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Conservation and restoration of riparian zones: impacts of legal and land use changes

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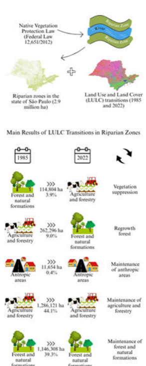
HIGHLIGHTS

- Designing legal amendments to reduce long-term conflicts and environmental impact.
- Using spatial analysis to reveal the state of native vegetation can improve land management.
- Optimization of environmental legal analyses through GIS tools.

GRAPHICAL ABSTRACT



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ABSTRACT

Riparian vegetation plays a key role in maintaining biodiversity and ecosystem services, and in Brazil it is legally protected as Permanent Preservation Areas (PPA) under the Native Vegetation Protection Law (Law 12,651/2012). However, the definition of riparian PPA widths has changed over time, creating challenges for environmental management and regularization. In this study, we analyzed land use and land cover dynamics in riparian PPA of São Paulo State, Brazil, comparing conditions in 1985, under the 1965 Forest Code (Law 4,771/1965), and in 2022, under the current legislation. We assessed the effects of legal changes, land use transitions, and the principle of temporality applied by the state environmental agency, which allows regularization of anthropic uses established before 1986. We used geoprocessing and spatial statistics to identify land use dynamics and clusters of maintenance, suppression, and regeneration of native vegetation in PPAs. In 1985, agriculture and forestry dominated these PPA areas (54%), while in 2022 forest and natural formations became

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predominant (49%). The most relevant land use transition was the regeneration of native vegetation from pastures, totaling 262,297 ha. Anthropic areas increased by 113%, concentrated in the São Paulo metropolitan region. Of these, 11,654 ha (0.4% of total PPA) were already occupied in 1985 and may be considered regular under the temporality principle (i.e. not in conflict with legislation). Our results suggests that legal expansion of PPA widths after 1986 contributed to natural regeneration, particularly in southern and northeastern regions of the state, but agricultural uses remain the main drivers of riparian degradation. The integration of geospatial analyses with legal frameworks offers critical support for management, enforcement, and the design of incentive-based policies to promote restoration beyond minimum legal requirements.

Introduction

Riparian vegetation promotes connectivity between patches, enabling the gene flow of fauna and flora, and are central to the preservation of species (Arroyo-Rodriguez et al., 2020). The maintenance and ecological restoration of riparian forests in anthropic landscapes presents multiple benefits for biodiversity and provision of ecosystem services (Mello et al., 2020). The preservation and restoration of forest vegetation along rivers, as well as in the headwaters of river basins, favors the control of erosion and reduction of surface runoff, promoting the infiltration of water into the soil (Veiga et al., 2019; Fritzsons and Mantovani, 2021). Riparian areas therefore deserve special attention in ecological restoration programs at the landscape level (Meli et al., 2019).

In Brazil, riparian areas are targets of special protection by the Native Vegetation Protection Law (NVPL), Federal Law 12,651 (Brasil, 2012). This law, approved in 2012, establishes categories of specially protected areas in the country's private properties, such as the Permanent Preservation Areas (PPA). These areas present restricted occupation, applicable to both urban and rural properties, and established in a variable range along rivers, around springs, lakes or water reservoirs, in areas of high slope, among other fragile areas (Brasil, 2012). PPA must be maintained with native vegetation, and intervention in a PPA is exceptionally permitted in cases of public utility, social interest, or low environmental impact (Brasil, 2012). In the case of riparian PPA associated with water bodies, the NVPL defines a variable range of protection, established depending on the width of the watercourse, with the greater the width of the water body, the greater the range protected as permanent preservation.

Despite the need to keep PPA effectively protected for the adequate performance of their environmental functions, there are situations in which the owner is entitled to fail to promote the restoration of these spaces. In urban areas, riparian PPA are often degraded and occupied by consolidated structures. According to Santos Junior et al. (2022), 121,000 hectares of Brazilian urbanized PPA were occupied by edifications in 2020, which corresponds to 29% of total urbanized PPA in the country. These occupations, which in addition to being difficult to reverse, may be subject to regularization. This is because the protection dimensions associated with PPA have been modified over the years since the publication of the first Forest Code in 1934, through the 1965 Forest Code, which had several significant changes until its repeal with the publication of the current version of the legislation given by Law 12,651/2012 (Valera et al., 2019).

In this history, from 1965, the year of publication of the Forest Code through Law 4,771, until the change made by the publication of Federal Law 7,511 on July 7, 1986, the PPA of watercourses were defined in a range 5 meters wide for watercourses up to 10 meters wide; and in a strip equivalent to half the width of the water body for rivers more than 10 meters wide. Furthermore, Law 4,771/1965 did not delimit any protective strip around springs or water reservoirs, and only protected flora, that is, strips not occupied by native vegetation were not protected (Brasil, 1965; Azevedo and Oliveira, 2014). In 1986, the Forest Code underwent changes regarding the delimitation of riparian PPA. CONAMA Resolution 004/1985 established 50-meter PPA around springs, and established a 30-meter wide PPA strip for water reservoirs/lakes in urban areas and 100 meters for impoundments in rural areas. In July 1986, Federal Law 7,511 was published, which changed the PPA ranges from 5 to 30 meters for watercourses up to 10 meters wide, and established variable PPA ranges from 50 to 200 meters wide, according to the width of the water body. The sizes of riparian PPA in each historical period and according to each legal diploma are presented in a Table in Supplementary Material (Table S1).

