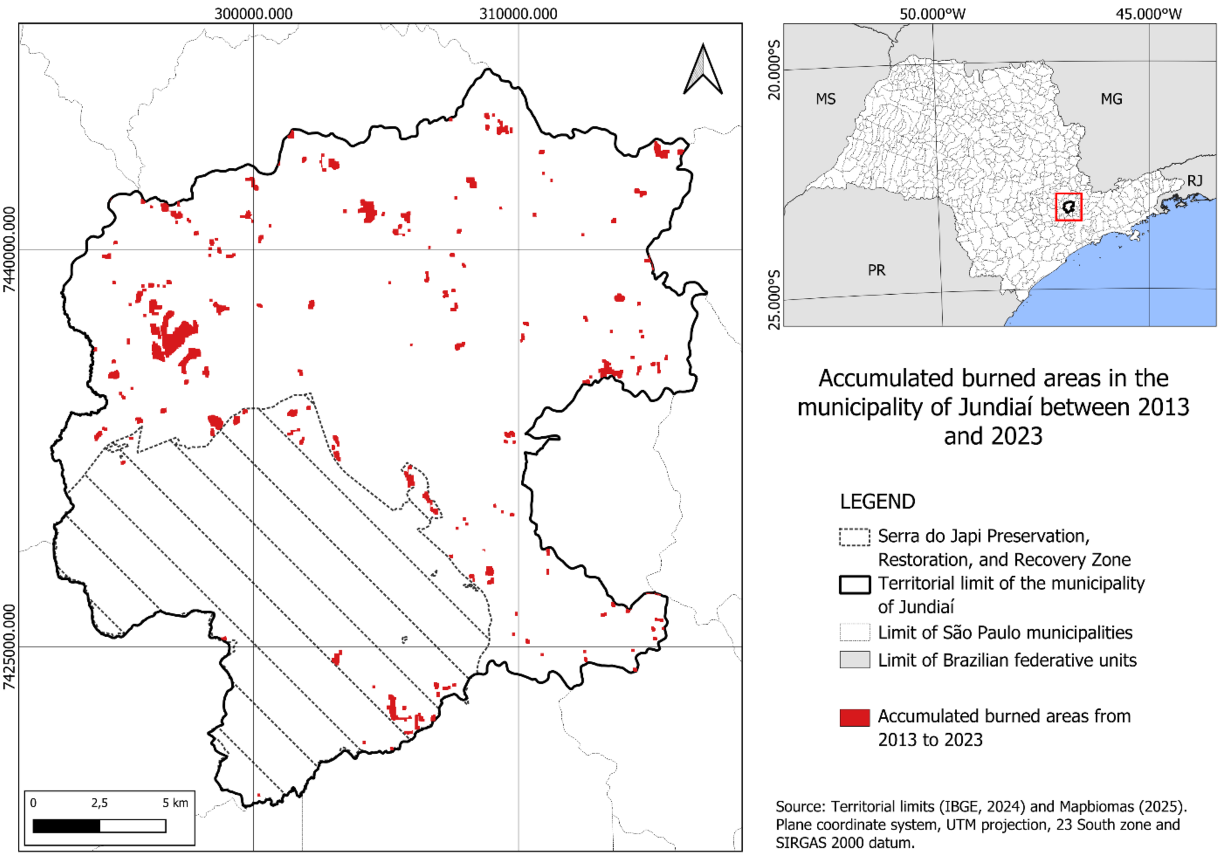
Analyzing cloud-computing data while accounting for potential seasonality effects revealed no drastic changes in vegetation cover within the Serra do Japi Preservation, Restoration, and Recovery Zone that could cause a significant fluctuation in the region's average annual NDVI, nor within the Serra do Japi Biological Reserve. Moreover, the increase in the average NDVI in Jundiaí, including the Serra do Japi, significantly impacts the municipality, underscoring the Serra's importance to the region. This finding aligns with Schrammeijer (2024), who emphasized that protected areas located within or near urban environments play a crucial role in environmental conservation. Such areas contribute to ecological resilience by preserving biodiversity and providing ecosystem services that benefit surrounding urban regions. The study highlights that urban protected areas help stabilize and improve vegetation indices in adjacent cities by mitigating pressures from urban deforestation and enhancing ecological stability. Consequently, the authors concluded that these reserves can positively influence the quality of the neighboring urban ecosystem.

