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A new contribution to multicriteria analysis of rural property eligibility for payments for ecosystem services

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FOREST MANAGEMENT

ABSTRACT

Background: Payment for Ecosystem Services (PES) is a key instrument for conserving Ecosystem Services on rural properties. Implementing PES programs across large jurisdictions requires rigorous and transparent methods for selecting eligible areas. Multi-Criteria Decision Analysis (MCDA) integrated with Geographic Information Systems (GIS) is widely used for this purpose. However, MCDA faces challenges such as subjectivity in weight assignment, limited replicability, and underutilization of public geospatial data, such as the Rural Environmental Registry (CAR). Consequently, the literature lacks a robust framework combining MCDA transparency with optimized GIS procedures to generate objective eligibility indices. This study presents a methodological proposal to determine PES eligibility within sub-watersheds using MCDA.

Results: The highest eligibility levels were observed in properties with well-preserved areas, especially conserved Permanent Preservation Areas (PPA), high spring densities, and proximity to priority conservation zones, accounting for 4.83% of the total area. In contrast, the lowest eligibility occurred in regions dominated by intensive land use, pastures, and agriculture, with 26.7% and 17.19% classified as "Very Low" and "Low," respectively. In total, 134 properties were analyzed, demonstrating diverse land-use patterns and distinct conservation contributions.

Conclusions: This research applied an MCDA-based methodology to CAR data to support property selection in PES programs. The model quantifies landowners' role in protecting native vegetation to reduce deforestation pressure, while also identifying low-eligibility areas as targets for future ecological restoration. Although the study meets its core objective, the approach faces limitations related to the scale of geospatial data and the complexity of mapping cultural ES.

Keywords: *Ecosystem services; environmental zoning; geographic information systems; rural environmental registry.*

HIGHLIGHTS

MCDA identified 4.83% of the area as highly eligible for PES.
Conserved areas offering ecosystem services have greater eligibility.
Intensive land use accounts for 26.73%, and 17.19% has low eligibility.
This methodology connects public data to decision-making to optimize PES programs and boost environmental restoration.

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INTRODUCTION

Payment for Ecosystem Services (PES) has become an important instrument for environmental conservation on rural properties, encouraging practices that improve water quality and availability, conserve soil, maintain biodiversity, and protect ecosystem services (ES) (Kroeger *et al.*, 2019). These services correspond to the benefits nature provides to society, directly or indirectly, through ecological functions and processes essential to maintaining life on the planet (Groot, 1992; MEA, 2005).

According to the classification proposed by the Millennium Ecosystem Assessment, these services are grouped into four categories: provisioning, regulating, supporting, and cultural (MEA, 2005). In this context, the increasing valuation of ES has broadened its application as an environmental management tool, especially in actions aimed at conservation and ecological restoration (Wunder *et al.*, 2020; Ito, 2022). As part of this process, PES began to be implemented in different countries as mechanisms for providing economic incentives for the conservation of natural resources and the maintenance of ES.

PES programs originated in the United States with the Conservation Reserve Program (CRP), created in 1985 to encourage conservation practices in rural areas. In Latin America, the first initiatives occurred in the 1990s in Colombia, but it was Costa Rica that consolidated the first federal PES program, the PPSA, in 1997, establishing legal frameworks, governance mechanisms, and financing through FONAFIFO. Mexico also advanced in implementing PES focused on water and biodiversity conservation, which was later integrated into the National PES Program.

In Brazil, in addition to the National Policy on PSE, programs such as Proambiente, Bolsa Floresta, and Produtor de Água have strengthened initiatives focused on water, soil, biodiversity, and carbon conservation. Other countries have also developed relevant experiences, such as Ecuador, Peru, China, and South Africa, with actions aimed at the recovery of river basins, water management, and poverty reduction. Furthermore, private initiatives, such as that of the company Vittel in France, have demonstrated the application of PES in pollution control and water quality protection. Problems have been identified in the literature after the start of the development of the programs, mainly in voluntary programs that depend on collaboration (Pereira & Sobrinho, 2017).

The effective implementation of these programs still faces significant operational and territorial challenges. Although consolidated initiatives, such as the METSO program in Finland, show positive results in environmental conservation, limitations related to the voluntary selection of areas by rural landowners remain relevant (Batpurev *et al.*, 2025). In this model, properties undergo eligibility assessments; however, the spatial dispersion of the selected areas can compromise the formation of ecological corridors, hinder the prioritization of critical areas, and reduce the effectiveness of long-term environmental planning. Furthermore, the absence of standardized criteria for the selection and integration of areas represents an additional obstacle to territorial management.

