v. 68, p. 629-655, Jul./Dec. 2026 http://doi.org/10.5380/dma.v68i.99616 e-ISSN 2176-9109

DMA Desenvolvimento e Meio Ambiente

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A Legal-Compliance Scenario for Native Vegetation and Permeable Areas protection in a Water-Source Protection Area

Cenário legal de cumprimento da proteção da vegetação nativa e áreas permeáveis em área de mananciais

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Article received on **May 12, 2025**

Final version accepted on **May 6, 2026**

Published on **November 4, 2026**

Abstract: Large urban centers face conflicts over land use and land cover, especially in environmentally sensitive areas. Brazil has specific legislation protecting special areas and native vegetation, including Permanent Preservation Areas (Áreas de Preservação Permanente, APP), Legal Reserves (Reservas Legais, RL) and Watershed Protection and Recovery Areas (Áreas de Proteção e Recuperação dos Mananciais, APRM). Geoprocessing tools allow mapping the legally expected land use and land cover, and comparing it with current situations to identify gaps that may jeopardize water resources and biodiversity. This study is an analysis of land use and land cover types in legally protected selected areas, based on a comparison with current situations (2021). It was motivated by the legal framework available for Watershed Protection and Recovery Areas (APRM) in Mogi das Cruzes Municipality, São Paulo State, Brazil. We assume that this comparison reveals gaps in environmental protection. Geospatial databases from public portals, environmental laws and land use planning regulations were processed with geoprocessing techniques to spatialize legal scenarios and compare it with current 2021 land use and land cover cases. Non-compliance with native vegetation protection reached 32.2%, mainly due to agricultural activities. On the other hand, permeable surfaces (permeable areas), including urbanized zones, recorded a significant degree of compliance with the legislation. The conclusion provides a proposition to create a legal scenario and to assess compliance with legal provisions contributing to native vegetation conservation if they were incorporated into territorial planning.

Keywords: legal scenario; permanent preservation areas; legal reserve; land use and land cover; environmental conservation.

Resumo: Os grandes centros urbanos enfrentam conflitos relacionados ao uso e à cobertura da terra, especialmente em áreas ambientalmente sensíveis. O Brasil dispõe de leis específicas que regulam a proteção de áreas especiais e de vegetação nativa, como as Áreas de Preservação Permanente (APP), as Reservas Legais (RL) e as Áreas de Proteção e Recuperação dos Mananciais (APRM). A utilização de ferramentas de geoprocessamento permite espacializar o cenário de expectativa legal de uso e cobertura da terra e, ao compará-lo com a situação atual, identificar omissões que podem gerar pressões sobre os recursos hídricos e a biodiversidade. Este estudo analisou os tipos de uso e cobertura da terra em áreas de proteção legal selecionadas, comparando a situação recente (2021) com o cenário legal elaborado para as Áreas de Proteção e Recuperação dos Mananciais em Mogi das Cruzes/SP. Parte-se da premissa de que essa comparação revela lacunas de cumprimento da proteção ambiental. A pesquisa utilizou base de dados geoespacial de portais públicos, leis ambientais e de ordenamento territorial, aplicando técnicas de geoprocessamento para espacializar cenários legais e comparar com o uso e cobertura da terra recentes (2021). O estudo identificou descumprimento de até 32,2% da proteção das áreas de vegetação nativa no cenário legal, causado principalmente por atividades agrícolas. Por outro lado, constatou-se um grau significativo de cumprimento nas

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áreas permeáveis, inclusive na zona urbanizada. A conclusão propõe a criação de um cenário legal e a avaliação do cumprimento dos dispositivos legais que, se incorporados ao planejamento territorial, podem contribuir para a conservação da vegetação nativa.

Palavras-chave: cenário legal; áreas de preservação permanente; reserva legal; uso e cobertura da terra; conservação ambiental.

1. Introduction

Land use and land cover are fundamental characteristics inherent in landscape. Therefore, understanding these variables is part of planning and decision-making processes. Accurately mapping them is crucial to assess environmental changes and human activity impacts on a specific region of interest (Araújo Filho et al., 2007).

Native vegetation cover and land use are regulated by specific legal instruments, including land use regulations, municipal master plans and other environmental protection laws. In addition to protected areas classified as Conservation Units (*Unidades de Conservação,* UC) (*Lei n. 9.985*, 2000), Brazil holds areas specifically designated for native vegetation protection and preservation, most notably Permanent Preservation Areas (*Áreas de Preservação Permanente,* APPs) and Legal Reserves (*Reserva Legal,* RL) (*Lei n. 11.428*, 2006; *Lei n. 12.651*, 2012) (Hassler, 2005; Miguez et al., 2012). APPs are essential areas for water resources, landscape, geological stability and biodiversity preservation at the private property level (*Lei n. 12.651*, 2012). Some specific cases also show RLs in rural areas or in urban properties set to conserve and protect biodiversity (*Lei n. 12.651*, 2012).

São Paulo State also implements additional legal protection mechanisms focused on vulnerable areas. Watershed Protection and Restoration Areas (*Área de Proteção e Recuperação de Mananciais*, APRM) encompass one or more sub-basins containing water sources of regional interest for public supply. They are subject to environmental and urban planning guidelines and standards established under state legislation. These laws set parameters such as the vegetation cover ratio and the permeable area rates (*Lei n. 9.866*, 1997; *Lei n. 15.913*, 2015). These parameters will be discussed at the regional level and regulated through municipal zoning laws. They are particularly relevant in areas prone to flooding and irregular settlements, which are often observed in many basins in São Paulo Metropolitan Region.

APRMs are distributed across strategic areas in São Paulo State. Alto Tietê Cabeceiras APRM, also known as APRM-ATC, encompasses Salesópolis, Biritiba Mirim, Mogi das Cruzes and Suzano municipalities, as established by the APRM-ATC Act (*Lei n. 15.913*, 2015).

Municipal Master Plans and Land Use and Occupancy Laws (*Plano Diretor Municipal,* PD) are responsible for defining general guidelines and specific rules for land use and occupancy, as provided under the City Statute Act (*Lei Federal n. 10.257*, 2001). Urban planning parameters include the permeable areas requirement, minimum lot size, maximum building

coverage ratio, minimum setbacks and the floor area ratio (Ministério do Desenvolvimento Regional, 2019). These urban planning parameters are essential for ensuring orderly territorial development, promoting tree planting and the expansion of vegetated areas by maintaining permeable areas (Coelho et al., 2021).

The mere existence of environmental protection laws is not enough to safeguard vegetation in preservation areas or to comply with permeable area requirements. Effective enforcement of the law requires coordinated actions focused on environmental monitoring, as well as oversight by environmental and legal institutions, alongside standardized monitoring methodologies to prevent data inconsistencies and improve the efficiency of environmental licensing and technical assistance provided to landowners (Fatorelli & Mertens, 2010; Brancalion et al., 2016; Santos et al., 2021).

Violations of native vegetation protection laws are quite common. They result from the construction of legal scenarios such as land-use and land-cover maps illustrating the expectations of different legal provisions (Hardt et al., 2012; Issii et al., 2020). Geospatial techniques enable the spatial representation of these different land use and cover legal expectations, and also allow their comparison with the current situation. This process provides information for the environmental management of protected areas (Hardt et al., 2012; 2013; Cabral et al., 2016; Issii et al., 2020; 2024; Santos et al., 2021; Perera-Valderrama et al., 2023).

The aim of this study is to analyze gaps in compliance with regulations protecting native vegetation and permeable areas in a basin in São Paulo Metropolitan Area. Therefore, a legal protection scenario was established for a basin in Mogi das Cruzes Municipality, São Paulo State, Brazil. The developed techniques and the analyzed data have the potential to support public and private organizations responsible for managing and planning the use of legally protected areas in the assessed basin.

2. Materials and methods

Two land use and land cover maps were produced: a map of the current situation (2021) and a map representing the legal scenario for native vegetation and permeable areas, as provided under the PD regulations. These maps were compared in order to assess legal compliance. Geographic Information System (GIS) tools, specifically the QGIS® software, version 3.28.3, were used in the analysis.

2.1. Study site

The study covered the peri-urban and rural areas of Mogi das Cruzes Municipality, in São Paulo Metropolitan Region (*Região Metropolitana de São Paulo,* RMSP). This area has approximately 445,000 inhabitants and a population density of 624.3 inhabitants/km^2 (Fundação Sistema Estadual de Análise de Dados, 2023). Its economy is diversified, and includes the service

sector (61.3%), industry (22.4%), taxes net of subsidies (13.2%), and agriculture and livestock (3.13%) (Fundação Sistema Estadual de Análise de Dados, 2023).

The study site covers 3,500 hectares of a Jundiaí River sub-basin named "Downstream Jundiaí Reservoir", located Southwestern Mogi das Cruzes Municipality (Figure 1). The site was selected because it is frequently affected by flooding and characterized by irregular settlements (Instituto de Pesquisas Tecnológicas, 2014).

