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Analysis of land use and land cover dynamics in buffer zones: the case of protected areas in the state of São Paulo, Brazil

Análise das dinâmicas dos usos e coberturas da terra em zonas de amortecimento: o caso das áreas protegidas no Estado de São Paulo, Brasil

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Abstract: Buffer zones (BZs) play an important role in achieving positive conservation outcomes in protected areas (PAs) by establishing land use regulations aimed at minimizing negative impacts caused by human activities. However, challenges remain regarding their effectiveness in management. This study analyzed changes in landscape conditions in the surroundings of 25 PAs located in the state of São Paulo (Brazil) from 1985 to 2022. Whenever changes were detected, land use and land cover dynamics were also assessed. For this purpose, the percentages of natural habitat were quantified within the BZs and in their respective external zones (EZs). The results indicated that, in most cases, no changes occurred in the landscape condition of the BZs throughout the analyzed period. Only one PA – the Ribeirão Preto Ecological Station – showed changes in its BZ, and these were positive. Among the stable BZs, 14 exhibited positive conditions, and 10 showed negative conditions for biodiversity conservation. Regarding the EZs, only 3 PAs showed changes in the landscape condition. In most cases, the BZs presented landscape conditions that were comparable to or worse than those of their respective EZs, contrary to what would be expected for these areas. The observed changes in BZs and EZs were predominantly associated with agricultural expansion, particularly sugarcane cultivation. The findings are expected to support improved territorial management in the surroundings of PAs by informing the development of targeted actions aimed at mitigating the identified vulnerabilities.

Keywords: landscape condition; nature conservation; anthropogenic activities; environmental management; regulations.

Resumo: As zonas de amortecimento (ZA) desempenham um papel importante para o alcance de resultados positivos de conservação em áreas protegidas (AP), ao estabelecerem regras de uso da terra para minimizar os impactos negativos causados pelas atividades antrópicas. Entretanto, desafios persistem quanto à efetividade de sua gestão. Este estudo analisou as mudanças nas condições da paisagem no entorno de 25 AP localizadas no estado de São Paulo (Brasil), no período de 1985 a 2022. Quando identificadas, as dinâmicas de uso e ocupação da terra também foram avaliadas. Para tanto, foram quantificadas as porcentagens de habitat natural nas ZA e nas respectivas zonas externas (ZE). Os resultados indicaram que, na maioria dos casos, não houve alteração na condição da paisagem das ZA ao longo do período analisado. Uma única AP – a Estação Ecológica de Ribeirão Preto – apresentou mudanças na ZA, neste caso positivas. Entre as ZA estáveis, 14 apresentaram condições positivas e 10 apresentaram condições negativas para a conservação da biodiversidade. Quanto às ZE, somente 3 AP apresentaram alterações na condição da paisagem. A comparação entre as duas zonas proporcionou a percepção de que, na maioria dos casos, as ZA apresentaram condições da paisagem iguais ou inferiores às respectivas ZE, o que contradiz com o esperado para essas zonas. As alterações observadas, tanto nas ZA quanto nas ZE, estiveram predominantemente associadas à expansão agropecuária, com destaque para a cana- de- açúcar. Espera-se que os resultados contribuam para o aprimoramento da gestão territorial no entorno das AP, subsidiando a formulação de ações específicas voltadas à mitigação das vulnerabilidades identificadas.

Palavras-chave: condição da paisagem; conservação da natureza; atividades antrópicas; gestão ambiental; regras.

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1. Introduction

A globally recognized definition of a protected area (PA) is that proposed by the International Union for Conservation of Nature (IUCN), namely: "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008, p. 8). In Brazil, such spaces take various forms, namely Conservation Units, Permanent Preservation Areas, Legal Reserves, Indigenous Lands, or Internationally Recognized Areas (Medeiros et al., 2004; Medeiros, 2006).

Among these possibilities, Conservation Units play a prominent role in the organization of the national protected area system. The National System of Nature Conservation Units (SNUC, in Portuguese), established by Federal Law nº 9985/00, provides an integrated framework for the creation, implementation, and management of conservation units. The SNUC organizes Conservation Units into two major groups, according to their objectives and management restrictions: Integral Protection Units, which aim to preserve ecosystems with minimal human interference, allowing only the indirect use of their resources; and Sustainable Use Units, which allow the direct use of the environment, provided that it ensures the long-term availability of renewable environmental resources and ecological processes (*Lei nº 9.985*, 2000). Conservation Units may be created and administered by the federal, state, or municipal levels.

The aforementioned law defines a buffer zone as "the surroundings of a conservation unit, where human activities are subject to specific norms and restrictions, aiming to minimize negative impacts on the unit" (*Lei nº 9.985*, 2000). The term buffer zone became widely used after a strategy launched by the UNESCO Man and the Biosphere Programme in the 1970s, which introduced a zoning model for Biosphere Reserves consisting of a protected "core area" surrounded by a "buffer zone" and then a "transition area" (Li et al., 1999; Martino, 2001).

In Brazil, the management body of the Conservation Unit is responsible for establishing specific rules to regulate the occupation and use of resources in buffer zones, through the Management Plan (*Lei nº 9.985*, 2000). However, it is interesting to note that, although the management body is responsible for outlining such rules, buffer zones are located outside the boundaries of the Conservation Unit and, consequently, outside the jurisdiction of this management body (Lima & Ranieri, 2018). This configuration can lead to conflicts and difficulties in the effective implementation of the rules, highlighting a major challenge in the management of these areas.

Considering this context, the present study sought to test the following hypotheses: the landscape condition in buffer zones tends to improve over the analyzed period; and the landscape condition in buffer zones is better compared to their respective external zones.

The external zones, defined for this study, have variable widths and an area similar to their respective buffer zone, with a territorial extension beginning immediately after the buffer zones' external boundaries. Unlike buffer zones, external zones are not subject to the same land-use rules. Thus, it is assumed that, in a scenario of regulatory effectiveness, buffer zones should exhibit better landscape conditions compared to external zones.

The landscape condition was assessed using the percentage of natural habitat (see Table 3, Section 2.2) within buffer zones and external zones. Habitat loss is a major problem in landscapes originally covered by forest ecosystems and is directly associated with fragmentation processes. Studies grounded in Landscape Ecology demonstrate that the reduction of habitat cover can lead to the crossing of critical thresholds, where spatial configuration compromises connectivity and population viability, affecting the achievement of biodiversity conservation goals (e.g., Fahrig, 2003; Villard & Metzger, 2013; Banks-Leite et al., 2014).

