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Trends in Land-Use and Land-Cover Change: Key Insights for Managing the Atlantic Forest Transition

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Abstract: Studies on land-use and land-cover change patterns contribute to better informed management decisions for the conservation and restoration of Atlantic Forest fragments and their megabiodiversity. In recent decades, the phenomenon of forest transition has been observed in several parts of the biome, including in highly urbanized and metropolitan areas such as Campinas, in the state of São Paulo. Here, we examine land-use and land-cover change (using MapBiomas data with 30 m spatial resolution) within the Campinas Environmental Protection Area, where natural forest cover increased from 9% to 17.1% of the total area between 1985 and 2023. Exogenous socioeconomic factors, including the gradual replacement of agricultural activities by tourism development and the designation of areas through successive ecological–economic zonings, are presented as possible causes of the decrease in deforestation and the stabilization and recovery of the remaining natural forest cover. Our analysis reaffirms evidence from other studies showing that secondary succession in abandoned pastures contributed to the forest transition process identified in the region. Strongly decreasing trends were identified for pasture areas and strongly increasing trends for forest formations and urban infrastructure. Based on analysis of forest formation transitions conducted at 5-year intervals between 1985 and 2020, we observed different patterns of net change between the local, regional, and macroregional levels and the state and biome levels. Our analysis of land-use and land-cover transitions for the most recent years (2018 to 2023), including the period of validity of the EPA Management Plan, indicates that the ecological–economic zoning instrument is effective in containing potential threats; however, it has limitations, since losses of forest formation were observed in all five conservation zones. We emphasize that, although we can attest to the effectiveness of ecological–economic zoning, which in the EPA region has undergone incremental adaptations favorable to the forest transition process, this management instrument is subject to changes in its limits and regulations based on the governance system established at its different levels.

Keywords: governance; zoning; protected area; forest fragments; Atlantic Forest

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1. Introduction

Habitat loss is the main cause of reduced species diversity in ecosystems at a global level, including in Brazilian tropical forests [1–3]. Forest habitat degradation occurs in many cases through fragmentation of natural forest cover (NFC hereinafter). This process reduces the core areas of fragments that provide greater protection to species and at the same time increases edge areas which are more vulnerable to disturbances, as indicated by edge effect studies [4,5]. Depending on the degree of fragmentation, these ecosystems may undergo a regime shift or transformation when they reach a tipping point at which a return to their previously existing structure and functions is not possible [6–8]. In this sense, efforts to conserve forest ecosystems seek to prevent the advancement of fragmentation processes or the reaching of a fragmentation threshold beyond which species communities, which depend on a minimum forest area, begin to decrease in richness and abundance [9,10].

In the Atlantic Forest, fragmentation has been occurring since the colonial period leading to the isolation of populations and negatively affecting habitat specialist and endemic species [3]. Of the original extent of the biome's natural vegetation (1.1 million km^2), approximately 28% remains in the landscape, with around 83% of all fragments smaller than 50 ha and only 0.03% larger than 10,000 ha (77 fragments) [3,11–14]. These numbers demonstrate the importance of small fragments to reduce isolation, as they can provide refuge for species by forming ecological corridors between larger fragments. This increased connectivity favors biodiversity conservation in the biome through genetic exchanges among different populations [14].

Currently, in Brazil, the Atlantic Forest biome has between 300,000 and 320,000 km^2 of native vegetation [11,15]. According to the 2022 National Populational Census, 64% of the Brazilian population lives in 3080 municipalities within the biome. Consequently, remaining forest fragments are often located near anthropized and metropolitan areas, in a region with high population density (35 inhabitants/km^2) compared to the national average of 23.4 inhabitants/km^2 [16]. In addition to traditional and quilombola communities, the biome is home for 20 indigenous peoples distributed across 146 indigenous lands encompassing 9200 km^2 or 0.8% of the biome's total area [3,17]. Along with this sociocultural diversity, the biome's megabiodiversity of plant and animal species makes it one of the eight most important areas among the twenty-five hotspots of great relevance for conserving life on the planet [12]. This extraordinary biodiversity is characterized by high levels of endemism, with 40% of the 21,300 species belonging to taxonomic groups that developed and occur only in this region [3,12,14]. Of the total number of species in the biome, 9% are at some level of extinction threat, reaching 1924 species (1544 plants and 380 animals) that represent 60.6% of all threatened species in Brazil [18,19].

Historical factors, such as the formation of urban centers and highways, along with geographic conditions, including slope, configure the current mosaic of remaining Atlantic Forest fragments, which generally occur in areas unsuitable for housing, agriculture, and other human activities [20–22]. To conserve these forests and other areas of ecological relevance, 1736 protected areas (accounting for 59% of the protected areas in the country) have been established. Of these, 33% are fully protected while 67% are for sustainable use, covering 115,500 km^2, or 10% of the biome [23]. However, most remnants of natural vegetation occur on private rural properties, outside protected areas [24]. The LULC on these properties largely accounts for the degradation and fragmentation that have occurred since historical times [14,24].

Despite a history of degradation [25], trends indicate increasing forest cover in developed countries [26] and more recently in developing countries [27], including the Brazilian Atlantic Forest [28]. This inflection or turning point [29] in the NFC trajectory from net loss to net gain, when regeneration rates exceed deforestation, is known as "forest transition" [26,27,30–32]. Since these changes in trends were observed, studies have sought to identify the causes behind reduced deforestation followed by expansion through spontaneous or assisted regeneration [33]. More or less consensual hypotheses, such as the idea that economic development leads to increases forest cover or that there is a relationship between population growth and deforestation, face the limits imposed by the complexity of socio-ecological systems with their numerous variables [26,34–37]. Nevertheless, understanding the causes of forest transition is essential to support decision-making regarding the essential role that forests play in human well-being, biodiversity conservation, and mitigating the effects of the climate crisis [35,38]. It should be considered that, depending on the successional stage of forest formation, the provision of ecosystem services and species diversity may vary [31,39,40]. In the Brazilian Atlantic Forest, despite a significant increase in forest areas, there is evidence of a progressive rejuvenation of native vegetation cover in recent decades due to the replacement of mature forests by secondary succession [32,41].

Lambin and Meyfroidt (2010) argue that the particular realities of countries or regions lead to different sets of causes of forest transition, which may be endogenous socio-ecological forces (e.g., depletion of a given forest resource due to previous use practices) or exogenous socio-economic factors (e.g., urbanization, economic development, or globalization). From this perspective of forest transition theory, many studies investigate the phenomenon of forest recovery and its causes at the regional [30], national, and biome levels [24,32,42], as well as at the global level [26,35]. However, few publications have focused on the local level or on multiple-use protected areas.

To better understand the forest transition process and its causes at the local level, we conducted a sequence of four analyses focusing on the Campinas Environmental Protected Area (Campinas EPA hereinafter) and its NFC. Our guiding questions were as follows: (i) What are the main LULC changes that occurred during the period of the available historical data series from 1985 to 2023? What trends of increase or decrease in area do each of the LULC classes present? (ii) What is the pattern of net NFC losses/gains to/over other LULC classes at 5-year intervals within the EPA? Does this pattern resemble or differ from the patterns at the regional and biome levels? (iii) Considering the LULC in 1985 and in 2023, what is the spatial distribution of NFC transitions (net losses and gains) in the EPA? On which rural properties did these transitions occur? What is the spatial distribution of the most recent NFC transitions including the period of the EPA Management Plan that was implemented (2018–2023)? (iv) What governance and management processes are related to these NFC transitions? Did the ecological–economic zoning instrument contribute to the forest transition process at the local level?

2. Materials and Methods

This study employs a geospatial data analysis combined with descriptive statistics of the landscape utilizing a time series of thematic maps of LULC followed by an analysis of governance and management processes. First, we assess LULC changes and their trends based on data from the last decades, from 1985 to 2023 (Supplementary Material File S1). Based on this assessment, we conducted a comparative analysis of the patterns of net losses/gains of NFC to/over other classes in LULC transitions at 5-year intervals (between 1985 and 1990, 1990 and 1995, 1995 and 2000, 2000 and 2005, 2005 and 2010, 2010 and 2015, and 2015 and 2020), at local, regional, metropolitan, state, and biome levels (Supplementary Material File S2). The third analysis focused on the elaboration of thematic maps that spatially represent transitions in areas where NFC was maintained, lost, or recovered between 1985 and 2023 as well as during the most recent period in which the EPA Management Plan was in effect (Supplementary Material File S3). In the fourth analysis, aimed at identifying potential causes for the forest transition, we conducted a keyword search in the Google Scholar database for publications on governance and management in the EPA region (Supplementary Material File S4). We also performed qualitative and quantitative coding and categorization of 290 registries of ordinary and extraordinary meetings of the EPA Management Council held between 2005 and 2023 (Supplementary Material File S5). These analyses of secondary data (publications and meeting registries) support the discussion of the present study (Figure 1).