In rural properties, the most important device in the sense of reducing the restoration of these spaces is article 61-A of the NVPL, which allows the recognition and maintenance of existing agro-silvopastoral systems in PPA until 06/22/2008, with the counterpart of restoration of a portion of these protected area (Brasil, 2012; Brancalion et al., 2016). Guidotti et al. (2017) reported that these modifications reduced the protection. Such a reduction in the ecological restoration range may increase sediment input, as riparian forest structure, canopy cover, and age are closely linked to the hydrochemical and biological conditions of tropical streams (Ogasawara et al., 2025). Overall, river basins dominated by agricultural land use, including in PPAs, tend to exhibit lower physical-chemical water quality indicators and changes in channels geomorphology compared to basins with a higher proportion of native forests (Hepp and Pastore, 2020; França et al., 2023). Even with the adoption of good agricultural practices, such as no-tillage, crop rotation, water detention ponds, and terrace, their effectiveness in maintaining water quality is lower than that of forest maintenance or restoration in an adequate width, as riparian buffers narrower than 8 meters can act as sources of sediments instead of barriers (Guidotti et al., 2020).

Changes in the delimitation of riparian PPAs, as well as in the interpretation and application of the law, have significantly affected environmental management and licensing at the state level (Borges et al., 2011; Garrastazú et al., 2015). Monitoring these areas is challenging due to legal complexity and geographic dispersion, given that 58% of São Paulo's fluvial system consists of first-order streams spread across the state (Taniwaki et al., 2018). Geospatial analysis can be used to track land use changes, detect irregularities, assess compliance with environmental law and support territorial management, such as forest restoration (Almeida et al., 2025; Majumdar and Avishek, 2023; Issii et al., 2024).

In the State of São Paulo, the Environmental Company of the State of São Paulo – CETESB, the agency responsible for environmental management and licensing, uses the principle of temporality in evaluating occupations and uses of PPA that cannot be classified as being of public utility or social interest, or low environmental impact, and which, therefore, are at odds with current legislation (Braz et al., 2025). Based on temporality, anthropic occupations carried out until 1986 in the areas that are now PPA are considered regular, as long as the PPA in force at the time of its implementation is respected. In this case, the occupations are subject to continuity, with the owners having the right to use (Gavioli and Hossomi, 2020).

In this scenario, estimates of degraded riparian PPAs may be influenced by the application of the principle of temporality, particularly in highly urbanized regions such as São Paulo State, where most of its 645 municipalities have outstanding debts in preserving riparian vegetation (Murakami et al., 2023). We hypothesize that changes in environmental legislation can promote an increase in forest cover within protected areas. Additionally, we hypothesize that anthropogenic areas eligible for regularization under the principle of temporality are spatially isolated and do not extend continuously along PPAs, representing a minor proportion of the total PPAs area. This study aimed to analyze the panorama of riparian PPAs in São Paulo in 1985 and 2022, characterizing the predominant land use and occupation within these protected areas, as well as the processes of ecological restoration and suppression of native vegetation that occurred over this period, based on the PPA delimitation criteria established by the NVPL. Since the time series begins in 1985, the study also provided, for the first time, an estimate of the extent of PPAs occupied by anthropogenic uses under the framework of Law 4, 771/1965, prior to the 1986 amendments, that remain in this condition until 2022, and which could therefore be subject to regularization under the principle of temporality adopted by CETESB.

Methods

Study region

The study was carried out in the Permanent Preservation Areas of São Paulo state, Brazil (Fig. 1). São Paulo state encompasses an area of 24.6 million hectares, and population of 45 million people, being the most populous and urbanized Brazilian state. Divided into 645 municipalities, the state had the largest domestic product in Brazil (Seade, 2023).

Amid high population density and economic dynamism, São Paulo is located in two relevant tropical biomes, considered global biodiversity hotspots (Myers et al., 2000): the Atlantic Forest and Cerrado, biomes that are threatened by the fragmentation, and their replacement by agricultural uses or urbanization (Strassburg et al., 2017; Lira et al., 2021). Despite the situation of general degradation in both biomes, recent studies indicate a net increase in native vegetation in the state, especially due to the intensification of agriculture and abandonment of areas that are unsuitable to agriculture (Calaboni et al., 2018). These areas include places close to riparian zones, where natural regeneration of forests is more likely to occur (Molin et al., 2018).

Databases

The land cover data were obtained from the database provided by MapBiomas (MapBiomas, 2022), which is an interinstitutional initiative that has been annually mapping changes in land use and cover throughout the Brazilian territory, from 1985 to the present day. The mapping is carried out using images from the Landsat series, with a spatial resolution of 30 meters, and includes various classes of land use and cover (Souza et al., 2020). For the present study, the raster files referring to the mapping of land use and cover in the state of São Paulo for the years 1985 and 2022 were used, as well as the raster file referring to the transitions observed between 1985 and 2022 in the state, both from the MapBiomas 8.0 collection. The final year in the analysis was chosen because it was the final year available in the 8.0 collection used in our study.

