University of São Paulo
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Riparian zones (PPAs) in the landscape of the sub-basins of the Corumbataí and Piracicaba rivers in front of the New Forest Code (NVPL) of 2012

Laura Piacentini Casarin

Dissertation presented to obtain the degree of Master in Science. Area: Applied Ecology

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SUMMARY

RESUMO

Zonas ripárias (APP) na paisagem das sub-bacias dos rios Corumbataí e Piracicaba frente ao Novo Código Florestal (NVPL) de 2012

No Estado de São Paulo, a escassez de recursos hídricos tornou-se pauta constante nas discussões sobre segurança hídrica. Nesse contexto, a proteção e recuperação da cobertura florestal desempenha um papel fundamental no aumento da resiliência dos sistemas de abastecimento de água. A fim de contribuir para o desenvolvimento de políticas específicas de proteção e restauração da dinâmica do desmatamento regional, o objetivo foi avaliar a supressão da mata ciliar em Áreas de Preservação Permanente (APPs) e sua relação com os tipos de uso e ocupação do solo, bem como o impacto da Lei de Proteção da Vegetação Nativa (LPVN) sobre esses padrões. Para isso, analisamos a evolução espacial e temporal da cobertura de APPs ribeirinhas nos municípios de Corumbataí, Rio Claro e Piracicaba, inseridos nas sub-bacias dos rios Corumbataí e Piracicaba, através da classificação orientada a objetos de imagens de satélite de alta resolução espacial RapidEye para os anos de 2009, 2014 e 2019 e técnicas de geoprocessamento. A análise envolveu aspectos relacionados ao uso e cobertura da terra, à estrutura da paisagem e às condições e configurações das APPs. Constatou-se que está ocorrendo um processo de fragmentação dessas áreas de preservação permanente. O sistema agropastoril é o fator com maior influência de impactos nas APPs, além da predominância de pastagem e cana-de-açúcar em cerca de 50% e 30%, respectivamente, das áreas avaliadas. Porém, os impactos decorrentes da implantação da LPVN não foram homogêneos entre as classes de uso antrópico, trazendo diferentes dinâmicas de recuperação da mata ciliar e surgimento de novos desmatamentos em todas as classes de imóveis rurais avaliados. Situações irregulares em relação à legislação e preservação ambiental foram detectadas, principalmente na classe de imóveis rurais pequenos (até 4 Módulos Fiscais) os quais concentram a maior quantidade de corpos hídricos, entre 30% e 50% das APPs, em ambas as sub-bacias. Além das pastagens, o tipo de uso do solo que requer maior atenção devido às tendências de expansão nas APPs foi silvicultura nos três municípios, um indicativo de influência econômica na região. Os resultados ajudam a compreender os primeiros impactos da LPVN nos padrões de uso e ocupação das APPs, revelando a existência de dinâmicas distintas dentro de um mesmo tipo de uso do solo e classes de imóveis rurais, assim como a influência do histórico de colonização e ocupação das terras na região. Compreender a dinâmica regional de uso e ocupação das APPs, as características de suas políticas de governança e produção agrícola na área é fundamental para direcionar os esforços de conservação e maximizar sua eficiência.

Palavras-chave: Área de Preservação Permanente, Lei de Proteção da Vegetação Nativa, Legislação ambiental, Zonas ripárias, Geoprocessamento

ABSTRACT

Riparian zones (PPAs) in the landscape of the sub-basins of the Corumbataí and Piracicaba rivers in front of the New Forest Code (NVPL) of 2012

In the State of São Paulo, the scarcity of water resources has become a constant agenda in water security discussions. Within this context, the protection and recovery of forest cover play a key role in increasing the resilience of water supply systems. In order to contribute to the development of specific protection and restoration policies for the dynamics of regional deforestation, the objective was to evaluate the suppression of riparian forest in Permanent Preservation Areas (PPAs) and its relationship with the types of land use and land cover, as well as the impact of the Native Vegetation Protection Law (NVPL) on these standards. For this, we analyzed the spatial and temporal evolution of the coverage of riparian PPAs in the municipalities of Corumbataí, Rio Claro, and Piracicaba, inserted in the sub-basins of the Corumbataí River and Piracicaba River, through the object-oriented classification of RapidEye high spatial resolution satellite imagery for the years 2009, 2014 and 2019, and geoprocessing techniques. The analysis involved aspects related to land use and land cover, the landscape structure, and the conditions and configuration of the PPAs. It was found that a process of fragmentation is taking place within these areas of permanent preservation. The agropastoral system is the factor with the greatest influence on impacts on the PPAs, in addition to the predominance of pasture and sugarcane in about 50% and 30%, respectively, of the evaluated areas. However, the impacts arising from the implementation of the NVPL were not homogeneous among the classes of anthropic use, bringing different dynamics of recovery of riparian forest and the emergence of new deforestation in all classes of rural properties assessed. Irregular situations in relation to legislation and environmental preservation were detected, mainly in the class of small rural properties (up to 4 Fiscal Modules) which concentrate the largest amount of water bodies, between 30% and 50% of PPAs, in both sub-basins. In addition to pastures, the type of land use that requires greater attention due to expansion trends in PPAs was forestry in the three municipalities, an indication of economic influence in the region. The results help to understand the first impacts of the NVPL on the patterns of land use and cover of the PPAs, revealing the existence of distinct dynamics within the same type of land use and classes of rural properties, as well as the influence of the history of colonization and land occupation in the region. Understanding the regional dynamics of the use and occupation of PPAs, the characteristics of their governance policies, and agricultural production in the area is essential to direct conservation efforts and maximize their efficiency.

Keywords: Permanent Preservation Area, Native Vegetation Protection Law, Environmental legislation, Riparian zones, Geoprocessing

1. INTRODUCTION

As an interface environment between terrestrial and aquatic ecosystems, riparian zones present a natural gradient of disturbances that sustain a sensitive spatial and temporal mosaic of environments with few parallels in other systems. Thus, they are places of particular interest for biodiversity conservation, ecological processes, and ecosystem services maintenance (Naiman and Décamps, 1997; Burdon et al., 2013; Bleich et al., 2014).

However, changes in land use and agricultural management practices are often associated with some type of impact on riparian zones which, in turn, mitigate such effects on water bodies (Leal et al., 2016). Riparian vegetation suppression can result in significant impacts on hydrological and biogeochemical processes (Sweeney et al., 2004; Deegan et al., 2011; Bleich et al., 2014), and lead to structural and functional changes in biological communities, considering its role as habitat and ecological corridors (Nagy et al., 2015; Elliott and Vose, 2016).

Inevitably, by narrowing the vegetation strips, biodiversity conservation, and environmental services maintenance are greatly affected, reducing their effectiveness, and tending to restrict the environmental potential of Permanent Preservation Areas (PPAs), not only affecting the environment, but also has consequences for the human population, such as water quality, soil protection, crop pollination, and climate regulation, especially in regions with an excess of agricultural areas (Brancalion et al., 2016), and can result in the loss of functions such as the filtering performed by native vegetation, which retains sediments, pesticides, and fertilizers (Bicalho et al., 2010).

Currently, many countries have some protection policies for riparian zones (Chiavari and Lopes, 2017). In Brazil, vegetation strips surrounding water bodies and headwaters are among the supported environments within the concept of Permanent Preservation Areas (PPAs). Riparian zones use and occupation restrictions for conservation purposes have existed in the country since the 1920s. However, the consolidation of norms that guide these areas' definition, execution, and monitoring lasted for decades until the implementation of the Forest Code in 1965 (Federal Law nº 4,771/1965) and the several amendments following it. Currently, the protection regime for PPAs is governed by Federal Law no 12,651/2012, also known as the Native Vegetation Protection Law (NVPL).

The NVPL was the result of the 1965 Forest Code reformulation claim, mainly from the agricultural sector. This demand was based on the need to correct the legal insecurities resulting from the various amendments to the Forest Code, and the difficulties that rural landowners encountered in the environmental regularization of their properties after so many changes. There was also an implicit interest in sanctions amnesty related to deforestation, as well as the legalization of the maintenance of agricultural activities in protected areas that were historically occupied (Brancalion et al., 2016). The NVPL approval brought several flexibilities to the PPAs protection regime, many of which were met with objections by the scientific community (Silva et al., 2012) and the Federal Public Ministry (PGR, 2013).

In the PPA protection regime implemented since the 1965 Forest Code, vegetation strips must be kept at a minimum width of 50 meters around headwater, and from 30 to 500 meters for watercourses, depending on their channel width from its highest level in the flood season. Deforestation within these limits would entail legal sanctions and mandatory full restoration (Brasil, 1965).

The NVPL created an exception to this regime, bringing a more flexible set of rules for PPAs illegally deforested before July 22, 2008. In the so-called consolidated rural areas, instead of PPA complete restoration, the law requires the recomposition of smaller strips that can vary from 5 to 100 meters in width, depending on property size, and not on the river size. In other portions of the consolidated PPA, where there is no need for restoration, maintenance of agricultural, forestry, ecotourism, and rural tourism activities is allowed, including all associated infrastructure. However, these areas are not considered as a continuation of areas of agricultural or forestry production, therefore needing proper management of these lands, as these areas are conditioned on technical criteria for soil and water conservation, as is recommended in the Environmental Regularization Program (PRA) (Brasil, 2012ab).

The NVPL also dispose of new tools and systems to control and incentive the elaboration of mechanisms and public policies to finance the introduction of the law, which constitutes an advance considered important, with the creation of the Rural Environmental Registry (CAR), the Environmental Regularization Program (PRA), the Project for the Recovery of Degraded and Altered Areas and Environmental Reserve Quotas. These tools are fundamental for the systematic and integrated management of the law, in addition to enforcing and monitoring its execution (Brancalion et al., 2016).

Studies that assess the impact of these changes on riparian protection are still scarce, despite their importance (Nunes et al., 2019). Currently, it is estimated that these areas have an environmental liability of about 4.5 million hectares throughout the national territory (Soares-Filho et al., 2014). Vilela (2021) evaluated the influence of NVPL in the fragmentation of native vegetation in rural properties landscape and the effects on biome scale, reinforcing the importance of studying patterns of use and coverage within PPAs, as well as the impact of the law on them, and found that in Cerrado biome, the lower legal restriction of land use resulted in a greater inversion of the landscape matrix, and even though small properties showed higher rates of native vegetation conversion, medium and large properties are the ones that should be inspected due to their larger extensions and dominance of the landscape. Preto et al. (2022) observed that the type of land use and land cover, as well as different properties size, had different impacts on the conservation and deforestation of PPAs native vegetation after the implementation of the NVPL. Their results were similar to Vilela (2021), showing that in areas where the requirements for restoration were lowered by the NVPL, the rates of environmental liabilities' reduction were also low, whereas new advances in deforestation of riparian zones were observed, tending to concentrate more in smaller rural properties, but larger rural properties having the most responsibility for environmental liabilities and vectors of new deforestation.

Even though they are considered priority areas for biodiversity conservation, riparian zones in the State of São Paulo are generally surrounded by extensive agricultural areas, especially sugarcane. In just 20 years (1990 to 2011), the area cultivated with sugarcane in the state grew by 34,000 km², occupying approximately 25% of the arable land in the same state (Santos et al., 2015). The Piracicaba, Capivari, and Jundiaí River Basins (PCJ Basins) have a long history of human occupation and environmental change. About 33.6% of the landscape of these basins is covered by sugarcane (CBH-PCJ 2011), which, in turn, has favorable characteristics for its identification in satellite images, since it is a semi-perennial crop planted in large areas (Oliveira, 2011), while the native vegetation is found only in some fragments, such as on the banks of watercourses and in other PPAs, representing only 7.9% of the area of these basins (CBH-PCJ 2011).

This study analyzed the impact of NVPL on the use and occupation dynamics of riparian zones by mapping and analyzing the spatial and temporal evolution of Corumbataí, Rio Claro, and Piracicaba (SP) municipalities' land cover in PPAs, through digital processing of high spatial resolution satellite images of RapidEye, from 2009 to 2019. Using as a case study the sub-basins of the Piracicaba and Corumbataí rivers of the set of basins PCJ (Piracicaba, Capivari, and Jundiaí), an area of paramount importance in water resources management in the central-eastern region of São Paulo State, it was sought to answer three relevant questions within the scope of environmental governance:

(i) How are the composition and configuration of PPAs being affected by the different types of land uses and occupations prevailing in the Piracicaba River and Corumbataí River sub-basins?;
(ii) Which were the temporal changes in the PPAs conservation status in relation to current and previous environmental legislation?; and

(iii) Which were the impacts on the PPAs conservation status due to the legislation changes?

The overall objective was to analyze the spatial and temporal evolution of changes in land use of PPAs composition from 2009 to 2019, in conformity with current legislation, in the sub-basins of the Piracicaba and Corumbataí rivers, in the municipalities of Piracicaba, Corumbataí and Rio Claro, in the State of São Paulo located in the PCJ basins.

The specific objectives were (i) to map and quantify the drainage network and respective PPAs according to the categories defined by the NVPL and the 1965 Forest Code; (ii) to quantify the compliances and deficits of PPAs vegetation; (iii) to analyze the PPAs arrangement and spatial patterns using landscape metrics; (iv) And analyze the temporal changes caused by the change of legislation and its impacts on PPAs.

2. MATERIALS AND METHODS

2.1. Study area location and description

For this research, were chosen two sub-basins located in the PCJ river basin, the Corumbataí river sub-basin and Piracicaba River sub-basin, which in turn encompass three municipalities: Corumbataí and Rio Claro in the first one, and Piracicaba in the second one. The study area is located in a transition zone between the Cerrado and Atlantic Forest biomes in São Paulo state (IBGE, 2019; Figure 1). For a better assessment of the landscape management and public policies, we choose the spatial municipality scale.

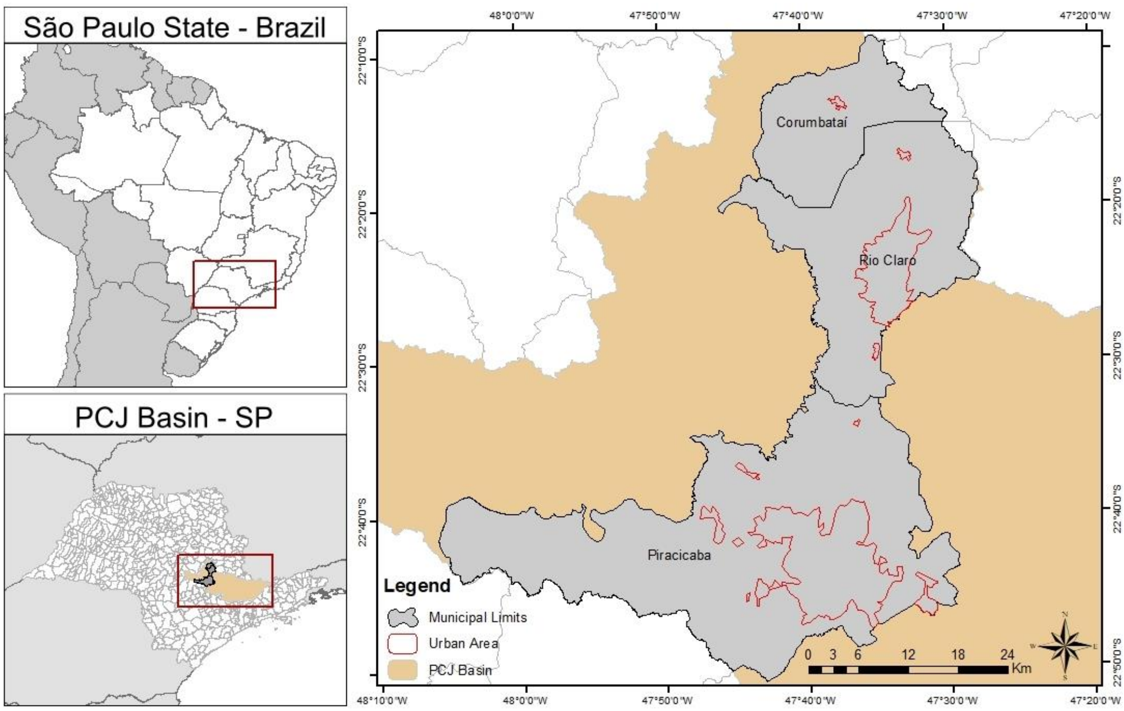


Figure 1. Location of Corumbataí, Rio Claro, and Piracicaba municipalities, São Paulo State, Brazil. The location of these municipalities and the Corumbataí and Piracicaba sub-basis inside the Piracicaba, Capivari, and Jundiaí (PCJ) River basin are highlighted in the larger map.

Corumbataí, placed at 22º13'12" S and 47º37'33" W, encompasses 278.6 km² and 4,072 inhabitants. The main land use is pasture encompassing 47.2% of the county area, followed by sugarcane (22.8%) and agriculture (10.8%), while natural forest covers 16.7% (IBGE, 2017). Rio Claro is located at 22º24'39" S and 47º33'39" W, covering an area of 498.4 km² and 209,548 inhabitants. In this county, while pastures encompass 28.8% of the total area, sugarcane is found in 37.4% and agriculture in 17% of the landscape, while natural forest covers 16.5% of it (IBGE, 2017). The climate of the Corumbataí sub-basin is classified as "Cwa" type, with an average temperature of 20.3 °C and an average annual rainfall of 1,575 mm (Köppen, 1918; Climate-Data, 2022a).

Piracicaba is located at 22º43'30" S and 47º38'56" W, comprising an area of 1,378.1 km² and 410,275 inhabitants The dominant land use in this county is sugarcane, encompassing 46% of the total area, pastures are found in 24.5% of it and agriculture covers 20.8%. Natural forest is found only in 8.4% of the county's total area (IBGE, 2017). Piracicaba sub-basin climate is classified as "Aw" according to Köppen (1918), with an average annual rainfall of 1,346 mm and an average temperature is 21.7 °C (Köppen, 1918; Climate-Data, 2022b).

Despite of the fact that Piracicaba River has a higher discharge, due to its very low quality for domestic consumption, the municipality withdraw water from the Corumbataí river to supply domestic use. With an average discharge of 64 $m^3.s^{-1}$ at the center urban portion of the river, and 92 $m^3.s^{-1}$ at the western rural portion (SSD PCJ, 2020), Piracicaba only withdraw water in emergencies cases. As the main source and most important river in the region and the most used for domestic consumption in all three municipalities studied, the Corumbataí river has a better water quality, fitting into several sections in Class 1, water that among some of the noble activities, can be destined to supply human consumption, after disinfection (Brasil, 2005). The average discharge for the Corumbataí river is 9 $m^3.s^{-1}$, being highest at the confluence with the Piracicaba River where reaches an average of 18 $m^3.s^{-1}$ (SSD-PCJ, 2020).

Corumbataí sub-basin relief is predominantly flat and slightly wavy, mainly covered by pasture lands and sugarcane crops, with altitudes ranging from 470 m to 1042 m, with an average of 660 m. Areas with a slope of less than 15% are predominant, representing 84% of the total area. Areas with a slope above 15% are less representative, with only 17% of the landscape. Due to the high areal extension favorable to mechanization, an agricultural expansion is found in this sub-basin, especially with sugarcane in the southern portion, occupying 29% of the area. As the predominant land use, pasture occupies 44% of the area, mostly in the northern and western portions. Pastures are found in as 43.4% of the area occupied by Red-Yellow Acrisol/Lixisol and 21.5% of Red-Yellow Ferralsol, which constitute the predominant soil groups (Valente and Vettorazzi, 2002).

Piracicaba sub-basin relief is considered a rugged terrain when in comparison to other regions of sugarcane production in São Paulo State, with altitudes ranging from 420 m to 780 m, with an average of 528 m. Areas with slopes with less than 5% are predominant, encompassing 42% of the area, while 20% of the area has slopes higher than 12%, being less suitable for mechanization. Areas that are flatter and more fertile, geographically located in the eastern and southwest portion of the municipality, are used mostly for sugarcane production, while pastures and forest remnants are mostly found in areas with higher slopes. Predominantly, several types of Ferralsol, soil that has high-water retention capacity, are found at the northeast portion, whereas the northern region and most of the central and southern portions of the municipality have a predominance of Red-Yellow Acrisol/Lixisol (Barreto et al., 2006).

The natural landscape of the Piracicaba and Corumbataí river basin region have undergone small changes until the first half of the 19th century. Indigenous people who inhabited the land practiced hunting more than agriculture, and the first settlers used the land more slowly, using fallow for years for soil recovery. Two distinct landscapes could be distinguished: the valley, following the course of the Piracicaba River, which was already relatively anthropomorphized, with subsistence agriculture and commerce, following population growth. The other landscape was on the ridges, in the high altitudes of the Corumbataí river basin, which was still largely maintained in its original state, been altered with the arrival of coffee in the region at the end of the century (Garcia, 2000; Leonidio, 2013).

Due to low technology at the time of slavery, sugarcane farms needed wood for mills to run, therefore it was common to maintain large areas of native forest on large properties. As a consequence, until the end of the 19th century, areas of natural vegetation still were found in large fragments in the region (Leonidio, 2013).

This scenario was permanently changed with the emergence of coffee cultivation, especially in the ridge areas at the north of the Corumbataí basin. Participation of coffee in Brazilian exports exceeded 40% in the mid-nineteenth century, becoming the main crop production in the country in that period (Garcia, 2000; Ramos, 2001).

However, at the beginning of the 20th century, coffee plantation began to reduce, mainly in the Piracicaba basin, due to external crises that reduced export demand, bringing back sugarcane cultivation. A further expansion of this crop took place, dues to internal demands and technological advances in the new sugarcane mills. As a result, native forest resources were no longer necessary for sugar production and were soon replaced by the crop, continuing this process of intense changes in use until the 1960s, when only a few fragile fragments of native forest remained in the landscape of the Piracicaba and Corumbataí river basins (Garcia, 2000; Leonidio, 2013).

With a predominantly agricultural landscape, the sub-basins of the Corumbataí and Piracicaba rivers have currently a high economic development and intense level of native vegetation fragmentation (Grande et al., 2003). As a result of an intense and disorderly process of occupation and deforestation, native vegetation is restricted to sloping areas and isolated stretches around water bodies (Valente and Vettorazzi, 2005). Despite representing key areas of remnants of native vegetation, soil cover in the riparian environments is often dominated by pastures and sugarcane (Mori et al., 2016).

2.2. Methods

2.2.1. Data acquisition and analysis

Biophysical and anthropogenic data required to develop a geodatabase to answer our research questions were identified, located, compiled, and processed as digital libraries using ArcGIS Information System 10.3.1 (ESRI, 2015) and Erdas-Imagine Image Processing 9.3 (Erdas, 1999) licensed to CENA-USP the Geoprocessing Laboratory (LabGeo). Table 1 presents the GIS datasets derived from existing maps, census data, and satellite images. All data were imported, harmonized, and projected onto Mercator's Universal Transverse system, Datum WGS (World Geodetic System) from 1984 for zone 23 South.

Table 1. Detailing the research database, including description, source, and scale of data.

Data	Description	Source	Scale
Municipal limits	Political-administrative limits of the municipalities of Piracicaba, Rio Claro e Corumbataí/SP	IBGE	1:100,000
Land tenure	Limits of rural properties	SICAR	–
Digital Elevation Model	Digital topography of watersheds	SMA-SP; USGS Earth Explorer	1:50,000; 1:25,000
Hydrography network	Hydrographic and water bodies network, including headwaters	IBGE; SMA-SP; SICAR; CBH-PCJ	1:50,000; 1:50,000; 1:25,000
Permanent Preservation Areas (PPAs)	PPAs present in rural properties, as provided for by article 4 of Law No. 12,651, of 2012	Product of this research	–
Land use and Land cover in PPAs	Land use and land cover map obtained through RapidEye images	Product of this research	–
Land use and Land cover	Land use and land cover map obtained through SPOT images	SMA - SP	1:25,000
Land use and Land cover	Land use and land cover map obtained through MapBiomas maps Collection 6	MapBiomas	1:100,000
Consolidated areas	Anthropogenic occupation in APP of pre-existing rural properties on July 22, 2008	SICAR	–
RapidEye images	Orthorectified, with 16-bit radiometric resolution	MMA; Planet Labs Inc.	5 m

IBGE – Brazilian Institute of Geography and Statistics; SICAR – National Rural Environmental Registry System; SMA-SP – Secretary of the Environment of the State of São Paulo; CBHPCJ – Committee of Hydrographic Basins of the Piracicaba, Capivari, and Jundiaí rivers; USGS Earth Explorer – United States Geological Survey; MMA – Ministry of the Environment.

All the processing to obtain the main data used in this study is described in Figure 2. The main data consisted of hydrological networks, essential to delineate riparian PPAs widths, LULC maps for each year of 2009, 2014 and 2019 and land tenure maps were used to delineate consolidated use areas and areas that needed vegetation recomposition in the PPAs for each property size.

