



Challenges in applying payment for ecosystem services to protect geographically isolated wetlands in a Brazilian intensive agricultural region

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Abstract

Geographically isolated wetlands (GIWs) provide essential ecosystem services worldwide, including rainwater retention, aquifer recharge, and enhancing water availability – critical functions in the context of climate change. However, these wetlands face severe degradation driven by economic pressures, inadequate land management, and weak land use policies. Despite growing interest in conservation instruments such as Payment for Ecosystem Services (PES), the applicability of PES for conserving GIWs remains poorly understood due to the lack of spatial inventories and their limited recognition in policy frameworks, particularly in highly productive agricultural landscapes. This study assesses the feasibility of using PES as a conservation strategy for GIWs in a highly agricultural catchment in Brazil dominated by sugarcane cultivation. Using satellite imagery, we mapped GIWs and analyzed land use and land cover patterns within 50 m buffer zones, while critically examining how existing policy frameworks intersect with GIWs protection and PES design principles. Our findings reveal significant challenges to PES implementation, including a lack of formal protection status for GIWs, limited understanding of GIWs ecological functions and regional distribution, unclear private property rights, inconsistencies in interpretations of PES principles in policy frameworks, and restricted financial resource in a region where opportunity costs are high due to the profitability of agricultural production. PES alone appears insufficient to ensure GIWs conservation in the absence of regulatory protections and command-and-control mechanisms. These insights may inform decision-making in Brazil and other agriculture-dependent economies seeking to safeguard wetlands under intensive land use pressure.

Keywords Wetland conservation · Land use planning · Wetland mapping · Environmental policy instruments · Atlantic Forest

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Introduction

Globally, about 89% of wetlands remain unprotected or face ongoing threats from the rapid expansion of intensive land use, limiting land availability for conservation (Aticho et al. 2024). This issue is even more critical for small geographically isolated wetlands (GIWs), which are defined by their position in the landscape, surrounded by uplands and lacking well-defined surface water connections to other wetlands or water bodies (Tiner 2003). Despite their critical role in water quality, aquifer recharge, carbon sequestration, biodiversity support, cultural, recreational, and educational benefits (Leibowitz 2003; Junk et al. 2014), GIWs are particularly vulnerable to land-use change, invasive species,

water extraction, and climate change, demanding legal protection through a specific conservation strategy (Calhoun et al. 2017; Mehrani et al. 2023). Their degradation is particularly exacerbated in intensive agricultural landscapes, which have already been recognized as a major driver of wetland loss (Zedler 2003; Everard & Wood 2018). Current estimates posit that approximately 3.4 million km² of inland wetlands have been lost globally (confidence interval: 2.9–3.8 million km²), mainly due to conversion to agricultural uses (Fluet-Chouinard et al. 2023).

Brazil is an example of this dynamic, where land-use conversion continues to drive wetlands degradation despite its membership in the Ramsar Convention since 1996 and national efforts to formally recognize the importance of these ecosystems (Cunha et al. 2015; Durigan et al. 2022). The loss of natural areas (native vegetation, surface water, and coastal ecosystems) reached 33% of the national territory in 2023 (MapBiomass 2024). Land-use conversion for agriculture and pasture covers 47% of the Cerrado and 17% of the Pantanal, resulting in the loss of 580,000 ha of native vegetation within the Cerrado and 17% of water surface within the Pantanal (Bassani et al. 2025; MapBiomass 2024). According to Stuber et al. (2016), conservation priorities often favor larger or more prominent ecosystems, while small GIWs, particularly those in agricultural landscapes, remain overlooked and at high risk of degradation. This problem is intensified by a failure to delineate and legally protect small GIWs, which leave them more susceptible to land-use changes (Junqueira et al. 2024).

The degradation of GIWs in Brazil is particularly critical in São Paulo State, where the rapid expansion of sugarcane crops has encroached upon these vulnerable ecosystems (Junqueira et al. 2024). Since the 1970s, São Paulo has been the center of sugarcane production in Brazil, and the sector was structured based on increasing concentration of production by fewer companies, the increased use of modern technologies and cultivation methods (Brunner 2023). Currently, the state leads national sugarcane production, contributing 52% of the country's output (4,091,200 hectares) in the 2023–2024 period, with further expansion expected due to the growing demand for ethanol production (CONAB 2023). The use of heavy machinery, pesticides, soil amendments to correct natural low fertility, and fire during the drier season alter soil properties. These practices induce soil erosion, delivering sediments into GIWs modifying their natural biogeochemical functions, alter soil moisture regime, water quality and quantity, and biodiversity (Zuquette et al. 2020; Casagrande et al. 2021; Moreira et al. 2025; Miano et al. 2025). This territorial occupation model has severe environmental and social consequences, as it leads to the conversion of natural ecosystems and concentrates land ownership in the hands of a few large

farmers and agroindustry (Ferreira & Féres 2020). In this context, Payment for Ecosystem Services (PES) offers a potential strategy to reconcile agricultural land use with GIWs conservation. PES is a socioeconomic instrument that can be defined as a voluntary transaction (monetary or not), between stakeholders who implement conservation initiatives (provider-receiver) and those beneficiaries (user-payer) according to conditional and agreed rules (contracts) on the natural resources management (Wunder 2015). This approach is already widely deployed: globally, US\$36–42 billion is invested in PES annually, and Brazil alone hosts 80 such initiatives (Ruggiero et al. 2024). About half of these PES initiatives are included in the Water Producer Program (a PES framework developed by the Brazilian National Water Agency), which aims to increase water discharge and improve water quality (Mamedes et al. 2023). However, within our study region, this program, also supported by The Nature Conservancy, is only active in Extrema, in Minas Gerais State (TNC 2026).

Despite its popularity, the definition and effectiveness of PES remain widely debated (Wunder 2015). Theoretical models range from a Coasean perspective (Coase 1960) favoring private transactions without state intervention to a Pigouvian approach (Pigou 1932) relying on government regulation and incentives. In practice, however, PES has evolved into a flexible and mixed instrument, often integrated with other policy instruments (Pagiola & Platais 2007; Vatn 2010; Castro et al. 2024). In this sense, PES has been widely used for water resources management in different countries, such as Japan (Sim et al. 2018), Iran (Daneshi et al. 2020), Kenya (Rouillé et al. 2015), Australia (Banerjee and Bark 2013), and Mexico (Almeida-Leñero et al. 2017). In Brazil, PES have been more prominent in the Amazon Rainforest (focused on carbon sequestration) and Atlantic Forest (focused on water-related services), and they typically leverage existing regulatory frameworks (e.g. the National Policy of Water Resources), and public funds (e.g. water users charge) to incentivize sustainable development and forest conservation projects (Mota et al. 2023).

Regarding wetland conservation, there are some PES initiatives worldwide, such as in Canada: the Manitoba's wetland restoration project, which incentivizes landowners to increase the water stock, improve the aquifers recharge, sequester carbon, and enhance habitat conditions (Province of Manitoba 2024). In the United Kingdom, the Peatlands Strategy program focuses on carbon sequestration, with private investments from the International Union for Conservation of Nature (IUCN) support (Reed et al. 2013). While in Brazil, PES programs focusing on wetlands are being proposed by the academic community (Bolzan, 2022), but as far as we know, PES schemes designed specifically for GIWs conservation remain nonexistent. To address this gap,

this study evaluates whether PES constitutes an effective instrument for GIWs conservation, using the Corumbataí River Basin (São Paulo, Brazil) as a case study. Specifically, we: (1) quantify the extent of GIWs and associated land-use changes between 1985 and 2022, with emphasis on agricultural expansion; (2) compare visual interpretation of satellite imagery with automated land-use classification approaches; and (3) examine how existing policy frameworks, the protection status of GIWs, and PES design principles interact or potentially conflict.