The PPA were obtained from the High Resolution Mapping Project of Brazilian biomes, provided by the Brazilian Foundation for Sustainable Development (FBDS). This database mapped hydrography in all Brazilian municipalities using images from the RapidEye satellite from 2013 and with a spatial resolution of 5.0 meters. The project's vector files were made available to the public in 2018, at a scale of 1:25,000 (Rezende et al., 2018; FBDS, 2018). For the present study, vector files of riparian PPA existing in all municipalities in São Paulo were used.

Data analyses

The 27 land use and cover classes that occurred in the São Paulo state

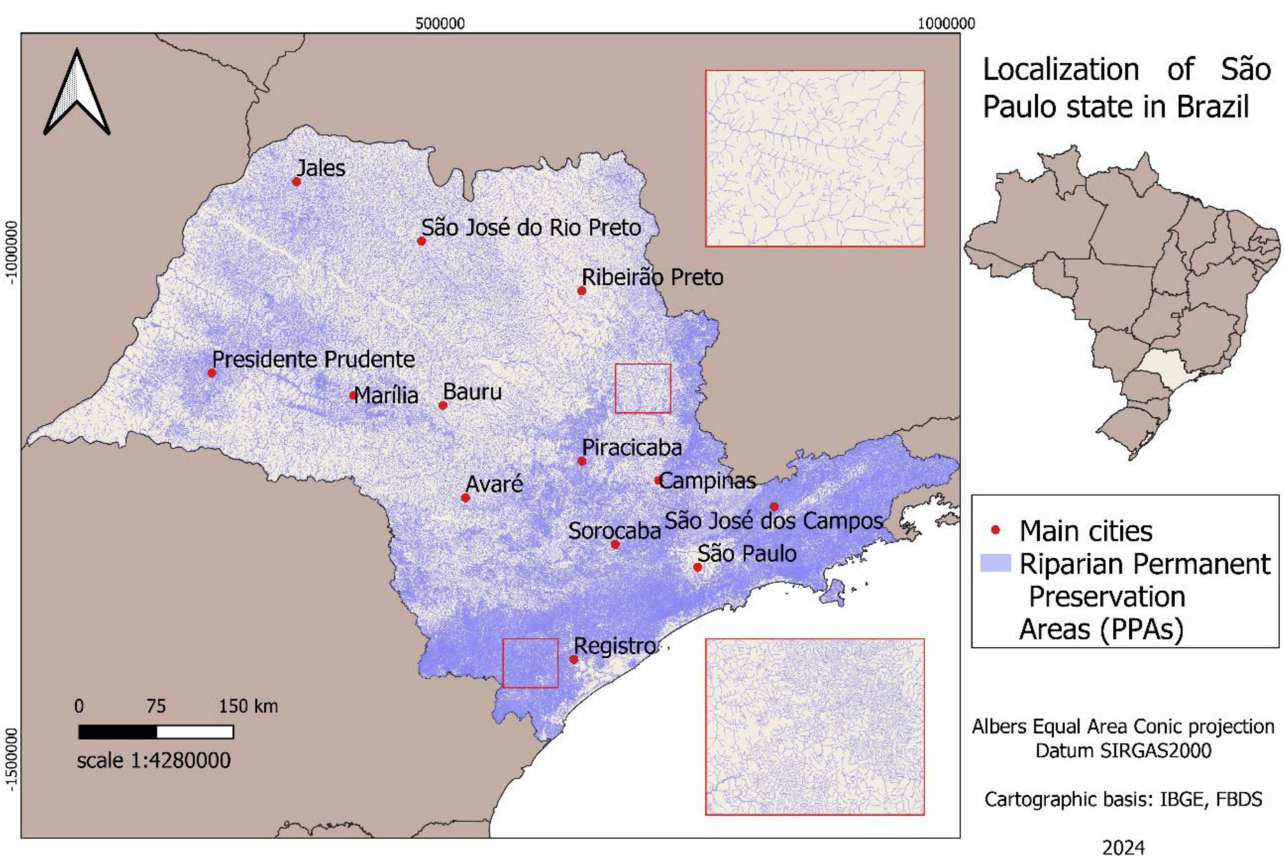

Fig. 1. Sao Paulo State (Brazil), its main cities, and riparian Permanent Preservation Areas (PPA).

were regrouped into four classes of interest: (i) forest and natural formations, (ii) agriculture and forestry, (iii) anthropic areas, which include predominantly urban areas and mining, and (iv) rivers and lakes (Table S2). Note that Mapbiomas products are annual land use and land cover maps, and combine images from both dry and rainy seasons, which may influence the total area classified as water. To address this variation, the median value of each spectral band for each pixel within a given year is calculated and subsequently used for land use and land cover classification (MapBiomas Project, 2025). Then, these rasters were vectorized, merged, and intersected with the PPA vector files using the ArcGis software. This process produced shapefiles of land use and land cover within riparian PPAs, following the measurements defined by the NPVL, for the state of São Paulo in 1985 and 2022, as well as the transitions between different classes over this period, following the methodology proposed by Gavioli and Hossomi (2020). Finally, the shapefiles were redesigned for Albers's conical equivalent projection in SIRGAS2000 datum, a projection recommended for calculating areas over large territorial extensions, as those encompassed by our study (IBGE, 2021).