In total, Jundiaí River basin encompasses other municipalities and covers approximately 19,170.00 hectares, most of which lie within the APRM-ATC (82.93%). This basin holds the Jundiaí River reservoir, which was completed in 1989 and is part of Alto Tietê Production System (*Sistema Produtor Alto* Tietê, SPAT). It was designed for multiple water uses, with emphasis on flood control, public water supply sources, irrigation, sewage dilution and recreation (Departamento de Águas e Energia Elétrica de São Paulo, 2023).

2.2. Geospatial database

We gathered available geospatial data in shapefile and raster format from public portals to spatialize legal requirements, and plot land use and land cover maps (Table 1). Data were originally collected from different reference systems and converted into SIRGAS 2000 datum.

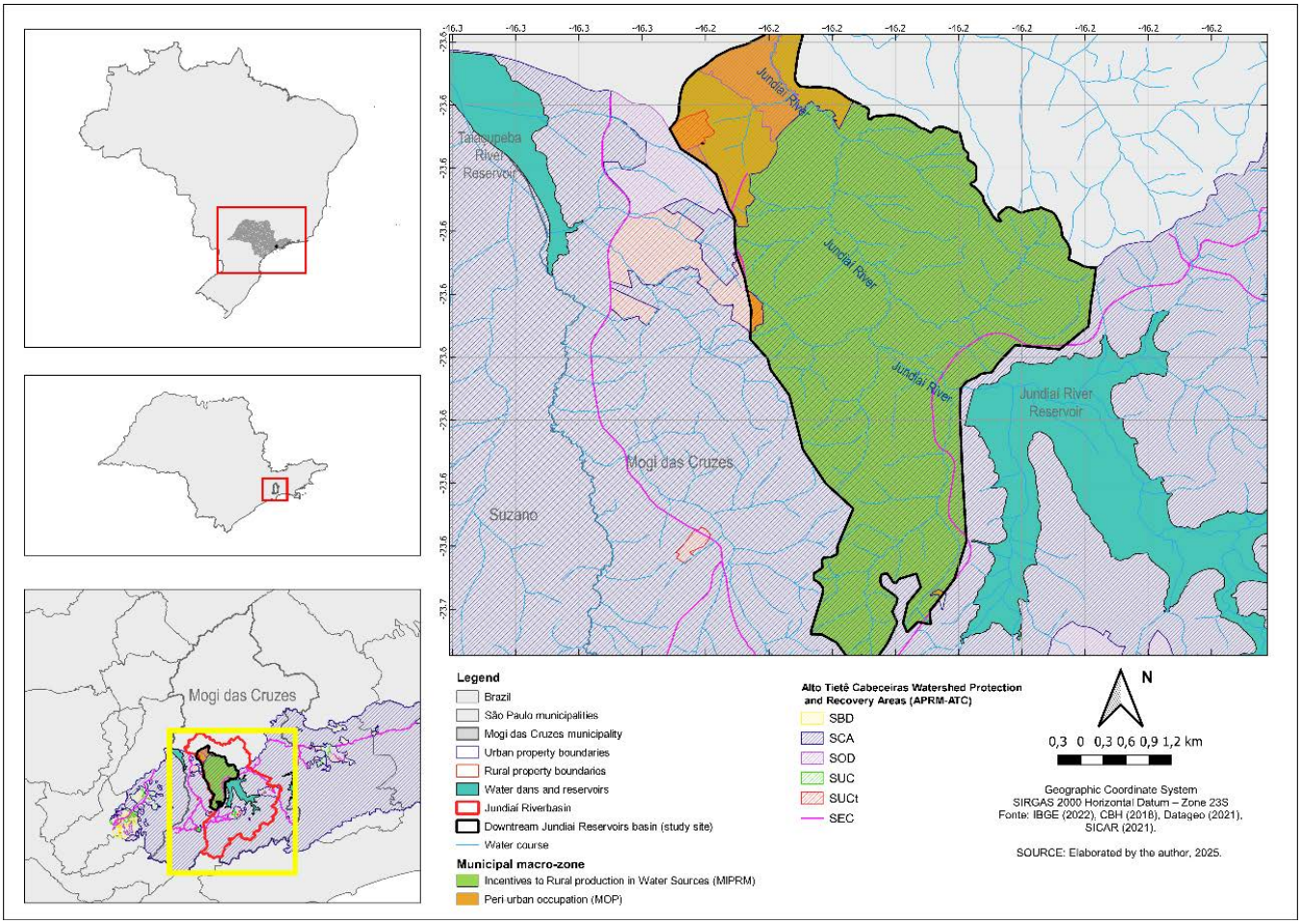


Figure 1

Study site location – Downstream Jundiaí Reservoir Basin, Mogi das Cruzes, São Paulo State, Brazil.

Legend: SBD: Low-Density Sub-area. SCA: Environmental Conservation Sub-area. SOD: Differentiated Occupation Sub-area. SUC: Consolidated Urbanization Sub-area. SUCt: Controlled Urbanization Sub-area. SEC: Special Corridor Sub-area.

Table 1 Geospatial database of the Downstream Jundiaí Reservoir Basin, Mogi das Cruzes Municipality, São Paulo State, Brazil.

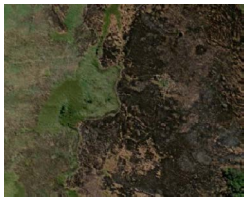
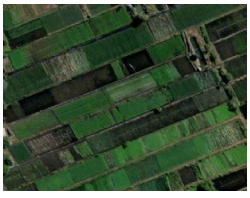
Data	Description
São Paulo State Hydrography; UGRHI 6 Hydrography; São Paulo Metropolitan Region APMs/APRMs; São Paulo Metropolitan Region Reservoirs	Set of shapefile-format files, 1:50,000 scale, from 2017/2018. (Comitê de Bacia Hidrográfica do Alto Tietê [CBHAT], 2023)
Land use and land cover map, 2021 and 2006	Project to map land use and land cover in Brazil at 30-meter resolution through Landsat images, for 2021 and 2006 (Mapbiomas, 2024)
Relief patterns; Flood susceptibility; Risk areas; Geology; Pedology	Susceptibility map of gravitational mass movements and floods: Mogi das Cruzes Municipality, SP, 2018, scale 1:50,000 (Instituto de Pesquisas Tecnológicas, 2014)
Territorial networks	Shapefiles of the Brazilian Political-Administrative Division, 1:250,000 scale, 2022 (Instituto Brasileiro de Geografia e Estatística, 2023)
Digital Elevation Model	Raster file of digital elevation data at 30-meter resolution, from 2011 to 2015. (OpenTopografy, 2023)
Master Plan of Mogi das Cruzes Municipality	Shapefiles representing the 2019 Master Plan spatialization at Mogi das Cruzes Municipality, SP (scale 1:45,000). (Prefeitura Municipal de Mogi das Cruzes, 2019)
Rural properties in Mogi das Cruzes Municipalities, São Paulo	Shapefile of rural properties in Mogi das Cruzes Municipality, São Paulo – registered at the Federal Rural Environmental Registry (CAR) (Sistema Nacional de Cadastro Ambiental Rural, 2023).
Land lots, blocks and tracts in the urban area of Mogi das Cruzes Municipality	Shapefiles provided by Mogi das Cruzes City Hall, 2019

2.3. Current situation (2021)

The current land-use and land-cover map derived from adjustments to the MapBiomas dataset (Collection 7, for the year 2021), which was plotted through the automated classification of 30-meter-pixel Landsat images (Mapbiomas, 2024). The “rock outcrop” and “land-use mosaic” classes were corrected based on ground-truth data collected during field visits and through Google Earth® images. The original thematic classes were also reclassified and expressed in a map legend consistent with this study’s aim: assessing legal compliance (Table 2).

Classification correction and reclassification were carried out by photo-interpreting of current orbital images obtained from Google Satellite® extension through the QGIS® Quick Map Services plugin. The observed features were classified according to tone/color, texture, size, shape, shadow, height, pattern and location (Florenzano, 2002). The resulting map accuracy was assessed based on a confusion matrix through the AcATaMa plugin (version 23.4). This procedure assumed a standard error of up to 0.5% and area-proportional sample allocation per class. In total, 397 ground-truth samples were photo-interpreted.

Table 2 The 2021 land use and land cover map legend for Downstream Jundiaí Reservoir basin in Mogi das Cruzes Municipality, São Paulo State.