Several studies have analyzed land use and land cover dynamics surrounding protected areas in Brazil (e.g., Terra et al., 2014; Amaral et al., 2019; Oliveira et al., 2020; Almeida-Rocha & Peres, 2021; Souza et al., 2024) and in other countries (e.g., Kintz et al., 2006; Yadeta et al., 2022; Mingarro & Lobo, 2023). However, the present study innovates by comparing officially established buffer zones managed by the same governing body with external zones of equivalent area, in a long-term temporal analysis. Furthermore, the analyzed areas are located in two biodiversity hotspots – the Atlantic Forest and the Cerrado – which increases the relevance and scientific contribution of the results.

Thus, by analyzing landscape conditions in buffer zones and external zones, this study aims to verify the differences between these areas, identify changes over the analyzed period, and understand which land uses are associated with the observed transformations. The results are expected to contribute to improving territorial management around Conservation Units, providing technical support for formulating public policies and strategic actions aimed at mitigating the identified vulnerabilities.

2. Methodology

2.1. Study area

The buffer zones of 25 Conservation Units located in the state of São Paulo (Brazil) were selected as the study area for this research. The state of São Paulo is home to two biodiversity hotspots – the Cerrado and the Atlantic Forest – and is also the most populous state (44,411,238 inhabitants) and has the largest urbanized area in the country (8,614.62 km^2) (Brazilian Institute of Geography and Statistics [IBGE], 2022).

The official buffer zone boundaries were established and made avail-

able by the environmental agency responsible for their management, the São Paulo State Forest Conservation and Production Foundation (*Fundação para a Conservação e a Produção Florestal do Estado de São Paulo*, in Portuguese), or simply the Forest Foundation. Based on these files, buffer zones were selected whose Conservation Units had a published Management Plan (verification conducted in 2021) and whose territories (Conservation Unit, buffer zone and external zone) were entirely continental (Table 1 and Figure 1).

The external zones were delineated specifically for this study using a semi-automated buffer generation model, according to the methodology described by Guerra et al. (2025), employing the graphical modeler of QGIS software. The width of the buffer corresponding to the external zone was iteratively adjusted until its area was equivalent to that of the respective buffer zone, allowing for a maximum variation of 10%. Any overlaps with Indigenous Lands and federal, state, or municipal Conservation

Table 1 Conservation Units selected for this study.

Acronym	Name of Conservation Unit	SNUC* group	SNUC* category
EEB	Sebastião Aleixo Da Silva (Bauru)	Integral Protection	Ecological Station
EEC	Caetetus		
EEI	Itapeti		
EEJ	Jataí		
EEPF	Paulo De Faria		
EERP	Ribeirão Preto		
EEX	Xitué		
PEA	Aguapeí	Integral Protection	State Park
PEC	Cantareira		
PECB	Carlos Botelho		
PECE	Campina Do Encantado		
PECJ	Campos Do Jordão		
PEI	Intervales		
PEITB	Itaberaba		
PEITG	Itapetinga		
PEJ	Jaraguá		
PEJU	Jurupará		
PEMCJ	Mananciais De Campos Do Jordão		
PEMD	Morro Do Diabo		
PEPF	Porto Ferreira		
PERP	Rio Do Peixe		
PETAR	Turístico Do Alto Ribeira		
PEV	Vassununga		
FEENA	Edmundo Navarro De Andrade	Sustainable Use	State Forest
FEG	Guarulhos		

Legend: State Park = IUCN Category II (National Park); Ecological Station = IUCN Category Ia (Strict Nature Reserve); and State Forest = Category VI (Protected Area with Sustainable Use of Natural Resources) (Dudley, 2008).
* SNUC stands for "National System of Nature Conservation Units", established by Federal Law nº 9985/2000.