Given this complexity, Multi-Criteria Decision Analysis (MCDA) stands out as a widely used approach to support decision-making, allowing the integration and weighting of environmental, economic, cultural, and management variables (Valente *et al.*, 2021; Lemos *et al.*, 2023). Its application in Geographic Information Systems (GIS) enhances the efficiency of spatial analyses and territorial planning, favoring more integrated and strategic environmental conservation processes (França *et al.*, 2020).

The use of MCDA in PES programs is still under-researched in the scientific literature. This limitation is mainly associated with the high dependence on expensive primary data and the underutilization of publicly available geospatial databases and land records for assessments at the rural property level (Anjinho *et al.*, 2022). Furthermore, many studies rely heavily on workshops and consultations with experts and local stakeholders, whose insights are crucial for understanding the socio-environmental and territorial specificities of the areas analyzed (Marttunen *et al.*, 2022; Nazari *et al.*, 2025; Santos *et al.*, 2026). Consequently, there is still a lack of robust methodological frameworks that transparently integrate MCDA, expert participation, environmental data, and local information. This methodological gap can increase subjectivity in decision-making processes and compromise the effectiveness of implementing PES programs in different territorial contexts. The scenario becomes even more challenging given the expansion of this market, driven by the growing interest of investors and rural landowners in joining financial compensation mechanisms aimed at environmental conservation.

The increasing valuation of natural resources in the global market amplifies the demand for greater transparency and equity in the selection of areas for PES. In this context, clear and standardized criteria are essential to guarantee equal opportunities for rural landowners (Luck *et al.*, 2012). In Brazil, Federal Law No. 14,119 established guidelines for the implementation of PES; however, methodological and operational gaps still exist that hinder the definition of objective criteria for prioritizing areas (Brazil, 2021).

In other words, the PES law serves as a basis to guide public policy, but does not provide implementation mechanisms. In addition to environmental conservation, PES also perform social, economic, and cultural functions by promoting income generation and strengthening public policies. Despite this, the social dimension remains under-considered in these programs. Among more than 161 global cases analyzed, only three explicitly incorporated indicators of social benefits, highlighting the need for more integrated and inclusive approaches (Nazari, *et al.*, 2025).

This study aimed to propose and validate a geospatial methodological framework to assess the eligibility of rural properties for PES using MCDA. It sought to identify eligible areas for the provision of PES to be benefited by the PES. Subsequent application in the case study area of Minas Gerais demonstrates the operational efficiency and analytical power of the framework.

MATERIAL AND METHODS

Characterization of the study area

The study area encompasses 46,564.95 hectares distributed across two sub-watersheds: the Preto River (39,280.83 hectares) and the Santana Stream (7,284.12 hectares). The watersheds belong to the Araçuaí River Hydrographic Region (JQ2) (Figure 1). They are predominantly located within the municipalities of São Gonçalo do Rio Preto and Felício dos Santos, in the central-northern region of Minas Gerais state.

The region features a high-altitude tropical climate (Cwb), marked by mild, humid summers and cool, dry winters. Annual precipitation ranges from 1,250 to 1,550 mm, with an average temperature of 20°C (Alvares *et al*., 2013). The dominant vegetation consists of grasslands typical of the Cerrado biome (Campo Limpo and Campo Rupestre) and Semideciduous Seasonal Forest (Colli-Silva *et al*., 2019; Costa *et al*., 2022).

Approximately 70% of the basin's agricultural production comes from family farming, including livestock and crops (IBGE, 2017). The area is highly conserved (87%), with anthropized zones primarily distributed along watercourses (Gorgens *et al*., 2021; Mucida *et al*., 2022). However, land use conflicts arise in certain areas due to incompatibility with landscape units (Gorgens *et al*., 2021; Mucida *et al*., 2022). These regions are often considered suitable for permanent preservation, particularly because of aquifer springs (Fernandes *et al*., 2013).

Multicriteria analysis

To assess the eligibility of rural properties for participation in the PES program, a MCDA was conducted. Geographic information layers were selected to assess provisioning, regulating, cultural, and supporting ES. The criteria and indicators were defined based on theoretical frameworks, drawing from recommendations in the literature and supported by expert input. The selected information layers included:

Conflict between Permanent Preservation Areas (PPA) and land use – Environmental and Productive Zoning (ZAP), IDE-SISEMA.

Priority conservation areas – IEPHA, IDE-SISEMA (SE cultural).