Material and methods

Study site

The GIWs studied are primarily located in the Paulista Peripheral Depression, a geological-geomorphological inland compartment between the basalt-sandstone cuesta and the Atlantic crystalline plateau in the São Paulo State, Brazil (IPT 1981). The Corumbataí river basin was selected

for this study considering its high number of GIWs distributed across five municipalities within the catchment (Fig. 1), its multiple water uses, and the significant decline in water availability in this region (Ussami & Guilhoto 2018; Junqueira et al. 2024).

The region experiences a tropical climate, with an average annual temperature of 21.6 °C and a mean annual precipitation of 1,366 mm, primarily concentrated between November and March (Cepagri 2013). The Corumbataí river basin was originally covered by Cerrado (Brazilian savannah) and Atlantic Forest, but the almost complete deforestation of this region occurred to open the land for intensive monoculture based on sugarcane, the remaining original vegetation is distributed in the small and disconnected fragments of secondary forest generally in the floodplain (Radambrasil 1983; Filoso et al. 2015).

The GIWs studied are mainly located in the interfluvies of the catchment, without visible connection with other water bodies (Furlan et al. 2024). This type of wetland are topographic depressions that are easily recognized in the landscape as they accumulate water from hydrological fluxes draining

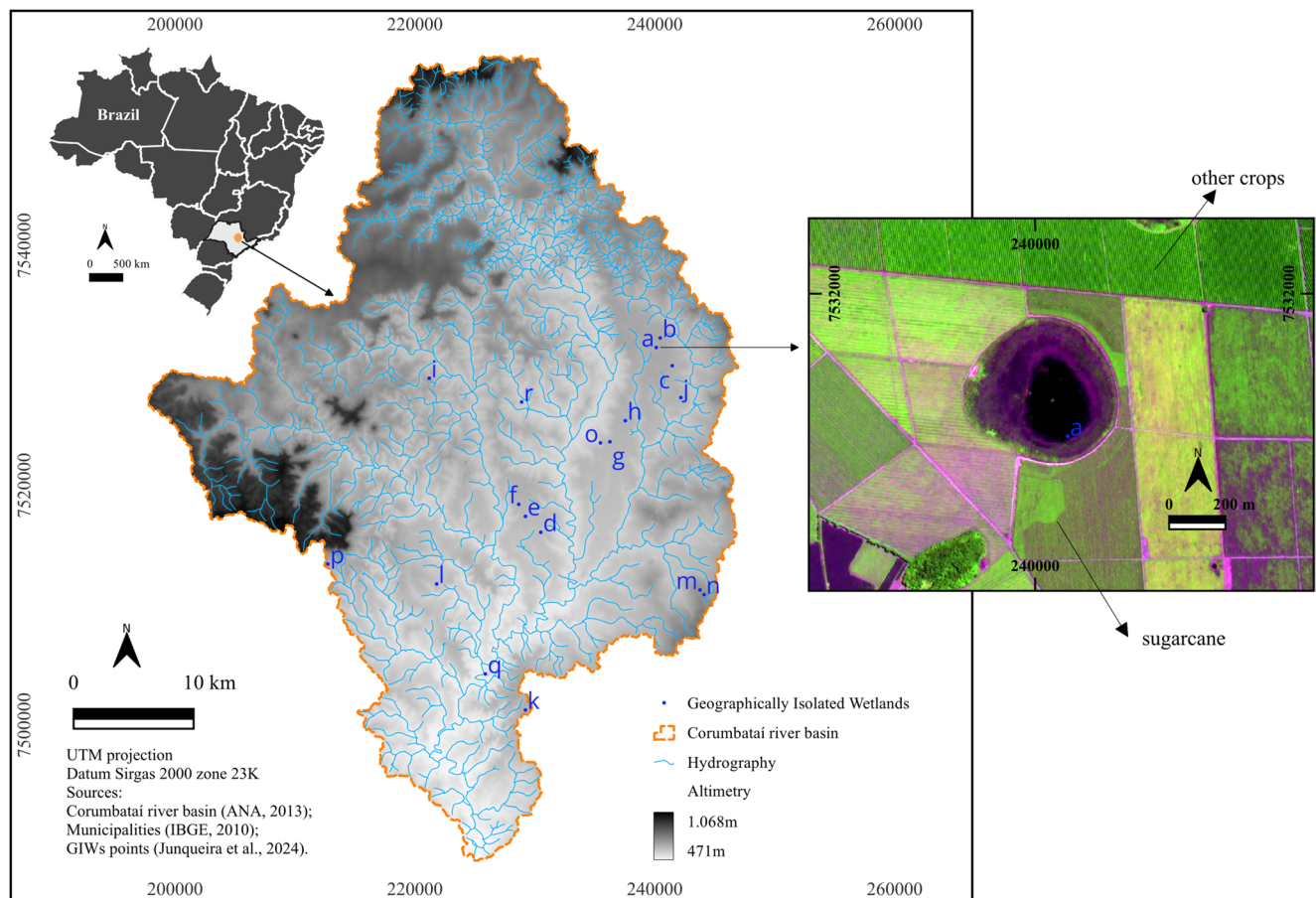


Fig. 1 Map of the study site delimitation with the location of 18 geographically isolated wetlands (GIWs) mapped in the interfluvies of the Corumbataí River Basin, São Paulo state, Brazil. Inset of the GIW 'a'

presents satellite imagery depicting surrounding land use patterns, characterized by sugarcane cultivation and other agricultural activities

from the higher elevations (Hayashi et al. 2016). The hydro-period of GIWs varies with regional climate and precipitation patterns, featuring flood pulses during the summer months, particularly from October to March (Furlan et al. 2021).

Regarding governance, GIWs in Brazil are not explicitly covered by regulatory protection, and the existing framework for wetland conservation is considered weak (Junqueira et al. 2024). Some of the GIWs are situated within two Environmental Protection Areas (APAs in Portuguese acronym): APA Cuesta Corumbataí and APA Piracicaba, which overlap in certain areas. APAs are classified as IUCN Category V protected areas (Protected Landscape/Seascape). However, APAs represent the least restrictive category of protected areas in Brazil and are generally characterized by high levels of human activity that exert significant pressure on natural resources. These areas also lack specific regulations for the management of GIWs (Carvalho et al. 2022). Furthermore, management plans available for consultation indicate that no PES projects are currently implemented in these areas.

GIWs delineation

GIWs delineation followed a hydrogeomorphological approach, which is considered more stable over time than ecological factors such as vegetation and improves wetland recognition in satellite imagery (Semeniuk & Semeniuk, 1995; Smith et al., 1995). Key diagnostic characteristics included: (1) the presence of topographic depressions, (2) circular or oval shapes, (3) surface water accumulation, and (4) absence of connections to other water bodies (Tiner 2003). The initial dataset of 26 GIWs, composed of points and identified by Junqueira et al. (2024) underwent a cartographic validation process.

All cartographic analysis was performed in QGIS software version 3.22.7-Białowieża, with a CBERS-04A raster band composition with 8-m spatial resolution acquired in March 2022, obtained from the National Institute for Space Research catalog (<https://dgi.inpe.br/catalogo/explore>). Satellite imagery acquired at the end of the rainy season (March) was used considering that GIWs in this region are primarily filled by rainfall (Furlan et al. 2021; Casagrande et al. 2021; Franco et al. 2024), and their maximum spatial extent is expected during this period, reducing potential underestimation of waterlogged areas. Relief features were analyzed to identify topographic depressions using a topographic map (1:10,000) from the São Paulo Geographic and Cartographic Institute (IGC, 1982) and a 30-m resolution digital elevation model (1:250,000) from Topodata/INPE Project (2008). To identify potential hydrologic connections, the hydrographic network from the National Water Agency (ANA, 2013) was overlaid with the other cartographic data.