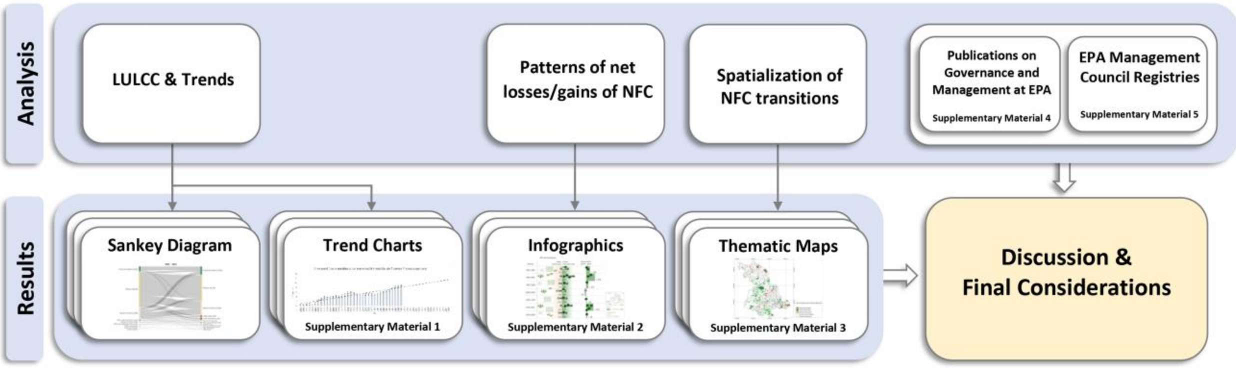


Figure 1. Methodological steps conducted in this study.

2.1. Study Area

The socio-ecological system focused in the analysis is the Campinas EPA in its political–geographical boundaries (Figure 2). Created in 2001, this protected area covers 222.7 km^2 and occupies approximately one-third of the municipality's territory. It is notable for its water supply potential for Campinas, the third most populous municipality in the São Paulo state with 1.14 million inhabitants [16]. It also stands out for the NFC of remaining fragments of the Atlantic Forest with significant biodiversity in a rural area dominated by pastures. Additionally, it has architectural heritage from the coffee production period that thrived from the 19th century until 1930, when the great international crisis affected the farms in the region, leading to the collapse of the activity [43–45]. The scenic beauty of the countryside, with vegetated areas, streams, lakes, and wildlife, interacts and is shaped by the customs and ways of life of the people who live there. This experience of rural life in closer contact with nature attracts visitors and fosters tourist activities, such as hotels, gastronomy, and outdoor activities (e.g., trekking) with potential for expansion. However, these characteristics have drawn the interest of real estate investors looking to develop high-end housing in gated condominiums, posing yet another threat to the conservation of NFC in the region [43,46–48].

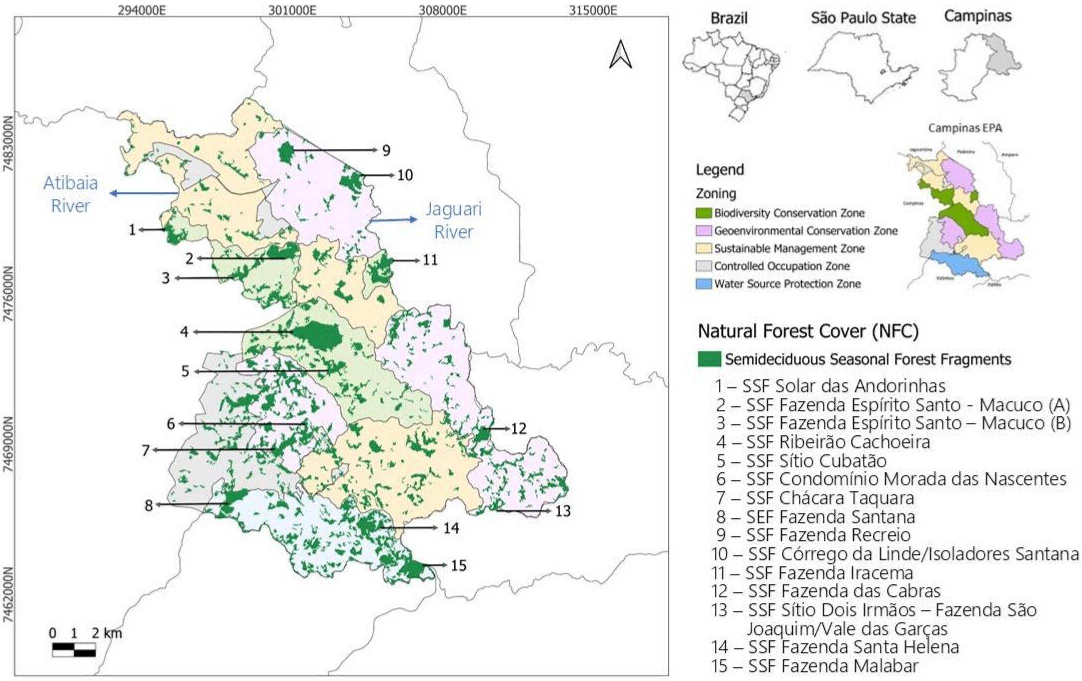


Figure 2. Campinas Environmental Protected Area and its main fragments of Semideciduous Seasonal Forest (SSF) in the year 2023. Adapted from the Management Plan (Campinas, 2019) [48].

2.2. Legal Context and Ecological–Economic Zoning

In Brazil, conservation units (known internationally as protected areas), are provided for in the National System of Nature Conservation Units, established in 2000 [49]. This system regulates the creation, implementation, and management of areas of socio-ecological importance. Conservation units are classified into 12 categories, divided into two groups: one of full protection, in which human presence is not permitted, and another of sustainable use, in which human presence is permitted according to the rules to each subtype. Environmental Protection Areas (EPAs) are one of the seven categories of the sustainable-use group. They are characterized by human occupation in natural environments and have the objective of regulating the occupation process and ensuring the sustainable use of natural resources.

At least since 1991, the municipal legislation of Campinas has established guidelines for the preservation of environments and natural resources within its limits, focusing on the current area where the EPA is located. The environmental importance of this region is reflected in the zoning plans of the Campinas Master Plans of 1991 and 1996, which identified the area between the Atibaia and Jaguari rivers (Figure 2) as one of the 7 macrozones of the municipality ("Macro-zone 1—Environmental Protection Area"). In 2001, with the objectives of conserving the natural heritage, protecting water sources, and controlling urban pressure, a law was decreed to create the Campinas EPA within Macrozone 1 [50]. This law also establishes the creation of a deliberative Management Council composed, in equal proportion, by public authorities, representatives of civil society organizations, and representatives of residents. In 2019, a new Management Plan was approved to regulate land use and occupation in the EPA region, defining 5 zones (Figure 2). This environmental zoning, which we will call ecological–economic zoning (EEZ hereinafter), was prepared based on an integrated analysis of environmental fragility and the structural connectivity of the landscape through ecological corridors between forest fragments [48].

2.3. Data Sources

We conducted spatio-temporal analyses of LULC with an emphasis on changes in NFC over the past 4 decades (1985 to 2023). Data were extracted from the collaborative annual LULC mapping network MapBiomas (https://brasil.mapbiomas.org/, accessed on 28 September 2024). The global accuracy of LULC classifications (v.9.0) for level 2 ("Forest Formation" or NFC class, the most relevant to this study) is 89.8%, with 7.2% allocation disagreement and 2.9% area disagreement [11]. This dataset includes 27 LULC classes for the most detailed level (level 4) and provides raster products with a spatial resolution of 30 m (derived from Landsat data). For the Campinas EPA region, 12 classes were identified for the period. We used vectorized files with the EPA boundaries, including the current EEZ of 2019, available on the Prefecture of Campinas website. We also incorporated the boundaries of private rural properties registered in the Rural Environmental Registry, provided by the Department of Agro-Environmental Sustainability of the Rural Environmental Registry System of São Paulo.

We gathered publications on governance and management by searching for relevant keywords on the Google Scholar platform between August 2020 and May 2021. We performed a documentary analysis of 290 registries of ordinary and extraordinary meetings of the Management Council of the Campinas EPA, for the period from 2005 to 2023, available on the Prefecture of Campinas website.

2.4. Data Analysis

Using the MapBiomas classification method [51], we analyzed the LULC of the initial (1985) and final (2023) years, as well as for each 5-year interval during this period, to estimate the percentages of LULC areas by class.