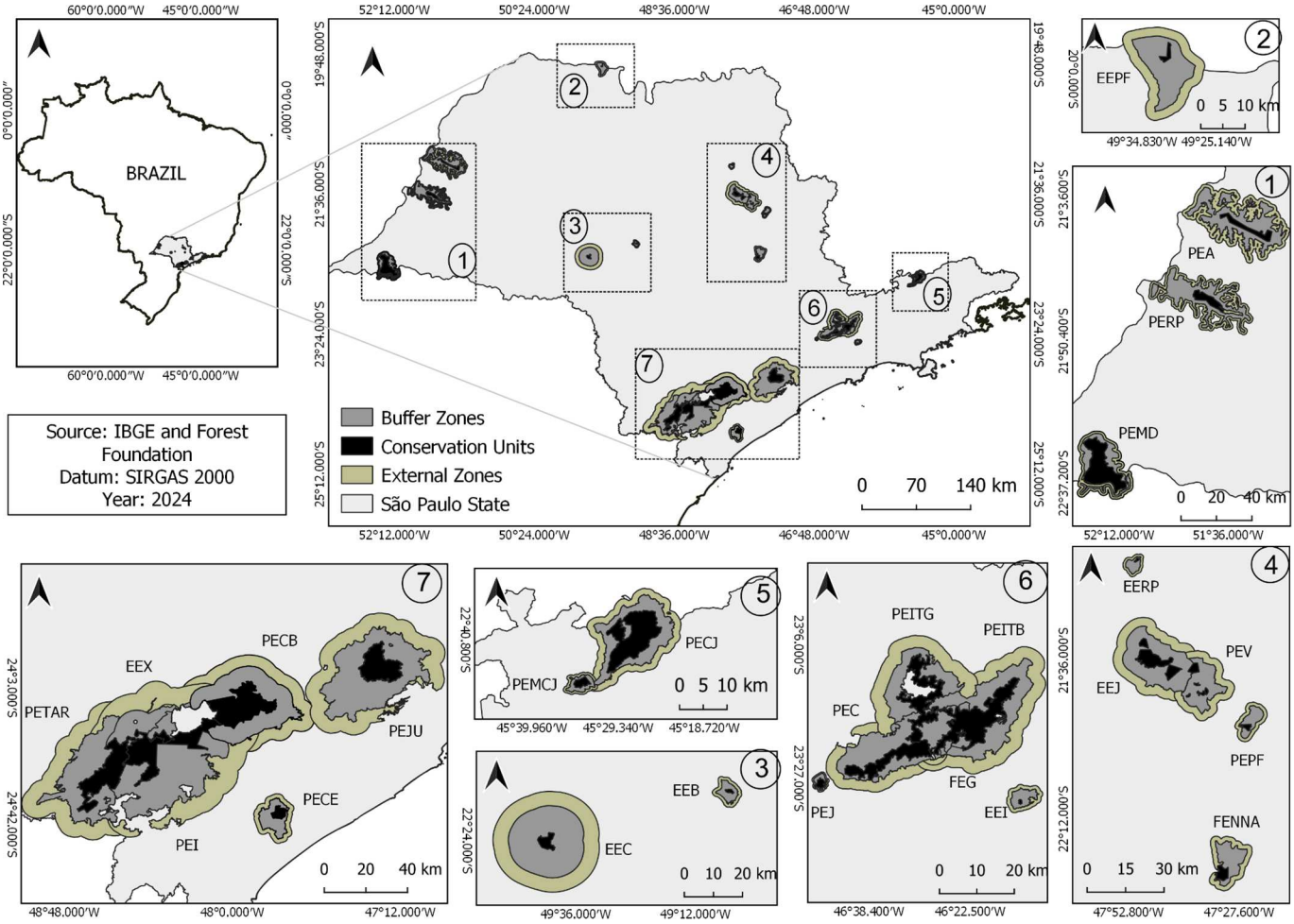


Figure 1
Location of the study area.

Units were excluded from the areas of the buffer zones and external zones. The boundaries of Indigenous Lands were obtained from the National Indigenous Peoples Foundation (FUNAI[1]); those of federal and municipal Conservation Units were obtained from the National Registry of Conservation Units (CNUC[2]); and those of state Conservation Units were obtained directly from the Forest Foundation.

2.2. Method

A temporal analysis was conducted for each Conservation Unit individually, aiming to assess the percentage of natural habitat within their respective buffer zones and external zones, considering two temporal benchmarks: the year in which the Conservation Unit was established and the year in which its current Management Plan was published. For this analysis, data from the Annual Land Use and Land Cover Mapping Project of Brazil (MapBiomas, 2024), Collection 8.0, were used. The original land use and land cover classes provided by MapBiomas were reclassified (Table 2). The reclassification processes and the extraction of areas by class were

1 Available at: https://www.gov.br/funai/pt-br/

2 Available at: https://cnuc.mma.gov.br/

Table 2 List of the original MapBiomas classes and the reclassified classes for this study.

New Classes	Original MapBiomas Classes
Natural Habitat	Forest Formation Savanna Formation Mangrove Floodable Forest Wooded Sandbank Vegetation Wetland Grassland Herbaceous Sandbank Vegetation
Natural non Forest Formation	Hypersaline Tidal Flat Rocky Outcrop Other non Forest Formations Beach, Dune and Sand Spot
Pasture	Pasture
Temporary Crops	Other Temporary Crops Cotton Rice
Soybean	Soybean
Sugarcane	Sugar cane
Perennial Crops	Other Perennial Crops Palm Oil
Coffee	Coffee
Citrus	Citrus
Forest Plantation	Forest Plantation
Mosaic of Uses	Mosaic of Uses
Non Vegetated Area	Other non Vegetated Areas
Urban Area	Urban Area
Mining	Mining
Water	River, Lake and Ocean
Aquaculture	Aquaculture

performed in ArcGIS Pro software, using the Reclassify (Spatial Analyst), Extract by Mask (Spatial Analyst) and Zonal Geometry as Table (Spatial Analyst) tools, supported by the arcpy and os Python packages. All data were organized and systematized in Microsoft Excel.

In this study, natural habitat was defined as the set of MapBiomas classes corresponding to remnants of natural vegetation formations native to the Atlantic Forest and Cerrado biomes, regardless of their conservation or restoration status. These classes were considered as natural habitats for native flora and fauna species. For fauna species, natural habitat can be defined as essential areas for shelter, food and reproduction. Thus, the loss or fragmentation of these habitats was interpreted as detrimental to the conservation of these species, while the matrix – although not necessarily

inhospitable to all species – was considered a selective filter, capable of restricting species mobility across the landscape.

Assessing landscape conditions was based on studies developed from the perspective of Landscape Ecology that identify critical habitat cover thresholds in the landscape associated with biodiversity conservation. Evidence indicates that below 10% habitat, the spatial configuration of fragments exerts little influence on the functional connectivity of the landscape, characterizing a negative scenario (Villard & Metzger, 2013). In landscapes with habitat cover between 20% and 33%, the minimum necessary for maintaining connectivity and supporting biodiversity can be observed (Fahrig, 2003; Banks-Leite et al., 2014). Above 60% habitat, the spatial configuration of fragments does not significantly interfere with connectivity, as predicted by percolation theory, configuring a positive scenario (Villard & Metzger, 2013). Based on these references, the values of 10%, 30%, and 60% natural habitat were adopted as critical thresholds in this study. Table 3 was developed based on these thresholds and served as the basis for classifying the condition of the analyzed landscapes. The percentage of natural habitat was calculated relative to the total area of each zone, considering all classes present in the landscape.

To analyze land use and land cover dynamics in the studied zones, transition matrices were constructed and Sankey diagrams were developed to identify and quantify the conversion flows between different classes over time. The generation of transition matrices was performed in ArcGIS Pro software, using the Combine (Spatial Analyst) and Tabulate Area (Spatial Analyst) tools. The Sankey diagrams were created in the Flourish platform, allowing for the graphical visualization of change flows between classes. All data were organized, systematized and analyzed in Microsoft Excel.

3. Results and Discussion

Among the Conservation Units analyzed, only one (EERP) exhibited a change in the landscape condition of the buffer zone over the study period. This indicates that, for most Conservation Units ($n = 24$), landscape condition in the buffer zones remained stable. Regarding the external zones, three (3) Conservation Units exhibited changes in landscape conditions (PECE, PEMD, and PEPF).

Table 3 Basis for the classification of landscape condition according to critical thresholds.