The polygons were delineated by visually tracing polygons around moist margins in satellite imagery at a scale of 1:2,500. The pansharpening method was applied to increase spatial resolution from 8 to 2 m, improving visual interpretation of wetland boundaries (Lang et al. 2015). A false-color band composition (bands 3, 4, and 1: red, near-infrared, and blue) was used to enhance contrast between moist margins and surrounding areas, taking advantage of the low reflectance of water in the near-infrared band (NASA Earth Observatory 2014). Wetland boundaries were identified by distinct soft violet and dark purple tones in the imagery, which indicate high soil moisture and organic matter content. In contrast, other land uses appeared as pink (urban areas and mining, highly reflective) and green tones (agricultural activities).

Of the 26 GIWs previously identified, 9 met all criteria adopted and were retained in this study. Additional 9 GIWs were included through interpretation of cartographic data, resulting in a final dataset of 18 GIWs. Some sites were excluded because waterlogged areas could not be visually identified in the satellite image, appeared potentially connected to nearby water bodies or close to river network, or were located outside the study area (see Table 1 in the Supplementary Material for additional details).

Analysis of the land use and land cover patterns

The analysis of land use and land cover (LULC) dynamics over time in the study catchment was conducted using MapBiomas Collection 8 data obtained free of charge from: brasil.mapbiomas.org/en/. The temporal dataset provided by the MapBiomas project spans from 1985 to 2022, encompassing the entirety of Brazil's territory. The classes considered were: (1) native vegetation (forested and non-forested, including forest formations, savannas, wetlands, and grasslands); (2) sugarcane; (3) urban areas (built-up and non-vegetated surfaces); (4) waterbodies (rivers, lakes, and aquaculture); (5) pasture; (6) forest plantation (silviculture); (7) mining; (8) mosaic (agriculture and pasture areas non differentiated by the algorithm grouped with other agricultural crops in this study). The project land cover classification was generated through pixel-by-pixel analysis of Landsat satellite imagery (30-m resolution), achieving an overall accuracy of 85.8% (MapBiomas 2022).

Using the same CBERS-4A image used for the GIWs delineation, an analysis of LULC patterns surrounding the GIWs was made using a 50-m buffer automatically generated in QGIS software for each site. Since no legal framework currently defines buffer zones for GIWs protection, we adopted the 50-m marginal strip requirement specified as Permanent Preservation Areas (APPs, in Portuguese acronym) for small lakes (<20 ha) under Brazil's Native Vegetation Protection Law (NVPL, Federal Law No. 12,651/2012). The analysis of

LULC in mapped buffer zones was conducted through visual interpretation at a 1:2,500 scale. The classes considered consistent with those of the MapBiomass project, with minor modifications, such as the inclusion of GIWs in the waterbodies class and excluding ‘Mosaic of uses’ class. The analysis results through satellite imagery were subsequently compared with MapBiomass data to assess mapping consistency, considering the use of different approaches. This comparison was made to evaluate the effectiveness of using a national land use database for the conservation and management of small GIWs.

Policy evaluation: aligning PES mechanisms with GIWs protection goals

Considering that practices to restore ecosystems and protect areas of great ecological importance are considered eligible for the development of PES in Brazil (according to Federal Law No 14,119/2021), this study aimed to investigate the suitability of existing policy settings for creating a potential PES scheme designed specifically for GIWs conservation. We chose Wunder (2005, 2015) definition to systematically identify where existing conservation policies fit or clash with the PES concept. This is the most cited definition of PES, which is based on a Coasean perspective and includes some key design principles (Table 1). Some critics considered this definition limited, since it presented intangible aspects for PES application, for example, related to inequity distribution of the payments, which can require nonvoluntary approaches according to the authors (Farley & Costanza 2010). Therefore, to address questions involving failures in this PES concept, a critical concept review was conducted based on international literature (e.g. Farley & Costanza 2010; Gómez-Baggethun & Ruiz-Pérez 2011; Vorlaufer et al. 2017; Guerra & Ranieri 2023). Despite being a limited literature review, these readings contributed to identifying relevant themes to be considered during PES design (such as equity, governance, and community participation), as will be discussed below.

Table 1 The four core Payment for Ecosystem Services (PES) principles, defined by Wunder (2005, 2015) as essential for effective and environmentally efficient programs

PES design principle	Description
Voluntariness	PES is a noncompulsory instrument, distinguishing from command-and-control mechanisms (e.g.laws, regulations etc.) because the potential providers have real land use choices
Conditionality	It implies that payments are made only upon verification of the provision of the contracted service
Additionality	The adopted initiatives promote positive externalities
Monitoring	What is bought needs to be well defined and directly measurable

To understand how existing policy frameworks support or hinder the implementation of PES for GIWs conservation, we conducted a structured document analysis, resulting in a comparison matrix (see Table 4 in results). The documents were analyzed using a qualitative content analysis approach (White & Marsh 2006), focusing on three main scientific questions: (1) Which policy initiatives are relevant for nature conservation? (2) What benefits each policy provides for GIWs protection status and, (3) How policy interacts with Wunder (2005, 2015) PES design principles. Given that GIWs are excluded from policy frameworks (Junqueira et al. 2024), protection status was defined as any general mention of wetlands in the policy documents analyzed. Policy documents selection prioritized relevance to the Corumbataí river basin context, encompassing laws, strategic plans, and municipal regulations. Relevant information collected was coded manually according to their relationship with each scientific question. Cross-referencing among documents was used to identify potential synergies or conflicts between PES mechanisms and actions related to wetland protection.

The analyzed policy frameworks included documents at national, state, catchment and municipal levels (Table 2). The Native Vegetation Protection Law (NVPL) was the Brazil’s primary regulatory framework for protecting waterbodies within private rural properties and represents the first national legislative effort to incorporate PES as a conservation mechanism. Subsequently, a dedicated PES policy was established, beginning with the National Policy for PES (Federal Law No 14,119/2021) and followed by the São Paulo State Policy for PES (State Decree No 66,549/2022). Also, to identify interplays regarding GIWs protection status and PES design principles, the National Strategy for Conservation and Sustainable Use of Wetlands (Ministry of the Environment Ordinance 445/2018) was consulted.

According to the National Policy for Water Resources (Federal Law No. 9,433/1997), river basins (catchments) constitute the territorial unit for water resources management, with basin plans serving as fundamental instruments for territorial planning. To identify guidelines in Corumbataí river basin, which is a sub-basin of the Piracicaba, Capivari and Jundiaí river basins (also called PCJ Basin), the PCJ basin plan was consulted. This document was developed by a committee comprising representatives from different societal sectors – civil society, government and water users—which selected PES as a high-priority action for this territory (PCJ 2020). To evaluate municipal guidelines, the Piracicaba PES program (Municipal Law No 8,013/2014) was considered, since the development of municipal PES programs in Corumbataí river basin remains limited (only 2 municipalities have established regulations).

Table 2 National, state, and local policy frameworks that incorporate Payment for Ecosystem Services (PES) for environmental conservation

Policy name	Scope	Law number	Year	Description
Native Veg-etation Protec-tion Law (NVPL)	National	12,651	2012	Provides for the protection of native vegetation
National Policy for PES	National	14,119	2021	Establishes the National Policy for PES
National Strategy for Con-servation and Sus-tainable Use of Wetlands	National	Ministry of Environ-ment Ordinance No 445	2018	Outlines strategic actions to be implemented by Brazil's Ministry of Environment (MMA) and the National Wetlands Committee
São Paulo State Policy for PES	State	66,549	2022	Regulates the application of the National Policy for PES, within the scope of the State of São Paulo
PCJ basin Plan	Catchment	–	2020–2035	Guide water resources manage-ment by develop-ing programs and projects while allocating finan-cial resources to promote hydrolog-ical sustainability
PES Piraci-caba Program	Municipal	8,013	2014	It is a program of remuneration for rural producers who adhere to sus-tainable practices to preserve their properties with potential for water production in the municipality

Results and discussion

GIWs delineation

A total of 18 GIWs were mapped, encompassing approximately 82.17 hectares at peak inundation during the summer of 2022. The largest area was 21.2 hectares, and the smallest area was 0.05 hectares. Following Tinner (2003) classification, the majority of the GIWs in our study area fall into a small category (<10 ha). Seven GIWs are less than 1 ha, eight are >1<10 ha, and only three are >10 ha (Fig. 2). Furlan et al. (2023) similarly quantified GIWs areas

using the photogrammetry method with their measurements showing close agreement with our results. Both methodologies employed similar delineation criteria for wetland boundaries and comparing the results, the difference was 0.62 hectares for GIW ‘e’ and 0.3 hectares for GIW ‘d’, corresponding to less than 5% variation, which can be attributed to methodological accuracy.