The higher annual precipitation levels recorded in the Serra do Japi region can be partially attributed to orographic effects related to its topography. The mountainous terrain of the Serra acts as a natural barrier to humid air masses originating from the surrounding lower areas. When these air masses encounter the Serra's elevation gradient, they are forced to ascend. This vertical movement causes adiabatic cooling, leading to condensation and, consequently, increased precipitation on the windward slopes. This orographic rainfall pattern is a well-documented climatological phenomenon in mountainous ecosystems and is crucial for explaining the localized increase in moisture availability. In the context of Serra do Japi, this natural process supports the persistence of humid microclimates, maintaining dense forest cover and enhancing ecological resilience. Moreover, the higher precipitation levels in Serra do Japi compared to nearby urbanized zones underscore its ecological role as a hydrological and climatic buffer within the regional landscape.

4.4 Fire incidence and environmental implications

Additionally, Figure 6 shows small fire-affected areas near potential areas for vegetation cover removal. This suggests a possible relationship between vegetation clearance and the occurrence of fire events. These areas, characterized by the alteration or thinning of natural vegetation, may represent zones of increased vulnerability to fires due to changes in LULC and their subsequent impact on local microclimates and flammability. The spatial association between these fire-affected zones and regions of vegetation removal underscores the importance of monitoring human-induced landscape changes, as they can influence fire dynamics and ecological resilience.

Figure 6 – Accumulated burned areas in the municipality of Jundiaí between 2013 and 2023.

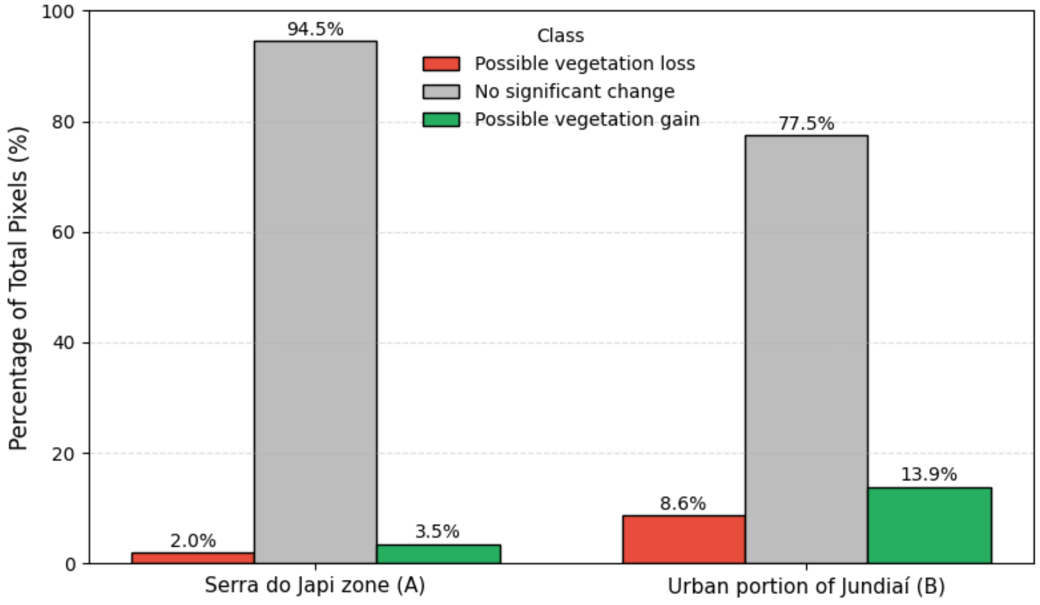


Source: Authors (2024).