MapBiomas Classification	Reclassification	Representation in the area	Associated aspects and main characteristics
Urbanized area	Urbanized area		Urban area is mainly characterized by residential, commercial and service buildings, with paved or unpaved public roads.
Forest Formation	Forest Formation		Area mostly featured by Atlantic Forest biome formations, mainly Dense Ombrophilous Forest, including arboreal pioneer formations and agroforestry systems.
Forestry	Forestry		Tree species planted for commercial purposes (e.g., pine and eucalyptus).
-	Floodplain vegetation		Vegetation featured by varying composition influenced by rainfall and waterbody levels, subject to systematic flooding at the high-water season and intense rainfall.
-	Shrub-tree vegetation		Shrub-tree clusters.
Pasture	Anthropogenic field		Open areas subject to human use. They include planted pasture, exposed soil and undeveloped lots in rural and urban areas.
Soybeans Other temporary crops	Agriculture		Areas covered with short- or medium-term agricultural crops, mainly by vegetable crops, whether perennial or annual.
Other non-vegetated areas	Other non-vegetated areas		Impervious surface areas (infrastructure, urban expansion or mining).
Rivers, lakes and the ocean	Waterbodies		Surface area of reservoirs or ponds.

SOURCE: Elaborated by the author, based on Google Earth images and on MapBiomas adjustments, 2026.

2.4. Legal scenario

The "legal scenario" was defined as the spatial representation of expectations set by legal provisions on land use and land cover. It reflects the environmental concept based on the current legal framework. Geoprocessing enabled the simulation of native vegetation cover and permeable areas protection requirements according to prevailing legal instruments. It was accomplished by employing the techniques used by Hardt et al. (2012; 2013) and Issii et al. (2020, 2024). The methodologies adopted to elaborate the legal scenario followed the technical framework proposed by Issii et al. (2020).

The established legal scenario encompasses all federal, state and municipal laws on native vegetation, permeable areas, and protection of peri-urban and rural zones. Federal Law n. 12.651/2012 (*Lei de Proteção da Vegetação Nativa,* LPVN); Federal Law n. 11.428/2006 and the associated Federal Decree n. 6.660/2008 on native vegetation protection in the Atlantic Forest Biome (*Lei da Mata Atlântica*, LMA); State law n. 15.913/2015, which enacted the APRM-ATC; and Municipal law n. 150/2019, which established the Mogi das Cruzes Municipality Master Plan (*Plano Diretor,* PD) and zoning. These regulations provided the basis for map elaboration in order to spatially comply with the requirements. This was achieved by the specific criteria and the protection rates set for permeable areas and native vegetation (Table 3 and Figure 2).

The assessed basin does not include protected areas under the National System of Nature Conservation Units Act (*Lei n. 9.985*, 2000). This information was verified through consultations with DataGEO (DataGEO, 2024) and the National Registry of Nature Conservation Units (Cadastro Nacional de Unidades de Conservação., 2024).

2.4.1. Native Vegetation Protection Act – Federal law n. 12.651/2012

Shapefiles of springs, watercourses, artificial reservoirs, and rural and urban property boundaries were compiled to spatially map the APPs and RLs supported by the LPVN (Table 1). APP mapping was conducted by using the buffer tool to project areas predefined width, starting from a line, point or polygon. Rural property boundaries and the current situation 2021 land use and land cover map were used to spatially draw the RLs. The rural property dataset collected from the Rural Environmental Registry (*Cadastro Ambiental Rural,* CAR) required adjustments given the overlaps between neighboring properties boundaries. Notably, 25% of the study site lacked property boundary information; therefore, this fraction of the RL area was not quantified.

Properties found to be non-compliant with RL requirements had their missing native vegetation identified and manually vectored within each property. Missing areas were located based on the following criteria:

i) ease of land use conversion considering the following order: shrub-tree vegetation > Forestry > anthropogenic grassland > other non-vegetated areas > agriculture;

Table 3 Legal protection criteria set for permeable areas and native vegetation in the Downstream Jundiaí Reservoir Basin, in Mogi das Cruzes Municipality, São Paulo State.

Legal provision	Area	Protection criteria			Legal provision interpretation and spatialization
		Permeability rate (%)	Vegetated area index (%)	Native vegetation *	
PD	MOP	60	-	-	Clip, node and attribute table tools to identify and project missing areas.
	MIPRM	Similar to APRM-ATC	-	-	
APRM-ATC	SOD	60	30	-	
	SUC	20	10	-	
	SEC	60	30	-	
	SUCt	20	10	-	
	SCA	80	40	-	
LPVN	APP	-	-	30 m buffer strip (watercourses up to 10 m wide)	Buffer tool to project the Permanent Preservation Area (APP) strip based on hydrography and topography.
		-	-	50 m radius around springs	
		-	-	50 m buffer strip measured from the *maximum maximorum* (maximum water level) elevation of Jundiaí Reservoir (elevation 756.76 m)**	
		-	-	Slopes with a gradient ≥ 45° (equivalent to 100% along the steepest slope line)	Selection of Permanent Preservation Areas (APP) based on topography
		-	-	Upper third of hills and mountains (elevation > 100 m and slope > 25°)	
		-	-	In *veredas*, within a 50-meter buffer strip extending from the permanently marshy and waterlogged area.	Not applicable
	RL	-	-	20% of the rural property***	Clip, node and attribute table tools to identify and project missing areas.
LMA	VN	-	-	Fragment of primary native vegetation	Not applicable
		-	-	Native vegetation fragment at a medium regeneration stage – clearing prohibited in rural areas; mandatory retention of 50% in urban areas.	Clip, node and feature table tools to identify and project missing areas.
		-	-	Native vegetation fragment at an advanced regeneration stage – clearing prohibited in rural and urban areas (following the law's enforcement in 2006)	

Legend: *Removal/intervention only allowed in specific cases established by legal provisions. **Criterion defined Federal Law n. 12.651/2012, as specified in Article 8, Item II, of State Law n. 15.913/2015. ***Excludes Legal Reserves in urban areas; the possibility of counting Permanent Preservation Areas (APP) toward the requirement or offsetting on properties outside the study site; specific provisions for small rural holdings; and the status of pre-2008 occupations. (Continued on the next page).

PD: Mogi das Cruzes Master Plan. APRM-ATC: Alto Tietê Cabeceiras Watershed Protection and Recovery Areas. LPVN: Native Vegetation Protection Act. LMA: Atlantic Forest Act. MOP: Peri-urban Occupation Macro-zone. MIPRM: Rural Production Incentive Macro-zone in Watershed Areas. SOD: Differentiated Occupation Sub-area. SUC: Consolidated Urbanization Sub-area. SEC: Special Corridor Sub-area. SUCt: Controlled Urbanization Sub-area. SCA: Environmental Conservation Sub-area. APP: Permanent Preservation Area (*Áreas de Preservação Permanente*). RL: Legal Reserve. NV: Native Vegetation.

ii) proximity to riparian buffer zones, and fragments of forest formation and/or floodplain vegetation;

iii) proximity to other RLs.

The spatialization of the LPVN set the Legal Reserve (RL) as a fraction of 20% of the property, regardless of APP coverage or other exception criteria, such as the potential RL offsetting on properties outside the study site. Legal criteria established to account for RLs in urban zones were not applied due to the lack of official information on those properties. Rural properties partially located within the assessed basin, but whose RL requirement was met in areas outside the basin, were not considered for the creation of new RLs. Conversely, RLs were preferentially spatialized within the assessed basin for properties whose RL requirement had not yet been fulfilled.

LPVN also established exceptions regarding native vegetation maintenance, as follows:

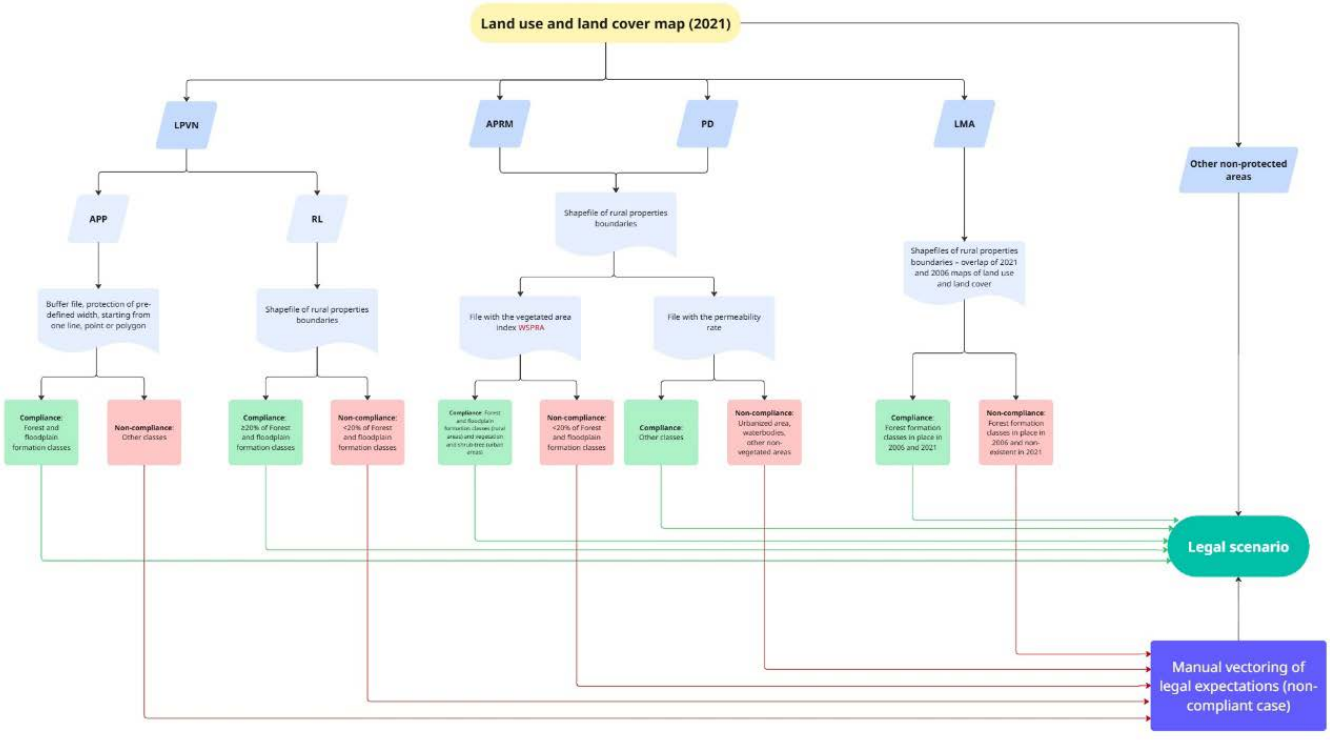
i) APPs designated for public utility, for social interest and occasional activities, or for those recognized as having low environmental impact (Article 8);