To identify trends of increase, stability, or decrease in the areas of the classes present in the Campinas EPA, we created a land-use and land-cover change trend index (LULCCti) resulting from the sum of the speed (θs) and the acceleration multiplied by time (θa.t), which in our case was 38 years (from 1985 to 2023). Since acceleration is a minor factor in our analysis, pertaining to the intensity of the loss or gain, while speed determines losses (negative velocity rate), stability (zero velocity rate), or gains (positive velocity rate), we added a constant (1/10) to the acceleration term to assign different weights to these variables. Both terms are multiplied by their respective coefficients of determination (R2), which vary between 0 and 1. When this value tends to 1, the linear model explains 100% of the variance in the data. All points fall perfectly on the fitted line. The speed and acceleration coefficients were obtained from the trend lines for the total area of LULC by year (for speed) and for the balance of area increase or decrease by year (for acceleration). The angular coefficient of these lines (values accompanying the variable x) represents the speed (θs) and acceleration (θa). The results of the trends are presented using a Linkert scale (categorized as strongly increasing, increasing, stable, decreasing, and strongly decreasing).

To define the value ranges for each degree of trends, we classified the values between 2% and −2% of the modulus of the largest LULCCti value as stable. For the LULCti values between 2% and 20% and between −2% and −20% of the modulus of the largest LULCti value, we categorized the degrees of increasing and decreasing trends, respectively. Values beyond 20% and −20% of the modulus of the largest LULCti value were classified as strongly increasing and strongly decreasing trends (see Supplementary Material File S1).

LULC transitions were evaluated for the interval between 1985 and 2023 and between 5-year intervals from 1985 to 2020 (1985–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020). We considered all transitions involving NFC and other classes identified using the MapBiomas transition classification method [51].

To analyze net gains and losses for the 5-year intervals, we subtracted the NFC areas converted to other classes from the areas of the other classes converted to NFC. Positive values indicate net gains, while negative values indicate net NFC losses. For a comparative analysis of the time intervals defined every 5 years from 1985 to 2020, we evaluated various levels, including the local level of the EPA, the regional level of the municipalities surrounding the EPA, the macroregional level of the Metropolitan Region of Campinas, the macroregional level of the state of São Paulo, and the level of the Brazilian Atlantic Forest biome (Supplementary Material File S2).

We produced thematic maps identifying the LULC transition locations where there were NFC losses and gains in the period from 1985 to 2023 with overlapping Rural Environmental Registry boundaries. The same LULC transitions analysis was conducted for the 5 zones defined by the Management Plan (2019). We analyzed the most recent period of the historical data series (2018 to 2023) to identify the locations and properties where NFC losses and gains have occurred after the establishment of the Management Plan (Supplementary Material File S3).

To gather secondary data, we initially conducted a keyword search in the Google Scholar database, selecting the main publications on governance and management in the EPA. From the first 50 most relevant publications, we analyzed the titles, abstracts, and sections of the works, selecting articles, theses, dissertations, and the other relevant gray literature until no new materials were found (see keywords and collector curve in Supplementary Material File S4). We then used the Grounded Theory method [52,53] to analyze the registries of the EPA Management Council meetings from 2005 to 2023. We coded them with terms that summarize the subject discussed in each excerpt, grouping these codes into 5 categories based on the occurrence of the subjects, namely: Ecosystems and Biodiversity, governance and management, Water Resources and Basic Sanitation, Tourism and Recreation, and Other Drivers of Change (Supplementary Material File S5).

3. Results

3.1. Landscape Composition (LULC), LULC Transitions, and Trends in the Campinas EPA

The NFC area increased from 9% of the total EPA area in 1985 to 17.1% in 2023 (Figure 3a). The classes that were most converted (transitioned) to forest formation in the period were "Mosaic of Uses" (11 km^2) and "Pasture" (7 km^2) (Figure 4). As described in the Mapbiomas Col. 9.0 legend, the "Mosaic of Uses" class for the Atlantic Forest biome represents the pixels in which it was not possible to differentiate between the pasture and agriculture classes. For this reason, we also evaluated both classes, which together showed a reduction from 88.5% to 71.2% of the total EPA area (Figure 3a). Urban infrastructure areas increased from 0.5% in 1985 to 4.3% in 2023. Planted forests (composed primarily of non-native species, mainly eucalyptus) increased from 0.1% in 1990 to 3.6% of the total EPA area in 2023, with a significant increase between 2015 and 2023. Other classes with smaller percentages of the total area ("Sugarcane", "Soybean", "Coffee", "Mosaic of Crop", and "Other non-vegetated areas") were grouped together, increasing from 1.4% to 5.9% of the total area between 1985 and 2023. While "Rivers and Lakes" decreased in area from 1.4% to 1.2% in the same period (Figure 3b). Despite the overall decreasing trend, the classes "Pasture" and "Mosaic of Uses" represent the main LULC classes, which combined form the landscape matrix. Small transitions (losses) in NFC occurred for "Pasture" (2 km^2), "Mosaic of Uses" (2 km^2), and "Forest Plantation" (1 km^2) (Figure 4).

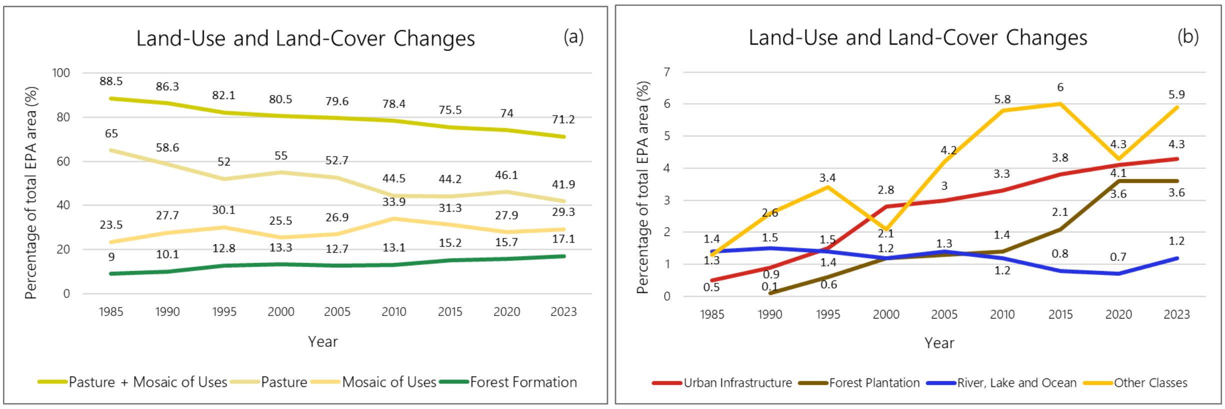


Figure 3. Land-use and land-cover changes in percentages of occupied landscape by class. (**a**) Major classes; (**b**) classes that occupy up to 7% of the total Campinas Environmental Protected Area.

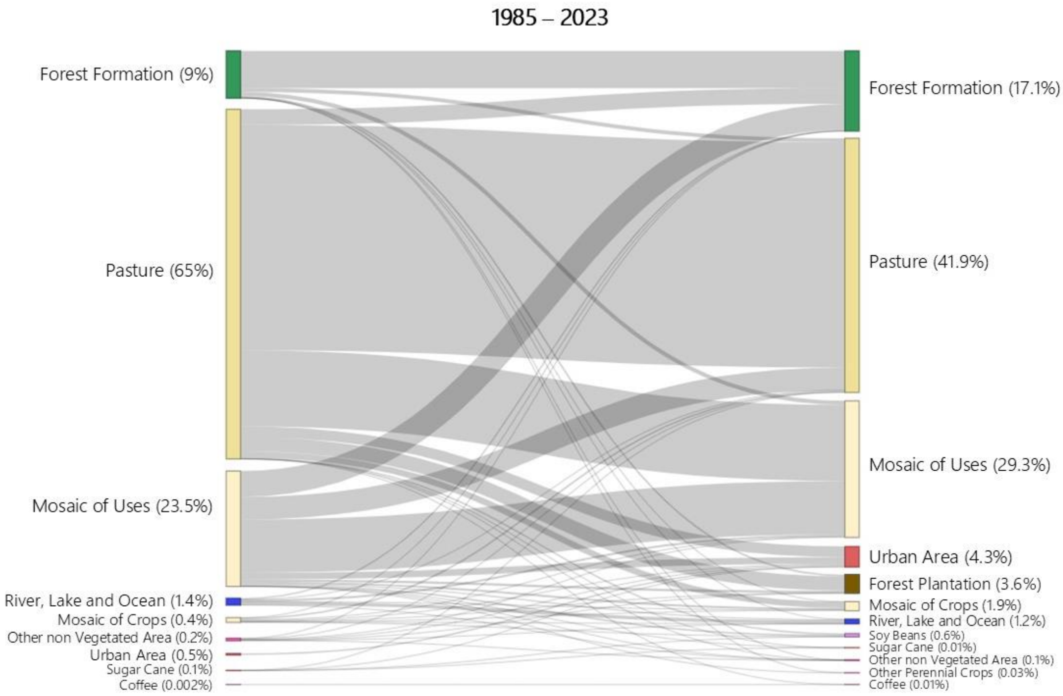
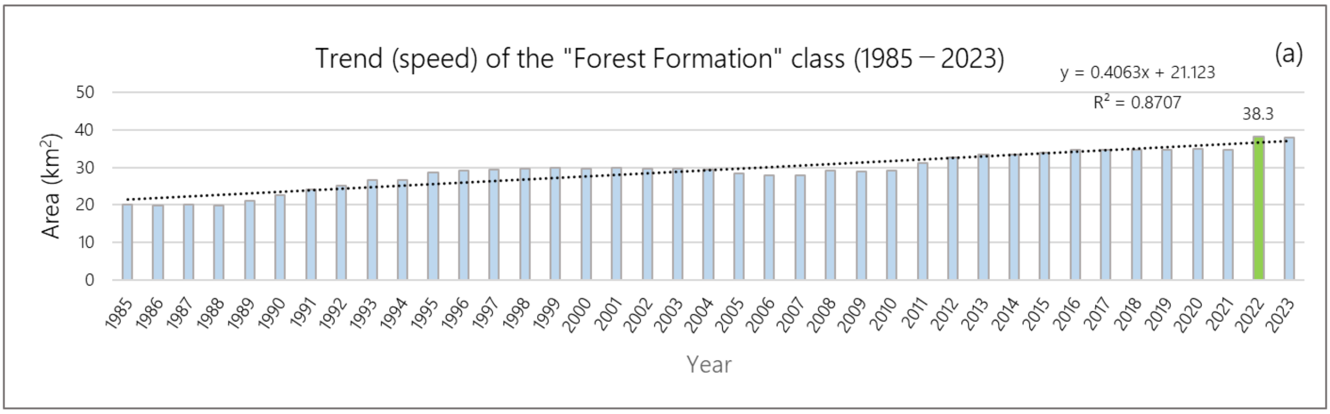