Critical Thresholds	Landscape Condition
Natural Habitat< 10%	Very Poor
10% < Natural Habitat < 30%	Poor
30% < Natural Habitat < 60%	Good
Natural Habitat > 60%	Excellent

Among the 24 Conservation Units that showed no changes in the landscape condition of the buffer zone, the following distribution was observed: seven (7) buffer zones classified as having excellent landscape conditions, seven (7) as good, nine (9) as poor, and one (1) as very poor. These results reveal that, although a significant portion of the buffer zones presents favorable conditions, a substantial proportion continues to experience conditions of concern, potentially compromising biodiversity conservation and the ecological functioning of the associated protected areas.

The comparison between landscape conditions in the buffer zones and external zones assessed whether buffer zones are fulfilling their expected role of mitigating anthropogenic impacts. In nine (9) cases (PEI, PETAR, PEJ, PEMD, PERP, EERP, FENNA, PEA, and PEPF), the buffer zone showed a superior landscape condition compared to its respective external zone. However, for most Conservation Units ($n = 16$), the landscape condition in the buffer zone was inferior to that of the external zone (EEX, PECB, PECJ, PEJU, PEMCJ, PECE, EEI, FEG, PEC, PEITB, PEITG, EEB, EEC, EEJ, PEV, and EEPF). This result partially contradicts the initial hypothesis of the study (i.e., that buffer zones would exhibit better landscape condition than their respective external zones) and suggests that the mere regulatory delimitation of these zones does not alone ensure better natural habitat conservation indicators. This finding converges with evidence widely documented in international literature, which points to the limitations and inefficiency in buffer zone management as a serious conservation challenge (e.g., Kintz et al., 2006; Terra et al., 2014; Amaral et al., 2019; Oliveira et al., 2020; Almeida-Rocha & Peres, 2021).

In all cases classified as counterintuitive, except for PECE – in which the external zone condition proved superior to that of the buffer zone – it was observed that both zones exhibited the same landscape condition. This pattern suggests that there were no significant differences in habitat percentages between the zones, considering the landscape thresholds adopted as reference (10%, 30%, and 60% natural habitat). These findings converge with the conclusions of Almeida-Rocha and Peres (2021), which demonstrate that the general state of buffer zones of protected areas in Brazil does not differ substantially from adjacent landscapes under unrestricted land use. It is important to note that in that study, the analyses were conducted based on the definition of a fixed radius of 3 km for all buffer zones.

All data concerning the landscape condition of the buffer zones and external zones analyzed in this article can be viewed in their entirety in Supplementary material A.

The detailed analysis presented in Supplementary material A identifies the Conservation Units in which changes in landscape condition occurred over the investigated period, specifically in the PECE, PEMD, and PEPF external zones, and in the EERP buffer zone. The temporal changes recorded were distributed as follows: in the external zone of PECE, between

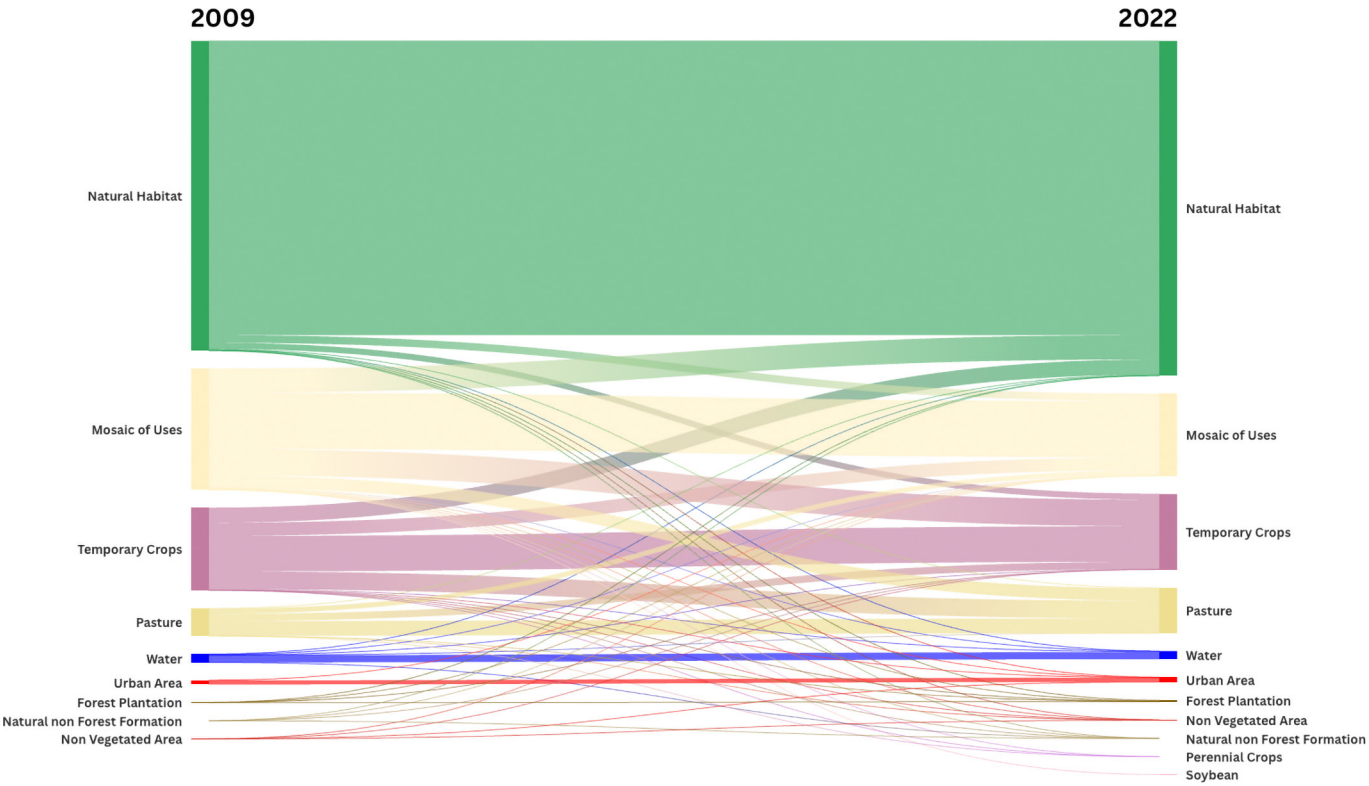
the publication of the management plan (2009) and 2022; in the external zone of PEMD, between 1985 and the publication of the management plan (2006); in the external zone of PEPF, in the intervals 1985–2006 (publication of the management plan) and 2006 (publication of the management plan)–2022; and, finally, in the buffer zone of EERP, between 1985–2011 (publication of the management plan) and 2011 (publication of the management plan)–2022.