Aboveground carbon (Green House Gas - GHG) emissions inventory– Brazilian Ministério da Ciência, Tecnologia e Inovação (MCTI), and Brazilian Instituto Nacional de Pesquisas Espaciais (INPE), SIRENE.

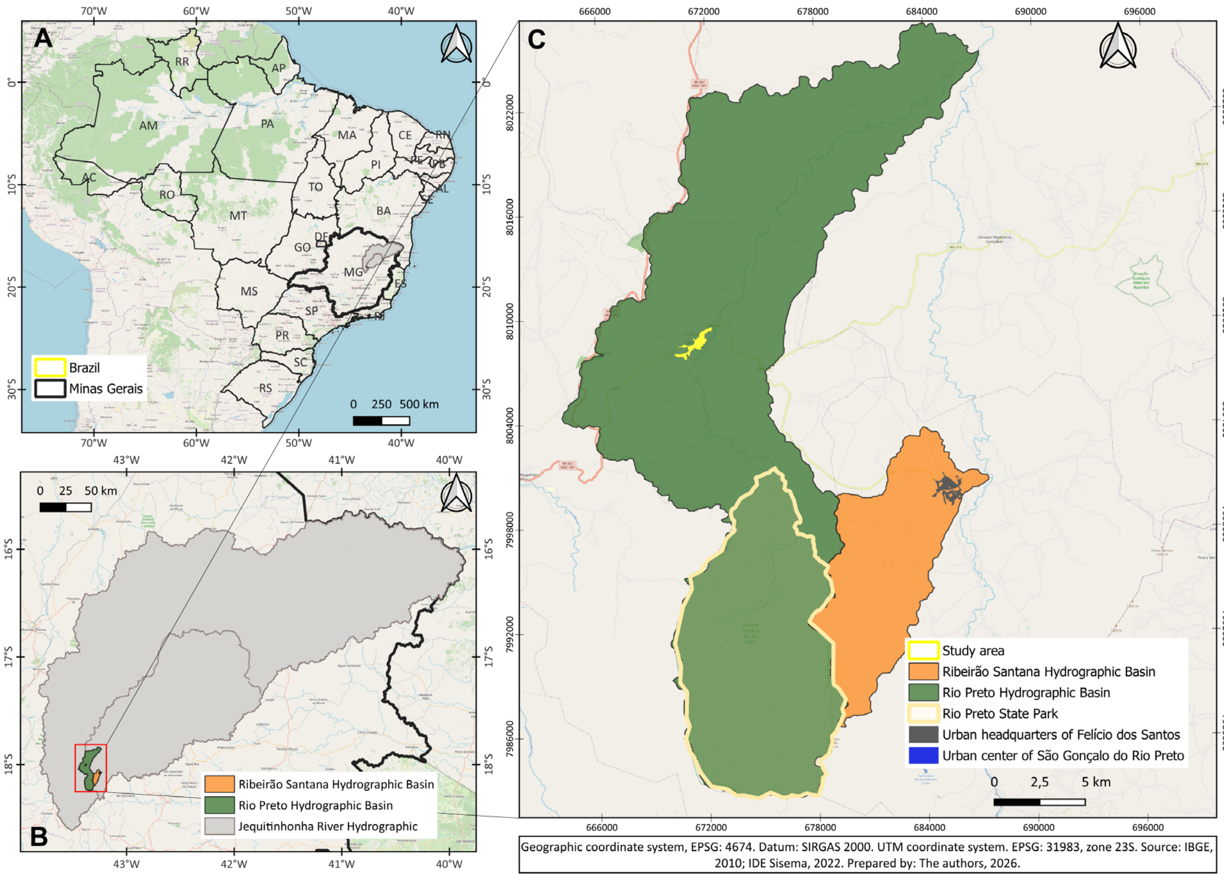

Figure 1: Location of the study area. A: context of Brazil. B: Jequitinhonha River Hydrographic Region (JQ1), Araçuaí River hydrographic circumscription (JQ2), in the central-northern region of Minas Gerais state. C: Ribeirão Santana and Rio Preto hydrographic basins.

Conservation Units (CU) of Rio Preto State Park and Buffer Zone map – IDE-SISEMA.

Land use and occupation (ecosystem services provision) – ZAP, IDE-SISEMA.

Spring density – ZAP, IDE-SISEMA.

Weights for ecosystem service provision were derived using a land-use and occupation methodology based on expert consultation for each land-use class (Supplementary material - Table 1) (Burkhard *et al*., 2009).