Figure 4. Sankey diagram with land-use and land-cover transitions in the Campinas Environmental Protected Area between 1985 and 2023.

The "Forest Formation" class exhibited a "strongly increasing" trend gaining 8.1% of the total area between 1985 and 2023 (Figures 4 and 5). In contrast, the "Pasture" class presented a "strongly decreasing" trend, experiencing the most significant percentage drop with a reduction of 23.1% of the total EPA area during the study period (Figure 3a). Although in practice they fall under the same coverage type, the main LULC transitions occurs between the "Pasture" and "Mosaic of Uses" classes, with a net gain of 23 km^2 for "Pastures" (Figure 4). The "Mosaic of Uses" class shows an "increasing" trend, rising by 5.8% of the total EPA area, but with greater losses to the "Forest Formation" class (11 km^2). When combining the "Pasture" and "Mosaic of Uses" classes, the calculated index (LULCCti) revealed a "strongly decreasing" trend, indicating a decrease of 17.3% of the total EPA for the same period (Figure 3a).



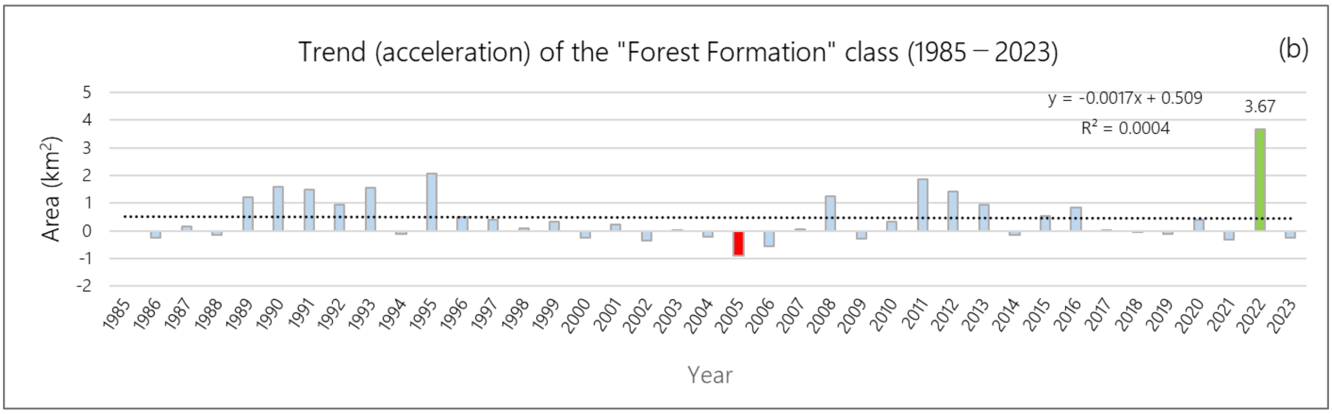


Figure 5. Speed (**a**) and acceleration (**b**) of LULC changes in area (km^2) of the "Forest Formation" class represented by the angles of the trend lines (coefficient of the variable x in the equations). Graphs generated from the total area of coverage occupied by the class in each year (**a**) and the accumulated or lost balance per year (**b**) in the period from 1985 to 2023. The green highlights indicate the year with the largest area of coverage (**a**) and the year with the largest balance of gain in area (**b**), and the red highlight indicates the year with the largest balance of loss in area (**b**). Other graphs with trend lines and equations of the other classes are presented in Supplementary Material File S1.

Other classes that exhibited an "increasing" trend between 1985 and 2023 were as follows: "Mosaic of Crops" and "Forest Plantation". The classes "Sugar Cane", "Soybean", "Coffee", and "Other Non-Vegetated Areas" showed a "stable" trend for the period. "Urban Infrastructure" showed a "strongly increasing" trend, while "River and Lake" showed a "decreasing" trend throughout the period (Table 1).

Table 1. Values and trends of growth, stability and decrease for the different levels of classes evaluated for the Campinas Environmental Protected Area in the period from 1985 to 2023. The arrows represent percentage ranges for different degrees of land use and land cover trend index (LULCti).

Class	**LULCCti** $[(\theta v.R_1^2) + (\theta_a.R_2^2).t/10]$		**Trend**
Forest Formation	0.3538	⬆	Strongly Increasing
Pasture	−0.9520	⬇	Strongly Decreasing
Sugar Cane	0.0001	➡	Stable
Soybeans	0.0172	➡	Stable
Coffee	0.0002	➡	Stable
Mosaic of Crops	0.0440	⬈	Increasing
Forest Plantation	0.1836	⬈	Increasing
Mosaic of Uses	0.0771	⬈	Increasing
Pasture + Mosaic of Uses	−0.8642	⬇	Strongly Decreasing
Urban Infrastructure	0.2120	⬆	Strongly Increasing
Other Non-Vegetated Areas	−0.0038	➡	Stable
River and Lake	−0.0387	⬊	Decreasing
⬆	20% ≤ LULCCti		Strongly Increasing
⬈	2% < LULCCti < 20%		Increasing
➡	−2% < LULCCti < 2%		Stable
⬊	−20% < LULCCti < −2%		Decreasing
⬇	LULCCti ≤ −20%		Strongly Decreasing

3.2. Forest-Cover Change Dynamics at Different Levels in the Atlantic Forest

In the LULC transitions assessment focusing on net changes in NFC over 5-year intervals from 1985 to 2020, we observed similar patterns between the Campinas EPA (Figure 6), the surrounding municipalities (regional level), and the metropolitan region (macroregional level) (Figure 7). Within the EPA, net gains in NFC occurred during the periods 1985–2000 and 2005–2020, while net losses occurred between 2000 and 2005. At both the regional and macroregional levels, we observed net losses in NFC between 1995 and 2000 and net gains in the other intervals, with a significant increase between 2010 and 2015.

At the state and biome levels, we observed a distinct pattern between the EPA and its surroundings. The turning point from net losses to net gains occurs in the state of São Paulo from the year 2000 onwards and in the biome from 2005 onwards (Figure 7). Despite this inflection from losses to net gains, the NFC decreased in the state from 5 Mha in 1985 to 4.8 Mha in 2023. The same occurred at the biome level, which declined from 30.5 Mha in 1985 to 28.3 Mha in 2023.