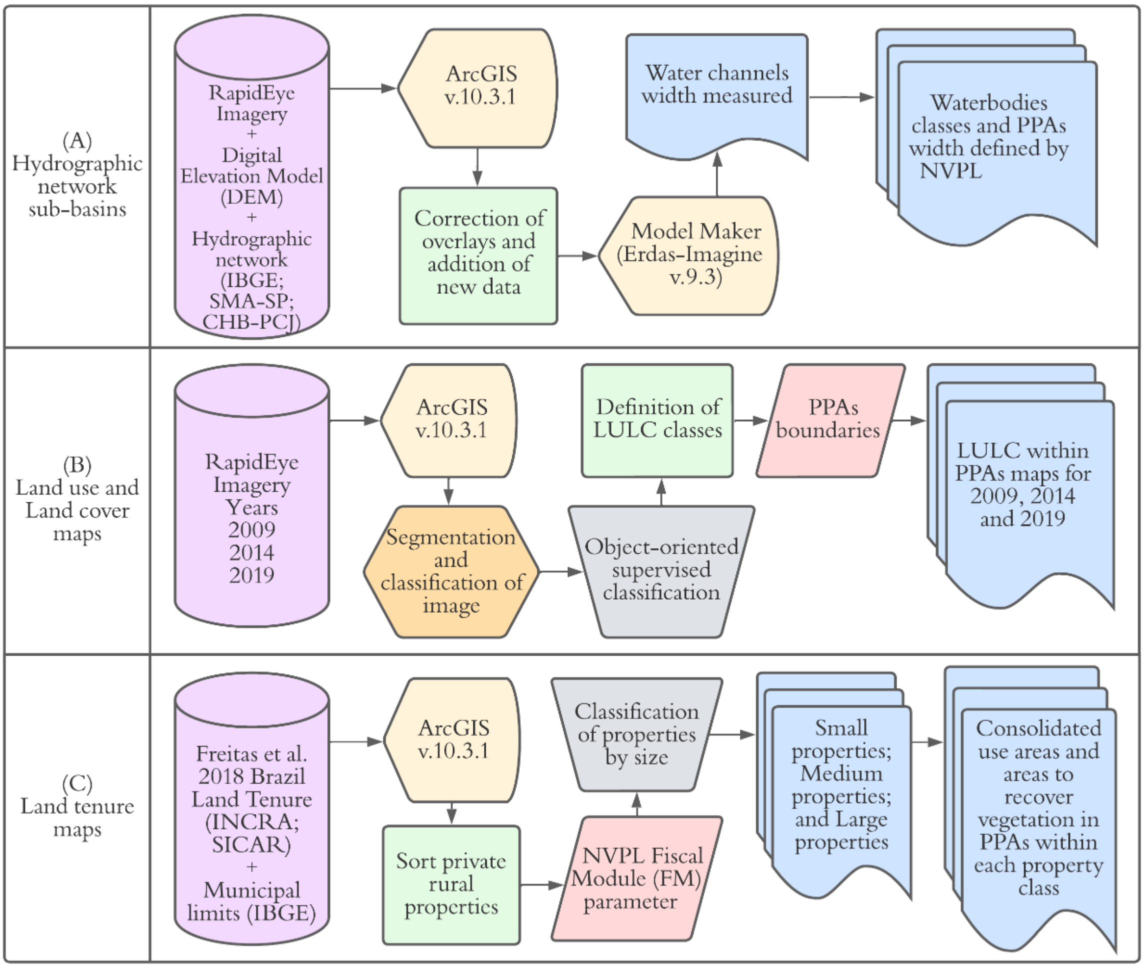


Figure 2. Flowchart for the methodological steps used to develop (A) hydrological network maps for each sub-basin (Corumbataí and Piracicaba rivers) also resulting in the definition of riparian PPAs maps; (B) Land Use and Land Cover maps for each year needed to evaluate temporal changes in riparian PPAs; and (C) Land tenure for all three municipalities also resulting in the composition of consolidated use areas and areas to recover vegetation maps for riparian PPAs in rural properties.

2.2.2. Landscape data sets description and processing

Although our study focuses on PPAs land use change analysis, understanding this process dynamics at the landscape level is a key element to pinpoint the role of drivers and impacts on PPAs composition and configuration. Moreover, land use and land cover (LULC) characterization of the three counties encompassed by our study area were assessed using the 2019 MapBiomas dataset collection 6.0 (2021). This dataset was generated by digital classification of Landsat satellite imagery (Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and the Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS), onboard Landsat 5, 7 and 8, respectively), using machine learning algorithms made available at Google Earth Engine platform.

The land tenure map was derived from a modified version of the one developed by Freitas et al. (2018), which offered a careful treatment of the problems of overlapping rural properties in the cadastral databases of the National Institute of Colonization and Agrarian Reform (INCRA) and the National Rural Environmental Registry System (SICAR). The Rural Environmental Registry (CAR) is a nationwide public registry mandatory for all rural properties and self-declared by the property's owners, thus can cause some inconsistencies and overlap between properties. Moreover, a correction before being used to evaluate rural properties environmental information is needed. In this version, only the polygons related to private rural properties were kept, with manual corrections being made based on the official SICAR database. As a result, polygons with confusing boundaries were adjusted and properties that were not yet included in the land network by Freitas et al. (2018) were added, as long as they did not overlap.

To delineate PPAs according to the NVPL, fiscal module (FM), a parameter for land tenure classification of rural properties by their size, must be set. This value is different for each municipality, according to the type of predominant land exploitation. For Corumbataí, 1 Fiscal Module (FM) encompasses 18 ha, in Rio Claro 14 ha, and in Piracicaba 10 ha. Next, the properties were separated into 3 categories, as defined in Article 4 of Act 8,629/93 (Brasil, 1993): Small property: rural properties that have an area up to 4 FM; Medium property: rural properties that have an area between 4 and 15 FM; and Large property: rural properties that have an area larger than 15 FM.

For the purposes of this study, only riparian PPAs (i.e., referring to water bodies and headwater) located in private rural properties were considered. PPAs corresponding to small dams, lakes, and ponds, or located in urban areas, were disregarded. To delimit the PPAs, water surfaces were initially extracted from land cover maps derived from RapidEye digital classification of high spatial resolution satellite imagery.

Water surface features were then complemented by the combination of river networks made available by the Piracicaba, Capivari, and Jundiaí River Basin Committees (ANA, 2013), and by the São Paulo State Environmental Bureau (SMA-SP, 2013). Considering existing divergences between these river networks, extracted through different methodologies and scales, as well as their limitations for detecting first-order water channels, manual corrections were conducted based on the SICAR database and visual interpretation of RapidEye satellite images. Water channels that were not present were included and a review of the boundaries was conducted.

Water bodies were evaluated in terms of their width through automatic measurement using the Model Maker tool of the Erdas-Imagine 9.3 software (Erdas, 1999), following the methodology proposed by Silva et al. (2013) as a basis. In this method, using both RapidEye satellite images and Digital Elevation Model (DEM), river channels were divided into five width classes, as provided by the NVPL (Brasil, 2012a): ≤ 10 m, 10-50 m, 50-200 m, 200-600 m, and > 600 m. Since this study's main goal was to evaluate the spatial and temporal dynamics of PPAs land use and not rural properties environmental regularity, riparian PPAs were delimited according to the criteria shown in Table 2. The NVPL changes the criteria for measuring the width of the river from the edge of the channel of its regular bed and no longer from the maximum flood level, and also and describes which water bodies should be considered for these APPs, like any perennial and intermittent natural watercourse, excluding ephemeral ones.

Table 2. The width (in meters) of the marginal strips to be preserved in the water PPAs as described in the Law of 2012 (BRASIL, 2012).

Law 12.651/2012	
Width of the watercourse (m)	**Width of the PPA strip (m)**
0-10	30
10-50	50
50-200	100
200-600	200
Headwater	50

2.2.3. PPAs land use and land cover maps

The riparian PPAs land use/cover maps were derived from the digital classification of RapidEye satellite images, with a 5 meters spatial resolution, provided by Planet Labs. The images have 16-bit and five optical bands, including blue (440–510 nm), green (520–590 nm), red (630–685 nm), red edge (690–730 nm), and near-infrared (760–850 nm). All images were obtained orthorectified and geometrically and radiometrically corrected (Planet, 2019), dated from the dry season (April to October) of 2009, 2014, and 2019, representing, respectively, 3 years before, 2 years after, and 7 years after the NVPL implementation, over a period of 10 years.

To derive the land use and land cover maps, initially, a mosaic of RapidEye images was submitted to a segmentation technique, which allows the surface features to be divided into spatially continuous and homogeneous regions, called objects, in which the pixels present similarity considering one or more properties (Haralick and Shapiro, 1985; Pekkarinen, 2002). While in pixel-based image analysis information inherent to objects in the scene ends up being discarded, the object-oriented approach allows variables other than the spectral information of each pixel to be considered in the classification, such as parameters related to the object shape and texture, and relationships between neighboring objects, among others (Hay and Castilla, 2008).

Land use and land cover maps were then obtained through the supervised classification by maximum likelihood of the objects defined in the segmentation step using ArcGIS. The algorithm training was divided into two stages: thematic classes of land use and occupation definition, and collection of training samples, of which were made for each year and for each satellite image. The thematic class definition was based on the predominant types of land use and occupation in the study areas, on targets spectral characteristics, and image spatial resolution. As a result, eight classes of land use and occupation were defined (Table 3).

Table 3. Classes of land use and occupation adopted in the present study.

Classes of land use and occupation	Definition
Water bodies	Natural or artificial water bodies
Native Vegetation	Areas of remaining arboreal vegetation
Agriculture	Areas of cultivation of agricultural species of commercial interest, except sugarcane
Forestry plantation	Areas of cultivation of non-native forest species of commercial interest
Sugarcane	Sugarcane fields
Pasture	Pasture areas with a predominance of herbaceous forage vegetation
Non-vegetated area	Areas of exposed soil without vegetation cover or under management
Urbanization	Urban areas or areas of urban influence, with the presence of residential or industrial infrastructure

As a final product, land use and land cover maps were obtained for the entire extension of the evaluated municipalities. Land use and land cover maps were then clipped within the boundaries of the PPAs, proceeded by manual corrections of boundaries between objects of each class, and the spatial and temporal dynamics of their classes were evaluated in a Spatial Analysis Tool (Figure 3).

Figure 3. Example of land use and land cover classification of PPA of river channels up to 10 m wide in the municipality of Corumbataí, for the year 2009 RapidEye image.

Rural areas that have any activities inside PPAs until July 22nd of 2008 are considered consolidated use and are not required to recover all lost vegetation, only within the minimum width for each size of property and watercourse, as stated in table 4. Any other deforestation that has occurred after this date in PPAs is required to recover all the lost vegetation within the minimum width for each size of watercourse, as stated in table 2.

Table 4. Minimum areas to be recomposed in meters (BRASIL, 2012).

Fiscal Modules (FM)	Watercourse width (m)	Watercourse PPA (m)	Headwater PPA (m)
≤ 1 FM		5	
1-2 FM	Any [1]	8	
2-4 FM		15	
	≤ 10	20	
4-10 FM	10-60	30	15
	60-200	Width/2	
	>200	100	
	≤ 10	30	
>10 FM	10-60	30	
	60-200	Width/2	
	>200	100	

[1]For properties smaller than 4 MFs, the width of the strip to be recomposed does not depend on the width of the watercourse.

An example of a consolidated use and recovery area map is seen in Figure 4, which was made using 2009 RapidEye satellite imagery as a closer image reference to 2008 map of land use and cover for the calculations of consolidated use and areas to recover vegetation for the properties. Moreover, these parameters were adopted in this study.

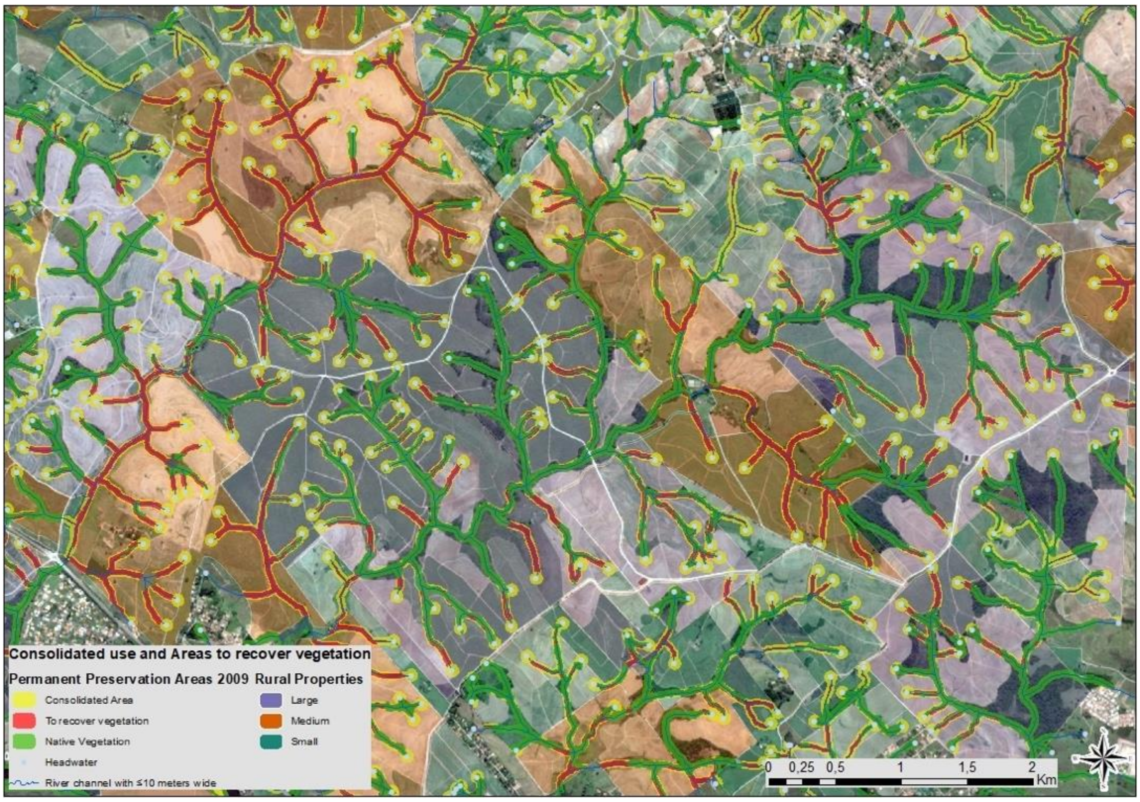


Figure 4. Example of the land tenure map and PPA composition map, generated by land use and land cover classification maps for the year 2009.

2.2.4. Accuracy analysis

To assess classification accuracy, reference points of the generated land use and land cover maps were obtained through the visual interpretation of high spatial resolution images, being a well-recognized approach in the analysis of the accuracy of thematic maps (Dorais e Cardille, 2011; Adami et al., 2012; Maxwell et al., 2014; Silva e Sano, 2016; Willkomm et al., 2019). Based on the work by Garcia et al. (2019), 240 points were proportionally established for the entire study area, divided into 30 points for each previously defined thematic class. These points were randomly generated using ArcGIS, within the PPA areas. The visual interpretation of the landmarks was performed by three experienced analysts, based on the 2019 RapidEye images and the auxiliary image bank of the Google Earth platform. The global accuracy was 94.4% and Kappa index value 0.92. The Kappa indices for the land cover maps were considered excellent based on the reference values (Landis and Koch, 1977).

2.2.5. Landscape metrics

Landscape metrics (or indexes) are most commonly used to describe and quantify its dynamic. Metrics serve to gather useful information on the landscape configuration or composition, such as the proportion of each land cover type (LCT) present, or what shape or size are the elements in the landscape. The benefit of landscape metrics is in comparing different landscape configurations, for example, measuring two or more different landscapes that were mapped the same way, assessing the landscape at different times, or making alternative scenarios for the same landscape (Gustafson 1998).

Class metrics are calculated for each patch type or class in the landscape, by aggregating the properties of the patches that belong to a single class type, there are two basic types of metrics: i. indices of the spatial configuration and the amount of the class, and ii. distribution statistics that allow first (and second) order statistical summaries of the metrics for the chosen class (McGarigal et al., 2002; 2012). Some class metrics characterize the aggregated properties without difference between the separate patches that compose the class, therefore, it is possible to quantify the configuration of patches at the class level, and characterize the class, by summarizing the patch metrics for all the patches that compose each class (McGarigal et al., 2002; 2012).

Using the 2009 and 2019 land use and land cover maps generated by image classification method within PPAs for the municipalities of Corumbataí, Rio Claro, and Piracicaba, processed through FRAGSTATS software version 4.2 (McGarigal et al., 2002) to compute the landscape metrics in each land cover class, five class indices were chosen and analyzed (Table 5): Percentage of Landscape (PLAND), Number of Patches (NP), Patch density (PD), Edge density (ED), Mean patch size (AREA_MN), Standard Deviation (SD_AREA), and Connectance Index (CONNECT) (McGarigal et al., 2002; 2012).

Table 5. Equations and summary description of the metrics of landscape composition and configuration calculated for the municipalities of Corumbataí, Rio Claro, and Piracicaba.

Equation		Description
$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$	Pi = proportion of the landscape occupied by patch type (class) i. aij = area (m²) of patch ij. A = total landscape area (m²).	PLAND equals the sum of the areas (m²) of all patches of the corresponding patch type, divided by total landscape area (m²), to convert to a percentage is then multiplied by 100. Note, total landscape

		area (A) includes any internal background present
$NP = n_i$	ni = number of patches in the landscape of patch type (class) i.	NP equals the number of patches of the corresponding patch type (class).
$PD = \frac{n_i}{A}(10{,}000)(100)$	ni = number of patches in the landscape of patch type (class) i. A = total landscape area (m^2).	Patch density (PD) equals the number of patches of the corresponding patch type divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares).
$ED = \frac{\sum_{k=1}^{m} e_{ik}}{A}(10{,}000)$	eik = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i. A = total landscape area (m^2).	ED equals the sum of the lengths (m) of all edge segments involving the corresponding patch type, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares).
$AREA\_MN = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}\left(\frac{1}{10{,}000}\right)$	Class-level calculation: aij= Area (m^2) of patch ij ni= number of patches in the landscape of patch type (class) divided by 10,000 (to convert to hectares).	AREA_MN (mean) at the class-level equals the sum, across all patches of the corresponding patch type, of the areas of the patches, divided by the total number of patches of the same type.
$AREA\_SD = \sqrt{\frac{\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{\sum_{j=1}^{n} a_{ij}}{n_i}\right)\right]^2}{n_i}}\left(\frac{1}{10{,}000}\right)$	aij= Area (m^2) of patch ij ni= number of patches in the landscape of patch type (class) divided by 10,000 (to convert to hectares).	SD (standard deviation) equals the square root of the sum of the squared deviations of each patch metric value from the mean metric value of the corresponding patch type, divided by the number of patches of the same type; that is, the root mean squared error (deviation from the mean) in the corresponding patch metric.

$CONNECT = \left[\frac{\sum_{j \neq k}^{n} c_{ijk}}{\frac{n_i(n_i-1)}{2}}\right](100)$	cijk = joining between patch j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user specified threshold distance ni = number of patches in the landscape of the corresponding patch type (class).	CONNECT equals the number of functional joinings between all patches of the corresponding patch type (sum of cijk where cijk = 0 if patch j and k are not within the specified distance of each other and cijk = 1 if patch j and k are within the specified distance), divided by the total number of possible joinings between all patches of the corresponding patch type, multiplied by 100 to convert to a percentage

3. RESULTS AND DISCUSSION

3.1. River network

Corumbataí and Rio Claro municipalities have both two classes of river width: up to 10 meters and between 10 and 50 meters. The first class represents more than 90% of all river channels in these sub-basins. Piracicaba municipality has three types of river width: up to 10 meters, between 10 and 50 meters, and from 50 and 200 meters. Once again, more than 90% of all river channels belong to the first class in this sub-basin.

A predominant dendritic river pattern was found in all sub-basins. Moreover, the drainage systems are characterized by large number of small size streams. Corumbataí river sub-basin is divided into two municipalities, Corumbataí, where forms the head of the Corumbataí river, and Rio Claro, where the river mouth forms the head of the Piracicaba river in the transition to Piracicaba municipality at the Piracicaba river sub-basin, where the river takes its full larger form.

The majority (98.5%) of Corumbataí municipality's river network is composed of streams with channels up to 10 meters wide, while 1.5% is made of river channels between 10 and 50 meters wide. Rio Claro municipality river network is similar, with a predominance of 91.2% of streams with channels up to 10 meters wide, and 8.8% of the network made of river channels between 10 and 50 meters wide. Piracicaba municipality's river network is composed of 96% of streams with channels up to 10 meters wide, 1.1% of river channels between 10 and 50 meters wide, and 2.9% of river channels between 50 and 200 meters wide (figure 5).

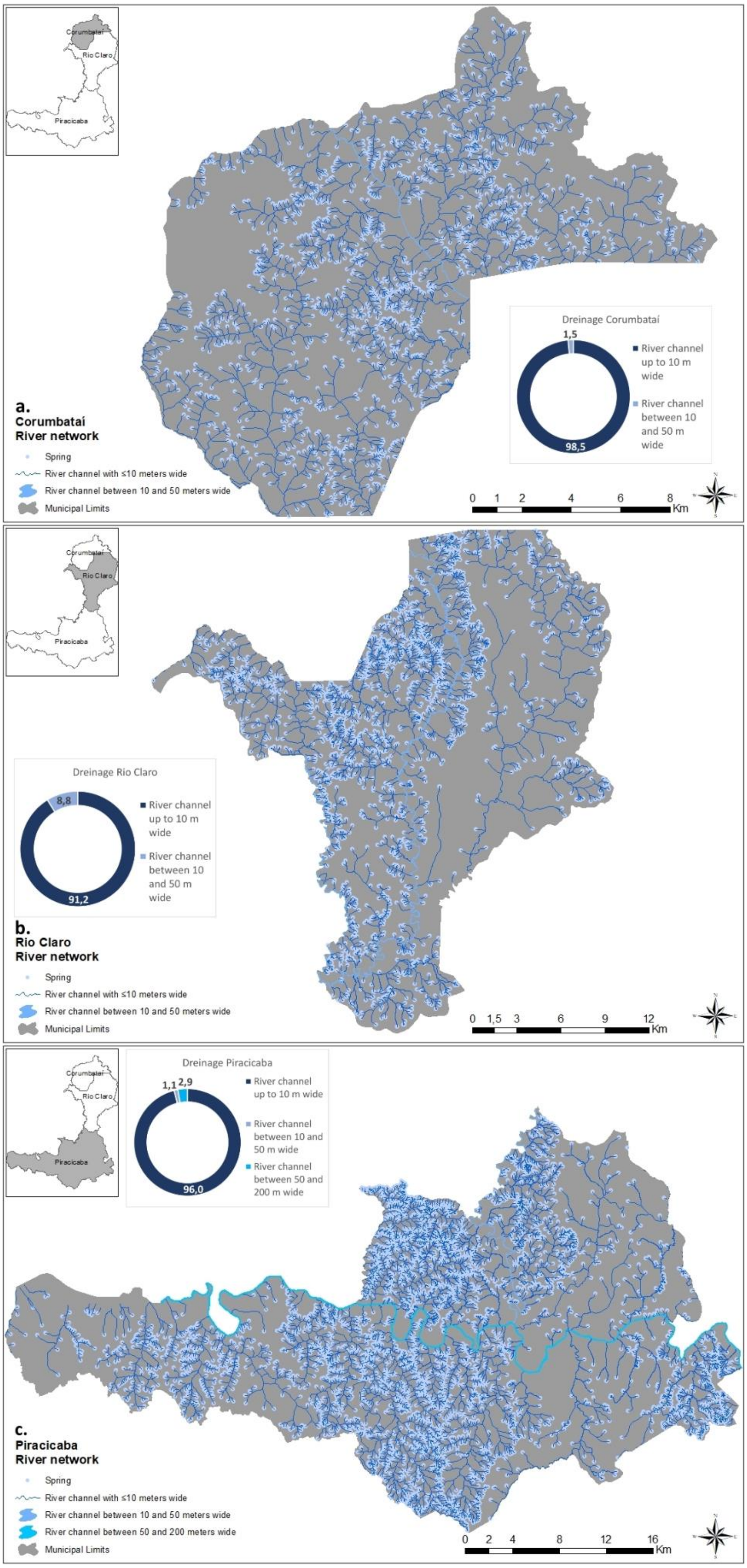


Figure 5. River Network and drainage percentages of each river channel class in Corumbataí (a), Rio Claro (b), and Piracicaba (c) municipalities within Corumbataí river and Piracicaba river sub-basins, located in São Paulo State, Brazil.