Table 1: PES Weights Eligibility Classification

Weight	PES eligibility	Ecosystem Services Offer
1	Insignificant	Nonexistent
2	Very Low	Very Little
3	Low	Little
4	Medium	Medium
5	High	Strong
6	Very High	Very Strong

The methodology sought to maximize the objectivity of the eligibility model by anchoring five of the six analysis layers in evidence consolidated in the scientific literature. By using bibliographic parameters for most criteria, the multi-criteria analysis restricts the influence of subjective judgments, reserving consultation with experts (Burkhard *et al*., 2009) exclusively for the land-use-based ES layer, where contextual calibration is necessary. This hybrid structure ensures that the final algorithm operates predominantly on a technical basis and is replicable. The figure 2 provides detailed information about this consultation.

To avoid overestimating areas due to structural redundancy, the layers were selected because they represent distinct dimensions of the forest system. Land use acts as an indicator of anthropogenic status, carbon quantifies the physical biomass stock, and the provision of ES assesses the flow of derived benefits (Provision, Regulation, Support, and Cultural) (Burkhard *et al*., 2009). Although correlated, the independent inclusion of these variables allows capturing nuances where a high carbon stock does not necessarily translate into high service diversity, mitigating double counting bias through multidimensional valuation.

The layers were processed and analyzed in QGIS (version 3.28.11), and each was assigned specific weights for PES eligibility, with a focus on ecosystem service provision (Table 1). The weights were inserted into the attribute table based on the characteristics of each information plan.

The six layers with their respective weights were rasterized, and the MCDA was the result of summing these layers using the raster calculator, as shown in Equation 1 and detailed in Equation 2:

$$\mathrm{ELEG_{PES}} = \sum_{i=1}^{n} \mathrm{X_i} \quad (1)$$

Where: $\mathrm{ELEG_{PES}}$ represents the combination of terms to obtain eligibility for PES; ∑ is the sum of the information layers; xi represents each term in the series; i is the index of the sum, and n is the upper limit of the sum. The calculation assumed that each layer already has its own internal weight, making it unnecessary to assign a weight to each information layer.

$$\mathrm{ELEG_{PES}} = [(\mathrm{PPA_{cons+ont}}) + (\mathrm{PA_{cons}}) + (\mathrm{CAS}) + (\mathrm{DIST_{CU}}) + (\mathrm{OF_{esp}}) + (\mathrm{C_o})] \quad (2)$$

Where: $\mathrm{ELEG_{PES}}$= Eligibility of areas for PES; $\mathrm{PPA_{(cons+ant)}}$ = Conserved and anthropized Permanent Preservation Areas; $\mathrm{PA_{cons}}$ = Priority conservation areas; ASC - Aboveground Carbon; $\mathrm{DIST_{cu}}$ = Distance to Conservation Units; $\mathrm{OF_{esp}}$ = Ecosystem Services Provision; $\mathrm{Co_s}$ = Spring density

To perform map algebra, the weights from Table 3 were added to the attribute tables of the information layers. The simple linear sum of the equations occurs when crossing the bases in the algebra. Using the results obtained from Equation 2, the data were reclassified employing the Natural Breaks classification method. This method identifies natural groupings within the data distribution, creating class intervals that reflect inherent patterns in the data (Table 2)

Table 2: Classification of Property Eligibility for PES.

Classification	Eligibility
8 – 13	Insignificant
13 – 16	Very Low
16 – 18	Low
18 – 21	Medium
21 – 24	High
24 – 31	Very High

Eligibility of rural properties for PES

In the study area, rural properties registered in the Rural Environmental Registry (CAR) were analyzed for eligibility for PES using data from SICAR. While urban areas should have been considered, the focus was on rural properties. These were categorized by area size as follows: (I) Smallholding: 0 to 40 hectares; (II) Small: 40 to 160 hectares; (III) Medium: 160 to 800 hectares and Large: Above 800 hectares (Brazil, 1993; Brazil, 2017).

An exploratory analysis was conducted, separating the area into 3 groups: group A in the northern portion, group B in the central portion, and group C in the southernmost portion. The CU was not considered. In group C, the exploratory analysis disregarded the CU. The exploratory analysis was conducted only among rural properties with Very High and High eligibility to identify priority properties for PES implementation. Properties with insignificant eligibility were excluded from the analysis.