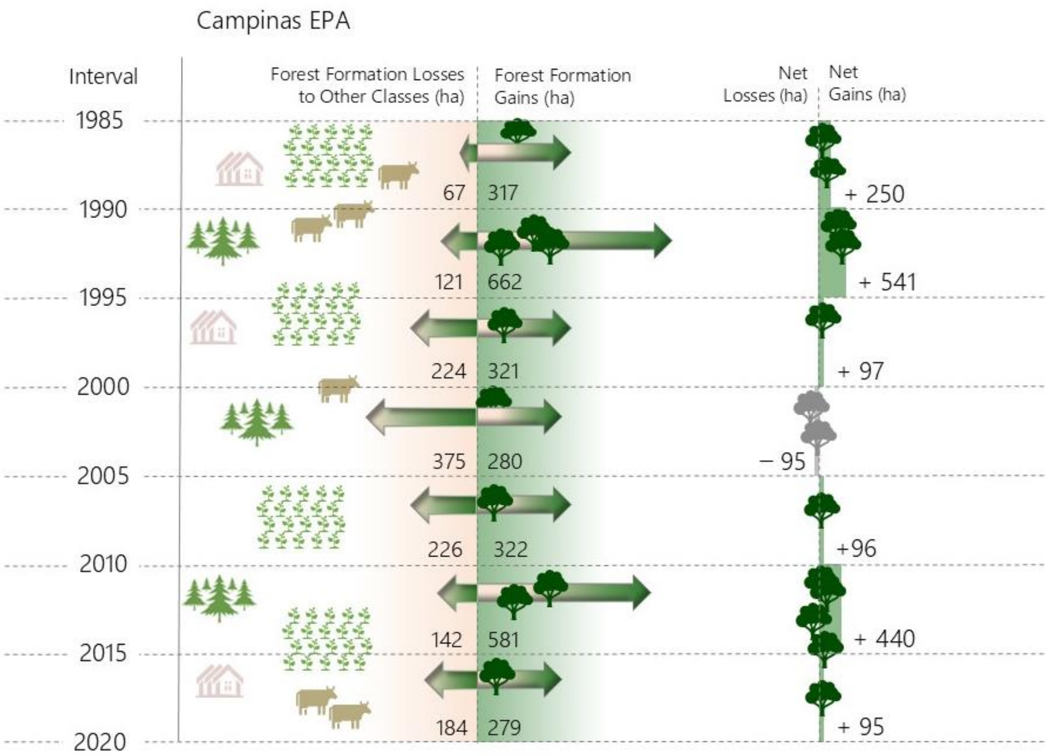


Figure 6. Land-use and land-cover transitions with losses, gains, and net changes of "Forest Formation" class per five-year intervals for the Campinas Environmental Protected Area between 1985 and 2020.

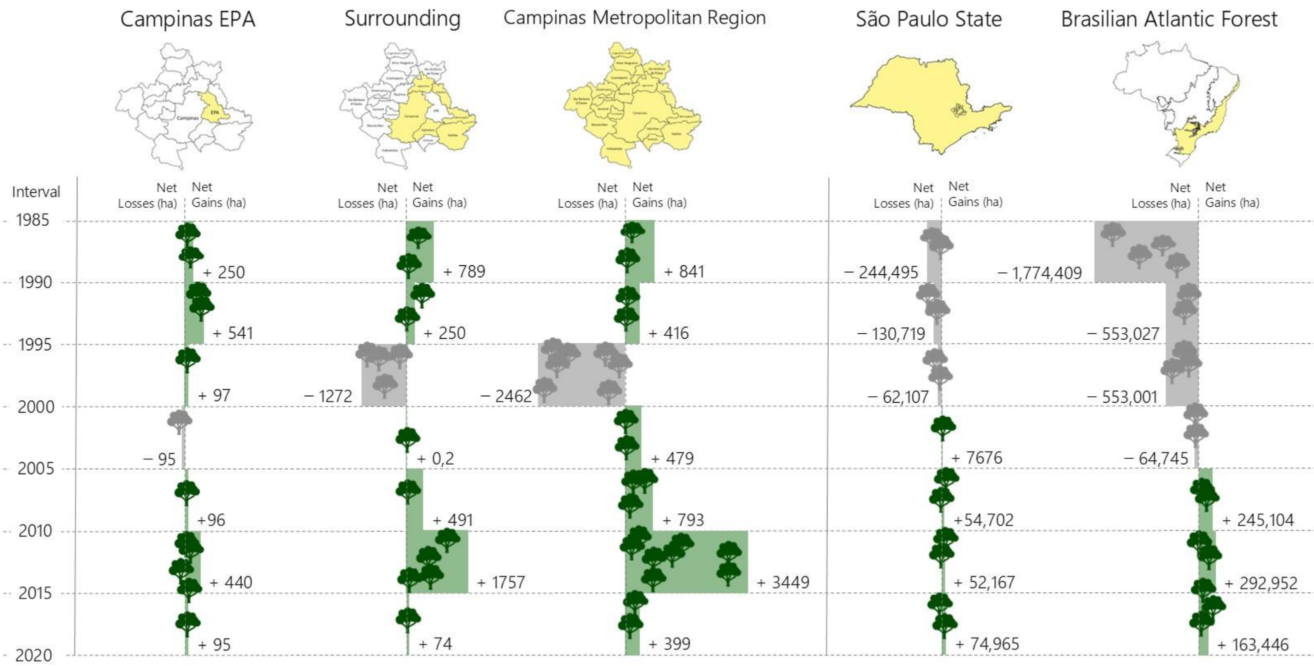


Figure 7. Forest formation net change (ha) per five-year intervals for the Campinas Environmental Protected Area, region surrounding the Campinas EPA, Campinas Metropolitan Region, São Paulo state, and the Brazilian Atlantic Forest biome between 1985 and 2020. Analyzed areas in yellow.

3.3. Spatialization of LULC Transitions with NFC Losses and Gains in the Campinas EPA

Figure 8 shows the spatial distribution of areas with transitions involving NFC between 1985 and 2023. During this period, the total area of NFC that remained in transition was 15.9 km^2. NFC losses to other classes accounted for 4.2 km^2 while NFC gains from other classes totaled 20.5 km^2, resulting in a net gain of 16.3 km^2 from 1985 to 2023. The largest NFC losses were for "Mosaic of Uses" (1.9 km^2) and "Pasture" (1.2 km^2). Differently, the largest NFC gains occurred in transitions from "Mosaic of Uses" (12.4 km^2) and "Pasture" (7.8 km^2). The study area of the Campinas EPA is occupied by 675 private rural properties according to Rural Environmental Registry data, which represent an area of 205.4 km^2 or 92% of the total EPA area. While most transitions involving NFC occurred in registered private rural properties, some transitions during the same period can be observed in unregistered areas and urban areas (Figure 8).

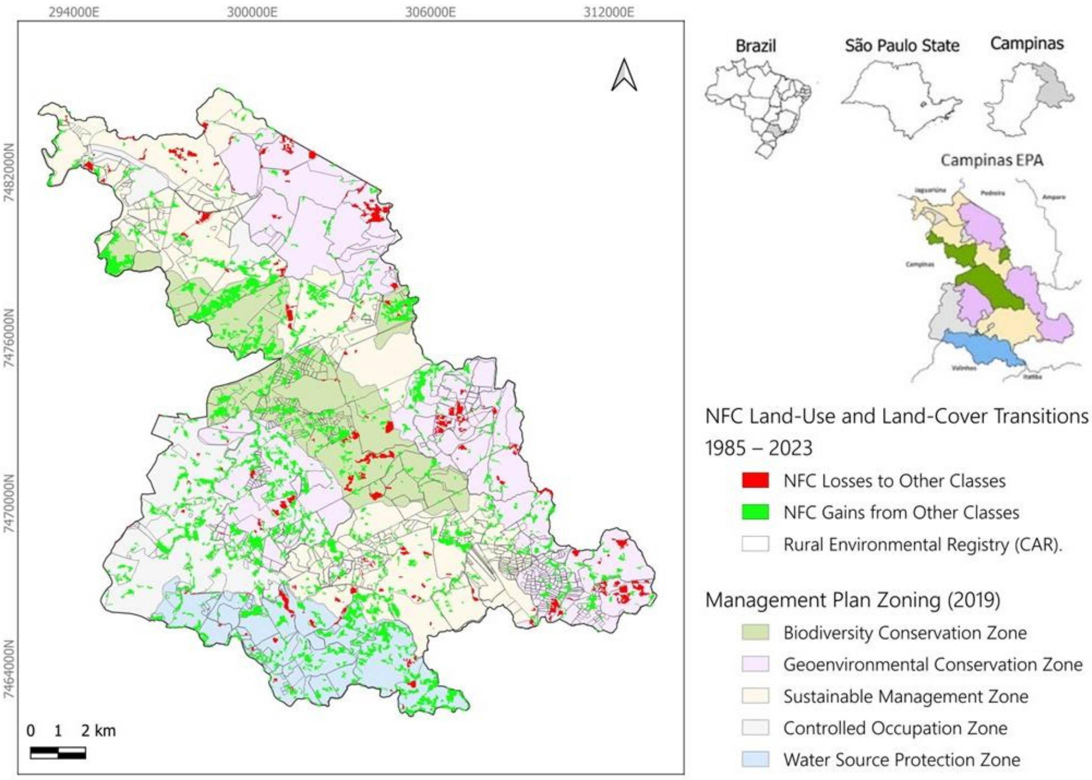


Figure 8. Natural Forest Cover (NFC) transitions in the Campinas Environment Protected Area with losses and gains for the period 1985–2023. Rural property boundaries registered in the Rural Environmental Registry.