The estimate APP area (or 50-m buffer zones surrounding the GIWs) encompassed 73.28 hectares, resulting in a combined total area of 155.45 hectares including both the wetlands and their buffers (Table 3). Satellite image analysis revealed that sugarcane cultivation dominated the immediately adjacent land use by 66% ($n=12$) of the GIWs, with the remaining sites influenced by mining activities and urban expansion. At the local scale, certain sites (e.g., GIW ‘a’ and GIW ‘c’) showed small patches of drier soil at the margins (visually identified by violet coloration in imagery), these areas were included in our calculations because they play an essential ecological role in maintaining wetland functionality due to their periodic flooding potential linked to precipitation patterns (Junk et al. 2014). The actual extent of GIWs may exceed our delineated boundaries due to their dynamic nature, as wetland perimeters naturally expand and contract in response to precipitation variability (Hayashi et al. 2016). Consequently, our static boundary delineation likely represents a conservative estimate of maximum GIWs extent, potentially underestimating the area requiring conservation protection during peak inundation periods.

LULC in the Corumbataí river basin and its impacts on GIWs

LULC changes in the Corumbataí river basin from 1985 to 2022, based on MapBiomas data, revealed a significant decline in native vegetation. Forest cover had been reduced to just 16% of this catchment in 2022, primarily remaining as fragmented riparian corridors, while Cerrado (savanna formations) remnants accounted for less than 1% of the total area (Fig. 3). This shift reflects the growth of human activities at the expense of conservation. Notably, sugarcane cultivation expanded by ~20,000 ha (1985–2022; Fig. 3), affecting some GIWs. Furlan et al. (2021) observed a loss of 12.27% in GIWs area during a year monitoring. Additionally, clay mining represents a significant economic activity in the catchment with potential for expansion (Scalco & Ferreira 2013). Although mining currently occupies only ~1% of the catchment total area, its proximity to two sites (GIW ‘d’ and GIW ‘f’; Fig. 2) poses a direct conservation threat. This activity disrupts hydrological regimes by altering river flows and increasing sedimentation rates (Lupinacci et al. 2022), potentially compromising wetland ecosystems.



Fig. 2 The spatial analysis included mosaics of the 18 mapped Geographically Isolated Wetlands (GIW) with their corresponding 50-m buffer zones, illustrating both the wetland areas and adjacent land use patterns impacting these ecosystems

Table 3 Summary of geographically isolated wetlands (GIWs) surrounding Land Use and Land Cover (LULC) observed through satellite imagery, containing the number of GIWs, and the sums of GIWs area, Permanent Preservation Areas (APP) – 50 m buffer zones—and total areas for each LULC category (wetland and surrounding 50 m buffer zone). The chosen categories were based on MapBiomas Collection 8 legend

Surrounding LULC	Number of GIWs within this surrounding LULC	GIWs area (ha)	APP area (ha)	Total area (ha)
Sugarcane and other crops	1	21.25	9.06	30.31
Sugarcane	6	45.33	34.34	79.67
Sugarcane and mining	2	4.35	6.87	11.22
Sugarcane and tree vegetation	2	4.75	6.87	11.62
Tree vegetation	1	0.22	1.69	1.91
Tree vegetation and urban area	1	1.59	3.40	4.99
Tree vegetation and pasture	2	0.67	3.52	4.19
Pasture	1	0.14	1.13	1.27
Urban area	1	0.66	2.40	3.06
Other crops	1	3.21	4.00	7.21
Sum	18	82.17	73.28	155.45

GIWs hydrology patterns are profoundly influenced by LULC changes, particularly the expansion of monoculture systems that occupy 24% of the Corumbataí river basin (MapBiomas 2022). Studies demonstrate that sugarcane monocultures elevate surface soil temperatures and increase evapotranspiration rates in cultivated areas, significantly

reducing local soil moisture (Gomes et al. 2017; Oliveira et al. 2022). Also, it is important to consider the expected negative impact from vinasse, considering that São Paulo State had a great number (37 events) of pollution cases related to vinasse contamination compared to other Brazilian states (Azevedo-Santos et al. 2024).

Considering that the algorithm frequently misclassified GIWs as nearby land use classes, GIWs areas could not be reliably identified using 30 m-MapBiomas data, limiting GIWs recognition in past periods. To address this gap, we compared LULC classifications from the MapBiomas dataset with our interpretation of satellite imagery used for polygons delineation (Fig. 4). Additionally, when the MapBiomas classification map was overlaid with the 50-m buffers around delineated GIWs, inconsistencies in land use classification became evident with this comparison. These discrepancies were mainly due to: (1) the absence of buffer vegetation, resulting in exposed soil adjacent to agricultural land, and (2) resolution constraints inherent to the 30-m Landsat imagery used in the automated classification—a known limitation for detecting narrow features such as riparian buffers and small water bodies, which are critical for the enforcement of environmental regulations like APPs (Furlan et al. 2023). In contrast, the 2-m resolution CBERS-04A imagery enabled more accurate delineation of small GIWs and their surroundings, offering greater precision for legal and conservation assessments (see Figs. 4 and 5).

Visual analysis of CBERS-04A imagery revealed that 50% of GIWs buffer zones were occupied by sugarcane cultivation. In contrast, 30 m-MapBiomas data for the same