RESULTS

Multicriteria analysis

After processing the datasets outlined in the methodology, final internal scores were calculated for each class within the information layers (Table 3)

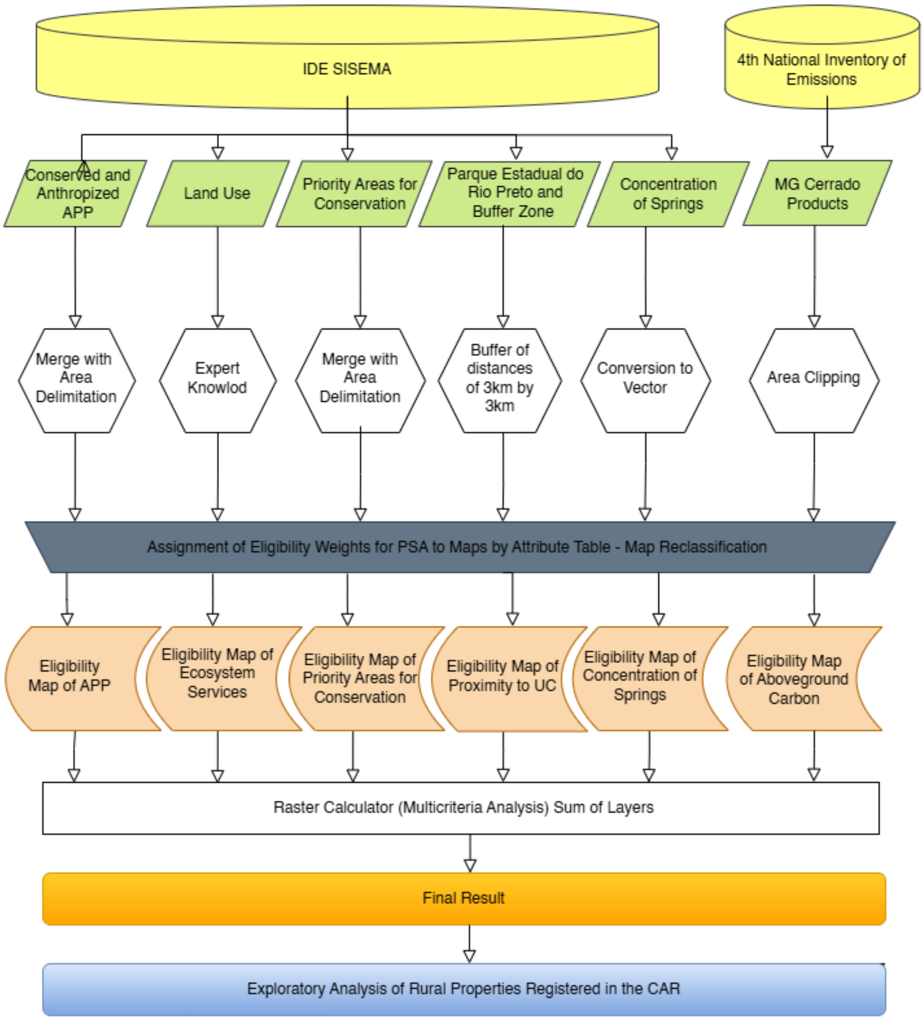

Figure 2: The methodology and the steps used in this study are summarized in the flowchart.

These scores reflect each class's relative contribution to the overall analysis and were used to assess PES eligibility. The information layers were reclassified according to eligibility and spatially represented in Figure 3A to 3F.

The eligibility of properties for PES was obtained through MCDA according to equation 2, and the data were spatialized for the study area (Figure 4). The eligibility for PES indicates 26.73% for very low class, 26.62% for medium, 17.19% for low, 16.73% for high, 8.81% insignificant, and 4.83% for very high (Table 4).

Eligibility for PES of rural properties

In the study area, rural properties with a CAR account for 82.96% of the study area, while 17.04% do not have the registry. 4.73% of the area of rural properties shows overlaps between properties, which may be due to the CAR being self-declaratory. Removing the overlaps, 95.47% of the area has a CAR registration (Table 5).

We generated the PES eligibility map for the study area by delimiting rural properties with CAR (Supplementary material - Figure 1A), which included 417 properties, representing 82.96% of the total area. The properties were classified by size (Supplementary material - Fig. 1B). The study area covers 46,564.95 ha, with 4.63% of the area lacking CAR registration. The classification of the properties showed the land distribution of the study area (Supplementary material - Figure 1B, Table 2). In the classification of the properties, we obtained 75% of the properties with up to 40 ha, followed by 19% between 40 and 160 ha, 3% of the properties with sizes between 160 and 80 ha, and 1% with an area above 80 ha (Supplementary material - Table 2).