Piracicaba river sub-basin has larger number of headwaters within its river network, totalizing 3,715, while Corumbataí river sub-basin has a total of 2,991 headwaters within its river network. Piracicaba river sub-basin also has the most extensive river channel of up to 10 meters wide (2,219.1 km), while Corumbataí sub-basin has a total of 1,647 km of this channels size (table 6).

For river channels between 10 and 50 meters wide, Corumbataí river sub-basin has a total of 103.2 km, while in Piracicaba river sub-basin this value is 26.1 km. Only Piracicaba river sub-basin has a river channel between 50 and 200 meters wide, which accounted for 67.0 km of the river network. Corumbataí river sub-basin has drainage density of 5.2, while in Piracicaba river sub-basin this value was 2.2.

Table 6. Mileage of each river channel size, number of points of headwaters, and drainage density for each municipality, along with municipal area for the municipalities of Corumbataí, Rio Claro, and Piracicaba within Corumbataí river and Piracicaba river sub-basins.

	Corumbataí	**Rio Claro**	**Piracicaba**
Municipal Area (km²)	232.099	488.734	1,378.1
Headwater (Points)	1,371	1,620	3,715
River channels up to 10 m wide (km)	686.3	960.7	2,219.1
River channel between 10 and 50 m wide (km)	10.3	92.9	26.1
River channels between 50 and 200 m wide (km)	-	-	67.0
Drainage density (km. km-²)	3.00	2.16	2.23

The drainage density of a watershed describes the physical parameters of a drainage basin, depends on both climate and physical characteristics, as the runoff in a watershed is affected by the type of the underlying rock and the permeability of the soil. Therefore., a more impermeable ground or exposed bedrock will eventually lead to more frequent stream as the surface water runoff is increased (Horton, 1932).

Corumbataí and Piracicaba river sub-basins are both in a rugged region, with higher relief found in the northern region, forming a denser drainage system throughout the watershed. Therefore, drainage density in the northern region of the Corumbataí river sub-basin located in Corumbataí municipality has a value of 3.00, as the relief in the region is defined by slightly high altitudes, forming large numbers of tributaries up to 10 meters with (686.3 km), that flow into a river channel between 10 and 50 meters width (10.3 km), forming the main the Corumbataí main stem, that flows towards the south into Rio Claro municipality. In turn, this area has lower altitudes, resulting in a less dense drainage network, with a value of 2.2. However, the number of up to 10 meters with channels is larger (960.7 km). Moreover, as more channels flows into the main stem, the number of river channels of width between 10 and 50 meters also increases, reaching 92.9 km, and continues to flow towards the south into Piracicaba municipality, until it forms the Piracicaba river mouth.

In the Piracicaba municipality, relief is flatter and has the lower altitude of the entire study area, resulting in a low drainage density value of 2.23. This region has a higher number of tributaries of up to 10 meters width (2,219.1 km) than the previous ones, but a smaller amount of river channels between 10 and 50 meters wide (26.1 km). A sole river channel between 50 and 200 meters wide with 67.0 km, the Piracicaba river is found in the middle of the watershed in the municipality.

As shown in other studies (Almeida et al., 2018) negative impacts on river basins have a strong relation with their drainage system, mainly due to the high number of channels of lower orders, which usually are primarily degraded by human activities. These are very sensitive areas and, for the most part, are located in rugged relief and therefore more susceptible to erosive processes. In our study area, a similar pattern was found, with more susceptible areas located in Corumbataí sub-basin.

3.2. Land Tenure

Overall, 4,313 properties were registered in our study area. Of this total, 1,924 properties were located in Corumbataí river sub-basin and 2,389 in Piracicaba river sub-basin. In both sub-basins, a total of 3,766 properties were classified as small size, 440 as medium size, and 107 as large size (Figure 6).

Piracicaba municipality encompassed the large number of rural properties, 2389 or 55.4%, more than half of the rural properties are concentrated in this municipality. In Rio Claro, 1322 were found, the equivalent to 30.7% of the total rural properties. The lowest number were found in Corumbataí municipality, with only 602 or 14%.

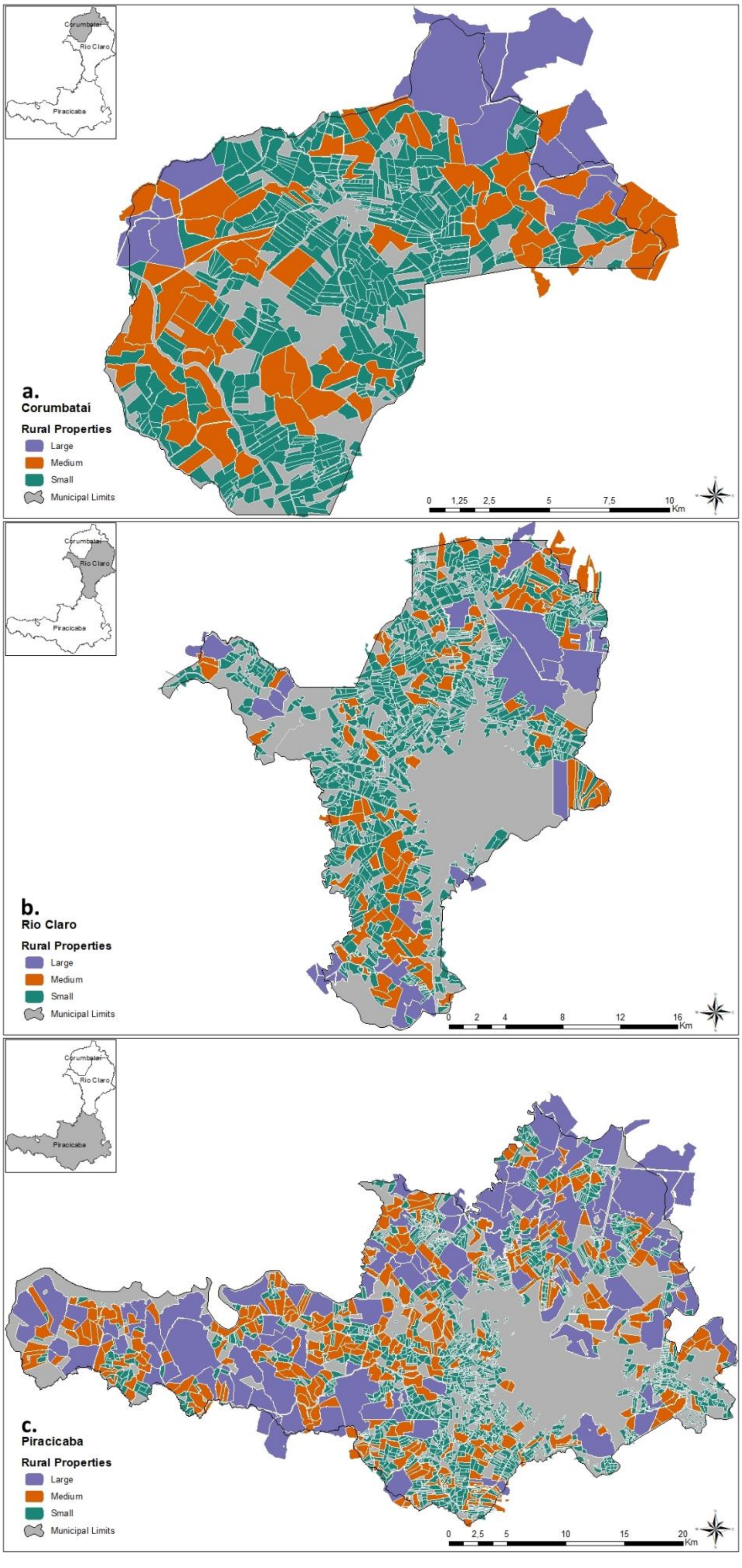


Figure 6. Land tenure for the municipalities of Corumbataí (a), Rio Claro (b), and Piracicaba (c), São Paulo State, Brazil, classified by property size, as in the NVPL 2012 Fiscal Module, for small (1-4 FM), medium (4-15 FM), and large (>15 FM). Source: Freitas et al. (2018).

As show in Figure 7, the spatial distribution among the three municipality by property size had a similar pattern, with Piracicaba concentrating the larger number of small, medium, and large farms, followed by Rio Claro and Corumbataí. Corumbataí municipality had registered 534 small properties, 59 medium properties, and 9 large properties, in Rio Claro municipality were registered 1,223 small properties, 83 medium properties, and 16 large properties; while in Piracicaba municipality had 2,009 small properties, 298 medium properties, and 82 large properties.

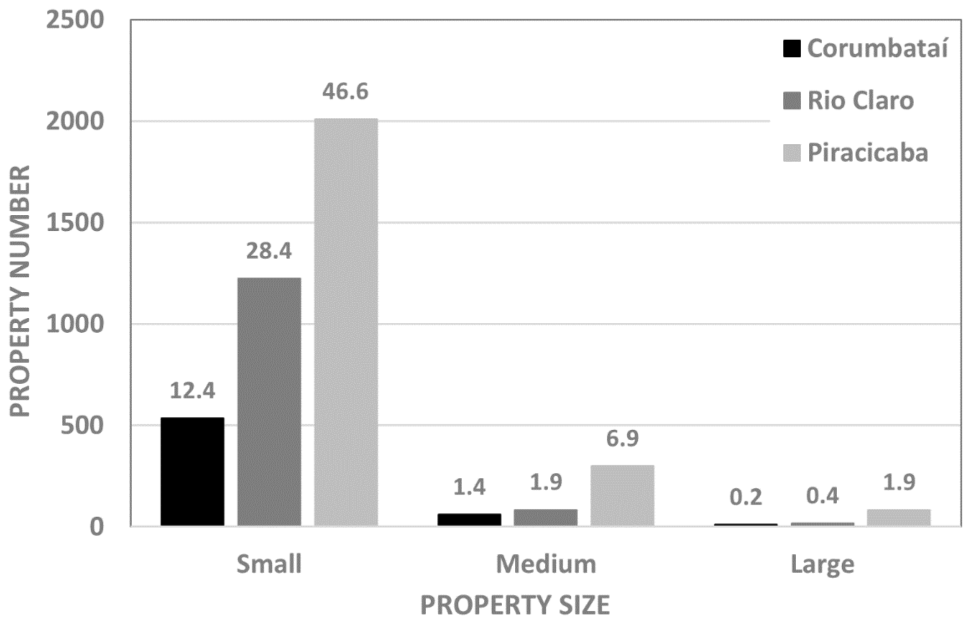


Figure 7. Comparison of the spatial distribution of rural properties in both sub-basins of Corumbataí River and Piracicaba River, in São Paulo Estate, Brazil.

In terms of areal extent, 134,200 ha were declared as belonging to rural properties in both sub-basins. Of this total, 21,994.71 ha (16.4%) in Corumbataí municipality, 32,505.9 ha (24.2%) in Rio Claro municipality, and 79,699.35 ha (59.4%) in Piracicaba municipality.

Figure 8 shows the comparison between the number of properties of each size registered and the percentage of area occupied by those properties in each municipality. Corumbataí is mostly occupied by small size properties with 36.3% of the total municipal area, medium size properties occupied 26.1% and large size properties occupied 16.5%. Rio Claro municipality small size properties encompass 34.9% of the area, while medium and large properties are found in 15.1% and 15.2% of the municipality area, respectively. In Piracicaba municipality, large properties occupied most of area with 26.7%, medium properties with 16.2%, and 14.9% small properties.

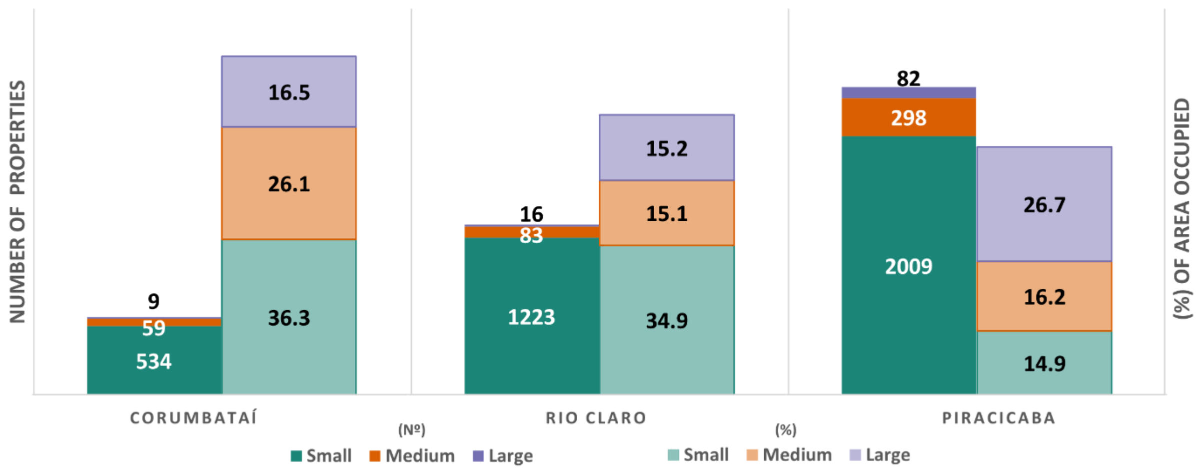


Figure 8. Comparison between the number of properties and percentages of area each class of property size occupied in the municipalities of Corumbataí, Rio Claro and Piracicaba, São Paulo, Brazil.

Although in lower number, large properties encompass most of the area in Piracicaba municipality, while the smaller ones present an opposite pattern and are spatially concentrate in both Corumbataí and Rio Claro municipalities. This is a result of different types of historical land occupation. Piracicaba, is larger in area and spreads in a flatter relief, having a long history of extensive agricultural production such as sugarcane. Sugarcane has been mostly cultivated in larger properties, which still is the dominant pattern. At both Corumbataí and Rio Claro municipalities, a more rugged relief and a different historical land occupation led to different types of crops being cultivated, such as pastures and annual crops. This, associated with the division of large properties into smaller ones in the heritage process, resulted in a landscape dominated by smaller farms.

The analysis of our 2019 PPAs LULC maps, shows that the predominant land use classes within rural properties (Figure 9) were both native vegetation and pasture. Small properties in Corumbataí municipality PPAs were mostly covered by pasture encompassing 58.1% of the area, while native vegetation covered 38.6%. Sugarcane and forestry plantation occupied almost the same area, 1.2% and 1.5%, respectively, and agriculture was found in only 0.7% of the PPAs. In medium properties, 61.5% PPAs areas were cover by native vegetation, followed by pasture (33.3%), forestry plantation (2.7%), sugarcane (1.8%) and agriculture (0.7%). Large properties held the larger area of native vegetation in PPAs, 74.3%, and the smaller area of pasture, 21.2%. Forestry plantation occupied 4.1%, while both sugarcane and agriculture occupied 0.3% and 0.1% respectively.

A similar distribution pattern of PPAs land cover was found in Rio Claro municipality, with native vegetation being the predominant in small (50.4%), medium (58.9%) large (73%)

properties. Pasture occupied the second-largest area in small properties PPAs, 42.6%, followed by medium (33%), and large (18.3%) ones. A similar pattern was found for sugarcane, which covered 5.7% of small properties, while 7.5% and 7.2% in medium and large ones, respectively. Both forestry plantation and agriculture occupied small portions of PPAs, with 0.8%, 0.3%, and 0.6% of forestry plantation, and 0.4%, 0.3%, and 0.9% of agriculture in small, medium, and large, respectively.

In Piracicaba municipality, PPAs land cover in rural properties presented some similar patterns of land use as in Corumbataí. Small properties were dominated by pasture (46%), followed by native vegetation (39.5%), sugarcane (13.7%), while agriculture and forestry plantation cover 0.4% and 0.8%, respectively. Medium properties presented an opposite pattern for native vegetation (44%) and pasture (36.4%), while sugarcane covered 18.3%, and agriculture and forestry plantation were found in 0.4% and 0.9%, respectively. Large properties had the larger area of native vegetation in its PPAs, 62%. Pasture covered 22.8%, sugarcane 14.2% of, while agriculture and forestry plantation were found covering both 0.5%.

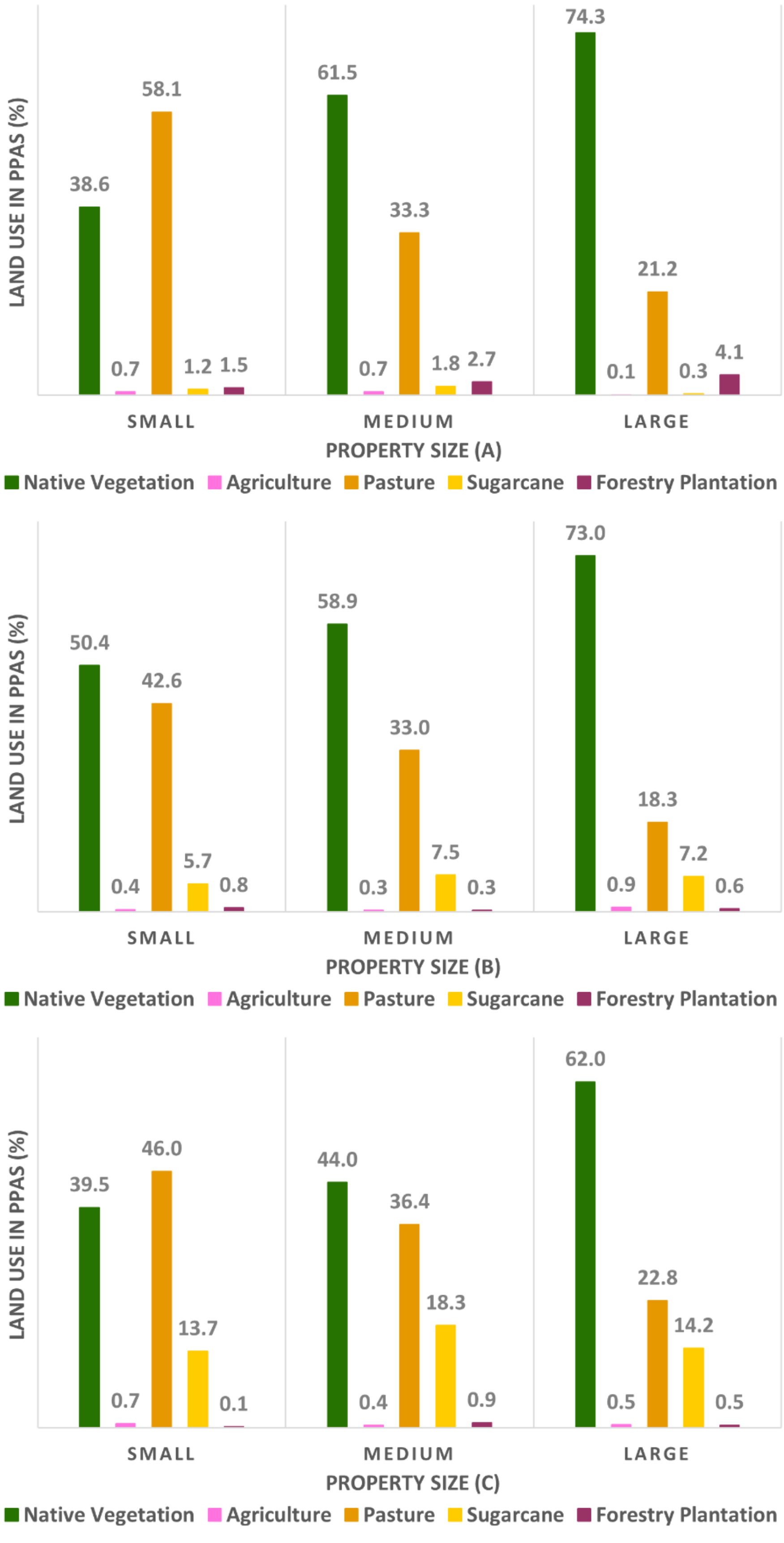


Figure 9. Land use in PPAs within rural properties classes in Corumbataí (A), Rio Claro (B), and Piracicaba (C) municipalities, São Paulo Estate, Brazil.

This different patterns of PPAs land use can be related to the landscape topography. Corumbataí's larger properties are located in the northern region, where the relief is steeper and extensive crops are difficult to grow and manage. Moreover, they are found in a smaller portion of the total area. Medium and smaller properties, besides being in larger number and occupy larger areas, are located in landscape more central regions, where the relief is flatter, allowing crops and pastures to be growth. In Rio Claro, larger properties are also located in higher lands, relief favors native vegetation conservation, while medium and small properties are located in flatter relief, spreading on a larger area, where smaller rivers are found. Moreover, in their PPAs pasture and sugarcane crops can be growth.

In Piracicaba, larger properties are located in most peripheral areas and occupy a larger portion of the municipality area. Therefore, most of smaller water bodies and its PPAs are also located in higher relief, where lands are favorable for native vegetation. Other types of land use are more commonly found in medium and small properties PPAs found in central areas, where a flatter relief favors sugarcane crops. In this region, medium properties are more prone for this crop cultivation, while pasture is mostly found in small ones.

Preto et al. (2020) assessed a similar pattern at Querência and São José do Xingu (MT) municipalities, where small and medium-sized rural properties predominated in numbers. Larger properties, although were in fewer numbers, dominated the landscape, concentrating 76% of the land. This pattern was associated to the main economic activities in the region, located in an Amazon and Cerrado transition frontier, where soybean production and cattle ranching, were the type of land use associated with larger environmental deficits in PPAs. A different pattern was found in Mirante do Paranapanema (SP), where a larger land concentration was found within rural settlements encompassing 26.9% of the landscape, while large properties encompassed 23.2% of the municipality area (Pimenta, 2019).

Schimitt et al. (2016) also noticed that most of natural vegetation (in primary and secondary stages) in the micro basin of Vargem dos Pinheiros River (SC) were mainly in slopes above 45%, where other type of land use such as perennial and annual crops was unfeasible. Moreover, areas with more favorable conditions for agriculture were responsible for the total vegetation suppression and land use was based on agriculture and cattle ranching carried in small rural properties. Therefore, land tenure is a complex process, drive by colonization process, biophysical characteristic, land use type and management practices, markets, among others, leading to different patterns.

3.3. Corumbataí and Piracicaba rivers sub-basins landscape characterization

The landscapes of all three studied municipalities were dominated by agricultural lands, encompassing 70.2%, 76.8%, and 86.7% of the total area of Corumbataí, Rio Claro, and Piracicaba municipalities, respectively (IBGE, 2017). The main land uses in all of them were pastures, crops, and sugarcane. However, a spatial pattern from north to south was found. The analysis of the 2019 land use map (MapBiomas dataset; Figure 10), showed that while Corumbataí (further north) is dominated by pasture and agricultural lands (about 62.2% of its total area), as we move towards the south, Rio Claro and Piracicaba are increasingly dominated by sugarcane (24.5% and 31.7%, respectively). An opposite pattern was found for native vegetation cover, which increases from south to north, encompassing 8.7% at Piracicaba, 15% at Rio Claro, and 21.2% in Corumbataí landscape.

Forestry plantation, due to a growing economic interest and associated with restoration work in PPAs with natural vegetation, has shown an increase from south to north, more noticeable and in larger areas in north Corumbataí representing 5.8% of the landscape, decreasing to only 0.9% in Rio Claro to grow a little more going south to Piracicaba with 1.2%. As for urban infrastructure, a decreasing pattern was noticed from south to north, with 10.2% of Piracicaba landscape, 9.7% in Rio Claro, and only 0.4% in Corumbataí.