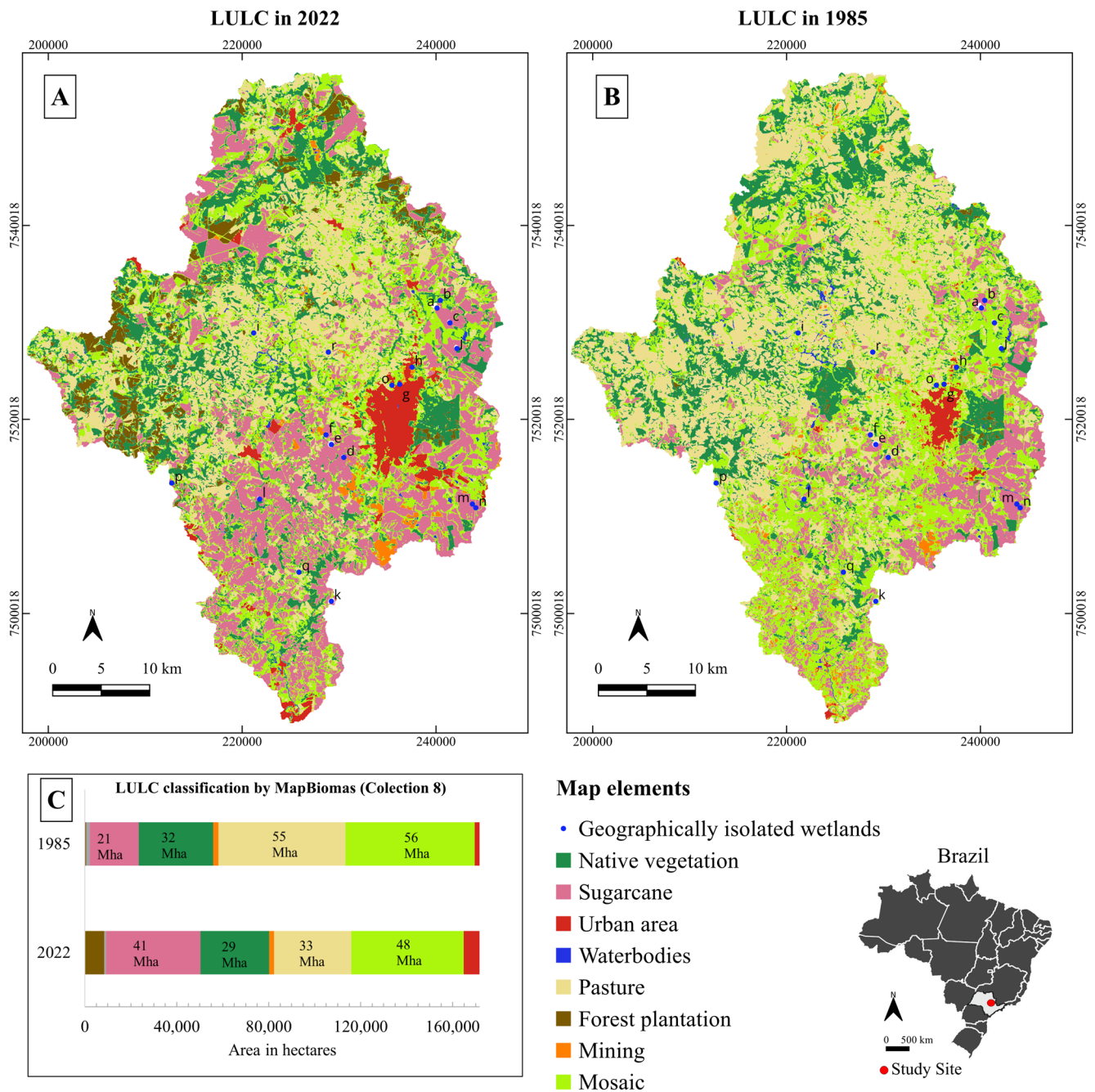


Fig. 3 A comparison of land use and land cover (LULC) maps highlights changes in the Corumbataí River Basin over a 37-year period, depicting (A) 2022 LULC, (B) 1985 LULC, and (C) the area covered by each class in 1985 and 2022. Data source: MapBiomas (Collection 8). The classes considered were: (1) native vegetation (forested and non-forested, including forest formations, savannas, wetlands, and grasslands); (2) sugarcane; (3) urban areas (built-up and non-vegetated surfaces); (4) waterbodies (rivers, lakes, and aquaculture); (5) pasture; (6) forest plantation (silviculture); (7) mining; (8)

mosaic (agriculture and pasture areas non differentiated by the algorithm grouped with other agricultural crops in this study). The graph (C) shows the areas accounted for each LULC class based on MapBiomas data, highlighting the increase in sugarcane crop area (from 21 Mha in 1985 to 41 Mha in 2022), while other classes decreased, such as native vegetation (from 32 Mha in 1985 to 29 Mha in 2022), pasture (from 55 Mha in 1985 to 33 Mha in 2022), and mosaic of uses (from 56 Mha in 1985 to 48 Mha in 2022), which are the main LULC classes in the study area

period indicated only 27% of sugarcane cultivation, with an additional 30% classified as mosaic (Fig. 4). This discrepancy suggests potential misclassification in MapBiomas,

where sugarcane fields were frequently categorized as mosaic or pasture within 50-m buffer zones. Notably, urban areas showed consistent classification between both

Fig. 4 Graphs illustrate the comparison between land use and land cover (LULC) classifications in the mapped geographically isolated wetlands (GIWs) and its 50-m buffer zones. The polygons mapped via satellite imagery were overlaid with the MapBiomass classification (Collection 8) to assess discrepancies, revealing low GIWs recognition in the automated classification. The algorithm frequently confused GIWs with surrounding land uses, likely due to (1) the absence of buffer vegetation, which exposes soil near agricultural areas, and (2) limitations in the classification method, particularly the 30-m resolution of Landsat imagery used by MapBiomass

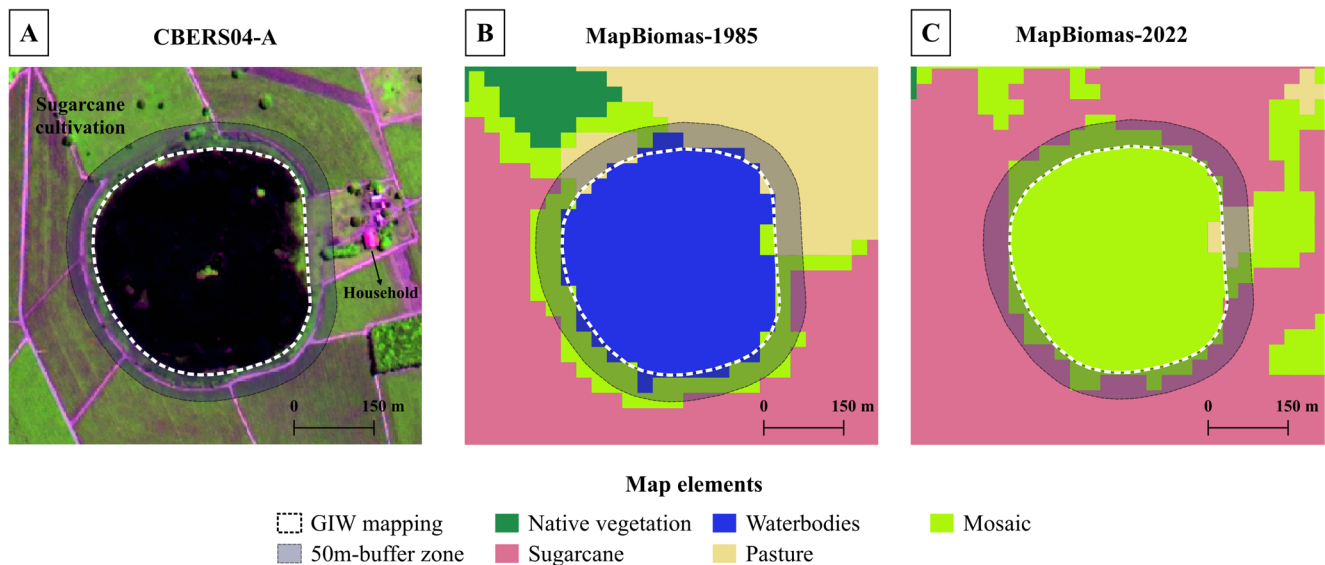
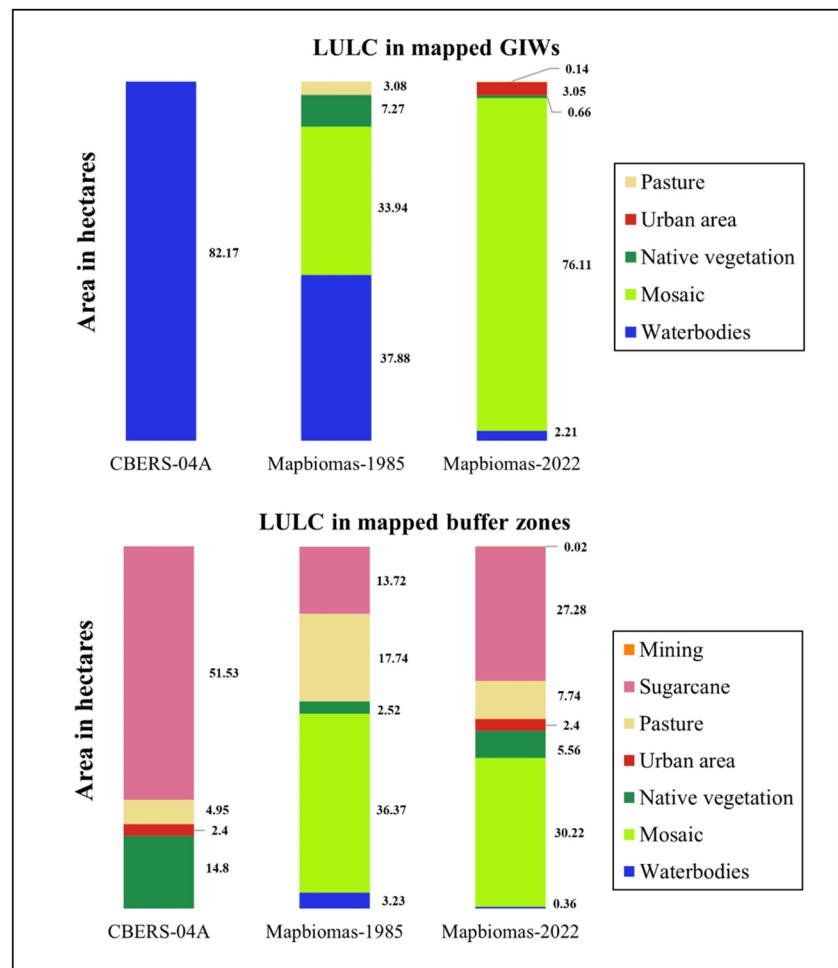