4.5 Statistical analysis of pixels reclassification

In Figure 7, we present the percentage of pixels in each class derived from the NDVI reclassification. Within the Serra do Japi Preservation, Restoration, and Recovery Zone (A), only 2.0% of pixels were classified as possible vegetation loss, 3.5% as possible vegetation gain, and 94.5% showed no significant change. This distribution corroborates the very low interannual variation in vegetation cover within the protected area.

Figure 7 – Percentage-based histogram of the reclassified pixels.



Source: Authors (2025).

By contrast, in the urban portion of Jundiaí (B), the municipal area excluding the Serra do Japi Preservation, Restoration, and Recovery Zone, variability was higher: 8.6% of pixels indicated possible loss, approximately four times the proportion observed in the protected area, 13.9% indicated possible gain, and 77.5% showed no significant change. These results suggest that land-cover dynamics are more pronounced in urbanized settings than in conservation areas, underscoring the role of Serra do Japi as an ecological buffer that helps mitigate human-induced pressures at the municipal scale.

A visual comparison between Figure 4 and Figure 7 reveals that the 2% vegetation loss within the protected zone is spatially concentrated along the transition belt at the southern edge, where the preservation/restoration boundary is within the urban fabric. This pattern suggests that edge-related pressures are the primary drivers of localized change. The contrast between stability within the conservation unit and the greater dynamics of change in adjacent areas aligns with global evidence indicating that protected areas reduce forest cover loss compared to their unprotected surroundings (Joppa & Pfaff, 2010).

4.6 Policy effectiveness, edge-zone fragmentation, and management implications

Accordingly, the consistent stability observed around Serra do Japi is a positive indication of the effectiveness of the preservation policies implemented by the public agencies responsible for conserving the region. NDVI stability suggests that these preservation measures have successfully maintained the integrity of the vegetation cover within the protected area. This finding aligns with Vancine et al. (2024), who demonstrated that, from 2005 onward, vegetation cover in the Atlantic Forest of Brazil stabilized and increased due to prevailing environmental legislation, in contrast to the significant decline observed prior to 2005. However, small losses of native vegetation were detected in areas adjacent to the preservation zone. This underscores the importance of environmental restoration and conservation efforts in Serra do Japi, particularly given their positive impact on areas south of Jundiaí, one of the most urbanized and densely populated regions. Vegetation loss within the city, especially in urban and inhabited areas, was somewhat expected due to limited supervision and legal protection.

A similar pattern was observed in the study by Aboud Neta et al. (2018), which analyzed changes in LULC in the Federal District (Brazil) using NDVI to monitor vegetation dynamics in urban and preserved areas. The authors reported a significant reduction in NDVI in urbanized areas, particularly along the edges of the Federal District, attributed to population growth and unplanned urban expansion. Furthermore, although protected areas exhibited greater NDVI stability, vegetation loss was identified in transition zones between preserved and urban areas of the Federal District, mirroring the situation in Serra do Japi. Nevertheless, forests within strictly protected zones consistently maintained high NDVI values, as observed in the Serra do Japi region.

However, the loss of vegetation cover observed in the Serra do Japi Preservation, Restoration, and Recovery Zone, although insufficient to cause drastic changes in the average annual NDVI, represents a potential risk of future human interference in the region. This suggests that restoration efforts should be prioritized. This fragmentation is consistent with the findings of Vancine et al. (2024), who reported that while the Atlantic Forest vegetation cover in Brazil stabilized from 2005 onwards, the number of forest fragments increased during this period, with significant implications for biodiversity. The reduction in fragment size increases vegetation's susceptibility to edge effects, including greater temperature extremes, higher light exposure, lower humidity, and elevated wind speeds compared to forest interiors (Murcia, 1995). These factors negatively affect vegetation by causing structural damage, increasing deadwood production, and altering growth and regeneration patterns (Harper et al., 2005). Such processes adversely impact ecosystem structure by modifying microclimates and carbon cycles (Magnago et al., 2017).