For the purposes of this study, anthropogenic uses considered eligible for regularization under the principle of temporality include urban uses and infrastructure, mining, non-vegetated areas (earthmoved areas and bare soil), and aquaculture infrastructure, excluding agricultural and forestry uses, in accordance with procedures adopted by CETESB (CETESB, 2024). Therefore, PPAs that were under these anthropogenic use in 1985 and remained so in 2022 were considered the universe eligible for regularization from the perspective of temporality.

We used the Univariate Local Moran's I (Anselin et al., 2006) for spatial analysis of land use and cover changes, defining cluster of occurrences of maintenance of anthropic uses, maintenance of native vegetation, regeneration of native vegetation, and suppression of native vegetation in PPA, per municipality between 1985 and 2022. Univariate Local Moran's I is a measure of spatial autocorrelation, designed to measure the difference between the values of a given attribute, associated with spatial location (Luzardo et al., 2017). As a result, the application of Moran's I generates a map of statistically significant clusters, which can be of four types (i) high-high (HH), composed of polygons with high values of the attribute under analysis surrounded of polygons also with high values of the same attribute, which constitutes a hotspot; (ii) low-low (LL), that is, composed of polygons with reduced values of the attribute under analysis, surrounded by polygons also with reduced values of the same attribute, configuring a coldspot for the attribute in question; (iii) high-low (HL) or (iv) low-high (LH), respectively indicating a polygon with a high or reduced value of the attribute surrounded by polygons with a reduced or high value of the same attribute, which configures clusters of extreme values (outliers) (Luzardo et al., 2017). We performed the Moran's I analysis using GeoDa software (Anselin et al., 2006).

Finally, we sought to understand the factors that may or may not influence the spatial clustering of four land-use and land-cover change patterns in PPAs: maintenance of anthropic uses; maintenance of native vegetation; regeneration of native vegetation; and suppression of native vegetation. We fitted Spatial Autoregressive Models (SAR) and Spatial Error Models (SEM) for each occurrence type and compared them using the Akaike Information Criterion (AIC). We employed 15 explanatory variables and examined the regression coefficients for each variable. We also performed variance partitioning, which enabled us to understand how each type of occurrence clustering was influenced by the measured variables versus the extent to which it was driven by intrinsic spatial distribution patterns. Further details of these analyses can be consulted in the Supplementary Material.

Results

The state of São Paulo has about 2.9 million hectares of riparian PPA delimited as established in the Law 12,651/2012, which corresponds to 11.78% of the state territory (Table 1). Agriculture and forestry was the predominant land use group in 1985, with 1.5 million hectares, or 53.95% of the PPA. On the other hand, the predominant use in 2022 was the forest and natural formations, with 1.4 million hectares, or 48.83% of the PPA. The anthropic areas had an increase between 1985 and 2022, passing from 15,950 hectares (0.55% of PPA) to 34,034 hectares (1.17% of PPA), or an increase of 113.37%. Meanwhile, the rivers and lakes coverage had a relevant decrease of about 38%, with a loss of about 23,567 hectares of water surface. The maps of PPA land use and coverage for the whole São Paulo state in 1985 and 2022 are presented in Figures S1 and S2.

Within each group, we observed different dynamics of the land use and cover classes. In forest and natural formations, the most relevant increases occurred in grassland formations, mangroves, wetlands, and forest formations. In the agriculture and forestry group, the mosaic of agriculture and pasture was the most relevant land use class in both analyzed years, presenting an increase of 4.58% over time. Pastures were the only land use class in the agriculture and forestry group that had a decrease, which means this land use led the overall decrease observed in this group. In the anthropic areas group, we only observed a decrease in other non-vegetated land uses, with urban areas, mining, and aquaculture presenting an increase of 113% between 1985 and 2022.

In São Paulo's riparian PPA, we observed 11,654 hectares anthropized in 2022 since 1985, when the PPA widths were established by the Law 4,771/1965 before the changes made in 1986, in smaller widths than those applied today (Fig. 2). Consequently, these areas, which represent only 0.4% of total PPA, can be considered as regular in the face of changes in environmental legislation. This area represents about 34% of total PPA occupied by anthropic uses in 2022, which was 34,034 hectares (Table S2). Thus, it is possible to estimate that around 22,380 hectares of anthropic uses in PPA are after 1986, when these areas already had legal protection in the widths currently considered. However, we cannot consider that all anthropogenic occupations after 1986 are illegal, as legislation allows certain PPA interventions, such as roads, sanitation, and energy projects (Brasil, 2012).