Figure 2 illustrates the dynamics of land use and land cover transitions in the external zone of PECE between 2009 (publication of the management plan) and 2022. During this period, natural habitat losses totaled 444.3 ha, resulting mainly from conversion to Mosaic of Uses ($n = 216.3$ ha; 48.7%) and Temporary Crops ($n = 173.4$ ha; 39.0%). Conversions to Pasture ($n = 25.6$ ha; 5.8%) and Forest Plantation ($n = 25.6$ ha; 5.8%) also contributed to the reduction of natural habitat, while the remaining classes accounted for a residual loss of 3.6 ha (0.8%).

In contrast, natural habitat gains in the same period and area reached 1,163.4 ha, largely exceeding the recorded losses. Most of this gain resulted from the conversion of areas classified as Mosaic of Uses ($n = 696.3$ ha; 59.8%) and Temporary Crops ($n = 436.0$ ha; 37.5%). The remaining classes together contributed 16.5 ha (1.4%) to the total gain.

The changes identified in the PECE external zone resulted in a final positive balance, with natural habitat gains exceeding losses. However, both losses and gains occurred mainly through the conversion of agricultural and livestock land uses. This pattern suggests that the local agricultural and livestock matrix acts as both a driver of suppression and as a driver of recovery.

Figure 2
Sankey Diagram – External Zone of PECE (2009–2022).



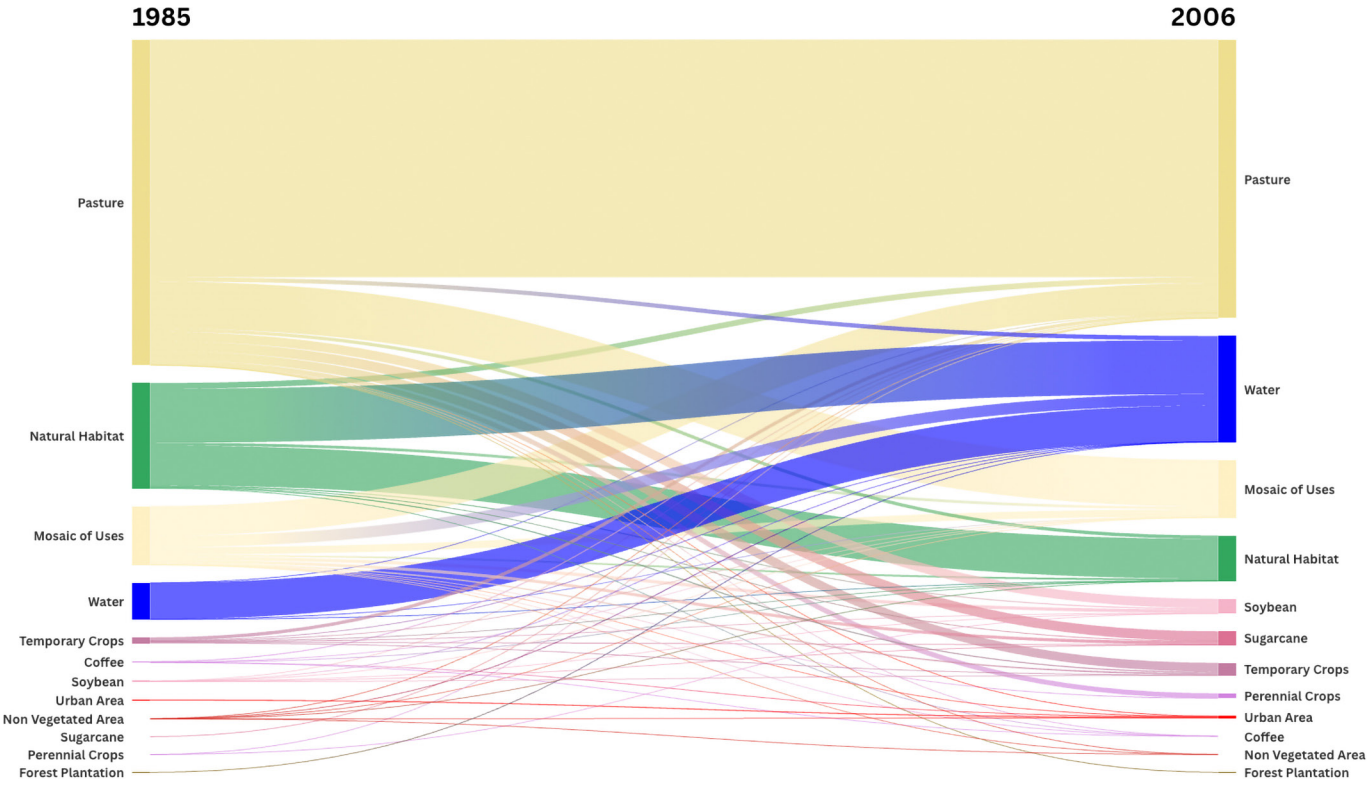
Consequently, the quantitative improvement in natural habitat cover in this zone may not necessarily imply an advance in the ecological quality of the landscape, as gains derived from the conversion of Mosaic of Uses and/or Temporary Crops may reflect secondary regeneration with limited ecological functionality. Nevertheless, it can be stated that the PECE case constitutes an example of counterintuitive behavior, as the external zone, with its changes, ultimately exhibited a better landscape condition than the buffer zone (Supplementary material A). Detailed data on land use and land cover transitions in the external zone of PECE are presented in Supplementary material B of this article.

Figure 3 illustrates the dynamics of land use and land cover transitions in the external zone of PEMD between 1985 and 2006 (publication of the Management Plan). During this period, natural habitat losses totaled 3,260.0 ha, resulting mainly from conversion to Water ($n = 2{,}681.3$ ha; 82.2%). Conversions to Pasture ($n = 286.4$ ha; 8.8%) and Mosaic of Uses ($n = 136.9$ ha; 4.2%) also contributed to the reduction of natural habitat, while the remaining classes accounted for a residual loss of 82.2 ha (2.5%).

Conversely, natural habitat gains in the same period and area reached 292.3 ha, numerically much lower than the recorded losses. Most of this gain resulted from the conversion of areas classified as Pasture ($n = 165.8$ ha; 56.7%) and Mosaic of Uses ($n = 99.8$ ha; 34.1%). The remaining classes together contributed 26.7 ha (9.1%) to the total gain.