The spatial analysis of LULC transitions for the most recent period (2018–2023), including the validity of the 2019 Management Plan, revealed 134.6 ha of NFC losses and 483.9 ha of NFC gains (Table 2). This resulted in a net change of 349.3 ha of NFC gains. We highlight the transition with the greatest NFC loss (77.6 ha), which occurred in the Geoenvironmental Conservation Zone in the Pedreira Dam region, and the transition with the greatest NFC gain (144.6 ha) occurred in the Biodiversity Conservation Zone (Figure 9). Additionally, we observed considerable NFC losses in the Water Source Protection Zone (23.3 ha) and in the Biodiversity Conservation Zone (21.7 ha). Significant gain was recorded in the Sustainable Management Zone (128.3 ha).

Table 2. Losses and gains (ha) by zone between 2018 and 2023 (including the period of the Campinas Environmental Protected Area Management Plan (2019). BCZ—Biodiversity Conservation Zone; GCZ—Geoenvironmental Zone; SMZ—Sustainable Management Zone; COZ—Controlled Occupation Zone; WSPZ—Water Source Protection Zone.

	BCZ	GCZ	SMZ	COZ	WSPZ	Total
NFC losses (ha)	21.7	77.6	9.1	2.9	23.3	134.6
NFC gains (ha)	144.6	86.4	128.3	47.7	76.9	483.9
Net change (ha)	+122.9	+8.8	+114.2	+44.8	+53.6	+349.3

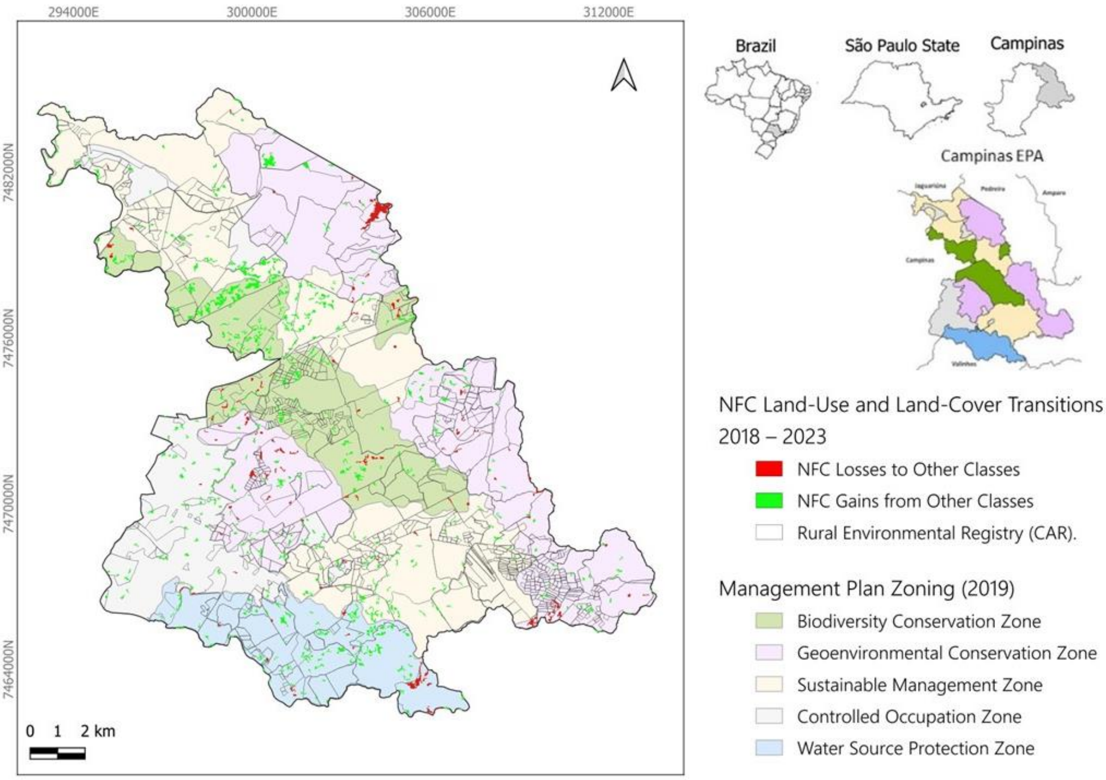


Figure 9. Losses and gains of "Forest Formation" class between 2018 and 2023 in ecological–economic zoning areas defined by Campinas Environmental Protected Area Management Plan approved in 2019.

3.4. Secondary Supporting Data

The search for references on governance and management in the Campinas EPA using keywords in the Google Scholar database yielded 61 publications, including 8 doctoral theses, 24 master's dissertations, 1 monograph, 2 books, 2 book chapters, 18 articles, 1 Management Plan, 1 newspaper article, 1 website, and 3 items that could not be found (Supplementary Material File S4).

Analyzing the 290 registries of ordinary meetings (OMs hereinafter) and extraordinary meetings (EMs hereinafter) of the EPA Management Council held between 2005 and 2023, we assigned 4241 codifications to 2663 citations from 66 codes grouped into five categories. Of the total coded citations, the majority (2095) referred to the "Governance and Management" category. Within this category, 117 citations referred to "Management Plan and EEZ". The 61 citations directly related to EEZ were divided into three groups: (i) potential non-compliances with EEZ (26); (ii) non-compliance with EEZ (5); and (iii) definitions and revisions of EEZ (30) (Figure 10) (Supplementary Material File S5).

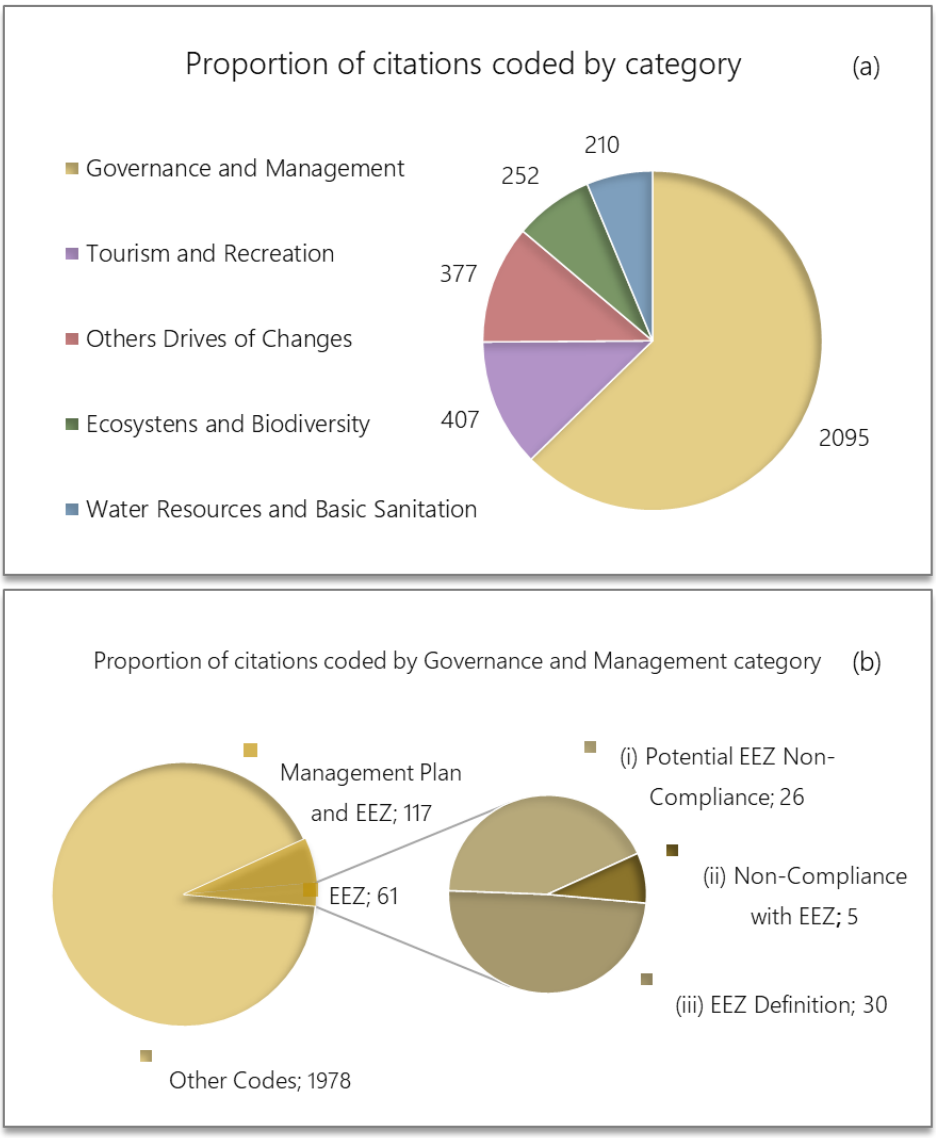


Figure 10. Proportion of citations coded by category (**a**) and by "Governance and Management" category (**b**) from Campinas Environmental Protected Area Management Council meeting registries for the period 2005 to 2023.