The predominant dynamic of land use in the riparian PPA is the regeneration of native vegetation in areas previously occupied by agriculture and forestry, especially pastures, which correspond to 262,297 hectares (Fig. 2). Other important transitions in the studied PPA were the replacement of native vegetation by agriculture and forestry uses (114,805 hectares), and the transformation of agriculture uses in anthropic areas (19,951 hectares) (Fig. 2).

Spatial distribution of land use and cover changes

The maintenance of anthropic areas was concentrated around the urbanized centers and regions, with a principal hotspot in the São Paulo`s metropolitan region (Fig. 3A). The suppression of native vegetation in the riparian PPA were concentrated, roughly speaking, in the same hotspots of maintenance and regeneration of native vegetation (Fig. 3B). The maintenance of native vegetation in riparian PPA was concentrated in a hotspot along the coastal and southern regions of the state (Fig. 3C). The process of regeneration of native vegetation observed between the years was distributed in a large hotspot located in the southern region of São Paulo territory (Fig. 3D), with a little spread in the central region. Another regeneration hotspot was identified in the Paraiba Valley, in the northeast region of the state.

The factors influencing clustering were partially explained by the explanatory variables: maintenance of anthropic areas (59.3%), suppression of native vegetation (32.4%), maintenance of native vegetation (50.9%), and regeneration of native vegetation (31.7%).

The most influential variables were: for maintenance of anthropic areas, Strict Protection Units (+); for suppression of native vegetation, Degree of Urbanization (−) and Sustainable Use Units (+); for maintenance of native vegetation, PPA degradation (−), Strict Protection Units

Table 1
Land use and land cover within riparian Permanent Preservation Areas (PPA) in the state of São Paulo in 1985 and 2022.

Classes of land use and coverage		1985		2022		Difference between 1985/2022	
		Area (hectares)	%	Area (hectares)	%	Area (hectares)	%
Forest and natural formations	Forest formation	1,123,478.31	38.56	1,269,717.93	43.57	146,239.62	13.02
	Savanna formation	6,860.74	0.24	6,824.37	0.23	−36.37	−0.53
	Mangrove	8,804.12	0.30	10,433.14	0.36	1,629.02	18.50
	Wooded sandbank vegetation	32,617.93	1.12	32,748.79	1.12	130.86	0.40
	Wetland	87,720.49	3.01	97,602.41	3.35	9,881.92	11.27
	Grassland formation	1,634.42	0.06	2,378.04	0.08	743.62	45.50
	Salt flat	55.61	0.00	20.56	0.00	−35.05	−63.03
	Rocky outcrop	1,557.63	0.05	1,540.96	0.05	−16.67	−1.07
	Herbaceous sandbank vegetation	1,545.08	0.05	1,470.55	0.05	−74.53	−4.82
	Other non forest formations	95.83	0.00	88.01	0.00	−7.82	−8.16
	Beach and dune	137.48	0.00	134.78	0.00	−2.7	−1.96
	Subtotal	1,264,507.84	43.40	1,422,959.54	48.83	158,451.70	12.53
Agriculture and forestry	Forest plantation	9,784.25	0.34	54,488.83	1.87	44,704.58	456.90
	Pasture	759,485.41	26.06	466,983.97	16.03	−292,501.44	−38.51
	Soybean	946.01	0.03	14,807.67	0.51	13,861.66	1465.28
	Sugarcane	18,150.46	0.62	49,379.98	1.69	31,229.52	172.06
	Cotton	0.01	0.00	0.16	0.00	0.15	1,500.00
	Coffee	1,367.53	0.05	4,094.15	0.14	2,726.62	199.38
	Citrus	290.86	0.01	927.34	0.03	636.48	218.83
	Other temporary crops	33,583.43	1.15	42,319.32	1.45	8,735.89	26.01
	Other perennial crops	205.91	0.01	3,551.86	0.12	3,345.95	1,624.96
	Mosaic of agriculture and pasture	748,150.54	25.68	782,442.10	26.85	34,291.56	4.58
	Subtotal	1,571,964.41	53.95	1,418,995.38	48.70	−152,969.03	−9.73
Anthropic areas	Urban area	7,661.02	0.26	29,611.24	1.02	21,950.22	286.52
	Mining	205.97	0.01	476,76	0.02	270.79	131.47
	Other non vegetated areas	8,071.33	0.28	3,864.45	0.13	−4,206.88	−52.12
	Aquaculture	12.15	0.00	81.24	0.00	69.09	568.64
	Subtotal	15,950.47	0.55	34,033.69	1.17	18,083.22	113.37
Rivers and lakes		61,263.24	2.10	37,696.69	1.29	−23,566.55	−38.47
Non observed		183.39	0.01	183.85	0.01	0.46	0.25
Total		2,913,869.15	100.00	2,913,869.15	100.00	0.00	0.00