These results underscore the urgent need to implement more rigorous preservation measures in these areas to prevent further environmental damage and protect biodiversity from potential human activities. The loss of vegetation within protected areas, even if occasional, increases the risk of additional human interference by weakening the local ecosystem and creating opportunities for illegal activities or uncontrolled urban expansion. This reinforces the importance of effective and preventive environmental management. As Laurance et al. (2012) demonstrated, protected areas are often ecologically interconnected with their

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surrounding habitats, and environmental degradation in adjacent regions adversely affects these reserves. Consequently, the loss of forest cover compromises ecosystem integrity, intensifies human pressure, and facilitates illegal exploitation and unregulated expansion.

Furthermore, this phenomenon was also observed by Pinheiro & Ribeiro (2022), who analyzed Palmas's urban transformations in the state of Tocantins (Brazil) since its founding in 1989. They found that although the city was with environmental attention, its disorderly growth led to the suppression of native vegetation. The authors emphasize that human interference, which removed native vegetation cover in the early years following the city's establishment, was directly linked to the subsequent rampant urbanization. Additionally, studies by Silva Junior et al. (2021), Matos et al. (2015) and Gameiro et al. (2022) explored the use of NDVI to monitor changes in vegetation cover, identifying both direct and indirect impacts of human activity on NDVI variation. In the Serrinha II Reservoir (Pernambuco state, Brazil), Silva Junior et al. (2021) observed a loss of riparian vegetation associated with drought events and inadequate soil management, both of which were indirectly influenced by human actions. In contrast, in the Itaparica Reservoir (Pernambuco state, Brazil), Matos et al. (2015) demonstrated that dam construction led to a drastic reduction in NDVI, directly affecting vegetation through changes in LULC and the local microclimate. This analysis is also consistent with the findings of Gameiro et al. (2022), who demonstrated the effectiveness of multitemporal remote sensing techniques in identifying land-use and land-cover changes in Brazilian ecosystems, reinforcing the value of long-term spatial monitoring for environmental conservation studies.

Despite the pressures of urban development and other human activities in the municipality, the Serra do Japi Biological Reserve has maintained significant vegetation cover, which is crucial for conserving biodiversity, regulating the local climate, and enhancing the quality of life of local communities. In addition to its ecological importance, Serra do Japi also plays a key role in maintaining regional hydrological balance and supporting water availability for nearby urban areas, including Jundiaí and São Paulo. This hydrological relevance aligns with the observations of Zuffo et al. (2023), who highlighted the critical interdependence between forested catchments and water-supply resilience in southeastern Brazil.

Thus, the conservation and preservation policies implemented in Serra do Japi have proven effective to date. In summary, the results of this analysis underscore the importance of continuously monitoring vegetation cover in both areas and implementing conservation and sustainable management measures to preserve these ecosystems. Therefore, although the findings indicate encouraging signs of stability in vegetation cover, public sector agencies and non-governmental organizations must remain vigilant and proactive in protecting and preserving these natural areas.

5 CONCLUSION

This study assessed the effectiveness of environmental preservation efforts in Serra do Japi by analyzing vegetation cover dynamics from 2013 to 2023 using NDVI time series, false-color composites, and precipitation data. The results indicated overall vegetation stability in both the Serra do Japi Biological Reserve and the surrounding municipality of Jundiaí, with consistently high NDVI values throughout the decade.

Despite overall stability, spatial analyses revealed localized vegetation loss in the southern portion of the Preservation, Restoration, and Recovery Zone, particularly near Santa Gertrudes, a neighborhood located at the transition between urban development and the conservation area. This region experiences intense real estate pressure and LULC change, including the replacement of native Atlantic Forest vegetation with eucalyptus plantations. These findings underscore the importance of monitoring urban-conservation interfaces, where enforcement is often weaker and ecological integrity is more vulnerable.

The variability in annual precipitation, including the severe drought period from 2014 to 2017, did not significantly impact the average NDVI values. This suggests ecological resilience in preserved zones, although some NDVI fluctuations may reflect short-term climatic variations rather than structural changes in vegetation. The stability of NDVI across the broader Jundiaí area is partly attributed to the ecological services provided by Serra do Japi, which help elevate the municipality's average vegetation index. However, edge areas continue to exhibit signs of fragmentation, increasing their vulnerability to fire events and anthropogenic disturbances. The spatial overlap between vegetation loss and burned areas underscores the need for integrated landscape management that accounts for ecological connectivity and fire risk.