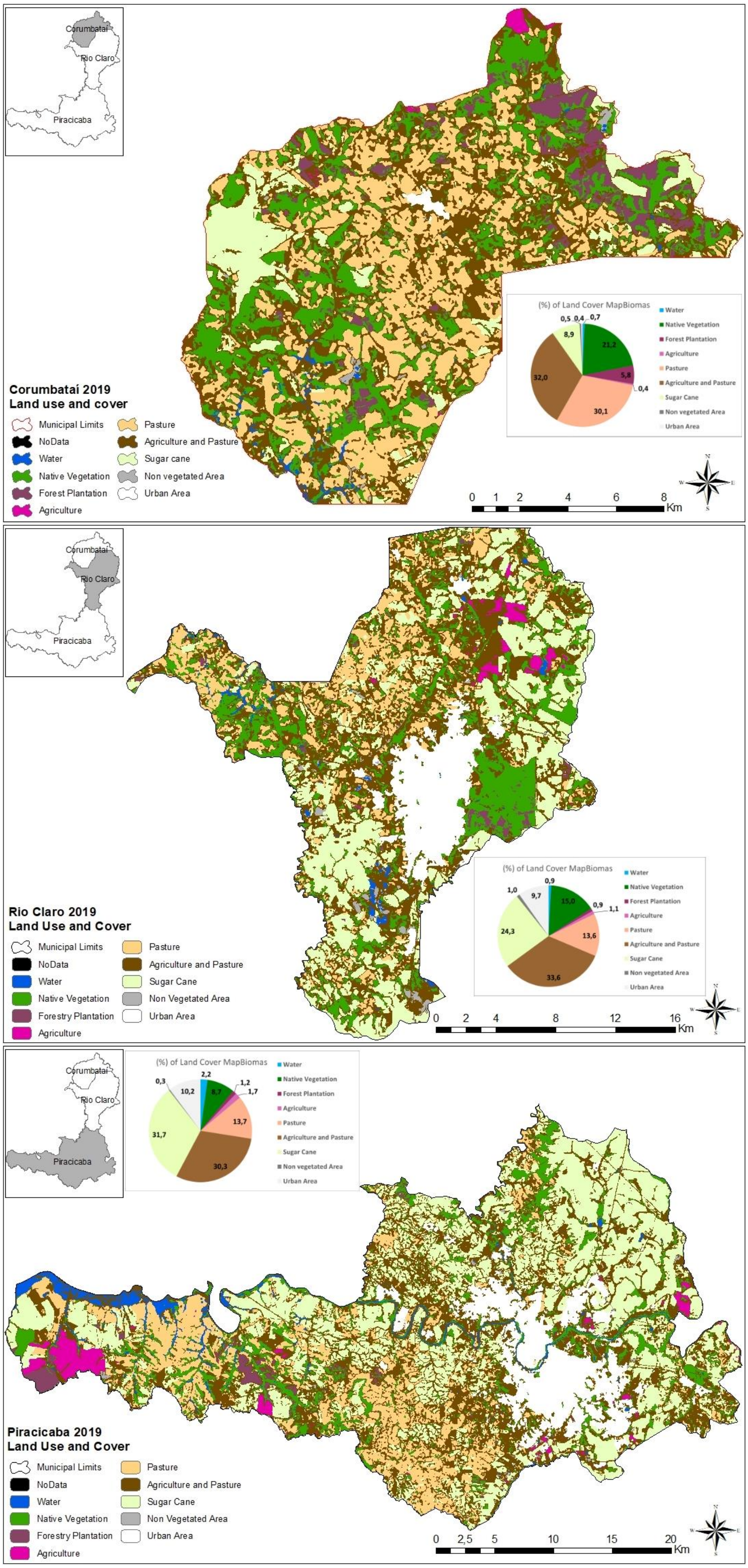


Figure 10. Characterization of Land Use and Cover of Corumbataí (a), Rio Claro (b), and Piracicaba (c), located in São Paulo State, Brazil. Source: Mapbiomas collection 6.0, 2019.

3.3.1. Land Use and Land Cover Changes in riparian PPAs

A total of 4,514 ha of riparian PPAs were analyzed in Corumbataí municipality, 6,893 ha in Rio Claro, and 15,407 ha in Piracicaba. Table 7 shows the percentages of occupied areas by land use and land cover classes through the years. In 2009, 51.5% of PPAs had vegetation deficits in Corumbataí, 40.7% in Rio Claro, and 47.6% in Piracicaba.

Table 7. Percentages of area occupation of classes of land use and land cover in riparian PPAs of municipalities of Corumbataí, Rio Claro, and Piracicaba for the years 2009, 2014, and 2019.

	Corumbataí (%)			Rio Claro (%)			Piracicaba (%)		
	2009	2014	2019	2009	2014	2019	2009	2014	2019
Native Vegetation	48.5	43.1	48.4	59.3	51.6	59.7	52.4	48.5	53.0
Agriculture	1.1	1.2	0.6	0.7	0.7	0.4	0.4	0.3	0.6
Forestry plantation	0.8	1.7	2.0	0.2	0.4	0.6	0.1	0.2	0.4
Sugarcane	1.4	1.3	1.3	5.5	5.3	5.5	15.5	14.8	13.2
Pasture	48.1	52.6	47.7	34.3	42.0	33.8	31.6	36.2	32.8

In 2009, 48.1% of the total Corumbataí PPAs area was covered by pasture, 34.3% in Rio Claro, and reaching 31.6% in Piracicaba. Sugarcane was the second class with the higher contribution to this deficit in this year, occupying 1.4%, 5.5%, and 15.5% of the PPAs total area in Corumbataí, Rio Claro, and Piracicaba respectively (figure 11).

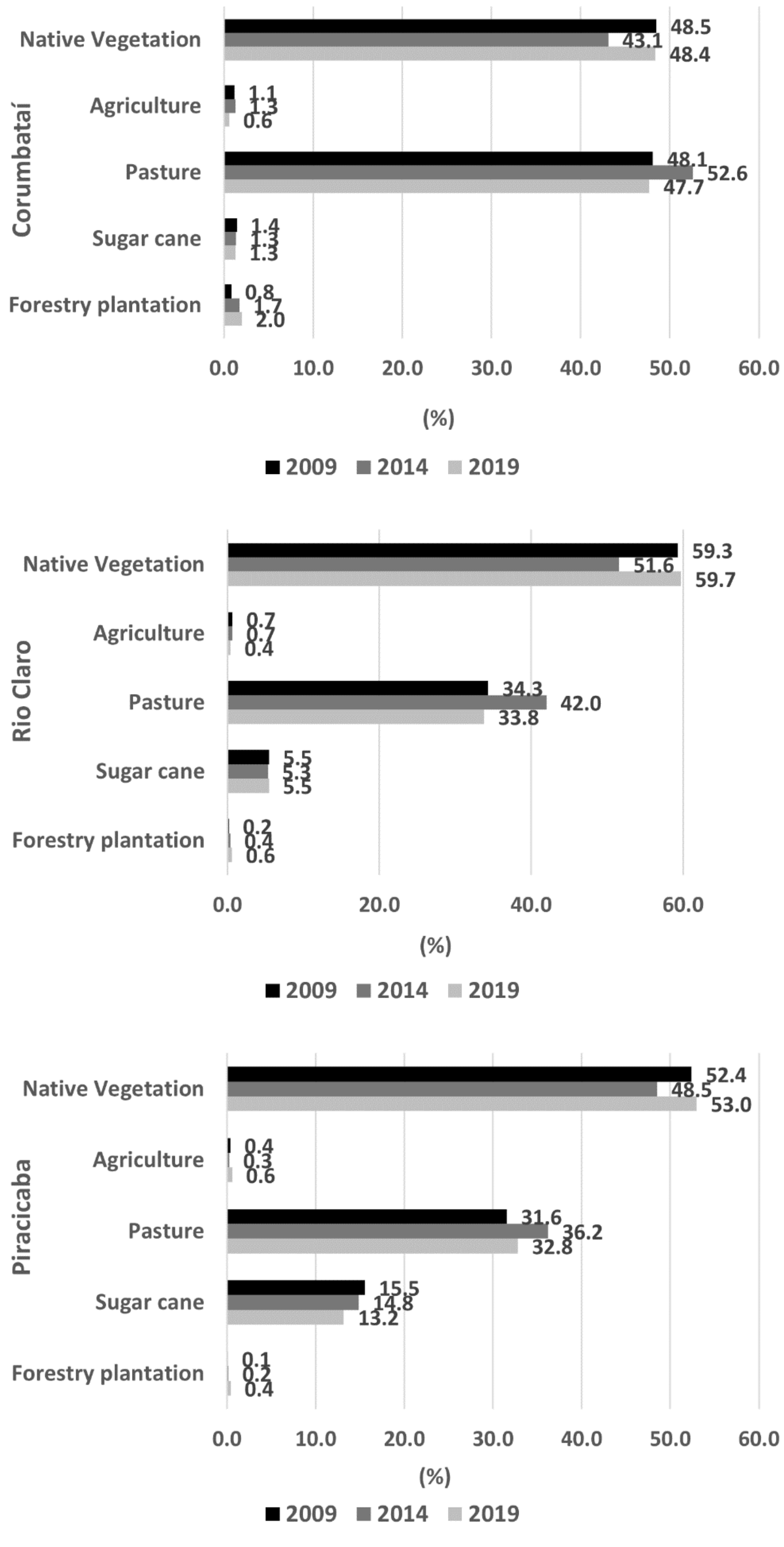


Figure 11. Representation of variations in the area occupied by each class of land use and occupation within the riparian Permanent Preservation Areas (PPAs) for the years 2009, 2014, and 2019 in the municipalities of Corumbataí, Rio Claro, and Piracicaba.

The first years after NVPL implementation were marked by different dynamics in land use. In 2014, land occupation in PPAs in all municipalities increased, and forest cover was reduced by about 5% in Corumbataí, reaching 7% in Rio Claro and 4% in Piracicaba. Pasture presented an increasing pattern in area in all municipalities in 2014, increasing about 4.5% in Corumbataí, 7.7% in Rio Claro, and 4.6% in Piracicaba, occupying an area larger than the riparian vegetation itself in the first one. Sugarcane had a different pattern, with a slight areal decrease, 0.1% in Corumbataí, 0.2% in Rio Claro, and 0.7% in Piracicaba. Other classes of land use such as agriculture had their areas reduced from 2009 to 2014 in both Corumbataí (-0.2%) and Piracicaba (-0.1%), while in Rio Claro it remained with 0.7%. However, forestry plantation increased its areas occupied in all municipalities, with a higher increase in Corumbataí with 0.9%, Rio Claro increase 0.2%, and Piracicaba 0.1% in the same period.

A natural vegetation recovery pattern was found from 2014 to 2019, with a decrease in anthropic land use and occupation in PPAs in all municipalities, reducing back to 51.6% in Corumbataí, to 40.2% in Rio Claro, and to 47% in Piracicaba. This process leads to an increase in vegetation coverage by 5.3% in Corumbataí, 8.1% in Rio Claro, and 4.5% in Piracicaba. Pasture presented the highest decrease, of about 4.9% in Corumbataí, 8.2 in Rio Claro, and 3.4% in Piracicaba, while agriculture and forestry plantation showed a different trend. Forestry plantations expanded 0.3% in Corumbataí and 0.2% in both Rio Claro and Piracicaba. Agriculture showed a slight reduction in both Corumbataí (-0.6%) and Rio Claro (-0.3%), while an increase in Piracicaba (0.3%). As for sugarcane, a decreasing pattern was found in Piracicaba of about 1.6%, while in Rio Claro increased 0.2%, Corumbataí it remained at 1.3%.

Another point of interest in this dynamic is the first loss of vegetative cover and then an increase of this vegetation in the PPAs, one of the possible causes of this, mostly between 2009 and 2014, may be associated with the change in the Forest Code (Federal Law 12.651/2012, NVPL) that occurred in 2012 and reformulated important laws about conservation of native vegetation, and riparian zones were the ones most changed, opening gaps for the non-recovery of lost vegetation within these areas. Whereas the increase in the period from 2014 to 2019 might be because of natural regeneration of abandoned areas or as a result of inspection and assessment of these irregular PPAs in rural properties, therefore a mandatory recomposition took place.

Figure 12 describes the overall transitions among classes of land use change in each municipality from 2009 to 2014 and from 2014 to 2019. With the values obtained in the matrix (Table 8), referring to the replacement of the area occupied by each class of land use and cover within riparian PPAs, it was verified that in the first period studied, between 2009 and 2014, natural vegetation fragments replaced approximately 23.6% and 19.3% of the areas of pasture, 21.6% and 7.8% of sugarcane, and 41.1% and 34.5% of agricultural crops in both Corumbataí river sub-basin and Piracicaba river sub-basin, respectively. In the same period, sugarcane replaced 3.9% and 3.3% of pastures, and 13.8% and 13.4% of agricultural crops. The opposite was also observed, as 49.4% and 13.7% of the sugarcane area was replaced by pasture.

Pasture was the main responsible for the deficits of riparian vegetation in all study areas, as shown by the loss of vegetation cover in riparian PPAs, 40% and 17.9% were replaced by pasture, and 1.5% and 3.3% were replaced by sugarcane in Corumbataí sub-basin and Piracicaba sub-basin in the first period evaluated.

The transitions from pasture to natural vegetation and from vegetation to pasture can be considered equivalent in the Piracicaba river sub-basin, but in the Corumbataí river sub-basin the conversion of vegetation areas to pasture was greater than the recovery of vegetation in areas of pasture in the first period evaluated. On the other hand, changes from sugarcane to natural vegetation obtained values higher than the opposite in both sub-basins, which can explain the reduction of this land use type in this period.

Regarding the raise in the percentage of areas occupied by forestry plantation and agricultural crops between 2009 and 2014 (Figure 11), it was found that the forestry plantation area replaced 13.6% of sugarcane areas, and 1.8% of pastures areas, overall, in both sub-basins. There was also a replacement of 79.1% and 17.2% of forestry plantation by natural vegetation fragments in the first period studied in Corumbataí river sub-basin and Piracicaba river sub-basin. These represent forestry areas that were explored and later abandoned or reforested with native vegetation, which were already in the process of regeneration and recovery of the area in the period.

As for the area occupied by agricultural crops, 1.6% was replaced from pasture and 2.1% from sugarcane. Surprisingly, forestry plantation was replaced the most by agricultural crops, 27.8% altogether in both sub-basins in this same period.

Table 8. Transition matrix of the area percentage of the land use and land cover classes in riparian PPAs in the two periods for Corumbataí, Rio Claro, and Piracicaba municipalities.

	Classes of LULC 2014 in Corumbataí (%)				
Classes 2009	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	77.8	0.7	20.0	0.3	1.1
Agriculture	14.9	33.2	40.5	5.9	5.2
Pasture	10.2	0.8	86.5	0.9	1.2
Sugarcane	11.3	0.8	26.8	47.1	13.4
Forestry Plantation	23.5	17.3	11.6	0.02	47.5

	Classes of LULC 2019 in Corumbataí (%)				
Classes 2014	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	90.5	0.3	7.8	0.2	1.0
Agriculture	28.8	14.7	32.5	9.2	13.8
Pasture	15.9	0.4	81.4	0.8	0.9
Sugarcane	5.0	0.2	41.9	50.1	0.2
Forestry Plantation	24.5	4.5	15.7	0.9	54.2

	Classes of LULC 2014 in Rio Claro (%)				
Classes 2009	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	77.0	0.5	20.0	1.2	0.1
Agriculture	26.2	14.8	43.8	7.9	5.8
Pasture	13.4	0.6	81.7	3.0	0.6
Sugarcane	10.3	1.2	22.6	65.3	0.2
Forestry Plantation	55.6	3.9	12.6	0.5	27.3

	Classes of LULC 2019 in Rio Claro (%)				
Classes 2014	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	89.8	0.3	7.7	1.0	0.3
Agriculture	45.0	8.9	27.4	10.5	7.1
Pasture	28.2	0.5	67.7	1.7	0.6
Sugarcane	9.5	0.2	13.3	76.4	0.04
Forestry Plantation	37.2	0.8	17.3	0.6	39.6

	Classes of LULC 2014 in Piracicaba (%)				
Classes 2009	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	77.3	0.2	17.9	3.3	0.1
Agriculture	34.5	17.3	32.9	13.4	0.0
Pasture	19.3	0.2	75.9	3.3	0.2
Sugarcane	7.8	0.1	13.7	78.3	0.01
Forestry Plantation	17.2	6.5	6.7	1.0	68.2

	Classes of LULC 2019 in Piracicaba (%)				
Classes 2014	Native Vegetation	Agriculture	Pasture	Sugarcane	Forestry Plantation
Native Vegetation	84.6	0.4	11.4	1.5	0.1
Agriculture	43.0	20.5	19.6	6.2	4.3
Pasture	25.7	0.7	68.2	2.8	0.1
Sugarcane	9.4	0.3	12.6	76.0	1.3
Forestry Plantation	7.5	10.6	2.8	0.01	76.8

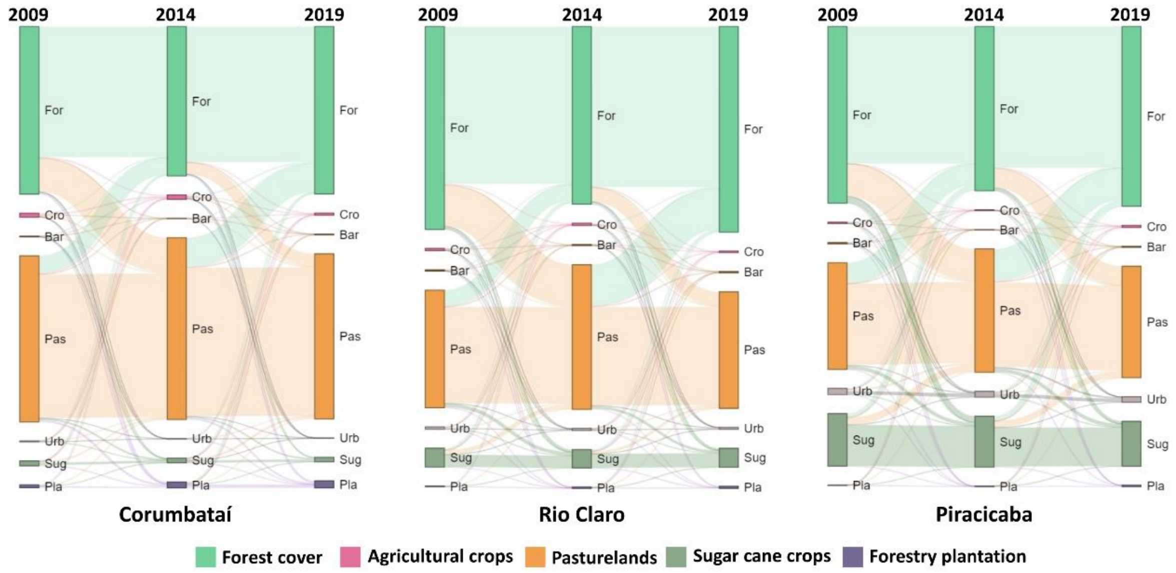


Figure 12. Land use and land cover transition for all pixels that have changed through time and in riparian Permanent Protected Areas (PPAs) in the Corumbataí and Piracicaba River sub-Basins from 2009 to 2019. The vertical boxes represent the proportion of the Corumbataí and Piracicaba River sub-Basins which each land use occupies in a certain year. The lines represent the change in land use and land cover that have occurred through the years, and the width of each line represents the amount of land that has been replaced with another use.

In the second period studied, between 2014 and 2019, natural vegetation replaced 1.6% and 9.4% of pastures areas, in both Corumbataí and Piracicaba river sub-basins, respectively, as well as 14.5% and 9.4% of sugarcane areas. Pasture had 2.5% and 2.8% of areas replaced by sugarcane, while converted 55.3% and 12.6% of areas of sugarcane, and 15.6% and 11.4% of areas of natural vegetation into pasture. Sugarcane converted 1.2% and 1.5% of natural vegetation areas in the period.

For this period, it was observed that the trend of increasing conversions of new pasture areas from areas of natural vegetation continued, despite having considerably reduced the absolute values in relation to the previous period, in the Corumbataí River sub-basin, while in the Piracicaba River sub-basin the values of conversion between pasture and vegetation are practically equivalent again, with a difference of approximately 2%. Whilst the trend of greater conversion of sugarcane areas to areas of natural vegetation was maintained in both sub-basins in this second period evaluated.

Forestry plantation continued to expand their areas of occupation in the sub-basins, replacing 1.4% of natural vegetation fragments altogether in both sub-basins, 1.6% of pastures, and agricultural crops had 20.9% and 4.3% of their area converted into forestry plantation in this period in Corumbataí river sub-basin and Piracicaba river sub-basin, respectively. Although, it had 33% and 2.8% converted into pastures, and 5.3% and 10.6% into agricultural crops.

Concerning the drop in the percentage of areas occupied by agricultural crops between 2014 and 2019, areas with agricultural crops were replaced by different uses, mainly by pastures (60% and 43.8%) and sugarcane (19.7% and 6.2%) in Corumbataí river sub-basin and Piracicaba river sub-basin, respectively, in the second studied period, which confirms that there were permutations of areas since the area of this class replaced areas occupied by other uses and coverages (Table 8).

In Corumbataí riparian PPAs in the municipality, a total amount of 481.4 ha has changed from native vegetation to different classes of land use, and a total of 244.5 ha of vegetation have been recovered in the first period from 2009 to 2014. In the second period, between 2014 and 2019, the total amount of deforestation was 181.1 ha, and the total vegetation recovery was 416.2 ha.

Figure 12 shows the transitions between classes of land use in PPAs in Corumbataí municipality, it's observed that pasture class was the one that presented, in absolute values, the largest extensions of area converted into forest cover, as well as new advances in deforestation, from 2009 to 2014, the class accounted for 221.0 ha (90.4%) of areas of recovered forest cover, and 436.5 ha (90.7%) of new deforestation, while from 2014 to 2019, it showed a slightly different scene, with 377.9 ha (90.8%) in areas with recovered vegetation cover against 152.3 ha (84.1%) in new deforestation.

For the period from 2009 to 2014, agriculture was responsible for 14.6 ha (3.0%) of new deforestation in PPAs and was responsible for 7.6 ha (3.1%) of areas of recovered vegetation. Forestry plantations were accountable for 23.7 ha (4.9%) of loss of vegetation, and 8.5 ha (3.5%) of vegetation recovered in the same period. From 2014 to 2019, agriculture impacts on PPAs have changed a bit throughout the municipality, new deforestation in Corumbataí were about 6.05 ha (3.3%), while vegetation recovery reached 16.2 ha (3.9%). Forestry plantation in PPAs have extended 19.7 ha (10.9%), and retreated 19.0 ha (4.6%) in PPAs vegetation.

PPAs in Corumbataí are mostly present inside particular rural properties, those representing roughly 83% (3,772.3875 ha) of all riparian zones (figure 13).

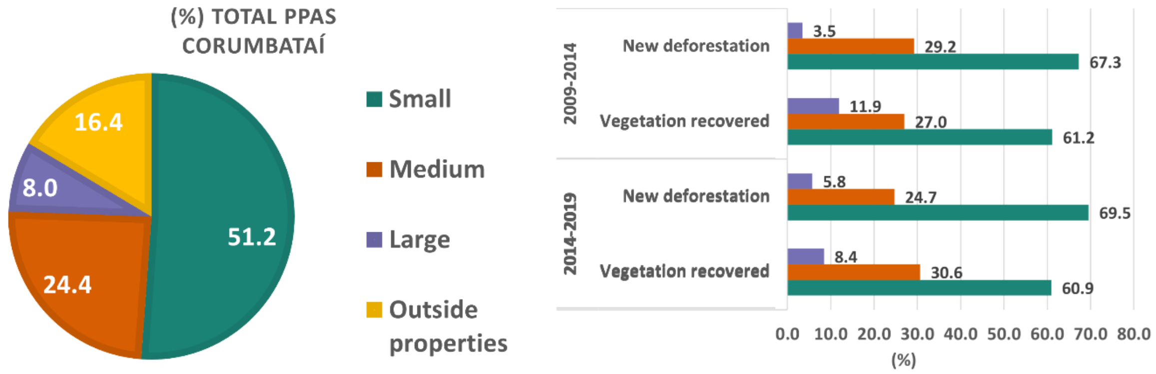


Figure 13. Riparian PPAs within each size property class in Corumbataí and contribution of each size of property in deforestation and vegetation recomposition observed in the period from 2009-2014 and 2014-2019.

Small properties held 51.2% (2,309.548 ha) of PPAs in the municipality, in the first period, between 2009 and 2014, they were responsible for 67.3% (259.6 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 61.2% (127.86 ha) of vegetation in the same period. For the second period, from 2014 to 2019, small properties were accountable for 69.5% (106.8 ha) of deforestation and 60.9% (208.40 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

Medium properties held 24.4% (1,101.595 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were accountable for 29.2% (112.6 ha) of deforestation in all PPAs within rural properties, while being responsible for 27% (56.41 ha) of recomposition of vegetation in the same period. For the second period, between 2014 and 2019, medium properties were responsible for 24.7% (37.9 ha) of vegetation loss, and 30.6% (104.80 ha) of vegetation recovery in PPAs within rural properties in the municipality.

Large properties held 8% (361.245 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were responsible for 3.5% (13.5 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 11.9% (24.79 ha) of vegetation in the same period. For the second period, between 2014 and 2019, large properties were accountable for 5.8% (8.8 ha) of deforestation and 8.4% (28.83 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

With pasture and forestry plantation being the classes of land use with larger impacts in both loss and gain of vegetation. Also, they were the most dominant classes in all sizes of rural property, the first being responsible for approximately 90% of new deforestation in all properties, whilst the second place stands on a maximum of 34% at large properties, and less than 15% in small and medium properties. At the same time, vegetation recovery is more evident in areas of pasture use in all properties, with an average of 90% of vegetation recovered from those areas, while forestry plantation remains second, with a recovery of a maximum of 12% at large properties, and less than 6% in small and medium properties (figure 14).

Figure 14. Relative contribution of each class of land use and occupation to the new deforestation and to the recovery of vegetation deficits observed in the period from 2009-2014 and 2014-2019, in Corumbataí properties. Small properties (a1), Medium properties (a2), and Large properties (a3). Values, in percentages, weighted in relation to the total area of new deforestation and vegetation deficits recovered, respectively, in the municipality PPAs.