ii) Continuation of agro-forestry-pastoral activities in consolidated rural areas up to July 22, 2008. This process includes the obligation to

Figure 2

Flowchart illustrating the legal scenario applicable to the study site – the Downstream Jundiaí Reservoir Basin, Mogi das Cruzes, São Paulo State.

Legend: LPVN: Native Vegetation Protection Act. APRM-ATC: Alto Tietê Cabeceiras Watershed Protection and Recovery Area. PD: Mogi das Cruzes Master Plan. LMA: Atlantic Forest Act.



restore the minimum riparian buffer zones based on the Fiscal Module (*Módulo Fiscal,* MF), ranging from 1 to 4 MF (Article 61-A); and

iii) Properties up to 4 MFs that recorded RLs rates lower than those required under Article 12 as of July 22, 2008 are exempt from restoring native vegetation. In these cases, the RL consists of the native vegetation present at that time (Article 67). Properties up to 20 hectares in Mogi das Cruzes Municipality may fall under these exceptions (equivalent to 21.34% of the municipality's territory), given that their MF is 5 hectares (Instituto Nacional de Colonização e Reforma Agrária, 2024).

Although, under the law, the absence of RL and APP is permitted in these specific situations, this possibility was not incorporated into the legal scenario for two reasons:

i) Lack of official information regarding properties falling under these legal exceptions; and

ii) Advocacy of the maximum protection scientific expectation set for the remaining native vegetation.

Exceptions established by the LPVN represent a regression because they were not addressed in the 1965 Forest Code (*Lei n. 4.771*, 1965), which mandated broader protection (Tambosi et al., 2015; Brancalion et al., 2016; Guidotti et al., 2017; Lopes et al., 2018; Mello et al., 2022). Previous studies have emphasized the relevance of keeping private natural reserves to safeguard habitats and biodiversity. This practice includes requirements to restore deforested native vegetation areas (Metzger, 2010; Hardt et al., 2013; Brancalion et al., 2016; Guidotti et al., 2017; Issii et al., 2024).

LPVN was deemed compliant only in land use areas identified as Forest Formation and Floodplain Vegetation. Forest Formation is herein understood as naturally occurring within the study site. The adopted legal scenario represents the technically feasible legal expectation substantiated by the basin's maximum possible protection, which would be ideal for conservation purposes.

2.4.2. Alto Tietê Cabeceiras Watershed Protection and Recovery Area (APRM-ATC), State Law n. 15,913/2015

Permeability rates (%) and vegetated area index (%) were spatialized based on the shapefile of sub-areas defined by the Alto Tietê Cabeceiras Watershed Protection and Recovery Area (*Área de Proteção e Recuperação de Mananciais – Alto Tietê Cabeceiras,* APRM-ATC (Figure 1, Table 3). Permeable areas were quantified according to their soil water infiltration potential, as nit is a relevant factor given the study site's flooding background. The vegetated area index was taken as part of the permeable area rate.

Land use not including buildings or structures were considered compliant with the permeability rate estimates, mainly with classes from

the current situation 2021 map, other than the "Urbanized Area", "Water Bodies" and "Other Non-Vegetated Areas". Classes "Forest Formation", "Floodplain Vegetation", "Forestry" and "Shrub-Tree Vegetation" were considered compliant with vegetated area index estimates. This rule does not apply to sub-area SCA, which requires native vegetation and falls under the "Forest Formation" and "Floodplain Vegetation" classes.

The proportion of land use and land cover classes meeting the legal requirements set for each property was also included in the estimates for properties identified as non-compliance with the vegetated area index (%) and permeability rate (%), at both the individual and manual scale. The vectoring of these areas was based on the following criteria:

i) Conversion to Forest Formation classes in rural areas and to Shrub-tree Vegetation in urbanized areas; and

ii) Potential connections with neighboring native vegetation fragments.

2.4.3. Mogi das Cruzes Municipal Master Plan, Supplementary law n. 150/2019.
The spatial distribution of the expected permeable area under the Master Plan (PD) derived from the municipal zoning shapefile (Table 1). Similar to the other regulatory maps, areas lacking land use information or lots and properties boundaries were excluded from the assessment.

The same criteria set established by the APRM-ATC Act were adopted to convert the current land us situation (2021) in order to meet legal requirements. This adjustment ensured compliance with the permeability rate provided for on the Master Plan (Table 3).

2.4.4. Native vegetation protection in the Atlantic Forest biome – Federal law n. 11.428/2006 and Federal Decree n. 6.660/2008
Starting from the year of its enactment (2006), LMA projection was carried out under the assumption that clearing the secondary native vegetation at advanced and medium regeneration stage (Article 21), whereas up to 50% clearing would be allowed in urban areas (Article 31, Paragraph 2) (*Lei n. 11.428*, 2006). Specific cases, such as the exception for properties belonging to small-scale rural producers (Article 9), were not considered due to the lack of geospatial data.

MapBiomas 2006 land use and land cover maps were employed to spatialize the legal expectation. The expectation of 100% protection was maintained for areas covered by forest formations (forests at various successional stages) in rural areas, and 50% protection was applied to urban areas. In addition, areas regenerated after the enactment of the LMA were identified by overlaying the current (2021) land use situation and land cover map with the 2006 map.

3. Results

The current (2021) land use situation and land cover map revealed a predominantly agricultural landscape (38.6%) and forested areas (28.9%) with a relatively small urbanized fraction (7.52%) (Figure 3 and Table 4).

LPVN accounted for the highest native vegetation protection expectation (46.9% of the study site) as it comprised 38.0% of the Forest Formation class and 8.9% of Floodplain Vegetation. However, only 47.1% of the assessed properties met the minimum RL requirement within their holdings. In order to fulfil this gap, 102 Legal Reserves were proposed for properties that did not meet this minimum, totaling 736.82 hectares of native vegetation (defined as described in the Methods section).

In total, 1,900 urban lots (12% of the basin) and 193 rural properties (63% of the basin) were assessed based on the application of LPVN criteria. The aliquot of 88.2% of the urban lots comprised less than 4 fiscal modules (1,337.25 hectares, 38.3% of the basin).

Compliance with all APPs in the basin reached 49.7%. APPs identified in the basin included protection zones along watercourses, springs and surface water reservoirs (Table 5). No slopes exceeding 45° (equivalent to 100% gradient along the steepest slope line) were identified in the study site, nor were any *veredas* (savanna wetlands characterized by shallow water streams and iconic Buriti palm trees, found in the Brazilian Cerrado), hills or mountains requiring APP designation.

Table 4 Land use and land cover rates based on the current situation 2021 map, the legal scenario and the assessed legal provisions for the Downstream Jundiaí Reservoir Basin, in Mogi das Cruzes Municipality, São Paulo State.

Land Use and Land Cover Class	Area (%)					
	Legal expectations				Full legal Scenario	Current 2021 land use situation and land cover
	LPVN	APRM-ATC	PD	LMA		
Forest formation	38.0%	34.9%	29.1%	31.6%	43.8%	28.9%
Forestry					0.5%	0.7%
Anthropogenic field					2.2%	2.7%
Shrub-tree vegetation		8.5%	12.0%		7.1%	10.4%
Urbanized area					6.4%	7.5%
Other non-vegetated areas					1.2%	2.5%
Waterbodies					0.3%	0.3%
Agriculture					27.7%	38.6%
Floodplain vegetation	8.9%	10.6%	8.4%	8.0%	10.9%	8.3%

Legend: PD: Mogi das Cruzes Master Plan. APRM-ATC: Alto Tietê Cabeceiras Watershed Protection and Recovery Areas. LPVN: Native Vegetation Protection Act. LMA: Atlantic Forest Act.