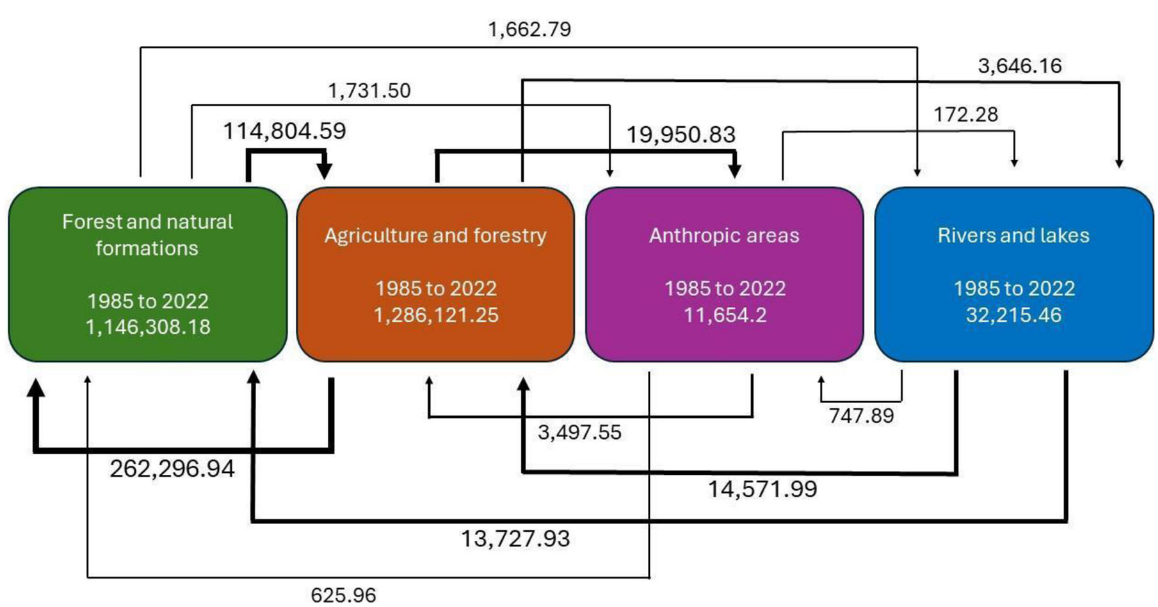

Fig. 2. Land use and coverage transitions (in hectares) in riparian Permanent Preservation Areas in the state of Sao Paulo, Brazil, between 1985 and 2022.

(+), and Sustainable Use Units (+); for regeneration of native vegetation, Water supply (−) and Temperature (+). Positive (+) and negative (−) signs indicate direct and inverse relationships, respectively. These variables explain the HH and LL spatial clusters identified through LISA analysis. Additional details are provided in the supplementary material.

Discussion

In this study, we analyzed the land use and land cover changes in PPA to assess the drivers of degradation and the effect of legal changes in the environmental regularization of these areas. Our findings highlight agropastoral uses as the main drivers of riparian PPA degradation. Moreover, our outcomes also prove the increase in the riparian PPA widths had a positive impact in native vegetation regeneration and resulted in a small portion of regular PPA according to the temporarity concept.

Based on our results, we hypothesize that the expansion of the widths of riparian PPA may have a positive impact in the regeneration of native