In Rio Claro riparian PPAs, a total of 880.7 ha of vegetation were lost, and 370.9 ha recovered from 2009 to 2014. From 2014 to 2019, 330.7 ha changed to other classes of land use, while 877.7 ha were reforested.

Figure 12 shows the transitions between classes of land use in PPAs in Rio Claro municipality, in the first period, pasture was responsible for 807.0 ha (91.6%) of new deforestation, and 313.1 ha (84.4%) of recovered vegetation. An opposite patter was observed from 2014 to 2019 with 273.4 ha (82.7%) of new deforestation and 812.2 ha (92.5%) of vegetation recovered.

Agriculture and sugarcane also have some impacts on PPAs, agriculture being responsible for 19.1 ha (2.2%) of new deforestation, for the years from 2009 to 2014, and 12.1 ha (3.3%) of vegetation were recovered from agriculture. Sugarcane crops were responsible for 48.8

ha (5.5%) of deforestation and 38.2 ha (10.3%) of new forest coverage. For the period of assessing these changes' impact from 2014 to 2019, impacts from agriculture on PPAs have alternated in the municipality, new deforestation were about 9.1 ha (2.8%) and 20.7 ha (2.4%) of vegetation recovered. Sugarcane crops in Rio Claro in the period had 37.0 ha (11.2%) of vegetation converted into the class, and 34.8 ha (4%) converted back into vegetation in PPAs.

PPAs in Rio Claro are mostly present inside particular rural properties, those representing roughly 69% (4,756.2 ha) of all riparian zones (figure 15).

Figure 15. Riparian PPAs within each size property class in Rio Claro and contribution of each size of property in deforestation and vegetation recomposition observed in the period from 2009-2014 and 2014-2019.

Small properties held 41.9% (2,891.89 ha) of PPAs in the municipality, in the first period, between 2009 and 2014, they were responsible for 57.7% (372.84 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 60.5% (159.05 ha) of vegetation in the same period. For the second period, from 2014 to 2019, small properties were accountable for 62.6% (148.595 ha) of deforestation and 55.8% (350.36 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

Medium properties held 16.7% (1,150.07 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were accountable for 26.9% (173.98 ha) of deforestation in all PPAs within rural properties, while being responsible for 22.5% (59.12 ha) of recomposition of vegetation in the same period. For the second period, between 2014 and 2019, medium properties were responsible for 22.4% (53.2 ha) of vegetation loss, and 28.3% (177.72 ha) of vegetation recovery in PPAs within rural properties in the municipality.

Large properties held 10.4% (714.225 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were responsible for 15.3% (99.07 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 17% (44.665 ha) of vegetation in the same period. For the second period, between 2014 and 2019, large properties were accountable for 14.9% (35.42 ha) of deforestation and 15.9% (99.675 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

With pasture and sugarcane crops being the classes of land use with the most impacts in both loss of vegetation and gain of vegetation, and the most dominant classes in all sizes of rural property, the first being responsible for approximately 90% of new deforestation in all properties, whilst the second place stands on a maximum of 21% at large properties, and less than 14% in small and medium properties. At the same time, vegetation recovery is more evident in areas of pasture use in all properties, with an average of 90% of vegetation recovered from those areas, while sugarcane crops remain second, with a recovery of a maximum of 21% at large properties, and less than 12% in small and medium properties (figure 16).

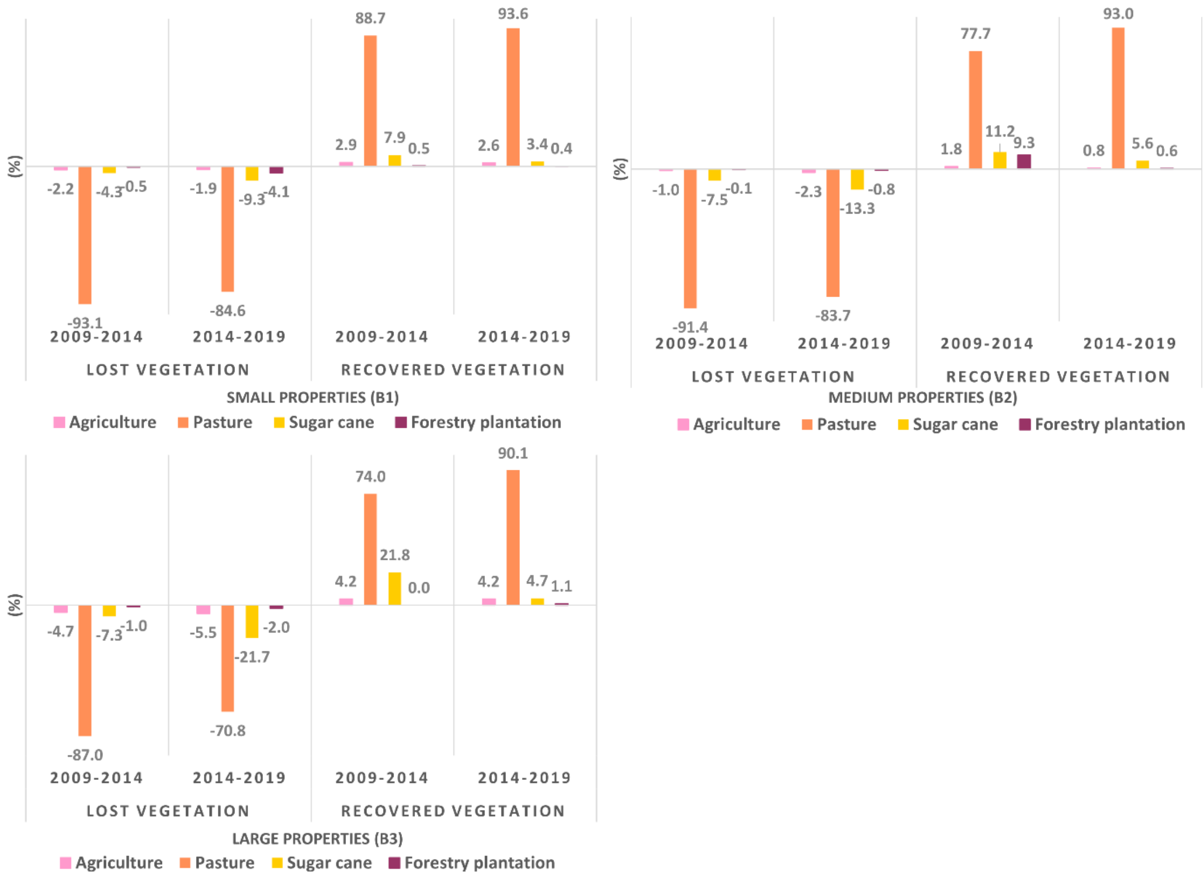


Figure 16. Relative contribution of each class of land use and occupation to the new deforestation and the recovery of vegetation deficits observed in the period from 2009-2014 and 2014-2019, in Rio Claro properties. Small properties (b1), Medium properties (b2), and Large properties (b3). Values, in percentages, weighted in relation to the total area of new deforestation and vegetation deficits recovered, respectively, in the municipality PPAs.

Piracicaba riparian PPAs from 2009 to 2014, had a total amount of 1,703.8 ha of new deforestation, and 1,128.7 ha of new areas of vegetation recovered. While in the second period, from 2014 to 2019, 1,005.4 ha of loss and 1,666.6 ha recovery of vegetation in the PPAs.

Figure 12 shows the transitions between classes of land use in PPAs in Piracicaba municipality, where it was observed that a similar trend was found for areas covered by pasture, in the first period, between 2009 and 2014, 1,421.7 ha (83.4%) were deforested, while 922.6 ha (81.7%) of vegetation was recovered in pasture areas. In the following period, from 2014 to 2019, was observed 853.8 ha (84.9%) of new deforestation and 1,432.1 ha (85.9%) of vegetation recovered.

Sugarcane was the second most important class in terms vegetation loss in PPAs from 2009 to 2014, when 261.1 ha (15.3%) of the new deforestation was associated to this class of land use. This loss was balanced out by a 182.7 ha (16.2%) recovered area of vegetation. From 2014 to 2019, 113.5 ha (11.3%) of vegetation were converted into sugarcane, while 214.9 ha (12.9%) were recovered to vegetation.

PPAs in Piracicaba were mostly found inside private rural properties, representing roughly 76.9% (11,846 ha) of all riparian zones (figure 17).

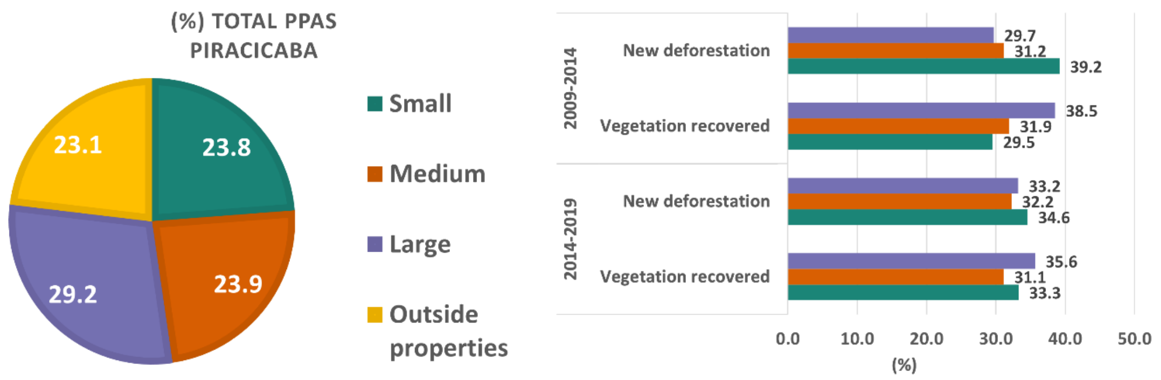


Figure 17. Riparian PPAs within each size property class in Piracicaba and contribution of each size of the property in deforestation and vegetation recomposition observed in the period from 2009-2014 and 2014-2019.

Small properties held 23.8% (3,665.05 ha) of PPAs in the municipality, in the first period, between 2009 and 2014, they were responsible for 39.2% (482.1 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 29.5% (252.13 ha) of vegetation in the same period. For the second period, from 2014 to 2019, small properties were accountable for 34.6% (271.9 ha) of deforestation and 33.3% (381.40 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

Medium properties held 23.9% (3,682.61 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were accountable for 31.2% (383.4 ha) of deforestation in all PPAs within rural properties, while being responsible for 31.9% (272.78 ha) of recomposition of vegetation in the same period. For the second period, between 2014 and 2019, medium properties were responsible for 32.2% (253.4 ha) of vegetation loss, and 31.1% (356.97 ha) of vegetation recovery in PPAs within rural properties in the municipality.

Large properties held 29.2% (4,498.33 ha) of PPAs in the municipality, in the first period, from 2009 to 2014, they were responsible for 29.7% (365.2 ha) of deforestation in all PPAs within rural properties, while being responsible for recovering 38.5% (329.27 ha) of vegetation in the same period. For the second period, between 2014 and 2019, large properties were accountable for 33.2% (261.2 ha) of deforestation and 35.6% (408.66 ha) of recomposition of vegetation in PPAs located inside rural properties in the municipality.

Pasture and sugarcane were the most dominant classes in all sizes of rural properties, and therefore associated with the impacts on both vegetation loss and gain. Pasture was responsible for approximately 88% of new deforestation, whilst sugarcane had a maximum of 28% at large properties and less than 19% in small and medium ones. At the same time, vegetation recovery was more evident in pasture areas in all properties, where an average of 80% of vegetation recovered was observed, while sugarcane had a recovery of a maximum of 24% at large properties, and less than 17% in small and medium properties (figure 18).

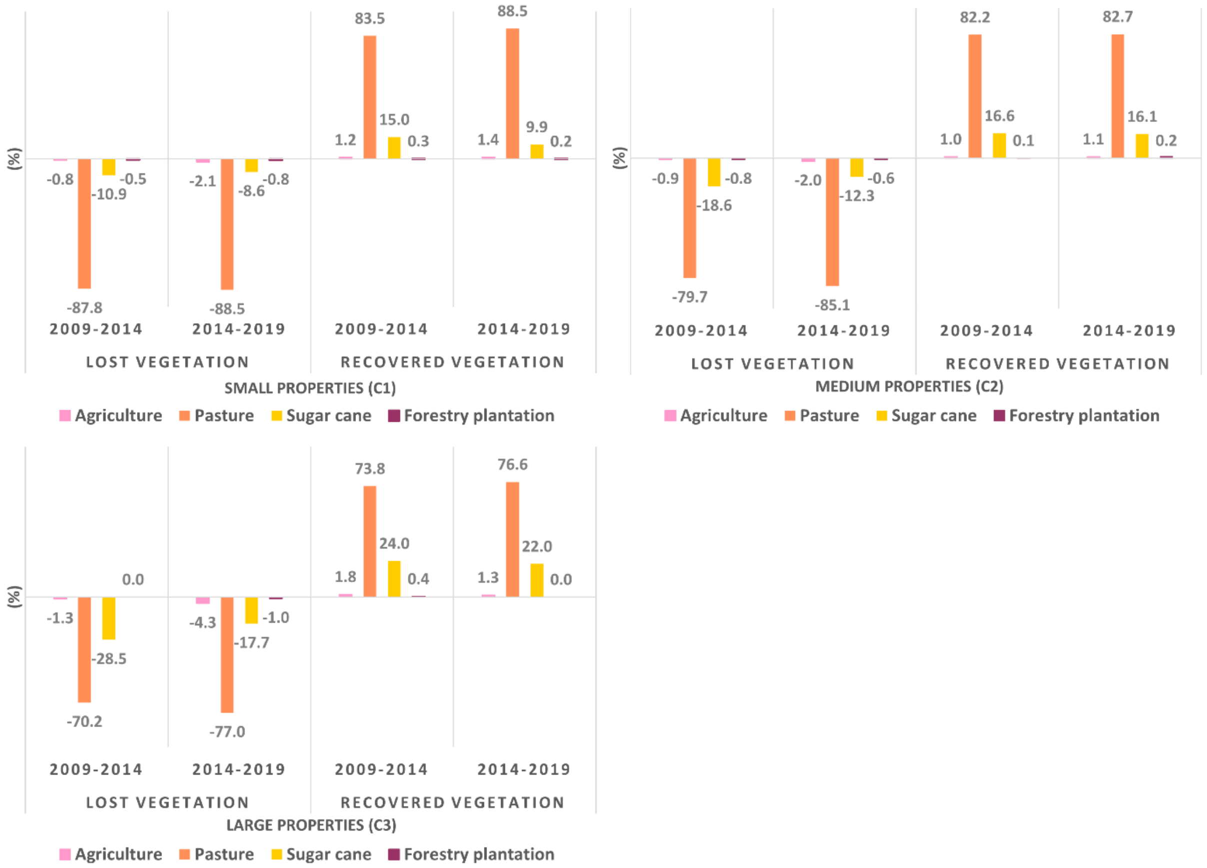


Figure 18. The relative contribution of each class of land use and occupation to the new deforestation and the recovery of vegetation deficits was observed in the period from 2009-2014 and 2014-2019, in Piracicaba properties. Small properties (c1), Medium properties (c2), and Large properties (c3). Values, in percentages, weighted in relation to the total area of new deforestation and vegetation deficits recovered, respectively, in the municipality PPAs.

However, considering forest gains and losses in relative terms, that is, in relation to the area occupied by the land use class in 2009 and 2014, some changes were observed in these scenarios (Figure 19). In Corumbataí, forestry plantation, agriculture, and pasture had the highest relative rates of deforestation, which were equivalent to more than half of their total areas. But agriculture and forestry also had the highest relative rate of recovery of vegetation observed in 2009 and 2014.

In Rio Claro, the same pattern was found for forestry, agriculture, and pasture with high relative rates of conversion of vegetation, also being the classes with the highest rates of vegetation recovering, while sugarcane had a small representation overall despite being the second with the most area occupied in the PPAs. While in Piracicaba, when looking from relative rates, sugarcane had the lowest rates of deforestation and recovery, while agriculture showed the highest rates of conversion and recomposition, followed by pasture and forestry plantation, despite the latter occupying the least amount of area in the PPAs.

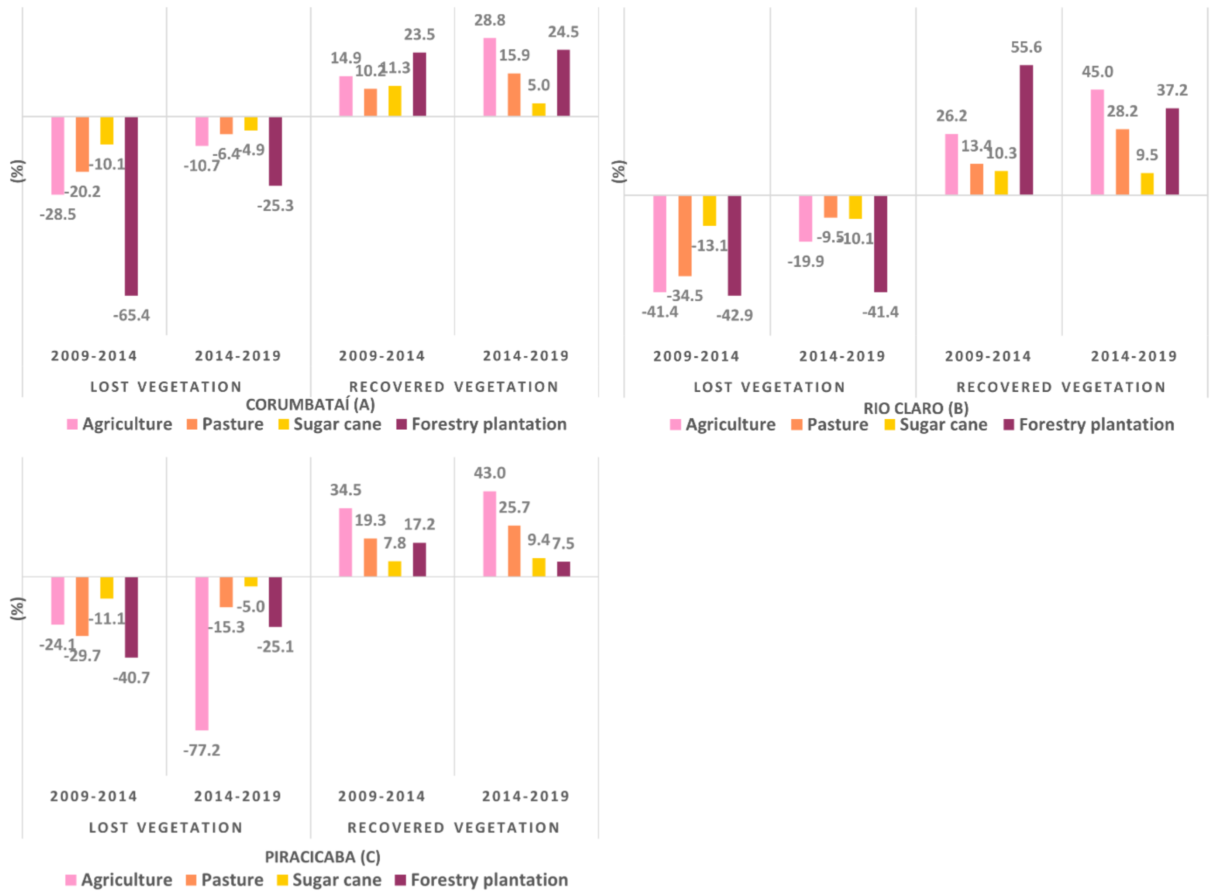


Figure 19. Relative rates of recovery of vegetation deficits (positive values) and the emergence of new deforestation (negative values) in the PPAs of Corumbataí (a), Rio Claro (b), and Piracicaba (c) between the years 2009 to 2014, and 2014 to 2019. Weighted values in relation to the area occupied by each class of land use and occupation in 2009 and 2014 (milestone 0) for each defined period.

In the period from 2014 to 2019, a reduction in the new deforestation trends is noticed overall in all three municipalities. In Corumbataí, land use classes kept the same positions as the period before, but at a rather lower rate, almost half of the previous ones. In Rio Claro, most classes did reduce, but forestry plantation kept the rate barely unchanged, whilst agriculture and pasture reduced by half its impacts. In Piracicaba pasture, sugarcane, and forestry plantation dropped by half, while agriculture raised more than 3 times its rate in new deforestation in this period, even though this class has only doubled its area of occupation within PPAs in this municipality.

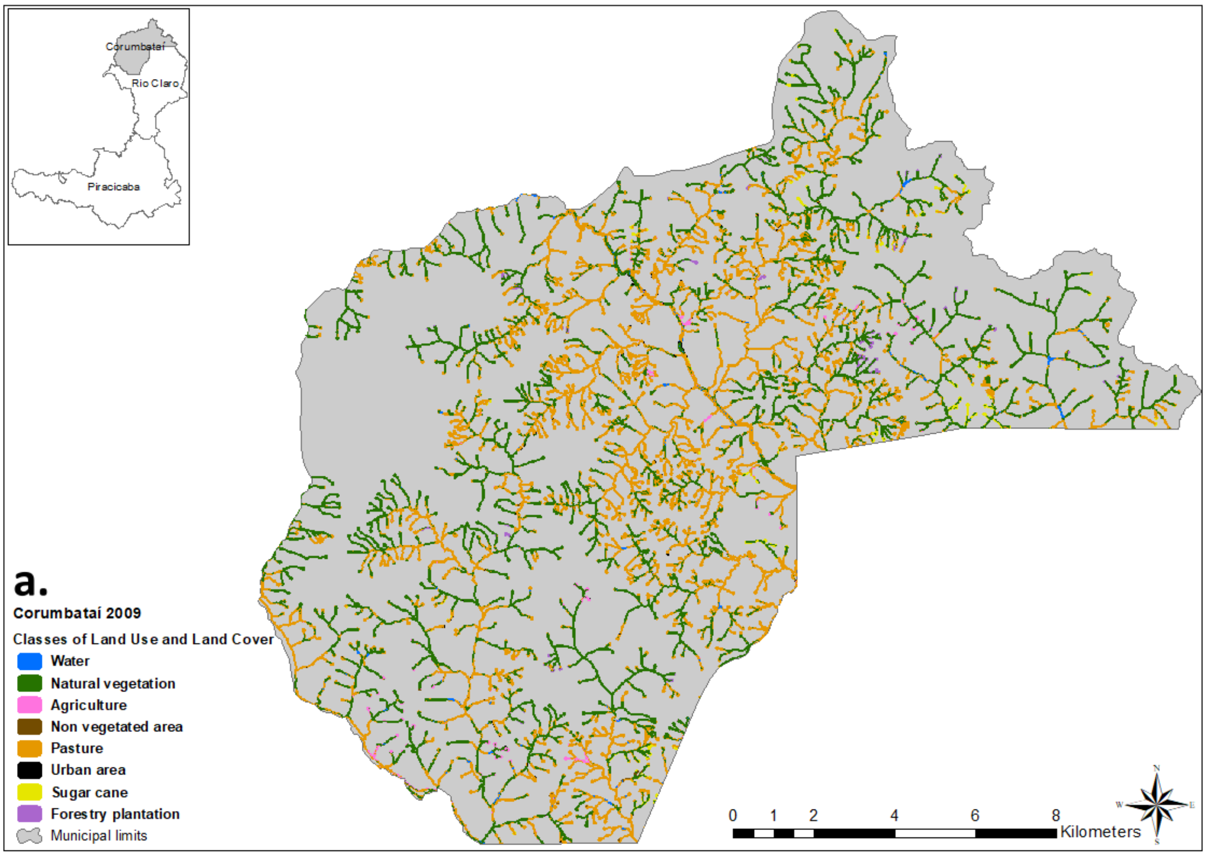
As for vegetation cover recovery, some classes doubled their rate, such as agriculture and pasture, while others presented a reduction when compared to the previous period. Corumbataí maintained with agriculture and forestry plantation as the highest rates of recovery, but the sugarcane rate decreased by half. Rio Claro's agriculture and pasture increased to almost double its previous rate values, while forestry plantation reduced almost a third, falling below the rate of new deforestation in the same period. Piracicaba's highest rates were also agriculture and pasture, but neither of these classes doubled its values, the increase was lower than the other two municipalities, and the rate of recovery from agriculture and forestry plantation was even lower than its deforestation rates of the same period.