The changes identified in the PEMD external zone resulted in a final negative balance, with natural habitat losses exceeding gains. The gains in this case are also mostly associated with classes of agricultural and live-

Figure 3
Sankey Diagram – External Zone of PEMD (1985-2006).

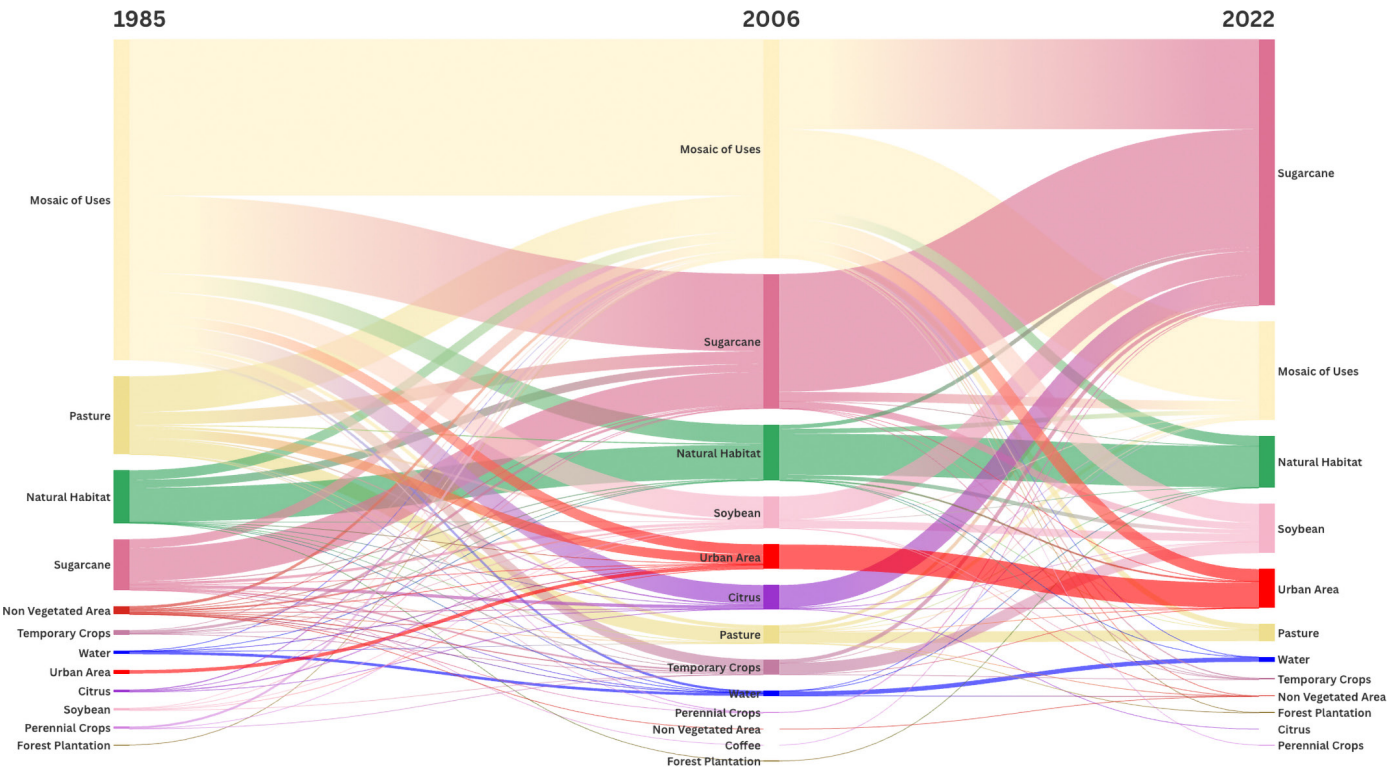


stock origin. This fact raises the same questions presented in the case of the PECE external zone regarding the ecological quality of this landscape. The intriguing aspect in this case lies in the fact that natural habitat losses are almost exclusively associated with conversion to Water, although there is also a smaller representation of conversion to Pasture and Mosaic of Uses. This can be explained by the construction of the Rosana Hydroelectric Power Plant dam, the closest to the mouth of the Paranapanema River (Fundação para a Conservação e a Produção Florestal do Estado de São Paulo [Fundação Florestal], 2006). The negative changes in the PEMD external zone make this case an example of expected behavior, as the buffer zone exhibited a better landscape condition than the external zone (Supplementary material A). Detailed data on land use and land cover transitions in the PEMD external zone are presented in Supplementary material C of this article.

Figure 4 illustrates the dynamics of land use and land cover transitions in the PEPF external zone between 1985 and 2006 (publication of the Management Plan), and between 2006 and 2022. In the first period, natural habitat losses totaled 212.0 ha, resulting mainly from conversion to Mosaic of Uses ($n = 107.3$ ha; 50.6%) and Sugarcane ($n = 90.1$ ha; 42.5%). The remaining classes accounted for a residual loss of 14.8 ha (7.0%).

Conversely, natural habitat gains in the same period and area reached 244.6 ha, a value higher than the losses, although numerically very close. Most of this gain resulted from the conversion of areas classified as Mosaic of Uses ($n = 208.2$ ha; 85.1%). The remaining classes together contributed 36.5 ha (14.9%) to the total gain.

Figure 4
Sankey Diagram – External Zone of PEPF (1985-2006-2022).



Although gain and loss values were close, the changes identified in the PEPF external zone resulted in a positive balance in the first analyzed period. However, the gains presented mainly derive from the agricultural and livestock sector, which makes this case similar to those previously evaluated.

In the subsequent period, natural habitat losses totaled 164.3 ha, resulting mainly from conversion to Mosaic of Uses (n = 53.2 ha; 32.4%), Sugarcane (n = 44.5 ha; 27.1%), Soybean (n = 44.5 ha; 27.1%), and Urbanized Area (n = 19.9 ha; 12.1%). In turn, natural habitat gains in this same period and area reached 122.9 ha, numerically lower than the losses, although still close. Most of this gain resulted from the conversion of areas classified as Mosaic of Uses (n = 114.4 ha; 93.1%).

Although total loss and gain values remained close in this second analysis period, it can be perceived that the pressures exerted by the expansion of Sugarcane, Mosaic of Uses, Soybean, and Urbanized Area stood out in the PEPF external zone and drove natural habitat losses in the area. These changes were sufficient to negatively impact the condition of this landscape, resulting in a return to the worst scenario regarding the percentage of natural habitat (<10%).