A comparative analysis between the current situation (2021) map and the legal scenario (the sum of legal provisions) was conducted through spatial overlay. This analysis enabled quantifying the extent of non-compliance with native vegetation cover. Native vegetation, which comprised the "Forest Formation" and "Floodplain Vegetation" classes, would account for 54.7% of the area under the legal scenario. However, this combined total only represented 37.2% in the current situation (2021) (Figure 3 and Table 4).

The contributions of legal instruments were assessed in separate, without considering overlaps between areas protected by different instruments. Conversely, their respective overlaps were accounted for when calculating the "legal scenario" values (Table 5). Notably, the RL represented the largest share of protection under the LPVN within the study site (17.9%), which covered approximately 625.3 hectares of the basin. The SCA sub-area received the most significant protection under the APRM-ATC Act based on both the vegetated area index (25.3%) and permeability criteria (50.6%), as it encompassed the largest portion of the basin (86.7%). Under the PD, the MIPRM macro-zone criterion provided the highest protection level (50.6%) when the same permeability criterion in the APRM-ATC Act was applied in the SCA sub-area.

Figure 3

Comparison between the current (2021) land use situation and land cover map, and the legal native vegetation and permeable areas protection scenario in the Downstream Jundiaí Reservoir Basin in Mogi das Cruzes Muncipality, São Paulo State.

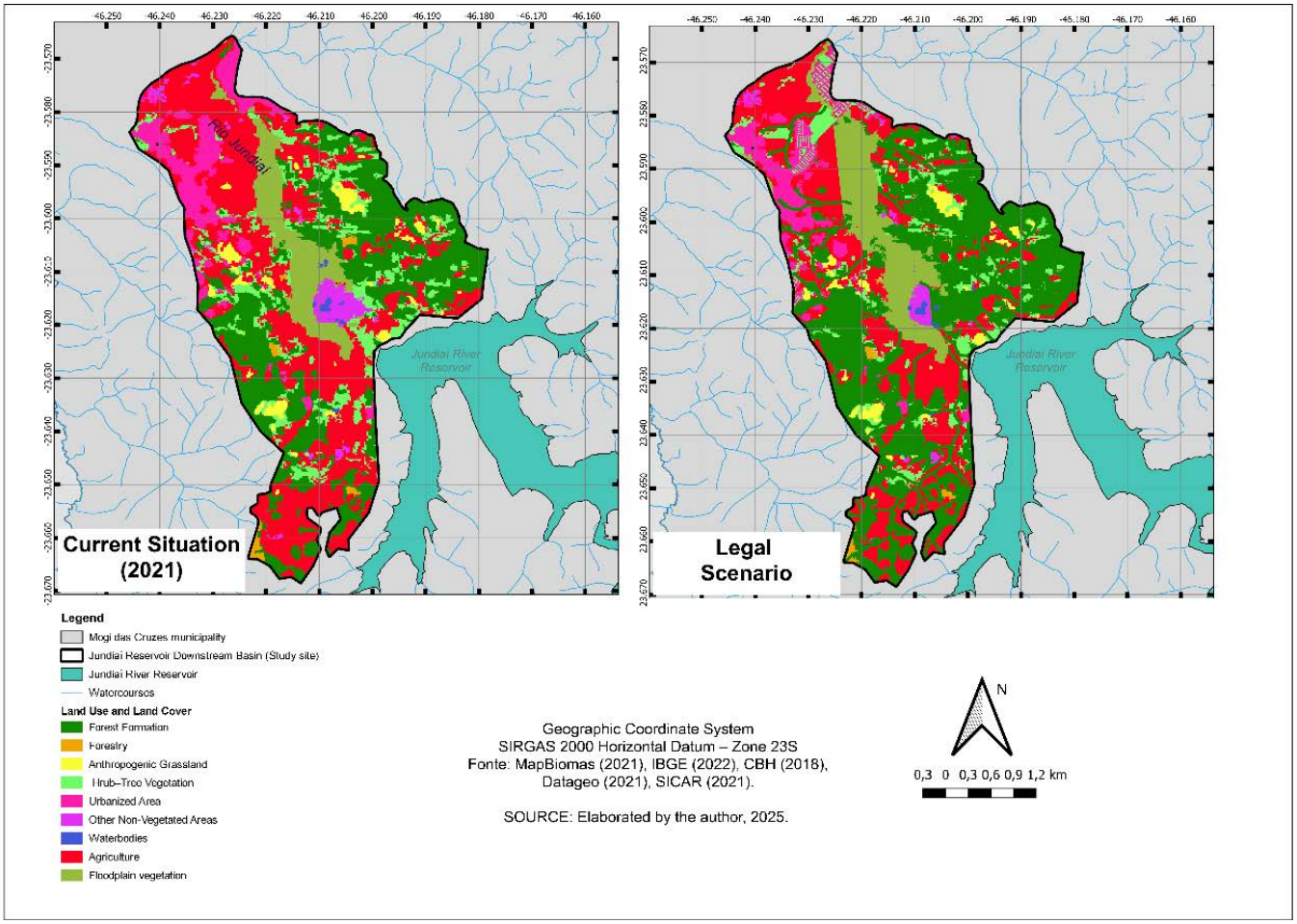


Table 5 Legally protected areas under the APRM-ATC Act, the Master Plan (PD) and the LMA ACT in the Downstream Jundiaí Reservoir Basin in Mogi das Cruzes Municipality, São Paulo State.

Protection Class	Legal Provision		Area (ha)	Protection provision for the basin (%)
Spring APP	LPVN		47,9	1,4%
Watercourse APP			478,8	13,7%
Jundiaí River Reservoir APP			1,1	0,0%
Legal Reserve			625,3	17,9%
Total:			**1,153.1**	**33.0%**
Vegetated area index	APRM-ATC	SUC	6.4	0.2%
		SUCt	3.6	0.1%
		SOD	44.9	1.3%
		SCA	882.8	25.3%
Total:			**937.67**	**26.9%**
Fragment at an intermediate succession stage within an urban zone	LMA		1,5	0,0%
Mid- to late-successional fragments in a rural area			977,3	28,0%
Total:			**978.73**	**28.0%**
Permeable area	APRM-ATC	SUC	12.9	0.4%
		SUCt	7.2	0.2%
		SOD	89.7	2.6%
		SCA	1765.6	50.6%
	Total:		**1875.4**	**53.7%**
	PD	MOP	244.8	7.0%
		MIPRM	1765.6	50.6%
	Total:		**2010.4**	**57.6%**
Legal scenario protection*	**Total (native vegetation):**		**1893.5**	**54.2%**
	Total (permeable areas):		**1875.4**	**53.7%**

Legend: *Overlaps between protected areas were not accounted for in the legal scenario analysis. PD: Mogi das Cruzes Master Plan. APRM-ATC: Alto Tietê Cabeceiras Watershed Protection and Recovery Areas. LPVN: Native Vegetation Protection Act. LMA: Atlantic Forest Act. MOP: Peri-urban Occupation Macro-zone. MIPRM: Rural Production Incentive Macro-zone in Watershed Areas. SOD: Differentiated Occupation Sub-area. SUC: Consolidated Urbanization Sub-area. SEC: Special Corridor Sub-area. SUCt: Controlled Urbanization Sub-area. SCA: Environmental Conservation Sub-area. APP: Permanent Preservation Area.

The current situation (2021) showed 32.2% legal non-compliance native vegetation protection measures applicable to the site. The highest non-compliance rate was recorded for the Agriculture class (71.4%) (Figures 4A and 5).

Among the assessed legal provisions, LMA accounted for the highest compliance level (87.5%), whereas LPVN recorded the highest non-compliance rate (20.8%), primarily due to agricultural use (16.1%) and shrub-tree vegetation cover (8.2%). Notably, Atlantic Forest areas regenerated between 2006 and 2021 (15.8%) exceeded the deforested areas at the legal non-compliance stage (12.5%).

With respect to compliance under APRM-ATC criteria, the vegetated

area index was not met in the SUC (0.0%) and SOD (0.0%) sub-areas. SUCt (11.5%) and SCA (54.7%) recorded partial compliance with it. The permeability criterion of the PD was not comply with the MOP (0.0% compliance) and was comply with in approximately 98% of the MIPRM. Nevertheless, an increase of 0.2% in Forest Formation (in rural areas) and 1.6% in Shrub-Tree Vegetation (in urban areas) relative to the total of vegetation found in the basin. it was observed in areas failing to meet permeability standards, which were replaced with vegetated cover in order to comply with legal requirements.