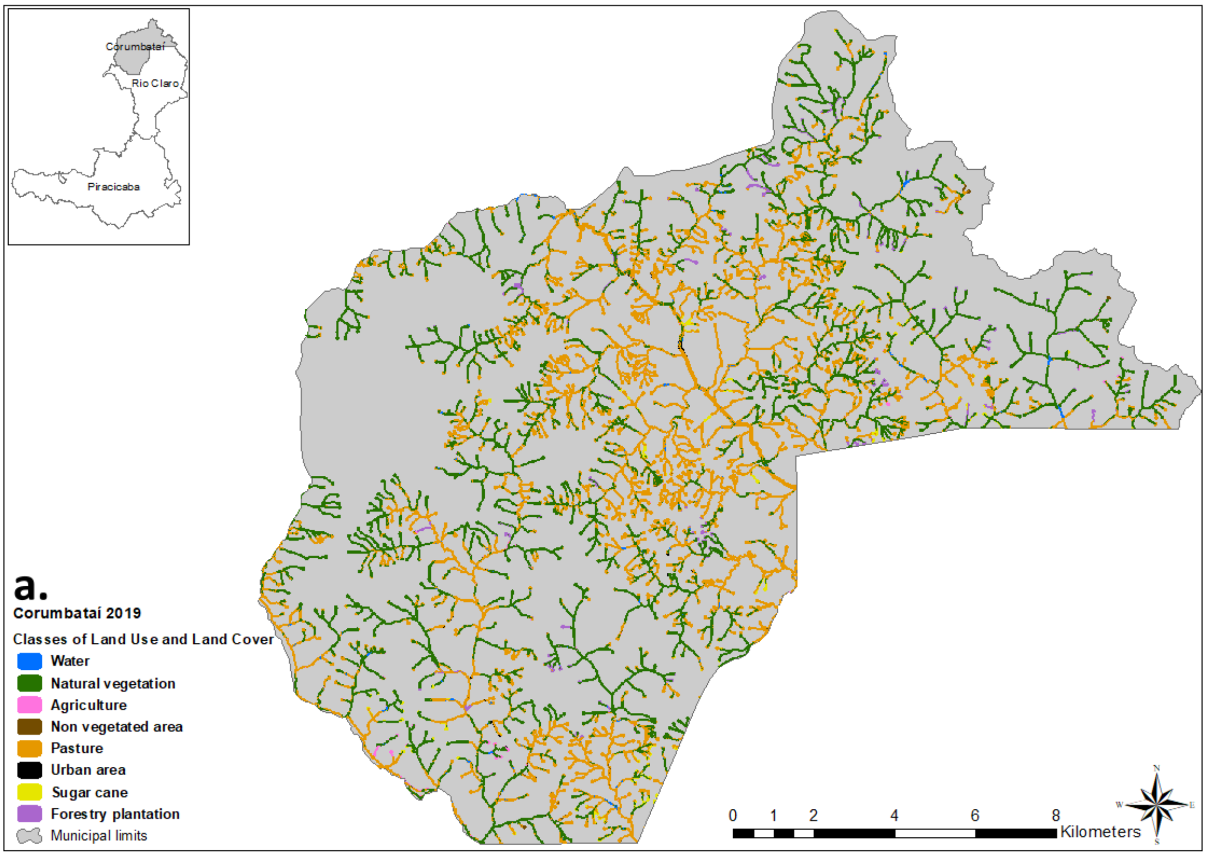
In the Corumbataí sub-basin, from 2009 to 2014, pasture, agriculture and forestry plantations showed an upward trend, as native vegetation was mostly converted into these classes; while in the Piracicaba sub-basin the replacement of new areas of riparian vegetation by sugarcane and pasture classes was greater than their recovery in the same period. The percentage of the area in the PPAs in both sub-basins occupied by native vegetation fragments reduced by an average of 5% in these 5 years evaluated. In the following period, an inversion of values was noticed overall, pasture and agriculture showed a downward trend, as native vegetation rates increased by replacing those land use, however, forestry plantations and sugarcane continued to expand in PPAs.

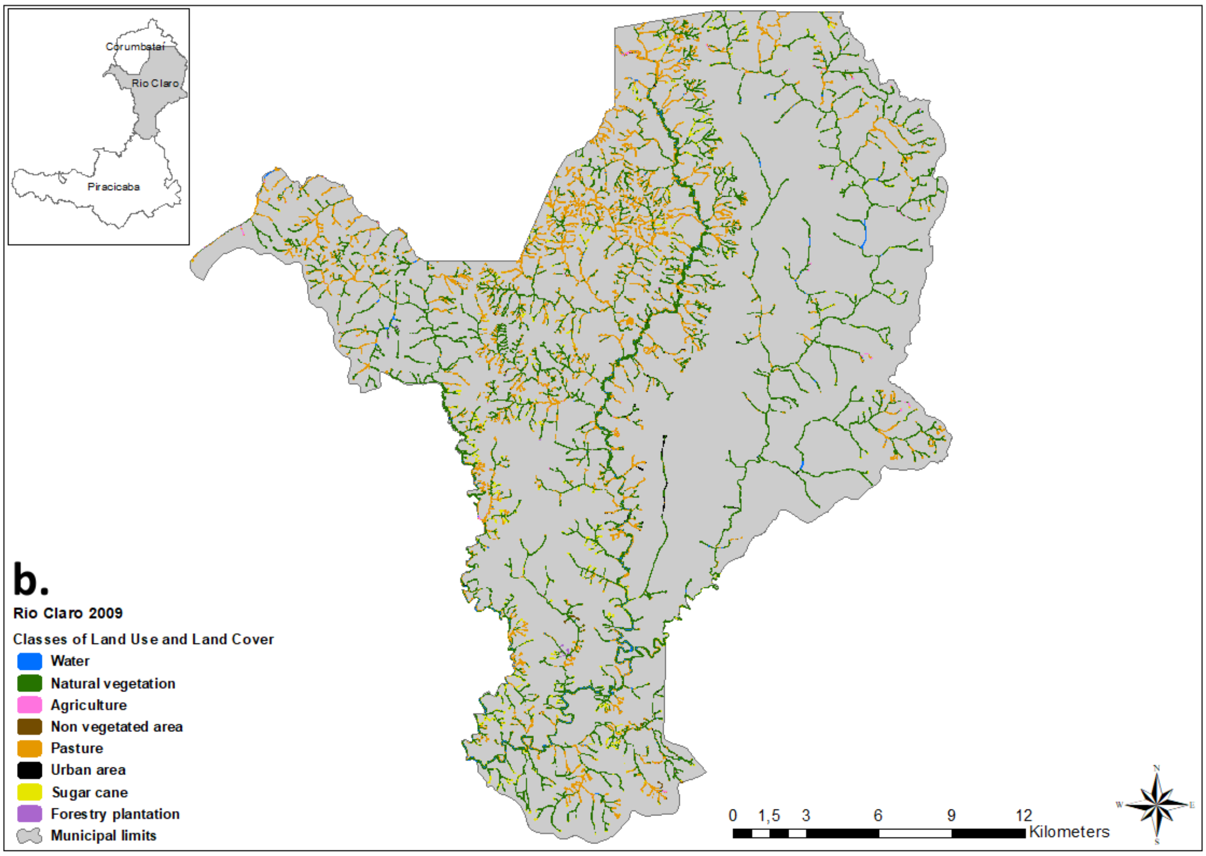
In Piracicaba sub-basin, sugarcane and pasture faced a replacement by natural vegetation in PPAs rates higher than new conversions into these land uses in the same period. The percentage of the area in both sub-basins for natural vegetation land cover increased by an average of 5.6%. Overall, the recovery of vegetation cover in PPAs has increased over time, in some cases exceeding new deforestation rates from the previous period. It must be noticed, that even though the classes of agriculture and forestry plantation had the least amount of area occupied in PPAs in the study area, they presented the highest rates of expansion within PPAs in both periods, hence the higher values of deforestation among all the LULC classes., while also having high rates of vegetation recovery.

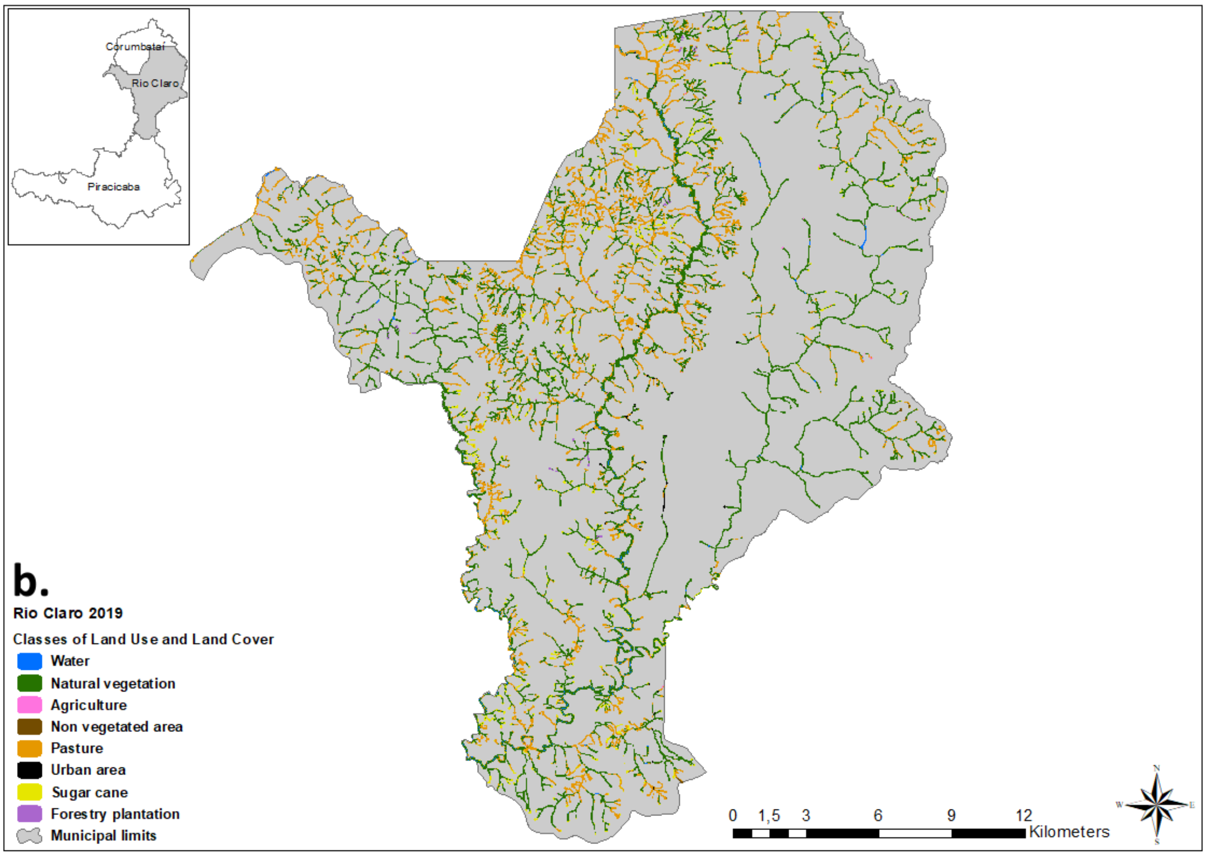
3.3.2. Permanent Protection Areas land use and land cover change metrics

To analyze PPA composition and configuration in 2009 and 2019, high resolution land use and land cover maps, derived from the digital classification of Rapid Eye images, were employed to calculate a set of landscape metrics to assess spatial and temporal patterns (figure 20). Overall, a total of 4,513 ha of PPAs in Corumbataí municipality, 6,930 ha in Rio Claro, and 15,562 ha in Piracicaba were analyzed.


Corumbataí
Rio Claro
Piracicaba
a.
Corumbataí 2009
Classes of Land Use and Land Cover
Water
Natural vegetation
Agriculture
Non vegetated area
Pasture
Urban area
Sugar cane
Forestry plantation
Municipal limits
0 1 2 4 6 8
Kilometers


Corumbataí
Rio Claro
Piracicaba
a.
Corumbataí 2019
Classes of Land Use and Land Cover
Water
Natural vegetation
Agriculture
Non vegetated area
Pasture
Urban area
Sugar cane
Forestry plantation
Municipal limits
0 1 2 4 6 8
Kilometers


Corumbataí
Rio Claro
Piracicaba
b.
Rio Claro 2009
Classes of Land Use and Land Cover
Water
Natural vegetation
Agriculture
Non vegetated area
Pasture
Urban area
Sugar cane
Forestry plantation
Municipal limits
0 1,5 3 6 9 12
Kilometers


Corumbataí
Rio Claro
Piracicaba
b.
Rio Claro 2019
Classes of Land Use and Land Cover
Water
Natural vegetation
Agriculture
Non vegetated area
Pasture
Urban area
Sugar cane
Forestry plantation
Municipal limits
0 1,5 3 6 9 12
Kilometers

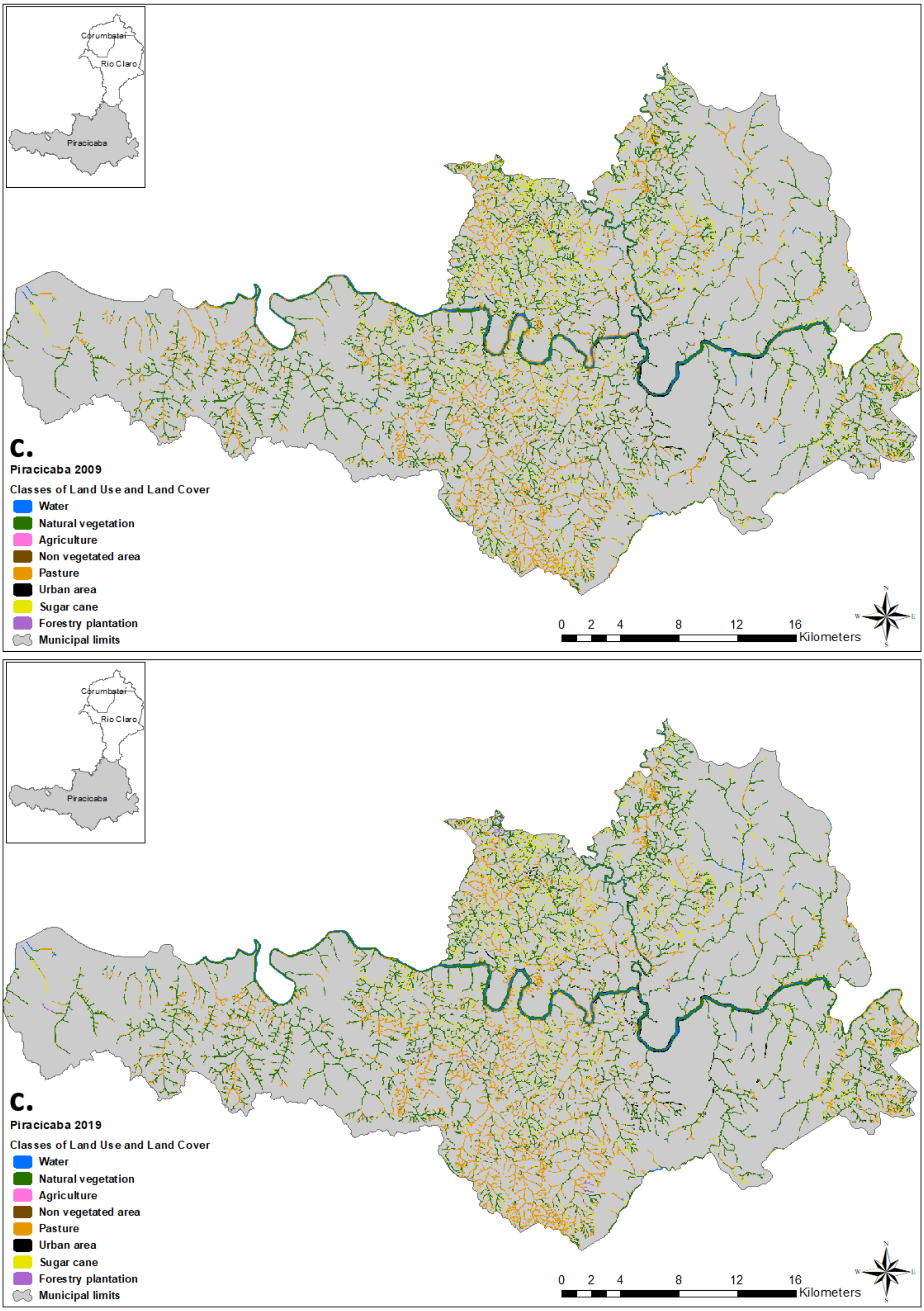


Figure 20. Land Use and Cover map in Permanent Protection Areas (PPAs) of Corumbataí (a), Rio Claro (b), and Piracicaba (c), located in São Paulo State, Brazil, derived from image digital classification of high spatial resolution RapidEye for the years 2009 and 2019.

As show in Table 9, native vegetation landscape metrics presented values fluctuation throughout the period of 2009, 2014 and 2019 in Corumbataí PPAs. The Number of Patches (NP), Patch Density (PD), Edge Density (ED) reduced from 2009 to 2019. However, the mean area of patches (MEAN) had a small increase, from 1.7 ± 4.9 to 2.0 ± 6.2 ha, while Percentage of area occupied (PLAND) also grew 5.3% between 2014 and 2019. In the first period, with the area reduction of this class by 5.4% and reduction from 1244 to 1176 in the number of fragments, the formation of smaller fragments occurred. The MEAN, maintained almost the same value, 1.8 ± 5.4 and 1.7 ± 4.9 ha, respectively, while a small reduction on ED, from 128.7 to 122.8 m/ha, was observed. Therefore, the fragment edge of these fragments became less dendritic.

In the second period, a probable process of fragmentation and formation of larger fragments can be seen due to the increase in PLAND and MEAN, associated with a reduction of 66 in NP and PD in and ED of 1.4 and 2.1 m/ha, respectively. Through the connectivity metric, it was noticed that the class of native vegetation had a low rate of connection between the fragments in the PPAs, as the values remained far from 1 in all the years evaluated, despite a small increase (from 0.11% to 0.13%) between 2014 and 2019, suggesting that the fragments of this class are a direct result of land use dynamics.

Table 9. Metric indices of land use and land cover classes in the PPAs for the years 2009, 2014 and 2019 in the municipality of Corumbataí.

Corumbataí								
		PLAND	**NP**	**PD**	**ED**	**MEAN Area**	**SD (AREA)**	**CONNECT**
Native Vegetation	2009	48.5	1244	27.7	128.7	1.8	5.4	0.12
	2014	43.1	1176	26.1	122.8	1.7	4.9	0.11
	2019	48.4	1110	24.7	120.7	2.0	6.2	0.13
Agriculture	2009	1.1	566	12.6	10.9	0.1	0.3	0.16
	2014	1.3	681	15.1	14.3	0.1	0.2	0.13
	2019	0.6	521	11.6	8.6	0.1	0.1	0.13
Pasture	2009	48.1	2874	64.0	123.4	0.8	3.9	0.08
	2014	52.6	2547	56.5	119.2	0.9	6.2	0.08
	2019	47.7	2648	58.8	113.7	0.8	5.5	0.08
Sugarcane	2009	1.4	334	7.4	8.9	0.2	0.3	0.37
	2014	1.3	309	6.8	8.2	0.2	0.3	0.40
	2019	1.3	280	6.2	8.1	0.2	0.3	0.38
Forestry Plantation	2009	0.8	204	4.5	5.6	0.2	0.3	0.74
	2014	1.7	278	6.2	9.9	0.3	0.5	0.44
	2019	2.0	396	8.8	11.8	0.2	0.5	0.38

PLAND – Percentage of Land (%); NP – Number of Patches; PD – Patch Density (#/100 ha-1); ED – Edge Density (m/ha); Mean Area – Average area of Patch (ha); SD (AREA) – Standard Deviation of Patch Area (ha); CONNECT – Connectivity between patches.

The second most dominant class in the landscape, pasture, hand an 4.5% increase in PLAND between 2009 and 2014, followed by a 5% reduction from 2014 to 2019. Both NP and the PD decreased of about 11% from 2009 to 2014, with an opposite pattern from 2014 to 2019, when an increase of about 4% was observed. The MEAN stayed almost constant from 2009 to 2014, while the ED reduced from 119.2 to 113.7 m/ha in this period. The same pattern of reduction was found from 2014 to 2019. When analyzing the period from 2009 to 2014, separately, formation of larger fragments due to the increase in MEAN and reduction in NP, PD and ED can be observed. The inverse process took place in the second analyzed period, when an increase in NP, PD and a reduction in ED and MEAN were found due to pasture lands fragmentation. Connectivity remained over the entire study period, with low values indicating a low degree of connection between fragments.

Sugarcane PLAND reduced about 0.1% from 2009 to 2014. In this period, there was a reduction from 334 to 309 in the number of patches, from 7.4 to 6.8 in PD and ED from 8.9 to 8.2 m/ha. The MEAN remained constant at 0.2±0.3 ha, indicating, together with the other indices values, a decrease in sugarcane fragments. Between 2014 and 2019, sugarcane PLAND remained at 1.3%. However, NP and PD showed a small decrease of about 9%, while ED and MEAN remained almost constant. Thus, a process of fragmentation of this class is taking place in the second analyzed period, although not very spatially expressive since changes in values are very low. The sugarcane class showed a higher degree of connectivity in the PPAs, being constant in the first (0.37% and 0.40%, respectively) and second (0.38%) periods, with fragment being more connected and closer.

Forestry plantation class increased throughout the period from 2009 to 2019, as did the ED. The NP and PD increased from 2009 to 2019, while MEAN keep constant. In the first period, a very low increase, of almost 1%, in PLAND was observed, while NP increased from 204 to 278 and PD from 4.5 to 6.2. ED increase from 5.6 to 9.9 m/ha, indicating that these fragments became border more dendritic. In the second period the values continued to increase due to a probable fragmentation process, NP and PD increased 1.4 time, ED 1.2. This translated in almost constant values of PLAND and MEAN. Forestry plantation showed the highest connectivity index between the fragments, approaching 1 in 2009, despite having a significant reduction in the first period (0.74% to 0.44%), and being constant in the second period.

As shown in Table 10, Rio Claro native vegetation experienced a fluctuation in values throughout the period from 2009 to 2019. NP, PD, ED increased from 2009 to 2019, while MEAN remained almost constant (2.5±7.6 to 2.6±9.1 ha) and an increase in PLAND of 8.1% between 2014 and 2019. In the first period, a PLAND reduction of 7.7% associated with a MEAN decreased (~0.4 ha) and ED from ~136 to 125 m/ha. In the second period, a probable process formation of larger fragments can be the reason of the increase in PLAND and MEAN, in addition to the increase of 177 in the NP and, consequently, in the increase of 2.6 and 15.7 m/ha in PD and ED, respectively. Connectivity metric indicated that native vegetation had a low rate of connection between the fragments in the PPAs, as the values remained far from 1 in all the years evaluated, despite a small decrease (from 0.11% to 0.10%) between 2009 and 2014, suggesting that the fragments of this class are a direct result of land use dynamics.

Table 10. Metric indices of land use and land cover classes in the PPAs for the years 2009, 2014 and 2019 in the municipality of Rio Claro.

Rio Claro								
		PLAND	**NP**	**PD**	**ED**	**Mean Area**	**SD (AREA)**	**CONNECT**
Native Vegetation	2009	59.3	1389	20.4	135.7	2.9	9.6	0.11
	2014	51.6	1390	20.2	124.9	2.5	7.6	0.10
	2019	59.7	1567	22.8	140.6	2.6	9.1	0.10
Agriculture	2009	0.7	719	10.5	8.3	0.1	0.2	0.09
	2014	0.7	689	10.0	8.6	0.1	0.2	0.10
	2019	0.4	896	13.0	8.8	0.03	0.1	0.06
Pasture	2009	34.3	4562	66.9	115.1	0.5	2.0	0.05
	2014	42.0	4030	58.7	113.6	0.7	3.1	0.05
	2019	33.8	4721	68.7	122.8	0.5	2.0	0.04
Sugarcane	2009	5.5	1905	27.9	36.5	0.2	0.4	0.08
	2014	5.3	1954	28.4	36.4	0.2	0.4	0.08
	2019	5.5	1883	27.4	36.9	0.2	0.4	0.08
Forestry Plantation	2009	0.2	75	1.1	1.3	0.2	0.3	2.49
	2014	0.4	119	1.7	2.8	0.2	0.5	1.38
	2019	0.6	198	2.9	4.1	0.2	0.4	0.76

PLAND – Percentage of Land (%); NP – Number of Patches; PD – Patch Density (#/100 ha-1); ED – Edge Density (m/ha); Mean Area – Average area of Patch (ha); SD (AREA) – Standard Deviation of Patch Area (ha); CONNECT – Connectivity between patches (%).

Pasture PLAND increased 7.7% between 2009 and 2014, followed by an 8.2% reduction from 2014 to 2019. As expected, NP and the PD decreased (4562 to 4030, and 66.9 to 58.7, respectively). The MEAN value was constant during this period, while ED had a reduction of 1.5 m/ha. From 2014 to 2019 MEAN again was almost constant and ED showed an increase of about 9.2 m/ha. Therefore, this class remained relatively constant during the study period, with a low connection between the fragments as indicated by the connectivity index.