Overall, the conservation strategies implemented in Serra do Japi have been effective in maintaining vegetation cover within the reserve. However, targeted restoration efforts and stricter enforcement are necessary in the buffer zones, particularly given the expansion of urban infrastructure. Continuous geospatial monitoring is essential for anticipating and mitigating threats, thereby ensuring the long-term ecological integrity of this vital Atlantic Forest remnant.

In addition to the results presented, this study underscores the importance of integrating science, technology, and environmental management to preserve critical areas such as Serra do Japi. The application of remote sensing techniques, combined with detailed geospatial analysis, highlights the strategic role of these methodologies in identifying environmental vulnerabilities and guiding conservation efforts. In the context of increasing human pressure and the impacts of climate change, the continuation of actions that promote continuous monitoring, sustainable management, and active restoration is essential to ensure ecological resilience and maintain the ecosystem services provided by Serra do Japi.

Ultimately, this study provides a robust scientific foundation for guiding future conservation and sustainable management policies, while also suggesting directions for further research. Future work involving remote sensing techniques in Serra do Japi could explore the use of high-temporal and spatial-resolution data, such as that provided by more recent sensors, including Sentinel-2, to monitor vegetation cover changes with greater precision and frequency. Another approach would be to integrate remote sensing data with climate information to predict the impacts of climate change on local vegetation, thereby enhancing understanding of the region’s ecological resilience. These studies would strengthen the scientific basis for conserving Serra do Japi and could be applied to other critical areas within the Atlantic Forest biome.

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Authors’ contributions

This work benefited from the complementary contributions of its authors to the development and quality of the research. Bruno Zomignani Perciani, an undergraduate student at the Federal University of ABC (UFABC) and the primary author, was responsible for several key stages, including the initial conceptualization of the study, the development and application of the methodology, the investigation process, the formal data analysis, and the drafting of the initial manuscript. Bruno also produced visual materials, such as graphs and maps, which supported the interpretation and presentation of the results.

In addition, UFABC faculty members and co-authors Dr. Victor Fernandez Nascimento, Dr. Vitor Vieira Vasconcelos, and Dr. Márcio de Souza Werneck played equally important roles, providing supervision, technical and intellectual support, and contributing to refining the methodological approach. Professors also participated in a careful, critical review of the manuscript, ensuring the accuracy of the concepts and analyses to maintain the scientific rigor, originality, and overall quality of the final study. It is important to note that although some portions of this text were refined with AI tools during drafting and language correction, the authors take full responsibility for the intellectual content, scientific arguments, and the accuracy of all data

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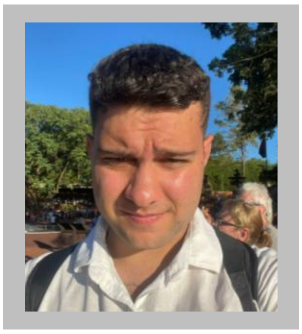
and analyses presented.

Conflicts of interest

I declare that there were no conflicts of interest during the execution of this work. All stages of the research were conducted transparently and impartially, with full commitment to ethics and scientific integrity.

Biography of the first author



Bruno Zomignani Perciani was born in Jundiaí, São Paulo, Brazil. He holds a technical degree in Plastics from SENAI Conde Alexandre Siciliano, in Jundiaí, and is currently pursuing a Bachelor of Science and Technology at the Federal University of ABC (UFABC). In 2022, he received the Lavoisier Award from the Regional Chemistry Council (IV Region), as well as the FIRST Dean's List Finalist Award at the FIRST Robotics Competition Regional tournament held in San Francisco, California, United States. His academic interests include geospatial analysis and data-driven approaches to sustainability. He is also engaged in research projects combining remote sensing and artificial intelligence.