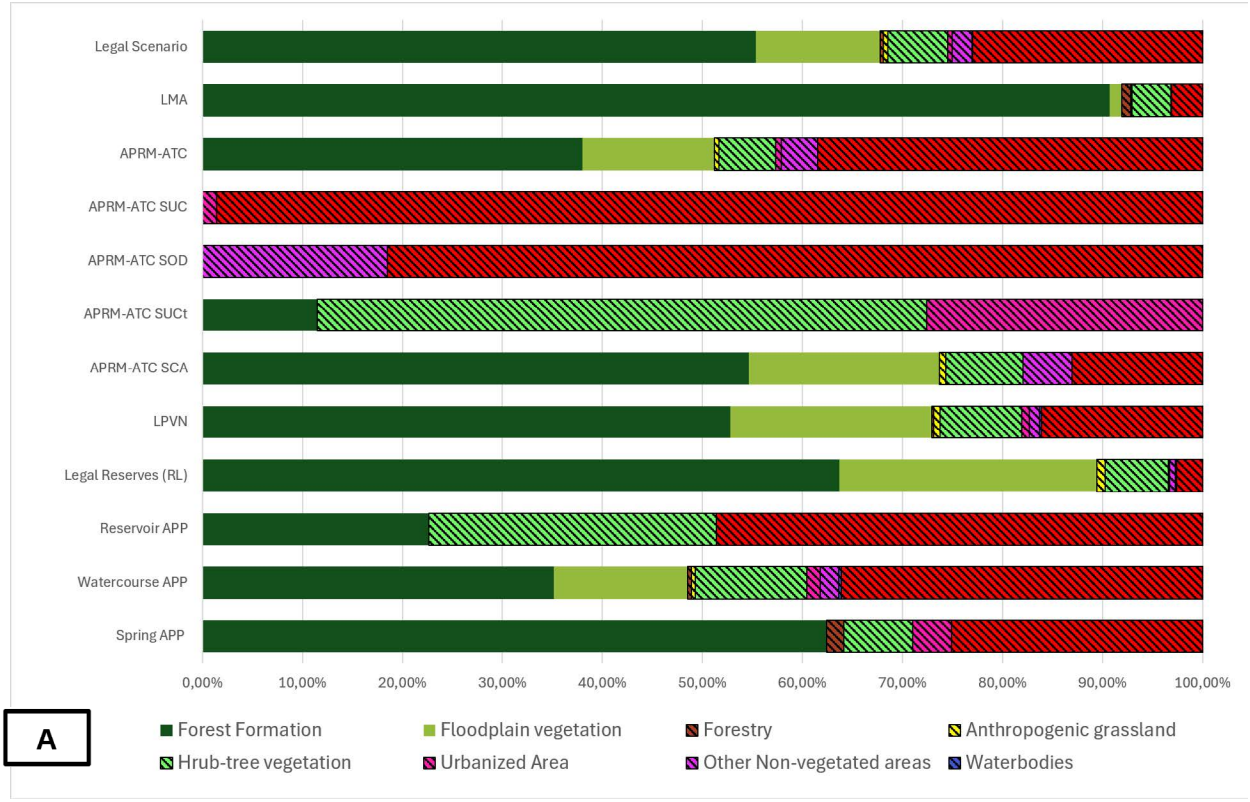
The Legal Reserve (RL) and the Permanent Preservation Area (APP) surrounding springs exhibited the highest levels of compliance with native vegetation cover, primarily within the Forest Formation and Floodplain Vegetation classes. Compliance reached 89.4% for RL and 62.4% for the APPs around springs based on the protection criteria provided by LPVN, in separate. In contrast, compliance with native vegetation cover was considerably lower in APPs associated with reservoirs (22.6%) and watercourses (48.5%) (Figure 4A and Table 5).

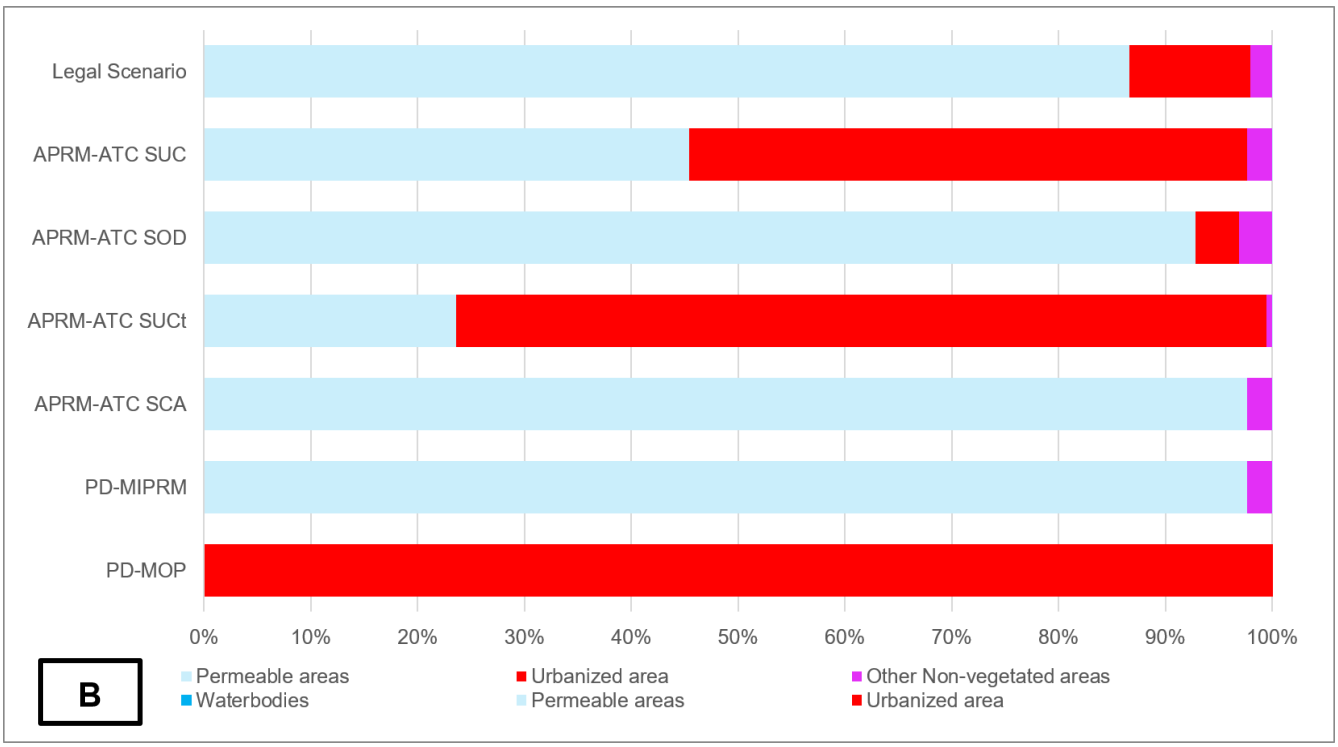
The study area was predominantly permeable (92.1%). The SCA sub-area, defined by the APRM-ATC Act and corresponding to the PD MIPRM macro-zone. It came closest to legal compliance as only 2% of it was classified as "Other Non-Vegetated Areas" class (Figure 4B). On the other hand, the Master Plan's MOP macro-zone area comprised lots lacking areas designated to soil permeability; consequently, it failed to meet the legal requirements. Overall, permeable areas played a key role in achieving 99.00% compliance with legal expectations.

Figure 4

Current (2021) land use situation and land cover in areas subjected to legal native vegetation (A) and permeable areas (B) protection requirements in the Downstream Jundiaí Reservoir Basin in Mogi das Cruzes Municipality, São Paulo State.*

Legend: *Hatched bars represent classes non-compliant with legal provisions. LMA: Atlantic Forest Act (Lei n. 11.428/2006). APRM-ATC: Alto Tietê Cabeceiras Watershed Preservation and Recovery Area (Lei n 15.913/2015). PD: Mogi das Cruzes Master Plan (Lei n. 150/2019). MOP: Peri-urban Occupation Macro-zone. MIPRM: Macro-zone for Incentivizing Rural Production in Watershed Areas. SOD: Differentiated Occupation Sub-area. SUC: Consolidated Urbanization Sub-area. SEC: Special Corridor Sub-area. SUCt: Controlled Urbanization Sub-area. SCA: Environmental Conservation Sub-area. APP: Permanent Preservation Area. RL: Legal Reserve.