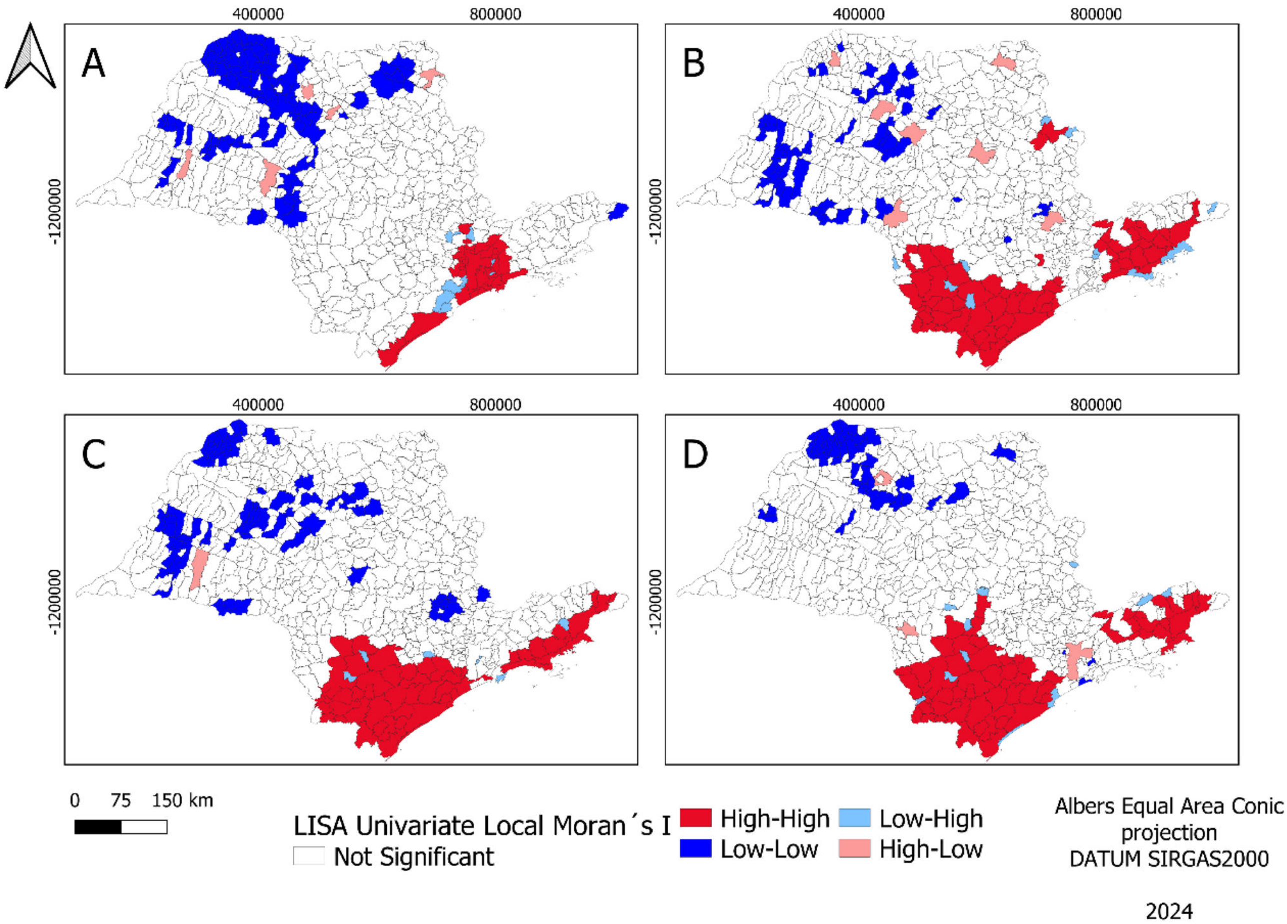

Fig. 3. Land use transitions in riparian Permanent Preservation Areas with Univariate Local Moran's I ("A": maintenance of anthropic areas, "B" suppression of native vegetation, "C" maintenance of native vegetation, "D" regeneration of native vegetation).

vegetation observed between 1986 and 2022. The legal expansion of riparian PPA widths could have facilitated to the abandonment of productive activities at least in part of these protected areas, resulting in the regeneration of native vegetation. The abandonment of agricultural exploitations motivated by low suitability of the areas or due to legal restrictions is an important driver of native forests regeneration (Calaboni et al., 2018; Aide et al., 2019; Leite et al., 2020). This process is favored by the proximity of water bodies, existing fragments and areas of steep slope (Molin et al., 2018), as occurred in the regeneration hotspots we identified in the most conserved and steepest regions of the state of São Paulo. While temperature and water supply emerged as the most influential variables in this cluster formation, the complete set of variables explained only 31.7% of the total variance, suggesting that unidentified processes beyond the scope of this analysis may influence the spatial distribution patterns observed. This finding diverges from established research demonstrating that elevated temperatures facilitate accelerated native vegetation recovery (Silva et al., 2023), given that our analysis identified regeneration hotspots predominantly in the cooler southern municipalities of São Paulo state (Vieira et al., 2009). Despite this observed increase in native vegetation, it is possible to infer that these new ecosystems are not equivalent to those that were lost. For instance, studies indicate that the forest transition observed in Atlantic Forest, the main biome of São Paulo state, conceals a destruction of older forests and a rejuvenation of native forest cover (Rosa et al., 2021; Piffer et al., 2022) that threatens ecosystem services by not offsetting losses of carbon stocks and biodiversity (Silva et al., 2025).

For areas of native vegetation maintenance, the explanatory variables demonstrating the greatest influence were PPA degradation, Strict Protection Units, and Sustainable Use Units. These results support the notion that native vegetation persistence is enhanced in regions with minimal PPA degradation and where multiple legal conservation mechanisms provide additional protective layers. The Ribeira Valley and Paraíba Valley regions, which concentrate the identified hotspots, similarly exhibit high concentrations of protection units and greater vegetation coverage when compared to coldspots. The Ribeira Valley is recognized for having the largest coverage of native vegetation in the state and large protected areas, such state parks (Leite et al., 2020), contributing both for vegetation maintenance and regeneration. On the other hand, the Vale do Paraiba is going through a process of forest transition, guided by the silviculture sector (Silva et al., 2017).

In the 2022 scenario a considerable portion of PPA is covered by agricultural uses, specially pastures and mosaic of agriculture and pastures. Considering Article 61-A of the NVPL, it is possible to maintain part of these agropastoral uses within PPA (Brancalion et al., 2016), and restoration to comply NVPL is required only for a minimum area, estimated at 768,580 hectares of degraded PPA (Mello et al., 2022). So, the expansion of forested riparian areas after the changes in the environmental legislation can reach this legal limit with the publication of the NVPL. This restoration limit can no longer be surpassed through simple legal enforcement. Instead, progress must rely on stimulation via economic incentives and other incentive-based mechanisms. Most of São Paulo state environmental deficits within riparian PPA are associated with sugarcane, orange, and cattle farms (Murakami et al., 2023), and these economic sectors should have specific environmental policies such as technical assistance for the intensification of production technologies, which can result in greater productivity in less explored areas, leading to the abandonment of marginal sites for commodities production. Moreover, socioenvironmental certification schemes and Payment for

Environmental Services associated with the ecological restoration of riparian PPA beyond the legal obligation can also play an important role in increasing native vegetation in riparian areas. Yet, aligning forest restoration with the bioeconomy is a challenge, but it can bring numerous economic, social, and environmental benefits (Krainovic et al., 2025).