Smallholdings constitute the majority in the study area. In the exploratory analysis, a total of 134 properties eligible for PES were selected (Table 6; Figure 5A), with 79 properties in São Gonçalo do Rio Preto, 48 in Felício dos Santos, 6 in Senador Modestino Gonçalves, and 1 in Couto Magalhães de Minas. Among the 134 selected properties, 67.16% are classified as smallholdings, 27.63% as small, 5.97% as medium, and 2.24% as large. To better visualize the properties, they were divided into 3 groups: A, B, and C (Figure 5B).

Table 3: Information Plans, Internal Data on the Provision of Ecosystem Services, and Eligibility of Rural Properties Weights Assigned for the PSE.

Information Plans	Ecosystem Services Offer	PES Eligibility Weight	Justificative
Riparian PPA			
Anthropized	Low	3	Considering the riparian PPAs, are protected by law for water provision, preventing siltation, etc.
Conserved	High	6	
Not applicable	Insignificant	1	
Priority Areas for Conservation			
Special	Very High	6	Priority for conservation according to IEPHA due to vulnerability
High	High	5	
Insignificant	Low	1	
Carbon Aboveground (ton per hectare) - tC/ha			
0 to 10	Very Low	1	The scale is based on the classification of the national inventory (MCTI, 2020).
10 to 20	Low	2	
20 to 30	Medium	3	
30 to 40	Medium-high	4	
40 to 50	High	5	
Above 50	Very high	6	
Proximity to Conservation Unit (CU)			
CU	Full Protection	6	Distances of 3 km from the Buffer Zone when not presented in the Management Plan (Brazil, 2010).
Buffer zone	High	5	
3 km	Medium-high	4	
6 km	Medium	3	
9 km	Low	2	
12 km or more	Very low	1	
Land use			
Continental Waters or Grassland Area	High	5	Weight classification by experts in zoning and ecosystem services - average (Burkhard et al., 2009).
Forest Area	Very high	6	
Mining or Uncovered Area or Roads	Insignificant	1	
Agricultural Crops or Pastures or Silviculture	Very low	2	
Springs density			
0 to 1	Very low	1	Kernel Density from ZAP shows that higher density correspond to more hydric-provision ES.
2 to 3	Low	2	
4 to 5	Medium	3	
6 to 7	High	4	
8 to 9	Very high	5	
10 to 11	Extreme	6	

Table 4: Distribution of Eligibility of Areas for PES.

Eligibility for PES	Weight	Percentage (%)
Insignificant	(1)	8,81
Very low	(2)	26,73
Low	(3)	17,19
Medium	(4)	26,62
High	(5)	16,73
Very high	(6)	4,83

Group A (Figure 6B, 6A) is predominantly characterized by grassland vegetation and a high density of springs. Despite their distance from the CU, these properties have conserved areas that qualify them for PES. Satellite imagery reveals some areas of degradation, but the land use and occupation map shows that the region's characteristic vegetation predominates. The eligibility of properties in Group A is driven by their conserved areas, which remain free of intensive land use (Figure 6B). These areas include preserved springs and riparian Permanent Preservation Areas. Selecting properties with these characteristics helps establish ecological corridors and protect biodiversity, among other benefits.

Group B contains many properties (Figure 5C) located near the urban center of São Gonçalo do Rio Preto. These areas exhibit more intensive land use compared to the other rural properties. The properties in this group are located near the Rio Preto State Park and a priority conservation area, enhancing their eligibility for PES. Most of these properties maintain preserved riparian PPAs. However, some properties exhibit high pasture land-use intensity, which may warrant further investigation. Additionally, several properties in Group B have nearly 100% of their area conserved (Fig. 5D), suggesting newly acquired or compensation areas. This analysis provides a basis for identifying properties and understanding their unique characteristics.

Table 5: Relationship Between Study Area Size and Area Size CAR

Rural Properties	Size (ha)	Percentage (%)
With CAR	38632,48	82,96
Without CAR	7932,46	17,04
Without Overlap	36885,32	95,47
With Overlap	1744,67	4,73

Table 6: Land Classification of Properties Eligible for PES in the Exploratory Analysis.