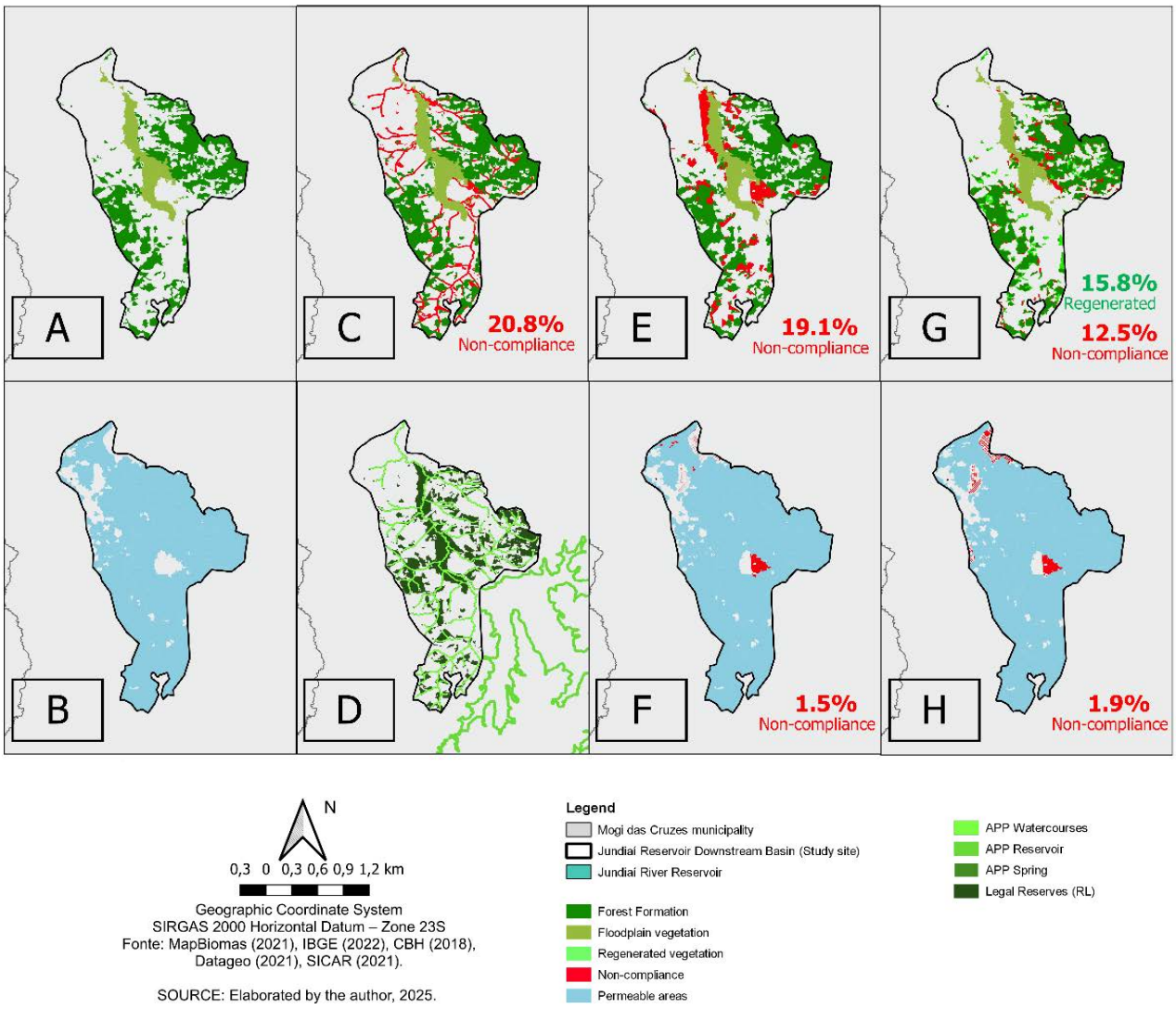


It was evident that 67,8% of the designated areas were compliant with the legal native vegetation cover requirements. However, 23% of the protected areas were occupied by agricultural activities (Figure 4A). In total, 87% of the legal requirements were met by permeable areas, which included 11% occupation by urbanized areas and 2.0% by other non-vegetated areas (Figure 4B).

4. Discussion

Agriculture is the primary productive activity in Mogi das Cruzes. This is the largest and most influential sector in the basin area (38.6%). Mogi das Cruzes is part of São Paulo's "Green Belt" and is particularly recognized for its persimmons and vegetables production (Sindicato Rural de Mogi das Cruzes, 2024). Furthermore, 86.7% of the study site falls within the Macro-zone for Incentivizing Rural Production in Watershed Areas (MIPRM), as established by the Master Plan (PD), which promotes the expansion of agricultural activities across a substantial portion of the basin.

Despite their relevance to the local economy, agricultural areas exhibited the lowest compliance with legal APPs protection requirements. This pattern reflects Brazil's historical pressure to convert native vegetation into agricultural and livestock farming land. Over the past three decades, 38% of the Brazilian territory has undergone such changes (Souza et al., 2020). Although the urban fraction represented a smaller share of the study site (7.52%), non-compliance was still observed in the Urbanized Areas class. This finding was also highlighted by Harano e Galvanin (2023), who



documented similar irregularities in the urban zone of Mogi das Cruzes Municipality.

Figure 5

Native vegetation (A) and current 2021 permeable area (B) maps, and maps of legal protection requirements in the downstream Jundiaí Reservoir Basin in Mogi das Cruzes Municipality, São Paulo State. Based on the Native Vegetation Protection Law – LPVN (C and D), Alto Tietê Cabeceiras Watershed Protection and Recovery Areas Act – APRM-ATC (E and F), the Atlantic Forest Act – LMA (G) and the Master Plan – PD (H).

The Master Plan did not provide guidelines for urban area expansion, and only 13.3% of the analyzed territory was reserved for urbanization through the MOP. This provision effectively limited the remaining area to rural uses. Land use restrictions within the basin were further reinforced by the enforcement of the APRM-ATC Act. However, the Acts' for certain land use conversions to construction sites (Vieira & Sartorello, 2020).

Non-compliance with environmental protection regulations is recurrent across several Brazilian regions. These figures are significantly higher in more urbanized areas of São Paulo Metropolitan Region (*Região Metropolitana de São Paulo,* RMSP), such as Diadema (SP), than those observed in the assessed basin. Non-compliance rates reached 68% for the LPVN and 32.2% for the APRM-Billings in Diadema (Issii et al., 2020). Compliance with the LMA was the highest (99.4%) and this rate was similar to that observed in our study (Issii et al., 2020).

Other authors have also identified non-compliance with legal provisions

in rural landscapes. Hardt et al. (2012) reported a 10% shortfall in meeting legal requirements within protected areas of Serra do Japi, in Jundiaí Municipality, São Paulo State. Similarly, Santos et al. (2021) assessed native vegetation cover in APPs and RLs in the Buranhém River basin, located on the border of Minas Gerais and Bahia states. Their findings revealed that a substantial fraction of RLs (41.8%) and APPs (74.7%) lack native vegetation.

Legal Reserve irregularities have been documented across several Brazilian regions (Santos et al., 2017; Paz et al., 2020; Dias dos Santos et al., 2021; Souza et al., 2024), reflecting the conflicting land uses observed in the protected areas of the study site. These irregularities are primarily associated with agricultural activities. Loss of native vegetation and disturbances caused by other land uses and land cover have also been reported in protected areas of other countries, including Peru (Vera et al., 2024), South Africa (Vukeya et al., 2023) and Indonesia (Segah et al., 2023).

These cases indicate that the non-compliance instances identified in this study reflect broader patterns observed both nationally and internationally. A recurring trend involves land uses conflicting with legal protections, particularly through the replacement of native vegetation with agricultural activities. This trend is further illustrated in studies on future scenarios, according to which native vegetation is replaced by pasture and crops (Agudelo-Hz et al., 2023).

The non-compliance rates reported by several Brazilian authors (Hardt et al., 2012; Gutierrez et al., 2017; Issii et al., 2020; Paz et al., 2020; Carvalho et al., 2021; Dias dos Santos et al., 2021; Santos et al., 2021; Souza et al., 2024) could be even higher if the previous 1965 law (*Lei n. 4.771*, 1965) were still in force, given that it established stronger legal mechanisms for native vegetation protection. The weakening of these mechanisms was enabled by the enactment of the LPVN in 2012 (Lima & Garcia, 2014). This new law introduced several contradictory provisions, including the reduction of protection standards for APPs (Guidotti et al., 2017; Lopes et al., 2018). In fact, the new legislation reduced the width of the protected strip by up to 99%, depending on the rural property size (Brancalion et al., 2016).

This study did not include APPs in the RL calculation and disregarded exceptions, such as small rural properties, ad it may have led to the overestimation of non-compliance. The aim of this approach was to maximize legislation's protective potential and to reflect the stance of the previous law, the 1965 Forest Code (*Lei n. 4.771*, 1965). Many authors have criticized the new legislation, the LPVN Act (*Lei n. 12.651*, 2012), which replaced the 1965 Forest Code (Tambosi et al., 2015; Brancalion et al., 2016; Guidotti et al., 2017; Mello et al., 2022). This criticism emphasized recommendations from the scientific community that were disregarded by decision-makers (Mello et al., 2022). Studies conducted in the aftermath of the LPVN enactment indicated significant impacts on the Atlantic Forest biome (Brancalion et al., 2016; Guidotti et al., 2017).