Fig. 5 Comparative figure of satellite imagery and MapBiomass land use and land cover (LULC) classifications revealing algorithm errors: **A** CBERS04-A image with geographically isolated wetland (GIWs)

polygon and buffer; **B** 1985 classification misidentifying sugarcane cultivation as pasture; **C** 2022 classification showing GIWs incorrectly classified as mosaic of uses

methods. Thus, the observed differences in agricultural uses classification may stem from temporal variations in cultivation stages (e.g., newly harvested versus mature crops) visible in the higher-resolution CBERS-04A imagery.

Fifty percent of areas originally classified as waterbodies in 1985 were misclassified as mosaic of uses in 2022 (Fig. 4). This discrepancy primarily results from methodological differences in mapping approaches and satellite image resolution limitations. While the MapBiomass algorithm was optimized for biome-scale assessments, GIWs mapping requires local-scale analysis for accurate identification (Fig. 5). This limitation reflects a broader challenge in Brazil, where wetlands, particularly those without tree cover, have historically been poorly represented in national vegetation maps (Durigan et al. 2022). Consequently, refining automated mapping methods through local-scale algorithm training is critical for obtaining precise LULC data, and supporting evidence-based policy development and targeted conservation strategies.

Although the MapBiomass classification showed discrepancies in GIWs identification, it remained consistent with broader catchment-level classifications like PCJ (2020). MapBiomass data show that sugarcane cultivation has expanded continuously, displacing other crops (e.g., soybeans, citrus, coffee) and affecting food production (Caldarelli & Gilio 2018; Canova et al. 2019). This expansion is driven by government incentives, mechanization, and land concentration, with large agricultural establishments controlling nearly half of Brazil's arable land (IBGE, 2017; Baccarin 2024). In São Paulo, sugar mills lease 80% of sugarcane fields from small landowners, owning only 20% directly—a trend increasing since 2017 (Baccarin et al. 2020). These current land-use trends directly contradict national wetland protection goals (Brazil, 2018), raising a critical policy question: should the government continue subsidizing activities that encroach on GIWs?

Previous studies have demonstrated that sugarcane cultivation compromises GIWs ecosystem services through sediment influx from upslope erosion, dry-season vegetation burning, exotic vegetation and exclusion of buffer zone (Casagrande et al. 2021; Furlan et al. 2023; Junqueira et al. 2024; Silva 2024). This challenge is not unique to Brazil. Globally, agricultural intensification has led to significant wetland degradation, for example, in Iran's Mediterranean region, poor rangeland management and agricultural expansion between 1987 and 2018 reduced wetland areas and water volumes in Ramsar sites (Mehrani et al. 2023). Similarly, in Georgia's Dougherty Plain, intensive farming with high herbicide and fertilizer inputs degraded GIWs (Stuber et al. 2016). A study in Carolina Bay, South Carolina, found that agriculture alone impacted 71% of GIWs, often compounded with logging pressures (Leibowitz 2003). Likewise, in Northeast China, farmland expansion between 1978 and 2008 led to substantial GIW losses (Ma et al. 2024).

Given this land-use dynamic, conservation strategies on GIWs must account for the influence of large-scale agricultural actors specially in wetlands buffer zones, given that water flows naturally converge toward these depressions (Durigan et al. 2022). Research underscores the importance of buffer zones in maintaining wetland functionality, particularly in filtering agricultural pollutants such as nitrogen (N) and phosphorus (P) (Walton et al. 2020). Studies suggest that uncropped buffers of 150–300 m around wetlands are necessary to maximize their ecological benefits (Sawatzky & Fahrig 2019). In Corumbataí river basin agricultural encroachment in GIWs directly threatens conservation efforts, highlighting the urgent need for specific policies that establish effective buffer zones, conservation measures and mitigation strategies.

Lacks between GIW protection status and PES design principles

Our analysis revealed significant gaps that remain between the policy framework and the PES design principles, like adaptations on PES voluntary nature, poor adoption of the additionality principle and uncertainty as to the proprietary rights (Table 4). These gaps were previously documented in other regions (Ioris 2010) and within the study area (Chiodi et al. 2013) and likely stemming from the instrument's rapid expansion ('PES boom') prior to the 2021 National PES Policy establishment—during which over 70 PES programs were already operational (Mamedes et al. 2023)—alongside competing market interests.

Brazil has several policies that promote the management of natural resources but does not have a specific policy or regulations for GIWs management (Table 3). Despite the NVPL (Federal Law No. 12,651/2012) cited types of wetlands (e.g., river springs, ponds, floodplains and mangroves), it fails to establish a comprehensive wetland classification system. This legislative gap resulted in inconsistent classification (or complete omission) of GIWs and other wetland types in territorial mapping, severely limiting understanding of wetland ecological functions and regional distribution (Piedade et al. 2012). The consequences of this broad lack of GIWs characterization become evident through analysis of the state, catchment and municipality policies. These findings align with Floress et al. (2017) results, which showed that experts agree that protected buffers zones and metrics to quantify ecosystem functions at the landscape scale are needed to improve technical feasibility in GIWs protection policies. Given this lack of characterization, the ongoing PES program in PCJ basins aims to conserve types of wetlands (e.g. river springs, riparian forests, and aquifer recharge areas) but GIWs conservation is not even cited. This critical gap persists even in the National Strategy for Conservation and Sustainable Use of Wetlands

Table 4 Analyzed policy framework and their interplay with geographically isolated wetlands (GIWs) protection status and payment for ecosystem services (PES) design principles