All sugarcane indexes indicate that this class remained also constant during the analyzed period. PLAND reduced from 2009 to 2014 about 0.2%, when there was an increase of only 49 fragments, increasing PD from 27.9 to 28.4 PD, while ED had no change (36.5 to 36.4 m/ha) and MEAN remained at 0.2±0.4 ha. In the period between 2014 and 2019, although some of the indices experience some value changes, they were not significant. Thus, sugarcane remained practically unchanged and with a small degree of connectivity in the PPAs.

The forestry plantation increased throughout the period from 2009 to 2019, as did the ED. The NP, PD increased, however this increase was not large enough to influence the MEAN. In the first period, PLAND had almost no change (an increase of 0.2%) and NP increased 1.5 times. PD also had an increase, from 1.1 to 1.7, while ED increase of 1.5 m/ha. In the second period PLAND increase again 0.2%, NP had a more significant increase of 79 patches, PD 1.2, and ED by 1.3 m/ha, but the MEAN was constant (0.2±0.5 to 0.2±0.4 ha, respectively). Forestry plantation showed the highest connectivity index, despite having a significant reduction in the first period from 2.49% to 1.38%, and a reduction of 0.62% in the second one.

Piracicaba PPAs land use metrics are shown in Table 11. In general, native vegetation class had fluctuation in values throughout the period from 2009 to 2019. NP, PD, ED indexes reduced from 2009 to 2019, as well as MEAN (3.1±12.1 to 2.5±9.4 ha). However, PLAND presented a 4.5% increase between 2014 and 2019, indicating that patches increased in size and connectivity. In the first period, an area reduction of 3.9% and in NP (2941 to 2378), associated with a PD decrease of about 4.0 was found, the MEAN remained almost constant (2.7±8.5 to 3.1±12.1 ha). These changes, associated with the decrease in ED from 122.4 to 103.6 m/ha, indicates that these patches border is becoming more strait. In the second period, PLAND increased to a value similar to the one found in 2009, MEAN had a very small decrease and NP an increase of 812 patches. Consequently, there was in the increase of 5.5 and 16.8 m/ha in PD and ED, respectively. The connectivity metric results indicate a low rate of connection between the fragments in the PPAs, as the values remained far from 1 in all the years evaluated, despite a small increase (from 0.05% to 0.06%) between 2009 and 2014, and reducing to 0.05% in 2019, suggesting that the fragments of this class are a direct result of land use dynamics.

Table 11. Metric indices of land use and land cover classes in the PPAs for the years 2009, 2014 and 2019 in the municipality of Piracicaba.

Piracicaba								
		PLAND	**NP**	**PD**	**ED**	**Mean Area**	**SD (AREA)**	**CONNECT**
Native Vegetation	2009	52.4	2941	19.4	122.4	2.7	8.5	0.05
	2014	48.5	2378	15.4	103.6	3.1	12.1	0.06
	2019	53.0	3190	20.9	120.4	2.5	9.4	0.05
Agriculture	2009	0.4	1550	10.2	6.5	0.04	0.1	0.03
	2014	0.3	864	5.6	3.9	0.05	0.2	0.07
	2019	0.6	2019	13.2	10.8	0.05	0.1	0.03
Pasture	2009	31.6	7127	47.0	88.5	0.7	2.9	0.02
	2014	36.2	6479	42.1	83.1	0.9	4.3	0.03
	2019	32.8	7641	50.0	102.2	0.7	3.4	0.02
Sugarcane	2009	15.5	6770	44.6	73.8	0.3	0.8	0.03
	2014	14.8	6250	40.6	62.7	0.4	0.9	0.03
	2019	13.2	6308	41.3	67.0	0.3	0.7	0.03
Forestry Plantation	2009	0.1	68	0.4	0.6	0.2	0.4	1.80
	2014	0.2	38	0.2	0.5	0.7	1.4	3.13
	2019	0.4	266	1.7	2.3	0.2	0.7	0.60

PLAND – Percentage of Land (%); NP – Number of Patches; PD – Patch Density (#/100 ha-1); ED – Edge Density (m/ha); Mean Area – Average area of Patch (ha); SD (AREA) – Standard Deviation of Patch Area (ha); CONNECT – Connectivity between patches (%).

There was a 4.6% increase in pasture PLAND between 2009 and 2014, followed by a 3.4% reduction from 2014 to 2019. NP and the PD decreased in this period, followed by an increase from 6479 to 7641 in NP and from 42.1 to 50 in PD in 2019. In the period of 2009 to 2014, MEAN was constant (0.7±2.9 to 0.9±4.3 ha, respectively), while ED experienced a reduction from 88.5 to 83.1 m/ha. During the following study period, a MEAN small reduction (0.2±0.9 ha) was observed, while ED increase by 19.1. However, when analyzing the period from 2009 to 2014 separately, the increase in MEAN and reduction in NP, PD and ED points to larger patches. The inverse can be observed from 2014 to 2019, when there was an increase in NP, PD and ED, and a reduction in MEAN, representing fragmentation of pasture areas. The connectivity index remained constant, with low values, indicating a small degree of connection between the fragments.

Sugarcane PLAND reduced from 2009 to 2014 about 0.7%. In this period, there was a reduction from 6770 to 6250 in NP, from 44.6 to 40.6 in PD and ED from 73.8 to 62.7 m/ha. MEAN present a small but not significant change. In the period between 2014 and 2019, PLAND decreased from 14.8% to 13.2%, however, the NP, PD and ED showed a small increase. Thus, these changes were not very expressive due to the changes in the values being very small. The sugarcane class showed a low degree of connectivity in the PPAs, not changing from 0.03% from 2009 to 2019, indicating that this class was distant to 1 with a lower connectance index among the fragments.

The forestry plantation class increased throughout our study period. From 2009 to 2014, PLAND was relatively constant (~0.1% increase), NP decreased from 68 to 38, and PD dropped from 0.4 to 0.2. Patches became a little bit larger, as indicated by the small increase in MEAN, from 0.2±0.4 to 0.7±1.4 ha, while ED reduction from 0.6 to 0.5 m/ha indicates a probable change in fragment format. In the second period, the values continued to increase in a probable process of class fragmentation, as can be seen with a 0.2% increase in PLAND, a more significant increase of 228 in NP and, consequently, in PD at 1.5, increase in ED by 1.8 m/ha, and with the MEAN reduction from 0.7±1.4 to 0.2±0.7 ha. Forestry plantation showed the highest connectivity index between the fragments, surpassing 1 in 2009, having a significant increase in the first period from 1.80% to 3.13%, and a reducing to 0.60% in the second period.

Landscape metrics are useful to quantitatively assess configuration and composition of the PPAs, as well as compare the mosaic dynamic among municipalities. As presented above, the three landscapes were composed by numerous fragments of native vegetation with a high degree of isolation, indicating that the landscape is highly anthropized. A reduced number of connections between forest remnants limits ecosystems functions and therefore their ability to provide PPAs ecosystem services. It was also observed that in addition to a process of fragmentation of the PPAs, not many changes were noticed in relation to the classes of land use and cover, and that those classes, such as pasture, sugarcane, and forestry plantation, are facing a temporal stability with small changes in the format and connectivity in the PPAs landscape, as observed in the period.

The observed contrast amongst classes of land use connectivity indexes, indicates that there is a higher level of connectivity between fragments of forestry plantation in all three municipalities. Together with the increase in the occupation of this class in PPAs, can be an indication of growth in the economic interest of this type of land use, while can also be used in restoration plans in PPAs, according to the NVPL.

A reduction in the area intended to native vegetation can be observed due to deforestation and reduced regeneration and recovery of natural vegetation. One of the probable causes of this observed decrease, mainly between 2009 and 2014, may be associated with the change in environmental legislation that occurred in 2012 with the implementation of the NVPL, which legalized most deforestation that occurred until 2008 and reduced the recovery sizes of vegetative strips in the PPAs to a minimum between 5 and 100 meters, in addition to less environmental inspection in compliance with this legal document, that is, with the rules aimed at protecting forests and other forms of vegetation.

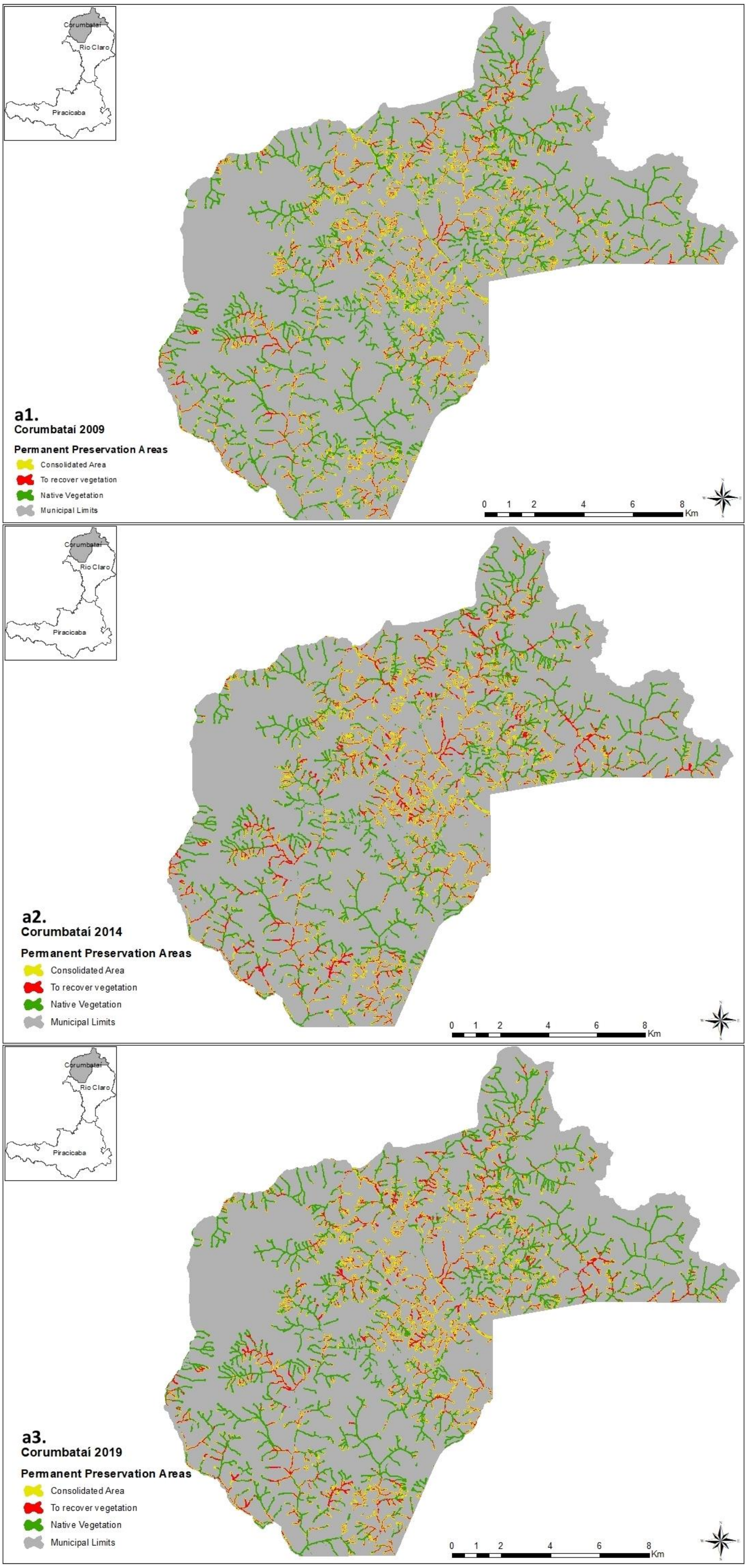
Casagrande (2005) also noticed this trend when analyzing a micro basin in the region of the municipality of Piracicaba for the years 1995 to 2000, where it was assessed a fragmentation process in the landscape, of which pasture was one of the classes most affected by it. Costa and Sparovek (2004) also evaluated the landscape changes of Piracicaba urban development in the year 2000, as fragmentation of native vegetation over the edges of the urban area of the municipality had increased towards north, northeast, and east, as most of the remaining native vegetation in larger fragments were located at west. Valente and Vettorazzi (2002) evaluated the Corumbataí river watershed and noticed that the sub-basins of Medium Corumbataí, Ribeirão Claro and Low Corumbataí had their forest cover more fragmented, and that this fragmentation was more intense in these regions in the year 2000.

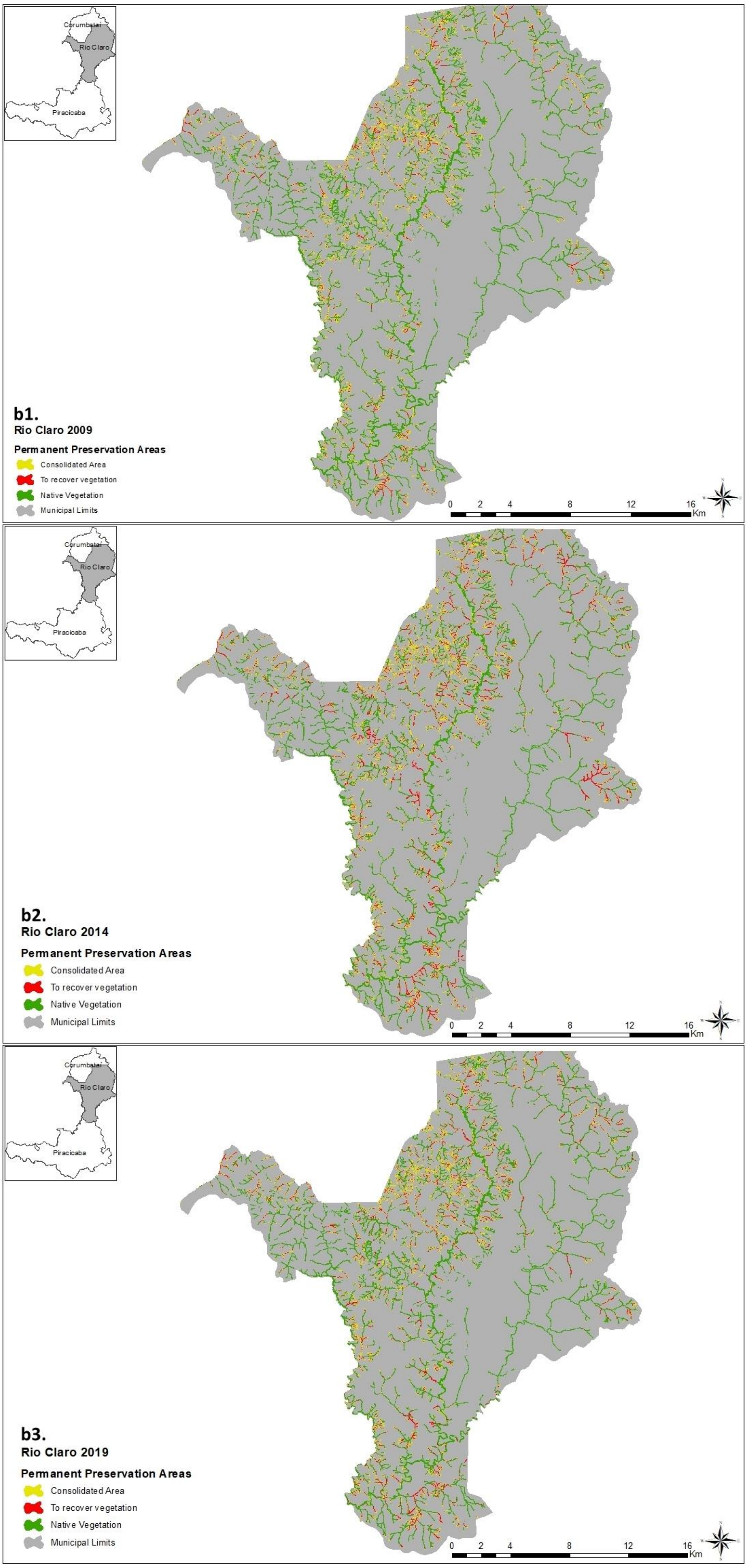
3.3.3. Consolidated use areas and areas to recover vegetation in riparian PPAs in rural properties

Riparian PPAs were then divided by the NVPL into three types: consolidated use areas, require recomposition of vegetative cover, and native or recovered vegetation cover. Table 12 presents the percentages for each law classified type of use in riparian PPAs. Figure 21 shows the temporal changes from 2009, 2014, and 2019 in PPAs for each municipality.

Table 12. Percentages of area occupation of classes in riparian PPAs of municipalities of Corumbataí, Rio Claro, and Piracicaba for the years 2009, 2014, and 2019.

	Corumbataí (%)			Rio Claro (%)			Piracicaba (%)		
	2009	**2014**	**2019**	**2009**	**2014**	**2019**	**2009**	**2014**	**2019**
Native Vegetation	52.7	47.5	52.8	65.4	58.1	65.4	57.3	54.0	57.5
Consolidated Area	34.2	31.6	29.6	25.6	23.5	21.2	27.4	24.5	23.4
To recover vegetation	13.2	20.9	17.7	9.0	18.4	13.3	15.3	21.5	19.1


Corumbataí
Rio Claro
Piracicaba
a1.
Corumbataí 2009
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 1 2 4 6 8 Km
Corumbataí
Rio Claro
Piracicaba
a2.
Corumbataí 2014
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 1 2 4 6 8 Km
Corumbataí
Rio Claro
Piracicaba
a3.
Corumbataí 2019
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 1 2 4 6 8 Km


Corumbataí
Rio Claro
Piracicaba
b1.
Rio Claro 2009
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 2 4 8 12 16 Km
Corumbataí
Rio Claro
Piracicaba
b2.
Rio Claro 2014
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 2 4 8 12 16 Km
Corumbataí
Rio Claro
Piracicaba
b3.
Rio Claro 2019
Permanent Preservation Areas
Consolidated Area
To recover vegetation
Native Vegetation
Municipal Limits
0 2 4 8 12 16 Km

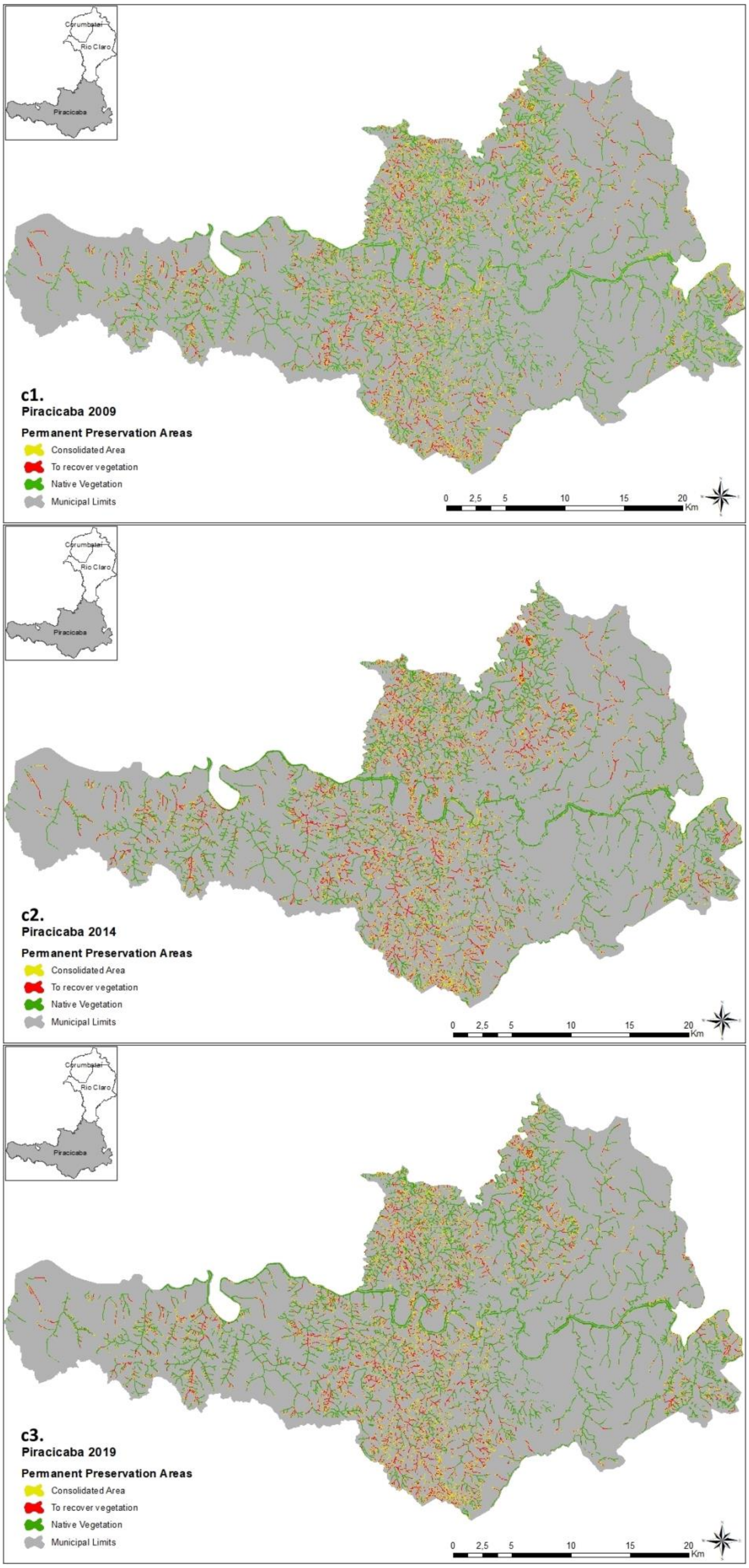


Figure 21. Consolidated use, areas to recover vegetation, and native vegetation map for PPAs in Corumbataí (a1, a2, a3), Rio Claro (b1, b2, b3), and Piracicaba (c1, c2, c3) municipalities, located in São Paulo State, Brazil, for the years of 2009, 2014 and 2019, respectively.

In the period from 2009 to 2014, about 5% PPAs vegetation in Corumbataí had been recovered from consolidated use areas and areas with a deficit of vegetation that was required to be recovered, but new deforestation reached about a 10% of increase in the same period, observed on the expansion of new areas to recover vegetation and a negative amount of 5% in overall vegetation coverage in the PPAs (table 12).

The majority of riparian PPAs within rural properties in this municipality were found in small properties, with approximately 2,300 ha (61%), split into 47% consolidated use areas, 13.5% areas of vegetation deficit, and 39% of vegetation cover as of the year 2009 (figure 22). In the transition to 2014, it was noticed that small properties were accountable for 64% (263.8 ha) of new deforestation in the PPAs, as well as responsible for 60% (124.9 ha) of regeneration of vegetation from consolidated use areas (84.3 ha) and areas of vegetation deficit (40.66 ha) (table 13).

Approximately 1,100 ha (30%) of riparian PPAs were located in medium size properties, split into 22% consolidated use, 16% areas of vegetation deficit, and 60% of vegetation coverage as of 2009. Until 2014, medium properties were responsible for 29% (119.7 ha) of new deforestation and for 26% (54.72 ha) of vegetation recovered in PPAs from consolidated use (23.6 ha) and from areas that needed vegetation recovery (31.06 ha).

Large properties had approximately 360 ha (9%) of all riparian PPAs in Corumbataí, split into 20% consolidated use areas, 14% areas of vegetation deficit, and 65% of vegetative coverage as of 2009. And through the years till 2014, they were responsible for 4% (16.27 ha) of new deforestation, while recovering 11% (24.2 ha) of vegetation from consolidated use areas (9.62 ha) and areas with a deficit of vegetation (14.6 ha) in the PPAs.

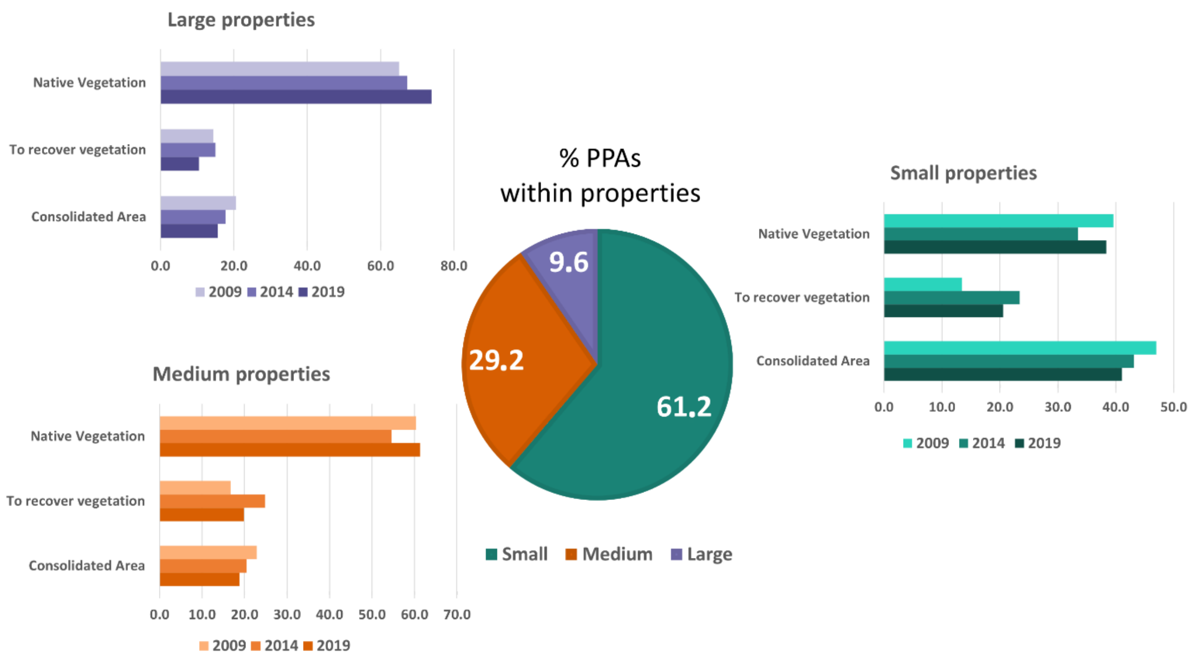


Figure 22. Riparian PPAs within each size property in Corumbataí, and the evolution in the percentage of native vegetation degradation and recovery, as well as consolidated areas in PPAs, for the years 2009, 2014, and 2019.