Instituted a few decades ago in the region, the EEZ management instrument has helped organize land use and occupation by dividing Campinas into macrozones and also delimiting the urban and rural zones. Macrozone 1, currently the EPA region, has been recognized since the early 1990s as a key area for water security and biodiversity conservation [43,54]. Updates to the EEZ boundaries and rules have been made with each revision of Campinas' Master Plan and the Management Plans of the macrozones. The latest version of EEZ included a methodology for defining Stable and Unstable Ecodynamic Units [48,55,56] and participatory workshops to incorporate community demands. Through this integrated analysis of the environmental fragility and structural connectivity of the landscape (ecological corridors between forest fragments), preliminary versions of EEZ were reviewed until the final version was published in the 2019 Management Plan, which is currently in use.

We gathered examples from the speeches of Management Council members in which the EEZ instrument was mentioned in three different situations related to NFC or associated ecosystems (e.g., watercourses, riparian forests, water source areas) (i) to prevent, report, or impose conditions on potential EEZ non-compliance; (ii) to report or sanction a factual

EEZ non-compliance; and (iii) to request a new definition or propose changes to existing EEZ boundaries for specific reasons or interests (Figure 10).

Among the situations that illustrate the potential effectiveness of EEZ (i) one example is the proposal to subdivide rural properties into smaller parcels around the Semideciduous Seasonal Forest (SSF hereinafter) fragment in Santana farm ("SSF Fazenda Santana") (Figure 2). This proposal is made in disagreement with the current legislation of the Campinas EPA, which designates these areas as unsuitable for urbanization (EM—4 December 2012). Another example involved restrictions on projects over 30% of its built-up area into a rural land within the water conservation zone, near to the Campinas water supply area (OM—7 April 2009) [57,58].

In some instances, the Management Council and/or the Prefecture deny authorization for companies to operate in violation of EEZ (OM—26 January 2016). In other cases, authorization is granted with conditions, such as in a project involving the suppression of NFC in a "permanent preservation area" (APP in Portuguese, which refers to a type of strict preservation area where human interference is prohibited), for the construction of a bridge over the Ribeirão das Cabras river, where approval was contingent through reforestation compensation in the area (EM—5 July 2022). Another example of EEZ-enforced restrictions is the impediment of mining activities in areas that are a designated tourist interest zone (OM—26 November 2013).

The EEZ instrument is also employed to prevent or minimize degradation caused by large-scale projects of social interest, for example the construction of an interstate gas pipeline [59], or the installation of a 500 kV line transmission that crosses the EPA territory. This removal of NFC requires environmental compensation through reforestation in areas with potential connectivity of forest fragments (ecological corridors) (EM—19 April 2011; OM—25 March 2014). There are also cases in which environmental impact studies rely on present territorial planning outlined in EEZ to license projects, even with opposing opinions from environmental councils. This is the case of road access in Macrozone 2, where urban expansion threatens the rural area of the EPA (Macrozone 1) (OM—13 May 2014; OM—26 August 2014) [60].

Another example of EEZ's effectiveness is its role in regulating forestry activities. For the Management Council to issue a land-use certificate, companies must adhere to specific conditions because they operate within a Geoenvironmental Zone that has areas susceptible to flooding, the presence of significant NFC remnants, and architectural works of historical and cultural value to Campinas (OM—30 June 2020). Among the imposed conditions are restrictions on the use of pesticides (OM—27 September 2022) [61].

Some situations highlight complaints or sanctions in which EEZ has not actually been complied with (ii). An emblematic example involved the removal of 40 ha of NFC for the construction of a dam on the border between the municipalities of Campinas and Pedreira [62]. This public utility project, which directly affects the EPA, was allowed by a change in the law that ignored objections from both the Municipal Environmental Council and the EPA Management Council (OM—31 October 2017). The compensation that was agreed was the reforestation of 210 ha in a permanent protection area surrounding the project. Additionally, financial resources were allocated to the EPA as part of this compensation (OM— 24 November 2020; OM—25 May 2021).

Examples of smaller infractions against EEZ regulations include mining activity in an environmental conservation zone, within a condominium subdivision. Council members called for actions against those responsible, including holding the condominium association accountable for the incident (OM—27 September 2011). Other examples include the expansion of livestock farming into water source areas (OM—27 September 2011), soil movement for housing construction (OM—27 January 2015), the closure of subdivisions in condominiums due to non-compliance with Water Source Protection Zone regulations (OM—27 September 2022), and the registration of a land parcel in a water zone by a Prefecture body disregarding a negative opinion from the Management Council (OM—27 September 2016) [57].

The third group of examples (iii) illustrates situations in which the definitions and changes of geographical boundaries and regulations of EEZ are discussed by council members. A recurring topic is the delimitation of urban and rural areas, primarily because the urban areas allow more flexibility in permissions for land use and occupation making them highly sought after by development sectors such as real estate (OM—28 March 2017; OM—24 April 2018) [58,63].

Discussions often center around land subdivision for urban purposes in areas located between rural and urban zones. In these cases, the council determines which rules should apply: either those for the rural zone or those for the urban zone (OM—7 April 2009; OM—29 March 2011; EM—17 April 2013). In other situations, requests for the revision of EEZ boundaries may also arise due to the need to include properties under a certain territorial order. (OM—29 March 2011).

Examples of areas where different zoning regulations intersect, and where the most restrictive regulations prevail, can be seen in the issuance of land-use certificates for parties, events, and fairs on the Cachoeira and São Joaquim farms. Although the Management Council authorizes these activities as they are permitted within the Sustainable Management Zone and the Geoenvironmental Conservation Zone (Figure 2), respectively, warnings are issued because these areas also fall within the Stellar Protection Area (APE in Portuguese), which has regulations on lighting and the use of explosives (OM—3 February 2021).

The creation of protected areas is another way of establishing rules for regions of ecological relevance, functioning as a form of EEZ. In this sense, efforts to protect forest areas are carried out by members of the Management Council, such as the attempt to create a new protected area for the "SSF Ribeirão Cachoeira" (Figure 2), the largest forest area of the EPA and the second largest forest area in Campinas (OM—31 May 2011; OM—28 June 2022). Another notable situation related to EEZ occurs when land-use and occupation rules for one macrozone affects an adjacent macrozone. In such cases, a National Environmental Council resolution establishes 10 km buffer zones, which can contribute to the conservation and therefore to the forest transition process in the region (EM—25 March 2010; OM—29 August 2017).

4. Discussion

The results from the LULC changes analyses align with evidence of a forest transition process underway in the state of São Paulo [30] and the Atlantic Forest biome [24]. However, for the metropolitan region, the municipalities surrounding the EPA, and the EPA itself, we observed a distinct net change pattern compared to for the state and biome levels. Small net NFC losses and gains that occurred between 1995 and 2005 were followed by gains, especially between 2010 and 2015. We can assume that this difference in patterns for the different levels may be associated with regional specificities including drivers of change as climate or governance and management processes since the biome occurs in different federation states [26,27] (Figure 7).

In this context, we emphasize that the forest transition process at a specific spatial level may exhibit causal relationships for net change that do not necessarily apply across other levels in the analysis of forest dynamics [64]. Despite this challenge, following Perz's critique of forest transition theory, we propose that the different spatial and temporal levels establish panarchical relationships within complex socio-ecological systems [6,64,65]. Furthermore, our local-level analysis suggests that the maturity of NFC can provide insights into the forest transition process [64]. While these questions about cross-level interactions and NFC maturity are highly relevant, we address them here primarily as context. Our main focus is on examining evidence of the zoning instrument as a potential driver of the forest transition process within the local level of the Campinas EPA.

Our findings support the hypothesis of NFC gains at the EPA local level due to land transitions from agriculture to pasture, as highlighted in previous studies [43,61,66]. Publications on governance and management in the EPA, along with registries of the Management Council meetings indicate that socioeconomic changes in recent decades, mainly with the replacement of agricultural activities by tourism, have favored the recovery of NFC [67].