Policies	Scope	Relevant policy initiatives regarding nature conservation	Benefits to GIWs protection status	Interplay with the PES design principles
Native Vegetation Protection Law (Federal Law No. 12,651/2012)	National	Identifies various wetland types (including river springs, floodplains and mangroves), though it does not specify the classification methodology employed Conceptualizes the Permanent Preservation Areas – APPs in Portuguese acronym Obligates native vegetation recompose in APPs along watercourses, considering some wetlands (e.g., river springs, lakes and ponds)	There are no direct benefits, since the law does not conceptualize GIW	Although the law establishes a form of PES to remunerate APP recovery activities, this idea contradicts the principle of voluntariness and additionality, since landowners are obliged to conserve APPs, and recovery implies an attempt to return the environment to previous conditions and does not constitute an additionality. Also, no indicators are established to distinguish actions that are minimally mandatory from those that are considered something more (additionality)
National Policy for PES (Federal Law No. 14,119/2021)	National	Encourages programs to ensure water security in regions subject to scarcity of water for human consumption Suggests coordinate actions with other policies (such as water resources, environment, agriculture, and others)	There are no direct benefits, since the law does not conceptualize GIWs	Define PES as: a voluntary transaction, whereby a payer of environmental services transfers financial resources or another form of remuneration to a provider of such services, under agreed conditions, in compliance with the relevant legal and regulatory provisions. Therefore, all PES design principles are considered
National Strategy for Conservation and Sustainable Use of Wetlands (Ministry of the Environment Ordinance 445/2018)	National	Establish the following strategic objectives: 1. promote actions that increase social participation in the governance of sites and their integration with environmental and water resources policies 2. promote integrated management of the landscape of Ramsar Sites and surrounding areas 3. consider the conservation and sustainable use of wetlands in territorial management instruments	There are no direct benefits to GIWs, because the national strategy is directed to Ramsar sites management (wetlands of international importance)	Promotes management and monitoring of Ramsar-sites, despite PES not being mentioned in the document
São Paulo State Policy for PES (Decree No. 66,549/2022)	State	Protects transition ecosystems Promotes the recovery of degraded areas	There are no direct benefits, since the law does not conceptualize GIWs	Follows the National Policy for PES definitions. Therefore, all PES design principles are considered
PCJ basin Plan (2020–2035)	Catchment	It has a specific PES program to conserve river springs, riparian forests, and aquifer recharge areas Attributes high importance for PES implementation in this catchment Allocates specific financial resources to subsidize municipal PES initiatives: a total of BRL\$ 2,800,000 from 2021 to 2035	There are no direct benefits, since the basin Plan does not cite GIWs existence	Some ongoing programs were cited, but their payments support environmental adaptation of properties that fail to preserve APPs, a clear violation of PES principles: voluntariness and additionality. Also, these programs lack detailed monitoring protocols
PES Piracicaba Program (Municipal Law No. 8,013/2014)	Municipal	Promotes recovery of riparian forests and implantation of native vegetation to protect springs and water resources	There are no direct benefits because municipal governments lack their locations in regional mapping systems	Follows the National Policy for PES definitions. Therefore, all PES design principles are considered. A municipal financial fund was established to raise funds for payments. However, the program's coverage area does not include the study area

(Brazil, 2018), which dealt with more focused strategies to Ramsar-sites (wetlands of international importance) and left small GIWs unprotected.

The National Strategy for Conservation and Sustainable Use of Wetlands (Brazil, 2018) enabled local, regional or state institutions to participate in management decisions.

Consequently, São Paulo state could develop a GIWs conservation policy, based on the experience of the APA Cananéia, Iguapé, and Peruíbe—a Brazilian Ramsar-site in the São Paulo coastal region (Ribeiro et al. 2020). Simultaneously, PES projects promoting GIWs conservation could be implemented in the PCJ basin, given that there are existing

PES projects. However, aligning GIWs conservation with PES programs primarily requires: (1) regulating GIWs protection through a comprehensive policy, (2) mapping and assessing ecosystem services being provided, and (3) integrating policy framework with Ramsar conservation strategies (Farley & Costanza 2010). This integration is crucial, given that Brazilian experiences demonstrate higher farmer participation in PES programs when consistent policies and clear governance frameworks exist (Zanella et al. 2014).

Although the policy framework adopts a PES definition closely aligned with Wunder (2005, 2015), some PES principles have been interpreted inconsistently. For example, despite being positive to vegetation recovery and increasing water production in degraded catchments, allowing APPs management within PES programs in NVPL (Art. 41-I) reflects a misinterpretation of the voluntariness and additionality principles. Since Brazilian landowners are legally required to maintain native vegetation coverage on their properties, APP restoration and management cannot be considered an additional action when minimum legal requirements have not been met by landowners with the financial capacity to comply, and, particularly, in areas where preservation is mandatory (Young et al. 2003; Linares et al. 2024). This contradiction may be associated with low adhesion rates with those established regulations and affects negatively GIWs, since there is a lack on protection status even without any law establishment (Rosolen et al. 2015). The absence of legal frameworks was also identified as a challenge for PES implementation in Madagascar mangroves (Rakotomahazo et al. 2023).

Analysis of the PCJ basin Plan revealed that managers attributes high importance for PES implementation in this catchment and allocate specific financial resources derived from water use charges to PES programs – a total of a total of USD\$ 500,000 (at current exchange rates) from 2021 to 2035 (PCJ 2020). The investments from municipal governments and river basin managers are identified as suitable for PES management, as evidenced by studies conducted in Brazil (Chiodi et al. 2013), Australia (Banerjee and Bark 2013), and Mexico (Cotler et al. 2022). However, despite water use charges emerge as a concrete financing option due to their stable and reliable nature, their allocation through competitive public calls makes them unsuitable for recurring payments (Jardim & Bursztyn 2015). Also, the historically low investment in the environmental sector by the Brazilian governments, presents a major challenge to subsidize continuous payments and ensure the effective operation of PES programs (Young 2005; Viana 2024).

The financial funds established under the National Policy for PES serve as a support instrument that encompasses different potential PES financing sources, including private investments. For example, in Piracicaba, part of this study,

we found that the municipal fund is composed of various income sources, such as compensatory measures, charges for the use of water resources, donations from individuals or legal entities, and national public funds. However, most municipalities lack financial mechanisms, like Rio Claro—which contains the highest concentration of mapped GIWs – thus, securing reliable payment sources remains a significant challenge. Furthermore, overcoming land opportunity costs presents another significant challenge, since PES proves most effective in locations with low land opportunity costs (Young & Bakker 2014). This challenge becomes more relevant particularly in regions with established agricultural development, where strong economic pressures favor maintaining livestock farming and sugarcane cultivation, as in our study site (Richards et al. 2017). Ruggiero et al. (2024) demonstrate this through PES payment examples ranging from under USD 17 to USD 3,460 per producer annually under high opportunity cost conditions, illustrating comparison difficulties due to varying conditions, criteria, compensation schemes, technical support, and PES models. Furthermore, Canova et al. (2019) documented landowner dissatisfaction in this region when PES payments fail to compensate opportunity costs adequately. Our analysis suggests that the primary challenge for PES implementation in this study site involves modifying the well-established LULC pattern, yet this goal conflicts with economic policies favoring agricultural expansion.

We found through literature review that stakeholder engagement is widely regarded as best practice in PES design (Guerra & Ranieri 2023). This finding indicates the need for future research to assess stakeholder interest in PES schemes specific to GIWs conservation through questionnaires and personal interviews. Some questions remain unaddressed, for example: How do landowners perceive GIWs ecological functions? What is their level of interest in managing GIWs, especially if rules were applicable? Furthermore, would they be willing to allocate agricultural land for conservation purposes? Given that the present study constitutes a preliminary, conceptual review, empirical investigations will be necessary to address these questions and effectively verify PES applicability.

Another challenge limiting PES implementation in GIWs is low engagement of landowners, something that already occurs in other ecosystems, but in this specific case can be affected by sugarcane high profitability (Chiodi et al. 2013; Richards et al. 2017; Canova et al. 2019). Also, a future consultation of landowners' interests associated with a socioeconomic characterization of the stakeholders is essential for determining appropriate PES payment structures, as various PES arrangements are available to accommodate different objectives, socioeconomic groups, and ecological and geographic contexts within each area

(Lundberg et al. 2018). The predominance of sugarcane and agro-industries in the study area significantly influences the allocation of public resources, since payments to landowners may lead to the concentration of financial resources within larger, more capitalized farms and agro-industries. The original PES framework proposed by Wunder (2005), rooted in Coasean economics theory assumes more efficient environmental outcomes through private transactions, but this approach is relatively difficult to apply to ecosystem services provision, since most of them constitute collective goods (Farley & Costanza 2010). In this context, the real-world PES programs in developing countries often deviate from theory due to high transaction costs and social inequalities, which require different PES designs to access desired environmental and social outcomes (Vorlauffer et al. 2017). This tension is evident in PCJ basin, where public PES programs like ‘Conservador das Águas’ achieve significant ecological gains (3000 ha of Atlantic Forest recovered, Richards et al. 2015) through PES principles deviations. Some critics considered that stakeholders have pushed to change the narrative about rural landowners—from framing them as ‘polluter-payers’ to ‘provider-receivers’—in order to secure economic benefits (Chiodi et al. 2013). This shift fits in with global trends, where PES is actively promoted by the World Bank and other actors pursuing financial gains (Henkel 2016).