Table 13. Percentages of new deforestation and vegetation recovery in riparian PPAs by property size in the municipality of Corumbataí, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		**2014 – 2019**	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	60.2	64.2	57.7	67.6
Medium	26.4	29.1	30.4	24.4
Large	11.7	4.0	8.8	5.7

From 2014 to 2019, was observed about 3.7% of new deforestation in Corumbataí riparian PPAs. However, there was an increase of 9% in vegetation recovered from consolidated use areas and areas with a deficit of vegetation, which can be noticed by the inversion of coverage rates, going from mostly anthropic use to vegetative cover in PPAs in this period (table 12).

In small properties, in 2014, 43% of all PPAs in Corumbataí were consolidated use, 23% were areas of vegetation deficit and 33% had vegetative coverage, in the transition to 2019, small properties contributed with 67% (102.33 ha) of new deforestation, and with 212.53 ha (57%) of vegetation recovered from consolidated use areas (78.6 ha) and areas of vegetation deficit (133.9 ha) in riparian PPAs.

Medium properties had, in 2014, 20% of their PPAs in consolidated use, about 24% with areas of vegetation deficit, and 54% with vegetation coverage, the changes between 2014 and 2019 can be noted with a 24% (37.01 ha) contribution in new deforestation in PPAs, as well as 30% (111.95 ha) of vegetation recovered from consolidated use areas (27.7 ha) and areas of vegetation deficit (84.2 ha).

As for large properties, in 2014, PPAs were divided into 17% consolidated use areas, 15% areas with a deficit of vegetation and 67% of vegetative coverage, and passing through to 2019, large properties were responsible for 5.7% (8.6 ha) of new deforestation while recovering 8.8% (32.35 ha) of vegetation from consolidated use areas (9.92 ha) and areas with a deficit of vegetation (22.43 ha).

When seen from this overall point of view, small properties are the ones to blame for most deforestation in PPAs, but this is because they do have the majority of PPAs inside their lands. However, when seen from the properties point of view, these numbers are different and both small and medium properties have basically the same liability towards deforestation in PPAs, as in the period from 2009 to 2014, small properties deforested 11.5% of their PPAs and medium properties deforested 10.9%, while both recovered approximately 5%, with the big difference being that medium properties had almost half of PPAs that small properties had within their lands (table 14). Large properties presented the opposite, as their recover rates were higher than their deforestation rates within their lands, even though they had the least amount of PPAs in general.

Table 14. Percentages of new deforestation and vegetation recovery in riparian PPAs within the property in the municipality of Corumbataí, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		**2014 – 2019**	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	5.4	11.5	9.2	4.4
Medium	5.0	10.9	10.2	3.4
Large	5.9	4.5	9.0	2.4

From 2014 to 2019, an inversion of values took place in Corumbataí within its properties, as recover of vegetation exceeded deforestation, and again both small properties and medium properties had almost the same rates of recovery within their PPAs, 9.2% and 10.2%, as well as their deforestation rates, 4.4% and 3.4%, indicating that small properties recovered more in this period with double the amount of medium recovery rate. Large properties followed the tendency of recovery of vegetation, and considering the rates within their lands, they recovered 9%, with the most recovery of vegetation in the municipality by size and quantity of PPAs.

Rio Claro in the period from 2009 to 2014, had about 4.6% of the vegetation in the PPAs recovered from consolidated use areas and areas with a deficit of vegetation that was required to be recovered, but new deforestation reached about an 11% of increase in the same period, observed on the expansion of new areas to recover vegetation and a negative amount of 6% in overall vegetation coverage in the PPAs (table 12).

The majority of riparian PPAs in Rio Claro were found in small properties, with approximately 2,900 ha (61%), split into 40% consolidated use areas, 10% areas of vegetation deficit, and 50% of vegetation cover as of the year 2009 (figure 23). In the transition to the year 2014, it has been noticed that small properties were accountable for 57% (368.0 ha) of new deforestation in the PPAs, as well as responsible for 59% (162.5 ha) of regeneration of vegetation from consolidated use areas (116.9 ha) and areas of vegetation deficit (45.6 ha) (table 15).

Approximately 1,150 ha (24%) of riparian PPAs were located in medium size properties, split into 25% consolidated use, 17% areas of vegetation deficit, and 57% of vegetation coverage as of 2009. Until 2014, medium properties were responsible for 26% (171.5 ha) of new deforestation and for 22% (59.6 ha) of vegetation recovered in PPAs from consolidated use (27.5 ha) and from areas that needed vegetation recovery (32.06 ha).

Large properties had approximately 711 ha (15%) of all riparian PPAs in Rio Claro, split into 17% consolidated use areas, 11% areas of vegetation deficit, and 71% of vegetative coverage as of 2009. And through the years till 2014, they were responsible for 15% (100.44 ha) of new deforestation, while recovering 16% (45.3 ha) of vegetation from consolidated use areas (22.0 ha) and areas with a deficit of vegetation (23.29 ha) in the PPAs.

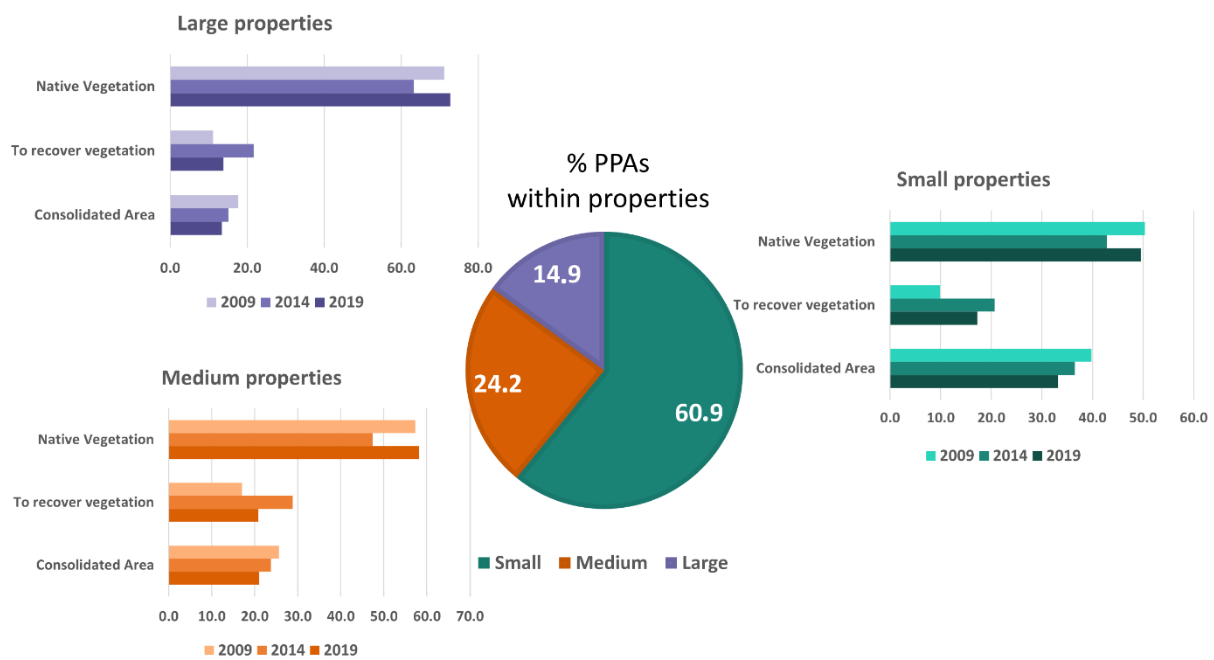


Figure 23. Riparian PPAs within each size property in Rio Claro, and the evolution in the percentage of native vegetation degradation and recovery, as well as consolidated areas in PPAs, for the years 2009, 2014, and 2019.

Table 15. Percentages of new deforestation and vegetation recovery in riparian PPAs by property size in the municipality of Rio Claro, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		**2014 – 2019**	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	59.5	57.0	53.9	60.3
Medium	21.8	26.5	28.2	21.5
Large	16.6	15.5	16.6	14.2

From 2014 to 2019, was observed about 4.2% of new deforestation in Rio Claro riparian PPAs, however, there was an increase of 10.4% in vegetation recovered from consolidated use areas and areas with a deficit of vegetation, which can be noticed by the inversion of coverage rates, going from mostly anthropic use to vegetative cover in PPAs in this period (table 12).

In small properties, in 2014, 36% of all PPAs in Rio Claro were consolidated use, 20% were areas of vegetation deficit and 42% had vegetative coverage, in the transition to 2019, small properties contributed with 60% (151.3 ha) of new deforestation, and with 336.9 ha (54%) of vegetation recovered from consolidated use areas (121.4 ha) and areas of vegetation deficit (215.5 ha) in riparian PPAs.

Medium properties had, in 2014, 23% of their PPAs in consolidated use, about 28% with areas of vegetation deficit, and 47% with vegetation coverage, the changes between 2014 and 2019 can be noted with a 21% (53.84 ha) contribution in new deforestation in PPAs, as well as 28% (176.34 ha) of vegetation recovered from consolidated use areas (38.2 ha) and areas of vegetation deficit (138.11 ha).

For large properties, in 2014, PPAs were divided into 15% consolidated use areas, 21% areas with a deficit of vegetation and 63% of vegetative coverage, and passing through to 2019, large properties were responsible for 14% (35.6 ha) of new deforestation while recovering 16% (103.9 ha) of vegetation from consolidated use areas (17.7 ha) and areas with a deficit of vegetation (86.2 ha).

When seen from this overall point of view, again, small properties had most deforestation in PPAs, still with the majority of PPAs inside their lands. However, when seen from the properties point of view, these numbers bring differences between properties accountability, and all properties have basically the same liability towards deforestation in PPAs, as in the period from 2009 to 2014, small properties deforested 12.7% of their PPAs, medium properties deforested 14.9%, and large properties 14.1%, while recovery rates went between

5.6%, 5.2%, and 6.4%, respectively (table 16). The big difference being that medium properties had less than half of PPAs that small properties had within their lands, and large properties less than a quarter. All properties presented deforestation rates higher than recovery rates in this period, but in general, large properties had the highest rates of deforestation by the amount of PPAs within their lands.

Table 16. Percentages of new deforestation and vegetation recovery in riparian PPAs within the property in the municipality of Rio Claro, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		**2014 – 2019**	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	5.6	12.7	11.6	5.2
Medium	5.2	14.9	15.3	4.7
Large	6.4	14.1	14.6	5.0

From 2014 to 2019, an inversion of values was also observed in Rio Claro within its properties, as recover of vegetation exceeded deforestation, and again all properties had closer rates of recovery within their PPAs, 11.6%, 15.3%, and 14.6% for small, medium, and large properties, respectively, as well as their deforestation rates, 5.2%, 4.7%, and 5%, indicating that medium properties recovered more in this period with half the amount of small properties' recovery rate, with barely a third of PPAs within their lands in comparison to small properties amount.

Piracicaba riparian PPAs, from 2009 to 2014, had about 6.5% of vegetation recovered from consolidated use areas and areas with a deficit of vegetation that was required to be recovered, but new deforestation reached about 9.5% of increase in the same period, observed on the expansion of new areas to recover vegetation and a negative amount of 3% in overall vegetation coverage in the PPAs (table 12).

The minority of riparian PPAs in Piracicaba was found in small properties, with approximately 3,615 ha (30%), split into 43% consolidated use areas, 13% areas of vegetation deficit, and 42% of vegetation cover as of the year 2009 (figure 24). In the transition to the year 2014, it has been noticed that small properties were accountable for 38% (484.7 ha) of new deforestation in the PPAs, as well as responsible for 29% (249.8 ha) of regeneration of vegetation from consolidated use areas (170.7 ha) and areas of vegetation deficit (79.07 ha) (table 17).

Approximately 3,670 ha (31%) of riparian PPAs were located in medium size properties, split into 32% consolidated use, 24% areas of vegetation deficit, and 43% of vegetation coverage as of 2009. Up until 2014, medium properties were responsible for 31% (394.9 ha) of new deforestation and for 31% (270.03 ha) of vegetation recovered in PPAs from consolidated use (121.6 ha) and from areas that needed vegetation recovery (148.39 ha).

Large properties had the majority of riparian PPAs, with approximately 4,470 ha (38%) of all in Piracicaba, split into 24% consolidated use areas, 17% areas of vegetation deficit, and 59% of vegetative coverage as of 2009. And through the years till 2014, they were responsible for 29% (370.4 ha) of new deforestation, while recovering 39% (335.8 ha) of vegetation from consolidated use areas (143.4 ha) and areas with a deficit of vegetation (192.3 ha) in the PPAs.

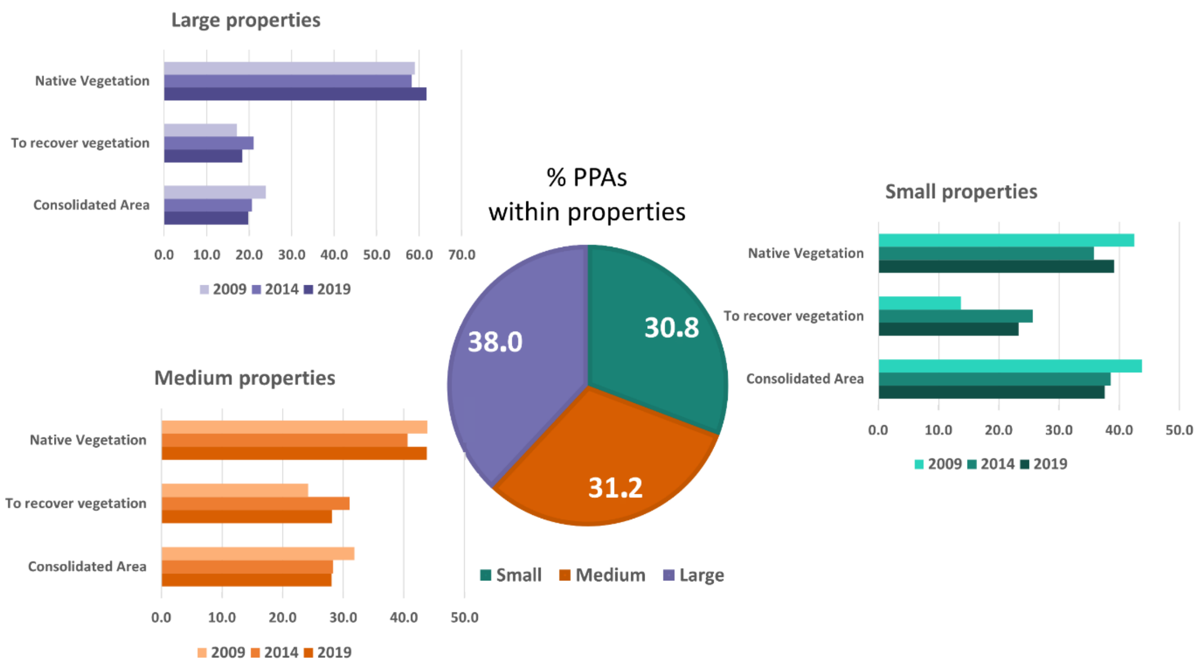


Figure 24. Riparian PPAs within each size property in Piracicaba, and the evolution in the percentage of native vegetation degradation and recovery, as well as consolidated areas in PPAs, for the years 2009, 2014, and 2019.

Table 17. Percentages of new deforestation and vegetation recovery in riparian PPAs by property size in the municipality of Piracicaba, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		2014 – 2019	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	29.1	38.6	32.6	34.2
Medium	31.4	31.5	31.4	31.9
Large	39.1	29.5	35.6	33.6

From 2014 to 2019, about 5.8% of new deforestation in Piracicaba riparian PPAs was observed. However, there was an increase of 8.9% in vegetation recovered from consolidated use areas and areas with a vegetation deficit, which can be noticed by the inversion of coverage rates, going from mostly anthropic use to vegetative cover (table 12).

In 2014, small properties held 38% of all PPAs in Piracicaba with consolidated use, 25% areas with vegetation deficit and 35% with vegetative coverage. In the transition to 2019, small properties contributed with 34% (263.8 ha) of new deforestation, and with 386.5 ha (32%) of vegetation recovered from consolidated use areas (119.8 ha) and areas of vegetation deficit (266.6 ha).

Medium properties had, in 2014, 28% of their PPAs in consolidated use, about 31% with areas of vegetation deficit, and 40% with vegetation coverage, the changes between 2014 and 2019 can be noted with a 32% (245.7 ha) contribution in new deforestation in PPAs, as well as 31% (372.19 ha) of vegetation recovered from consolidated use areas (75.86 ha) and areas of vegetation deficit (296.33 ha).

As for large properties, in 2014, PPAs were divided into 20% consolidated use areas, 21% areas with a deficit of vegetation and 58% of vegetative coverage, and passing through to 2019, large properties were responsible for 33% (259.17 ha) of new deforestation while recovering 35% (421.4 ha) of vegetation from consolidated use areas (90.1 ha) and areas with a deficit of vegetation (331.34 ha).

Although small properties encompassed the lower PPAs area whiting their limits, most of them were deforested. However, in terms of legal accountability, both small and medium properties have basically the same liability in terms of PPAs deforestation. From 2009 to 2014, small properties deforested 13.4% of their PPAs, medium properties 10.8%, while recovery rates were 6.9% and 7.4%, respectively (table 18). The main difference between these two types of farms was that small properties had almost the same amount of PPAs that medium properties within their lands, but their deforestation rates were higher by 20%. All properties presented deforestation rates higher than the recovery ones in this period, but in general, small properties had the highest rates of deforestation by the amount of PPAs within their lands.

Table 18. Percentages of new deforestation and vegetation recovery in riparian PPAs within the property in the municipality of Piracicaba, in the period from 2009 to 2014, and from 2014 to 2019.

	2009 – 2014		2014 – 2019	
	Vegetation recovered (%)	**New deforestation (%)**	**Vegetation recovered (%)**	**New deforestation (%)**
Small	6.9	13.4	10.7	7.3
Medium	7.4	10.8	10.1	6.7
Large	7.5	8.3	9.4	5.8

In the following period (2014 to 2019), a value inversion was also observed in Piracicaba within its properties, as vegetation recover exceeded deforestation. Again, all properties had closer rates of recovery within their PPAs, 10.7%, 10.1%, and 9.4% for small, medium, and large properties, respectively, as well as their deforestation rates, 7.3%, 6.7%, and 5.8%. These numbers indicate that small and medium properties recovered more in this period, both with similar recovery rates, as their PPAs quantity was also very alike. Large properties followed the same trend of increasing vegetation recovery, but considering they had the majority of PPAs within their lands, they recovered the least amount in the municipality by comparison with the other properties classes.

Small properties showed the highest rates of new deforestation overall, this is because they held most of the riparian PPAs areas as they were the larger in numbers of properties and land concentration, with the only exception being in Piracicaba sub-basin where large properties held most areas of PPAs and had most land concentration. Also, they were responsible for most of the vegetation recovery in both evaluated periods. It is important to point out that most of the areas occupied by croplands and pasture, are already under the consolidated use regime, which is foreseen in the legislation. However, it is necessary to recover a percentage of the native vegetation to adapt to the law and allow, at least, that the PPAs fulfill their ecological role.

There is also a trend of vegetation recovery inside consolidated areas in PPAs in both sub-basins. Despite this effort, it's also noticed a trend of deforestation of new areas outside consolidated areas, which can explain why the overall vegetation area does not increase as much as it should even after a large portion is recovered in the PPAs, and why deficits in the PPAs remains almost unchanged in comparison to when it was first assessed to the last year of the period. NVPL does not prohibit native vegetative restoration within consolidated areas, it rather encourages it, while new deforestation is not allowed. Therefore, it is possible that keeping the overall balance unchanged can be a mechanism to not comply with the current legislation.

In this context, Siqueira et al. (2016), while studying the ecological aspects of woody vegetation in PPAs, observed that the presence of consolidated areas can lead to changes in the structure and functioning of existing PPAs in Brazil, resulting in significant species and individual losses, making these areas fail to fulfill the environmental functions provided for in the legislation.

4. CONCLUSION

Land use and land cover dynamics in the studied region were dominated by pastures and sugarcane cultivation, which, in turn, had the most important influence on changes in landscape patterns and processes in the PAAs throughout the period. The dominance of pasture areas maintained in almost 50% of the area occupied in the PPAs in both sub-basins in relation to vegetation, accompanied by the great difference between the two classes in the values of number of fragments, average area of fragment, and high density of remnant fragments shows a territory with highly fragmented vegetation. This spatial pattern of landscape structure can compromise the functional integrity of the landscape, interfering with ecological processes and ecosystem quality.

At the start of the period studied, 2009, all Permanent Preservation Areas (PPAs) in both sub-basins assessed had deficit of vegetation cover, some reaching almost half of the areas, but native vegetation cover was still the matrix in the PPAs. However, in the following years, these deficits continued to increase as seen in 2014 where native vegetation cover got reduced as rates of new deforestation got higher, inverting the matrix to a more agricultural use of the PPAs. It must be considered that in this period, the NVPL got approved and sanctioned in Brazil, bringing new and controversial views for PPAs conservation methods, and that can be seen in this first period pattern, as the main change was the increase in areas of anthropic land use as a result of the reduction in the mandatory zone of recovery of native vegetation in PPAs within rural properties.

With the implementation of the NVPL, comes the new classification of land use in Permanent Preservation Areas (PPAs) as consolidated use areas, which took off the responsibility of recovering PPAs to their full form in all rural properties, thus allowing most of the deficits in these areas to continue as it was. Of 2009 vegetation deficits within rural properties in both sub-basins, more than half were considered consolidated use areas after the NVPL approval in 2012, and those areas were not required to be recovered by native vegetation in the following years. This dynamic changed the whole native vegetation recomposition of PPAs in rural properties, as the obligation of recovery was limited to small portions of PPAs, and the larger portion were still being occupied by other types of land use. Even though it is illegal to deforest new areas in PPAs, in both sub-basins were noticed a trend of new deforestation outside consolidated areas, at the expense of recovery of vegetation within some consolidated areas, therefore increasing rates of vegetation loss in PPAs. Although in the most recent period, the vegetative regeneration exceeded those previous deforestation in both consolidated areas and areas that were required recovery, as natural regeneration and recovery set place in some abandoned areas. The flexibilization of the current environmental legislation, with regard to the maintenance of consolidated areas in PPAs, tends to aggravate the environmental degradation presented for the sub-basins of the Corumbataí and Piracicaba rivers, with direct consequences on the environmental quality of the whole system.

Thus, the increase of forest fragments in the PPAs must be maintained and a work of recomposition of the riparian forest must be encouraged and carried out to recover the different stretches on the banks of the main and adjacent rivers, and in the headwaters of water bodies that are devoid of vegetation. Investments in smaller properties to increase restoration of native vegetation in PPAs must be made, since these types of properties has most of smaller waterbodies and therefore most of riparian PPAs that are key to improve landscape configuration and composition.

Irregular situations regarding environmental legislation and environmental preservation, with a view to ecosystem sustainability, were found in both sub-basins. These results are particularly important to understand the first impacts of the NVPL on the patterns of use and occupation of PPAs, revealing the existence of different dynamics within the same class of land use and occupation in different, but complementary, watersheds. In this sense, it is understood that changes in use and occupation in these areas, as well as the success of strategies for the protection and recovery of riparian vegetation, depend on several other factors, including market pressures, level of technological investment, management strategies, incentives for the recovery of deforested areas, among others. Thus, understanding the regional dynamics of use and occupation of PPAs, as well as their governance policies and the characteristics of agricultural production in the area, are important tools to better direct conservation efforts in these protected areas and maximize their efficiency.

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