Rural Properties	Number of Selected Properties	Percentage (%)
I (Smallholding)	90	67.16
II (Small)	33	24.63
II (Medium)	8	5.97
IV (Large)	3	2.24
Σ	134	100

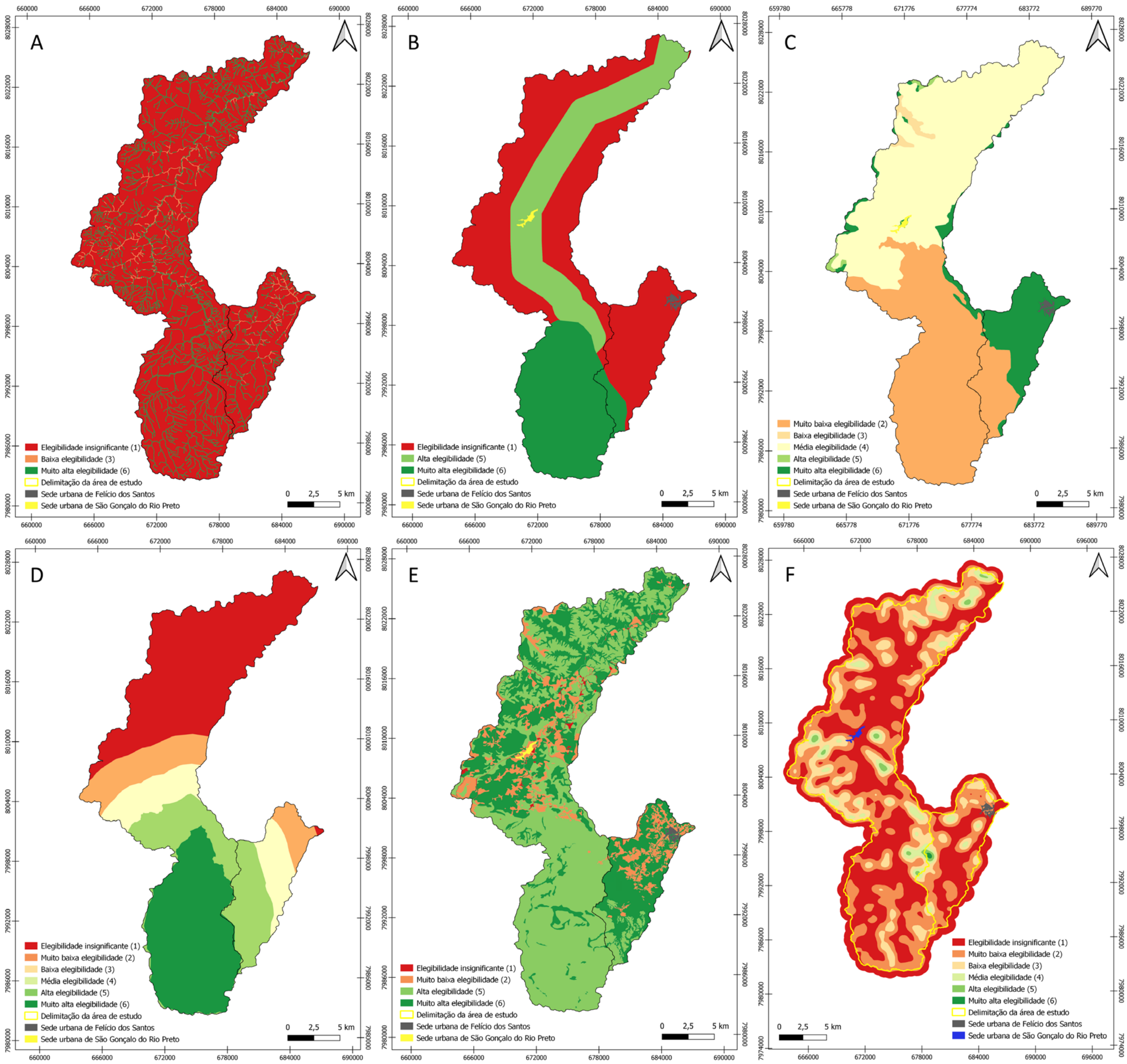

Figure 3: Reclassified Spatial Information Layers, ranked from 1 to 6 for PES eligibility: A) Conserved and anthropized Permanent Preservation Areas; B) Priority conservation areas; C) Aboveground carbon; D) Proximity to Conservation Units; E) Ecosystem Services Provision in land use and occupation; F) Spring density.

Group C includes rural properties with significant variability in size, predominantly marked by anthropogenic land uses such as pasture and agriculture, while maintaining large forest vegetation areas (Figure 5E). The selected properties in this group have a high percentage of native vegetation and preserved riparian PPAs. Notably, those near the Rio Preto State Park feature extensive rocky outcrops (Figure 5F), which support the grassland vegetation typical of the region. This characteristic adds to the environmental value of the properties in Group C.

According to the established criteria, the 134 properties selected by the MCDA have spatial configurations prioritized for PES. The exploratory analysis helps to validate this selection, potentially leading to the confirmation or alteration of the priority properties.