The lack of vegetation resulting from failures in native vegetation protection and the weakening of legal enforcement can expand urban heat islands, alter rainwater infiltration and have had negative affect on the quality of life of the population. Conversely, urban areas with tree cover improve the air quality and reduces noise (McPherson et al., 1994; Jack-Scott et al., 2013). In addition to reduced green cover increasing land surface temperatures (Al Kafy et al., 2021), it can also lead to decreased evapotranspiration (Tucci, 1999). These conditions may further compromise biodiversity and cause habitat isolation (Castro, 2005; Vukeya et al., 2023), soil compaction (Carvalho et al., 2021), biotic homogenization, reduced endemism and decline in carbon storage capacity (Lima et al., 2020).

This study mainly indicated non-compliance in APPs where land use and land cover classes, other than native vegetation, can also contribute to waterbodies siltation and soil erosion onset (Castro, 2005; Santos et al., 2021; França et al., 2022).

Although proximity to other protected areas, such as RLs, APPs, UCs or other legally protected zones, was one of the criteria adopted in this study for RL spatial mapping based on LPVN, most of them exhibited fragmented landscape and lacked connections with other vegetation patches. RL fragmentation in the basin was not an isolated case as it has also been documented in other Brazilian regions (Paz et al., 2020; Santos et al., 2021; Souza et al., 2024). In general, habitat fragmentation can have detrimental effects, as it facilitates human access to forest remnants and, consequently, increases exposure to fire, selective logging, hunting, biological invasions, edge effects and forest isolation (Lopes et al., 2018; Lima et al., 2020).

The failure to comply with legal requirements observed in the assessed basin highlighted the need for additional measures aimed at protecting and restoring native vegetation areas, as mandated by current environmental laws. The absence of a coordinating body to evaluate legal provisions, often observed during the environmental licensing process, contributes to this non-compliance. This scenario is also emphasized in the study by Santos et al. (2021), which highlights the importance of mapping, monitoring and enforcing the law in these protected areas, as well as the need for public policy incentives to maintain APPs. Payments for ecosystem services (*Pagamento por Seviços Ambientais,* PSA) (*Lei n. 14.119*, 2021) and other compensation forms are examples of such measures.

If we consider that the remaining Atlantic Forest biome currently represents approximately one-tenth of its original cover (Weber et al., 2021), the ongoing loss of native vegetation in the basin is a cause for concern. This profile places the Atlantic Forest among the most threatened forests worldwide (Ramanelli et al., 2022). On the other hand, regenerated forest areas (15.8%) in the "Forest Formation" class were identified in the current situation (2021), following the enactment of the Atlantic Forest Act

(LMA) in 2006. This total exceeded the extent of deforested areas (12.5%). Such a positive balance can contribute to achieve the Atlantic Forest conservation goals.

The analysis of legal scenario protection expectations has proven crucial for understanding the legal implications for forest and biodiversity conservation (Hardt et al., 2012; Issii et al., 2020, 2024). The development of legal scenarios has the potential to guide action planning, inform legal reviews and strengthen environmental enforcement. Consequently, it can support the advancement of sustainable land management practices.

Although measures to protect native vegetation and riparian areas, such as the 60 m to 100 m wide riverbank buffer zones in Australia and the 3 m to 100 m strips defined by the European Union Water Framework Directives, are often globally applied (Luke et al., 2018), their implementation and effectiveness still require further investigation. Examples include Quebec, where agricultural activities are prohibited within a 3-meter-wide riparian zone, and the United States, where The Clean Water Act mandates the protection of riparian buffer strips (Majumdar & Avishek, 2023). Assessing these legal frameworks can help to fulfil existing gaps by analyzing both compliance with, and the effectiveness of, such regulations.

With respect to the study's limitations, the estimates of legal compliance may have been influenced by the resolution of images used to produce the current (2021) land use situation and land cover map. The MapBiomas dataset, based on Landsat imagery with a 30-meter pixel resolution, may have blurred land use and cover details in the assessed protected areas, particularly in watercourse-associated APPs, which are defined by a 30-meter-wide buffer strip. MapBiomas (2024) also reports other limitations regarding map accuracy. This dataset was adopted due to the absence of official mapping data at the required analysis scale. Despite the robustness of MapBiomas, the historical time series derived from Landsat imagery may have constrained the detection of features in small protected areas, such as narrow APPs (Issii et al., 2020).

It is also important to note that not all rural property boundaries were analyzed, since the National Rural Environmental Registry System relies on self-declared information and data (Melo et al., 2021). It remains unclear whether these landowners simply failed to register in the system or whether their RLs were compensated in a different basin (Santos et al., 2021). Furthermore, the data used to map APPs around springs lacked the level of detail required for in-depth analysis, particularly for identifying receded or eliminated springs.

Consequently, the calculated legal compliance rate could increase or decrease if information about areas lacking rural property boundary data were available. These areas represented slightly more than 25% of the assessed basin. Many of the applied criteria, such as those related to APRM-ATC regulations, RL and Master Plans (PD), depend on rural or

urban plot boundaries. This situation does not imply that areas designated as MOP (*Macrozona de Ocupação Periurbana*) are fully urbanized. It rather indicates that, based on both the 30-meter resolution scale and on the assessed property boundaries, the requirements for permeable areas were not met. Instances of non-compliance regarding permeable areas were typically observed in urban sections, as revealed by higher-resolution images adopted in the study by Andrade et al. (2024). The use of such images would likely enable the identification of additional impervious surfaces within the basin.

Although the basin is predominantly permeable, it is important to note that different land use and land cover classes can lead to varying soil infiltration levels (Tucci, 1999; Kemerich et al., 2014). These variations require in-depth assessments through specific technical studies. The few impervious areas, such as the Urban Areas and Other Non-Vegetated Areas classes, which do not meet the legal requirements, are concentrated in the urbanized portion downstream the basin, where no vegetation fragments or tree clusters are present.

Despite these limitations, studies such as this one, enable the assessment of compliance with environmental legislation and underscore the relevance of adopting geoprocessing-based methodologies and constructing legal scenarios as integral components of public planning for land use management. For a considerable period-of-time, this integrated analysis of legal requirements was not incorporated into planning instruments, including municipal zoning and water resource management tools, such as basin plans and Environmental Protection and Development Plans (*Plano de Desenvolvimento e Proteção Ambiental,* PDPA) (Alvim et al., 2012; Ikematsu & Sandeville, 2013).

The use of geoprocessing is recognizes as essential for facilitating preliminary data collection and supporting public policy formulations (Harano & Galvanin, 2023). GIS and remote sensing tools are crucial for advancing remote monitoring and enforcement, given the challenges faced by public environmental agencies in conducting on-site inspections of environmental violations (Gaio, 2022).

Access to information on regulations applicable to specific territorial areas can serve as a communication tool to help landowners and other stakeholders understand their rights and responsibilities (Brancalion et al., 2016). Therefore, the method adopted in this study is recommended for creating legal scenarios, as it can provide a reference for developing plans related to land use management, forest and biodiversity conservation, besides enabling environmental enforcement. All these efforts depend, among other factors, on policymakers' political will.

5. Conclusion

Establishing the legal scenario and the associated protection expectations for the assessed basin area was crucial to understand its legal implications for forest and native vegetation conservation. A comparative analysis between the legal scenario and the current situation (2021) revealed gaps in compliance with native vegetation and permeable areas protection in the basin area. Native vegetation protection showed the highest compliance rates. None of the assessed legal provisions was fully met. The LPVN (Native Vegetation Protection Act) recorded the highest non-compliance rate (20.8%). The main issues concerned APPs and highlighted conflicts between land use and forest conservation.

Although the applied methodology may have led to some degree of overestimation, the geoprocessing tools set used for the spatial representation of regulations was efficient and practical, despite the challenges to translate legal provisions into a GIS environment. The study is relevant because, despite its limitations, it provides essential information to support competent authorities in addressing non-compliance and in generating information able to underpin future initiatives more closely aligned with local realities.

This study acknowledged (i) the difficulty of implementing planning tools such as the proposed methodology and (ii) the challenge of making its application feasible, as it requires political commitment and strengthened environmental agencies.

Notable limitations of the study included unavailability of data on all rural properties within the basin area, the absence of high-resolution land use and land cover maps, and lack of delimited areas qualifying for exceptions to mandatory native vegetation cover maintenance in APPs, such as zones reserved for public utility, social interest or low environmental impact. None of these datasets was provided by the Mogi das Cruzes municipal government.

Finally, the methodology adopted in this study should be incorporated into land use planning and biodiversity conservation efforts at both municipal and regional levels. Integrating these analyses into public planning instruments, or making them easily accessible for visualization, could significantly enhance communication with landowners and stakeholders regarding legal obligations and compliance across different parts of the territory.

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