Regarding land use dynamics, we identified that the main processes that occurred in the analyzed period were the changes from agricultural areas to native vegetation patches, the replacement of native vegetation by agriculture, and the anthropization of agricultural areas. Even in the most populated and urbanized Brazilian state, agriculture and pasture are the main vectors of deforestation and regeneration of native vegetation in PPA. Our findings align with other studies identifying agriculture as the primary driver of tropical forest loss worldwide (De Sy et al., 2019; Pendrill et al., 2022). Additionally, our study highlights that this dynamic also occurs in areas protected by environmental legislation, underscoring the need for stronger enforcement measures and the development of policies and mechanisms to support legal compliance. The explanatory variables explained 32.4% of the formation of hotspots and coldspots, of vegetation suppression, with Sustainable Use Units and Degree of Urbanization being the most influential factors, respectively. Sustainable Use Units are predominantly concentrated in the southern and western regions of the state. Given their less stringent protection framework relative to Strict Protection Units, these conservation areas may provide greater opportunities for anthropogenic land use expansion. Our results further demonstrated that the increase in anthropogenic uses in PPA occurred mainly in agricultural areas, suggesting that most of the urban or mining structures installed in PPA during the period did not directly result in the suppression of native vegetation, since such structures are typically situated in the peripheral zones of urban agglomerations. However, the expansion of anthropogenic uses over agricultural areas may have driven agricultural areas to expand into vegetated areas (Van Vliet, 2019).

The anthropized PPA that can be considered regular by the temporality concept represents only 0.4% of total PPA in the state. Despite the low representation in territorial terms, the maintenance of anthropic uses is concentrated in a well-defined hotspot located in the São Paulo's metropolitan region, that is home to about 22 million inhabitants or 47.8% of the state population (IBGE, 2024), and one of the most important conurbations in Brazil (Zimmermann et al., 2023). Notably, 56.8% of this anthropized area is located within municipalities classified as hotspots (see Fig. 3 and Table S3). All explanatory variables combined explained 59.3% of the total variance, with Strict Protection Units being the most influential factor. This relationship can be partially explained by the spatial overlap between the Serra do Mar State Park, a major Strict Protection Unit, and both the São Paulo metropolitan region and coastal municipalities. The regularization of anthropic uses in PPA in intense urbanized and populated regions may jeopardize the offering of ecosystem services in this degraded scenario, potentially worsening an already threatened environmental quality in this metropolitan region (Ikematsu and Quintanilha, 2023). However, our results show that even if the irregular anthropized PPA are restored, it will have a limited impact on the state's PPA deficits.

The geographic distribution of processes of maintenance, suppression, and regeneration of native vegetation in PPA follows the same pattern, with hotspots located in the Ribeira (southern region of state) and Paraiba Valleys (northeast region of state), indicating that these processes could occur simultaneously in the studied territory. Therefore, these regions are priorities for policies to encourage the maintenance of forests in PPA. Conversely, the coldspot for regeneration in PPA is located in the northern region of the state, which indicates a priority area to the enforcement of programs to encourage ecological restoration of riparian PPA, such as the *Programa Nascentes* (Chazdon et al., 2022).

Final Remarks

The identification of potential regularization areas, when conducted without the support of geospatial tools, are highly complex and costly. Currently, CETESB evaluates cases individually, requiring landowners to submit requests for the regularization of structures located in PPA. However, the quantification and mapping of these areas across the state of Sao Paulo can significantly streamline the regularization process. Furthermore, the information derived from land-use transitions within PPA provides valuable insights for environmental management agencies, enabling the identification of areas requiring enhanced oversight and enforcement, as well as programs to stimulate ecological restoration to reverse legal deficits. However, the information must be interpreted with caution and serves primarily as guidance, given that the pixel resolution of the land use and land cover data is 30 m, which corresponds to the typical width of most PPAs in São Paulo state. Furthermore, historical datasets are inherently limited by the technological capabilities available at the time of acquisition, constraining the temporal resolution of change analyses. For more comprehensive analyses of land use change patterns, future studies would benefit from evaluating land use transitions at shorter temporal intervals, which would provide greater insight into the dynamics and drivers of landscape transformation processes.

CRediT authorship contribution statement

VMC: Writing – review & editing, Writing – Original draft, Methodology, Software, Formal analysis, Data Curation. FRG: Writing – review & editing, Writing – Original draft, Methodology, Software, Formal analysis, Data Curation, Conceptualization. HLRAS: Software, Writing – review & editing. CDCO: Writing – review & editing, Conceptualization. PGM: Conceptualization, Writing – Review & editing, Supervision, Project administration.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used generative AI in order to script development for conducting Spatial Autoregressive Models (SAR) and Spatial Error Models (SEM) and variance partitioning. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2026.02.003.

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