Therefore, despite its growing adoption, we understood that PES is not a politically neutral instrument (Vatn 2010). Critics argue that adapting PES to realities in which the instrument is theoretically not necessary, artificially creating new problems to justify PES adoption, may potentially divert focus from environmental protection to market interests (Ioris 2010). Such neoliberal approaches to commodifying nature continue facing resistance (Martinez-Alier 2007). Despite strong institutional support for PES, multiple studies question its effectiveness (Ioris 2010; Richards et al. 2017) or report lack of tangible outcomes (Börner et al. 2017; Lu et al. 2018; Cotler et al. 2022). Linares et al. (2024) emphasize the need for careful evaluation, proposing criteria to determine PES suitability—particularly in relation to the legal status of the property. Although PES is often regarded as an alternative in contexts where command-and-control instruments fail (Hack 2015), in the case of GIWs there is no specific regulation providing such instruments. Therefore, it is not possible to consider failures in something that is not yet properly regulated. Also, literature suggests that PES should be part of a mix of instruments rather than an isolated solution (Perevochtchikova & Beltrán, 2012; Libanio 2015; Wunder et al. 2020; Burhanudin et al. 2021; Brasil 2021), and it should be associated with command-and-control instruments, planning tools, and a comprehensive policy.

Additionally, the absence of specific legislation defining GIWs protection status left undefined property rights, raising questions about GIWs alienability and complicating PES implementation. In many contexts, PES is presented almost as a stand-alone solution to environmental problems. However, it is important to emphasize the need for a stronger legal framework, as PES should be understood as an instrument embedded within a broader policy mix of public policies rather than as an isolated market mechanism (Börner et al. 2017; Engel et al. 2008; Muradian et al. 2010; Porras et al. 2008; Van Hecken & Bastiaensen 2010; Wunder et al. 2020). The literature indicates that its effectiveness depends on articulation with regulatory frameworks and other institutional instruments capable of ensuring equity, compliance with obligations, and legal certainty, particularly in the Brazilian context, where the logic of a “fully free market” tends to reproduce structural asymmetries (Ioris 2010; Henkel 2016; Bontempi et al. 2025). Such legal protection also includes a non-negotiable baseline (or minimum requirements), thereby allowing PES to function as originally intended: not to compensate landowners for the passive preservation of GIWs, but as a tool to incentivize additional improvements in ecosystem services provision (Linares et al. 2024). Furthermore, policy regulation is a main need, because if GIWs ecosystem services cannot be classified as private goods, PES may be an inadequate conservation tool (Farley & Costanza 2010). These challenges are particularly significant for our analysis given that clearly identified property rights and well-defined environmental services constitute established best practices for effective PES programs (Guerra & Ranieri 2023).

Integration of spatial and policy analysis and recommendations for future studies

Our findings suggest that effective policy efforts to protect GIWs must begin with accurate wetland delineation, which means including their entire catchment areas during area delineation considering that wetlands are highly influenced by surrounding dry lands (Hayashi et al. 2016). Some limitations of our study include that the polygon delineation did not encompass the entire area influenced by topographic depressions and did not account for wetlands hydrologic seasonal variability. Some waterlogged areas may completely disappear during the dry season, a factor that could be further affected by climate change and shifts in regional precipitation patterns (Furlan et al. 2023). Addressing this limitation would require high-resolution data and hydrological modeling, as well as a more precise assessment of the ecosystem services provided by GIWs and the losses associated with their degradation. These procedures are necessary to deal with the current lack of characterization and

explicit recognition of GIWs as a distinct wetland type in policy documents. Our study reveals that GIWs remain a wetland type that receives limited policy attention, which combined with increased land use changes driven by agricultural intensification have increased their degradation. However, our spatial findings align with previous studies that have documented preferential losses of GIWs (e.g. Van Meter and Basu 2015; Zuquette et al. 2020; Ma et al. 2024; Junqueira et al. 2024). Therefore, following accurate delineation, GIWs should be incorporated into management and territorial frameworks across multiple policy sectors, as existing disconnections between policy instruments currently hinder coordinated conservation efforts.

To support conservation efforts, we recommend conducting future studies to identify ecosystem services provided by GIWs, combined with assessments of public preferences for these services. As a preliminary analysis, our study was limited to a conceptual approach without considering preferences for specific ecosystem services and public interests. However, such considerations are relevant, given that certain ecosystem services and some PES arrangements may be valued more highly than others on local scale, which may influence conservation priorities and PES design (Canova et al. 2019).

Therefore, rather than being treated as a stand-alone solution, PES should be considered only after a clear regulatory framework defining GIWs protection status is established. In Brazil, command-and-control instruments such as the NVPL already provide explicit protection for rivers, lakes, and springs through APPs, but geographically isolated wetlands remain largely absent from these legal definitions. This regulatory gap creates uncertainty regarding property rights, conservation obligations, and the additionality of PES actions. Establishing a legal framework that explicitly recognizes GIWs, defines rules for spatial definition and baseline protection requirements is therefore a necessary first step. Only once such regulatory foundations are in place could PES operate effectively as a complementary instrument to incentivize conservation actions beyond legal obligations.

These findings are particularly relevant for Brazil and other countries with commodity-based economies, which will require optimized mapping approaches to identify degraded GIWs in intensively cultivated catchments (i.e. high-resolution topographic data and other field observations). It is also the first scientific attempt to evaluate PES applicability for wetlands conservation. Such approaches are needed to inform policy makers and stakeholders engaged in conservation planning. Considering lacks in existing literature, our study highlights several themes that can be addressed in future research, including: GIWs inventory initiatives, improved GIWs mapping approaches, patterns and drivers of GIWs degradation, interactions between

policy framework and PES design principles, and the applicability of PES schemes or other conservation instruments in policy-recognized GIWs and other wetlands.

Conclusion

The spatial approach used in this study represents the first attempt to map geographically isolated wetlands (GIWs) at Corumbataí river basin, offering critical data to support conservation and future research. The 30-m resolution MapBiomass data proved to be an insufficient source for accurately delineating GIWs and their surroundings, unlike higher-resolution satellite imagery, which enabled a more detailed mapping. This discrepancy underscores the necessity for future studies employing trained algorithms specifically designed to detect small GIWs within anthropized landscapes, which could contribute to establishing a comprehensive national wetland inventory. Also, delineating buffer zones around GIWs is an urgent priority to establish protective limits against further uncontrolled degradation, but additional data is required to correctly delineate individual GIW catchments. The current land use and land cover (LULC) scenario likely leads to an underestimation of both the actual extent of small wetlands and the ecosystem services provided, since cropland expansion negatively affects GIWs ecological conditions.

The degraded state of these GIWs combined with their ecological vulnerability contradicts the fundamental PES concept of "rewarding the protectors" and raises the preliminary conclusion that PES is not the most suitable tool for promoting conservation by itself, without a protective regulation promoted by a command-and-control mechanism. PES has gained traction as a tool for conservation, but it is not a universal solution, since there are significant challenges to PES implementation, including weak integration between policy framework, GIWs protection status, and PES design principles. Adopting PES as a voluntary economic instrument risks diminishing the non-economic value that GIWs have and favor current unsustainable land use practices. Also, to ensure these wetlands remain a collective resource rather than being subjected to private appropriation, conservation policies must prioritize public interest over selective economic gains, including stakeholders' participation in future research and conservation efforts. Finally, robust conservation initiatives are crucial for Brazil and other countries to fulfill its commitments under international agreements such as the Ramsar Convention and to reduce the ongoing ecosystem services losses.

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Data availability The datasets used in this study are publicly available and were sourced from the references cited within the article, the GIW dataset will be provided upon request. All relevant data can be accessed through the original publications or repositories as indicated in the reference list.

Declarations

Declaration of generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used DeepSeek V3 to improve English grammar, enhancing clarity, readability and objectivity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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

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