The analysis of the LULC change trend index revealed a "strongly increasing" trend in urban expansion within the Campinas EPA. Previous studies have suggested that this trend is strongly associated with real estate groups, which are taking advantage of the region's environmental amenities (e.g., climate, woodlands, parks, outdoor activities, nearby main roads/logistics) to speculate on land value and promote high-value housing development [43,47,57,63,66–69].

We found that forestry activity (planting of species for commercial purposes), which is encouraged by the EPA Law, has shown an "increasing" trend over the last decade, supported by feasibility studies [46,61] and the consent of the Management Council, which required compliance with the rules defined in the Management Plan. Our study also identified irregular activities, such as mining, soil moving, and deforestation, in "permanent preservation areas" (APP). These issues were previously documented in the EPA Management Plan of Sousas and Joaquim Egídio, which later became part of the EPA of Campinas [43,61].

4.1. Endogenous Socio-Ecological Forces and Exogenous Socio-Economic Factors

Forest transition processes at the regional, biome, or global levels occur due to a combination of endogenous socio-ecological forces (e.g., resource depletion from forest exploitation) and exogenous socio-economic factors (e.g., political, demographical, economical, and socio-cultural changes) [27,42]. In the Campinas EPA, we observed the prevalence of exogenous socio-economic factors as the primary drivers of this transition. Our review of the published literature and the Management Council meetings registries revealed no evidence of exploitation of forest and non-forest products from the natural vegetation. However, we consider governance and management processes at the local level, as the establishment of EEZ, to be endogenous socio-ecological forces. Although linked to external factors, these processes originate from and are constituted by the internal demands of stakeholders within the EPA itself.

Since the beginning of the 20th century, from the coffee production cycle to other agricultural uses and more recently to urban expansion and tourism development, external socioeconomic factors have driven LULC changes in the Campinas region [43,48,66]. Agricultural production in the region followed the broader economic cycle of coffee monoculture, prominent across several Brazilian states, including São Paulo. After the decline in coffee production, a new cycle of industrialization and technological advances promoted the diversification of agricultural crops and urban expansion, with the first subdivisions beginning to appear in the EPA region [70]. Just as coffee production in the EPA is driven by a macroeconomic cycle, the diversification of agricultural production and the subdivision of large farms were responses to external factors related to economic development through industrialization at both municipal and state levels. More recent land-use practices in the region (e.g., ecotourism, cycling tourism, astronomical observation, or environmental education activities promoted by schools) reflect sociocultural changes linked to ecological thinking that intensified in the second half of the 20th century [71–74].

These external socioeconomic and sociocultural factors, which contributed to the forest transition process, are manifested at the local level by the increase in forest areas, despite direct anthropogenic drivers of change [2] acting in the opposite direction, as deforestation of NFC in the EPA. Threats to conservation in the region are mainly related to urban expansion, identified in our results with a strong upward trend, including subdivisions of private rural properties into small plots to allow the construction of gated communities [47,60,75]. Such initiatives to expand the urban area over the rural area were accompanied by the conversion of natural habitats, increased consumption of water resources, increased contamination of soil and watercourses by the release of effluents, soil moving, mining, and the introduction of invasive alien species, among others [68]. Infrastructures of social interest such as access roads to gated communities, the installation of electricity transmission lines, the installation of gas pipeline, or the construction of dams are also important vectors of change in the region.

Endogenous socio-ecological forces, including indirect drivers of change like institutions and governance [2], influence forest dynamics at the local level. Our analysis of Management Council meeting registries, along with prior studies on governance and management, underscores the substantial political role that organized civil society groups play in decision-making forums and in shaping agendas for environmental conservation and sustainable development within the APA [67,76].

Different interests between socio-economic development and environmental conservation are discussed in the elaboration and revisions of EEZ. Restrictions and permissions, such as the installation of housing and commercial infrastructure in rural or urban areas, the removal of vegetation, and interventions in permanent preservation areas (APP) or water source protection areas, are discussed and voted on by counselors. These decisions are formalized into opinions sent to other institutional levels and, often having practical effects on NFC and associated ecosystems [57,63].

4.2. Contributions and Limitations of EEZ in Environmental Conservation in the Campinas EPA

The secondary data collected and analyzed support our hypothesis that the EEZ instrument is a contributing factor, among others, to the forest transition process at the local level. As demonstrated in our results, numerous examples illustrate how urbanization pressures, whether from real estate interests or other drivers of habitat loss, are contained or mitigated through the enforcement of current zoning definitions.

However, we highlight two weaknesses of EEZ. First, cases of non-compliance with the rules were identified late, leaving the Management Council to formalize complaints for possible application of sanctions through regulatory agencies (Public Prosecutor's Office and Environmental Police). In this context, limited material and human resources often hinder the ability to monitor, inspect, and communicate information on zone-specific restrictions, permissions, and penalties for non-compliance. Second, the EEZ instrument may have its limits and regulations changed by the articulation of sectors with political and economic power. In this case, we identify a governance system that is not yet fully geared towards adaptive co-management [77] in which power asymmetries are minimized in decision-making processes for the collective construction of desirable scenarios among stakeholders based on learning by doing.

4.3. Policies Promoting the Forest Transition Process in the Campinas EPA

In 2010, a municipal decree established the Green Areas Bank for reforestation purposes. Both public and private lands, whether urban or rural, are registered by the Municipal Department of the Environment, which is responsible for coordinating and managing forest restoration actions. The Council has reported several instances of compensatory actions carried out through the Green Areas Bank, for example, a cooperation agreement as compensation for the construction of a gated condominium in the EPA (OM—27 March 2008). Reforestation initiatives have also been promoted through partnerships with third-sector organizations in Green Areas Bank areas (OM—31 May 2007; OM—3 March 2009).

Other policies promote actions towards the conservation and restoration of NFC within the EPA, with the potential contributions to the forest transition process. The Payment for Environmental Services Program, established by municipal law, provides financial compensation to registered and qualified rural and urban landowners who comply with environmental preservation actions on their properties. The legislation in force since 2015 has subprograms such as Payment for Environmental Services Program—Water, Payment for Environmental Services Program—Soil, Payment for Environmental Services Program—Natural Scenic Beauty, among others. The Program's Management Council is currently running pilot work with Payment for Environmental Services Program—Water, but it is still too early to assess the Program's effectiveness for the forest transition process. Additional initiatives outlined in the 2019 Management Plan also aim to promote actions towards NFC conservation and recovery in the EPA. These actions, not yet evaluated as to their effectiveness for the forest transition process, are coordinated by technical chambers composed of counselors from the EPA Management Council, alongside a technical team of researchers. One example is the Biodiversity and Natural Resources Commission, which focuses on the restoration of priority areas, restoration of degraded lands and economic development within the EPA (OM—27 August 2019).

5. Conclusions

Conservation and recovery policies for the Atlantic Forest biome can be more effective when the causes of forest transition are known at the local level. Our study sought to understand the socioeconomic cycles and other internal dynamics of human relations with forest ecosystems with the intention of elucidating the causes behind reduced losses and increased NFC gains. We confirmed hypotheses from other studies that the shift from agricultural activities to a service- and tourism-based economy has enabled the spontaneous recovery of abandoned areas. Although these areas are not yet substantial, we identified policies that can contribute to forest transition, such as the Green Areas Bank, the Payment for Environmental Services Program, initiatives outlined in the Management Plan, and third-sector reforestation actions.

We highlight several examples that demonstrate the relevance of the EEZ instrument in maintaining and increasing NFC. At least since the early 1990s, both the government and different sectors of society began to consider the EPA region as an important source of ecosystem services for the municipality. We understand that this perception, which originated from a global movement to preserve natural environments, has motivated the establishment of several regulations that discourage deforestation and favor NFC recovery.

However, we also acknowledge the limitations of EEZ in the conservation and recovery of NFC. One key limitation is the challenge of its full compliance due to insufficient human and financial resources for monitoring and enforcing sanctions on violators. Additionally, we observed that in some cases, political factors and the economic power of the actors involved may prevail over EEZ regulations. Our analysis of LULC transitions for the most recent years (2018–2023), including the period under the 2019 Management Plan, identified deforestation in all five zones, although net gains still exceeded net losses.

Finally, while we can affirm the effectiveness of EEZ, which has undergone incremental adaptations over recent decades that have favored the forest transition process in the EPA region, we emphasize that this management instrument remains vulnerable to changes in its boundaries and regulations depending on the configuration of the governance system at various levels. In this sense, EEZ alone may not be sufficient to contain forest degradation, especially in the face of growing threats such as urban expansion associated with increasing demand for land and ecosystem services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13122020/s1, Supplementary Materials S1: LULC Changes trend index; Supplementary Materials S2: LULC Transitions Infographics; Supplementary Materials S3; Supplementary Materials S4: Search for references on Governance and Management at EPA Campinas; Supplementary Material S5: EPA Management Council Registries.

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