The expansion of Sugarcane in the landscape is evident and is not restricted to the conversion of natural habitat areas, also encompassing the replacement of other land uses, such as Mosaic of Uses, Soybean, and Citrus. This fact reinforces the agricultural and livestock sector as a major driver of environmental transformation. A new element in this case is urban expansion acting as a significant driver of landscape change, mainly associated with natural habitat losses.

Despite the variations observed in the landscape condition in the PEPF external zone, the buffer zone remained stable throughout the entire analyzed period. This behavior suggests that the PEPF buffer zone exhibited relative resilience to land use and land cover dynamics recorded in the external zone, indicating performance consistent with the expected function for this area (i.e., expected behavior) (Supplementary material A). However, it should be noted that the percentage of natural habitat in the landscape remains below levels considered ideal for biodiversity conservation, which reveals limitations in the ecological quality surrounding PEPF. Detailed data on land use and land cover transitions in the PEPF external zone are presented in Supplementary material D and Supplementary material E of this article.

Finally, Figure 5 illustrates the dynamics of land use and land cover transitions in the EERP buffer zone between 1985 and 2011 (publication of the Management Plan), and between 2011 and 2022. This was the only studied case with changes in the landscape condition in a buffer zone.

In the first period, natural habitat losses totaled 117.2 ha, resulting mainly from conversion to Sugarcane (n = 56.7 ha; 48.4%) and Mosaic of

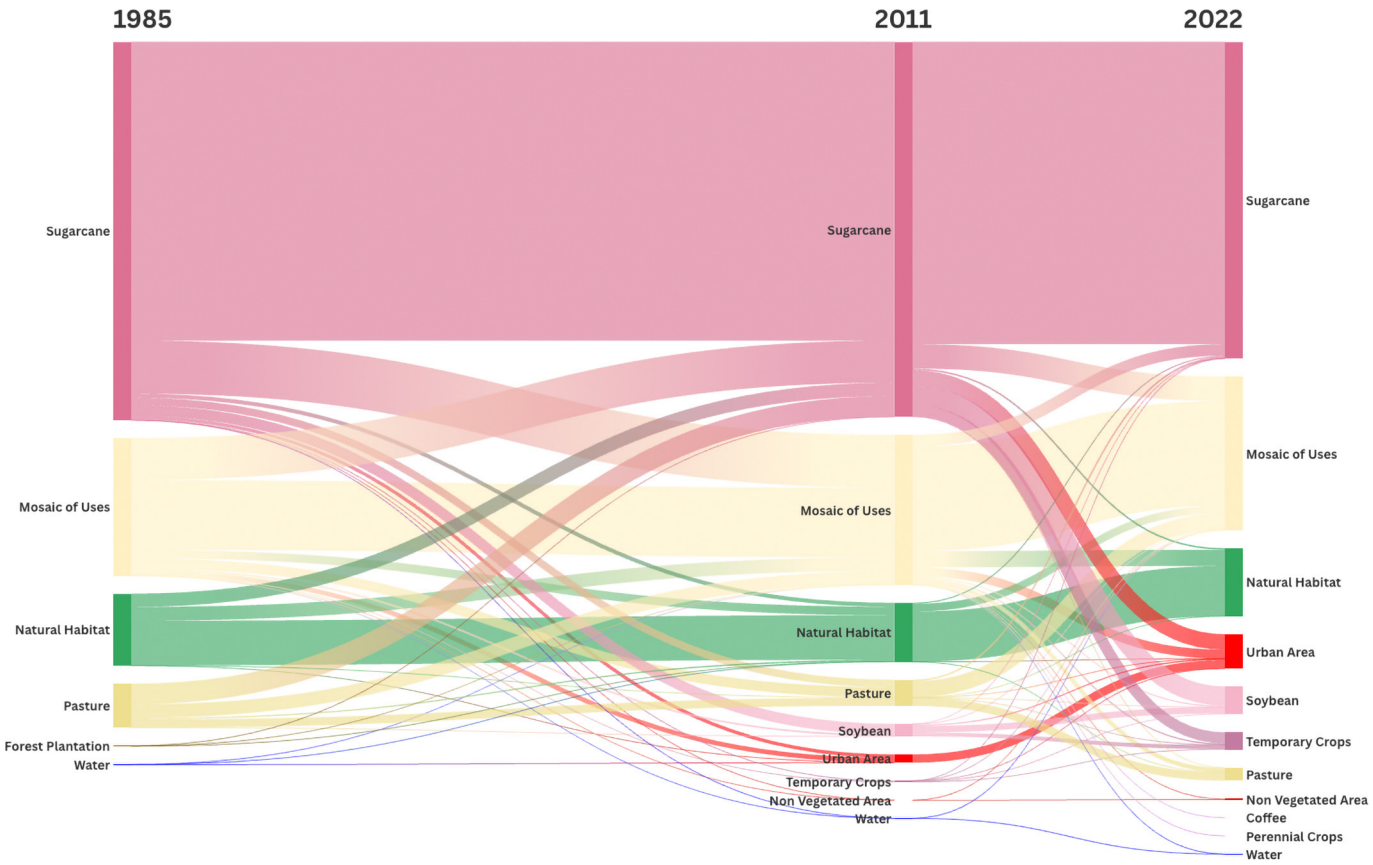


Figure 5

Sankey Diagram – Buffer Zone of EERP (1985-2011-2022).

Uses (n = 58.4 ha; 49.8%). The remaining classes accounted for a residual loss of 2.1 ha (1.8%).

Conversely, natural habitat gains in the same period and area reached 61.4 ha, which represents approximately half of the recorded losses. Most of this gain resulted from the conversion of areas classified as Mosaic of Uses (n = 35.8 ha; 58.3%) and Sugarcane (n = 17.1 ha; 27.8%). The remaining classes together contributed 8.4 ha (13.7%) to the total gain.

The changes observed in the EERP buffer zone resulted in a negative balance in the first analyzed period, as natural habitat losses were approximately double the recorded gains. Both losses and gains resulted predominantly from direct conversions involving classes associated with the agricultural and livestock sector, showing the influence of this activity on land use and land cover dynamics surrounding EERP.

In the subsequent period, a reversal of the balance was observed, with natural habitat gain (76.6 ha) approximately twice as high as losses (37.8 ha). Almost all gains resulted from the conversion of areas classified as Mosaic of Uses (n = 69.1 ha; 90.2%), followed by Sugarcane (n = 7.1 ha; 9.3%) and, residually, Pasture (n = 0.4 ha; 0.5%). Similarly, natural habitat losses were concentrated mainly in conversion to Mosaic of Uses (n = 32.7 ha; 86.5%) and Sugarcane (n = 4.8 ha; 12.7%). These results show evidence of the strong interaction between agricultural and livestock dynamics and the recomposition or suppression of natural habitat, indicating that the same

productive classes act simultaneously as drivers of conversion and reconversion of natural cover.

Due to the geographic proximity between the two Conservation Units (PEPF and EERP), both located in the interior of the state of São Paulo, similar territorial characteristics can be observed. Both areas are marked by the strong influence of the agricultural and livestock matrix in their surroundings, focusing on sugarcane expansion as the main driver of landscape transformation. Although urban expansion did not constitute a predominant driving force of natural habitat losses in the analyzed periods, its growing presence in the landscape reinforces the complexity of anthropogenic pressures affecting the Conservation Unit. Currently, EERP is practically embedded in the urban fabric of the municipality of Ribeirão Preto, a condition that intensifies the challenges related to the conservation and territorial management of its surroundings.

The fact that natural habitat gains in this case were also associated with classes of agricultural and livestock origin reinforces uncertainties regarding the ecological quality of the landscape. However, it can be stated that the EERP case constitutes an example of expected behavior, as the buffer zone, as well as its changes, ultimately exhibited a better landscape condition than the external zone (Supplementary material A). However, it should be noted that the percentage of natural habitat in the landscape remains below levels considered ideal for biodiversity conservation. Detailed data on land use and land cover transitions in the buffer zone of EERP are presented in Supplementary material F and Supplementary material G of this article.

This study analyzed natural habitat changes in the buffer zones and external zones of Conservation Units in the state of São Paulo (Brazil), over an extended temporal period (1985–2022). In general, the most significant transformations in landscape conditions were associated with the expansion of agriculture and livestock, focusing on sugarcane, as observed in the cases of PEPF and EERP. The prominence of this crop in regional territorial dynamics is not coincidental: the state of São Paulo concentrates approximately 50% of the harvested area of sugarcane in Brazil and leads the sector's exports, having reached a volume of 105.6 million tons in the last seven years (União da Indústria de Cana-de-Açúcar e Bioenergia [UNICA], 2023). This context indicates a strong integration of São Paulo's economy into the national and international chains of the sugar-energy sector and helps explain the intensity of the transformations observed surrounding the analyzed protected areas.

The conversion of forest areas into agricultural uses constitutes one of the main proximate drivers of deforestation (Geist & Lambin, 2002) and raises concern regarding the increasing pressure exerted on protected areas and their surroundings, with potential implications for biodiversity conservation (Rafaai et al., 2020). This process, however, is not limited

to localized land use decisions, and is often driven by synergies among economic, institutional, and political factors operating at different scales (Geist & Lambin, 2002). The Ecological-Economic Zoning of the state of São Paulo (*Decreto nº 67.430*, 2022) confirms that the central regions of the state are characterized by the strong integration between agricultural and livestock production and industrial activity, especially linked to the sugarcane chain. Considering the results presented here, it can be observed that this regional productive configuration has direct repercussions on the landscapes surrounding Conservation Units, indicating the need for greater coordination between regional development policies and environmental conservation strategies.

It is important to emphasize that the results found in this article reflect the reality of the studied cases, and generalization to all buffer zones in the country is not appropriate. Geist and Lambin (2002) argue that evidence from case studies indicates that no universal policy can effectively address tropical deforestation across all contexts. The authors assert the need for a detailed understanding of the complex set of proximate causes and underlying driving forces affecting forest cover changes in a given location prior to any policy intervention. This reinforces the importance of studies such as this one to support more assertive decisions by decision-makers in the management of protected areas and their surroundings.

Although the present study contributes by providing initial insights into the formulation of strategic actions aimed at managing protected areas and their surroundings, it does not exhaust the analytical and instrumental possibilities necessary for deepening the understanding of specific contexts and improving the governance of these areas. Future investigations could further explore the application of economic instruments in buffer zones, as well as the incorporation of Strategic Environmental Assessment into the development of Conservation Unit Management Plans and municipal Master Plans. In this regard, Lima and Ranieri (2018) highlight the persistent lack of integration among these territorial management instruments, underscoring the complexity and adverse implications of this disconnect for buffer zone management effectiveness.

4. Conclusions

The results of this study indicate that almost all Conservation Units, except for the Ribeirão Preto Ecological Station (EERP), present no changes in landscape condition regarding the percentage of natural habitat in their buffer zones between 1985 and 2022. This finding partially refutes an initial hypothesis of the study, which predicted an improvement in the landscape condition of buffer zones over the analyzed period. Although positive changes were recorded between 2011 (publication of the Management Plan) and 2022 in the buffer zone of the Ribeirão Preto Ecological Station,

this constituted the only case of detected variation. Regarding the external zones, three Conservation Units (Campina do Encantado State Park – PECE, Morro do Diabo State Park – PEMD, and Porto Ferreira State Park – PEPF) presented changes in the landscape condition within the same temporal interval. The comparison between the two zones showed that, in most cases ($n = 16$; 64%), the buffer zones exhibited landscape conditions equal to or inferior to their respective external zones. This result contradicts the expected outcome for these zones and partially refutes the other initial hypothesis of the study, which predicted a better landscape condition in the buffer zones.

In general, the transformations observed in the buffer zones and external zones were predominantly associated with the expansion of agriculture and livestock, focusing on sugarcane, as observed in the cases of Porto Ferreira State Park and the Ribeirão Preto Ecological Station. The results indicate that the regional productive configuration has direct repercussions on the landscapes surrounding the Conservation Units, indicating the need for greater coordination between regional development policies and environmental conservation strategies. Furthermore, they underscore the importance for greater integration between buffer zone management and Conservation Unit management to enhance the consistency and effectiveness of biodiversity conservation efforts. It is expected that the evidence presented here will support decision-makers and policymakers in developing and implementing targeted measures to address the vulnerabilities identified around Conservation Units.

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