DISCUSSION

Multi-Criteria Decision Analysis

MCDA is a fundamental methodological tool for mapping priority areas and determining eligibility for PES, as it enables the integration of multiple factors, adds scientific rigor, and promotes a fairer allocation of resources (Zhang *et al*., 2013; Langemeyer *et al*., 2016). Despite its broad applicability, the use of MCDA in PES programs still faces important challenges in the international context, particularly regarding the high subjectivity in criterion weighting and the limited integration of large-scale land registries and geospatial datasets (Marttunen *et al*., 2022).

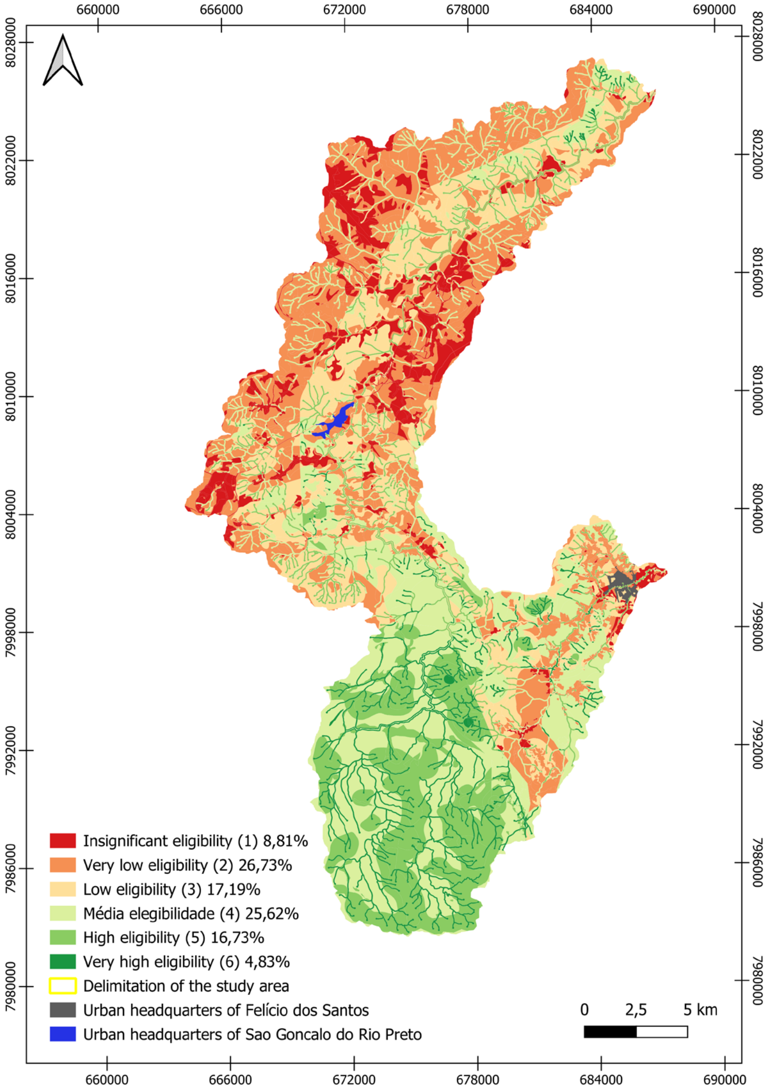

Figure 4: Eligibility of areas for PSE.

Nevertheless, the participation of specialists remains essential, since local environmental and socioeconomic conditions must be incorporated into the decision-making process. When expert knowledge is combined with methodological approaches supported by scientific literature, the reliability and consistency of the results are significantly improved (Cerveira *et al*., 2024). In this context, MCDA provides a transparent, data-driven framework that can transform regulatory requirements (e.g., riparian PPAs, legal reserves) into operational management indicators, thereby representing a key contribution to the large-scale implementation of PES programs worldwide. MCDA enables integrating environmental, economic, and social/cultural variables to define priority areas for conservation, thereby supporting more effective public policies for PES (Marttunen *et al*., 2022).

This is particularly relevant in regions such as the Upper Araçuaí River Basin, where the study area is located. This basin is the main tributary of the Jequitinhonha River, situated in the semi-arid region of northeastern Minas Gerais (IBGE, 2025). Located in the transition zone between semi-arid and dry sub-humid climates, the so-called Minas Gerais semi-arid region, and within the official limits of the Brazilian semi-arid region (Bispo *et al*., 2016), this basin plays an essential role in supplying water to twenty-three downstream municipalities that depend on the integrity of their water resources (IGAM, 2024). In this context, the adoption of a PES scheme based on this approach strengthens the management of springs and riparian forests, ensures greater water security, and promotes socioeconomic inclusion by compensating rural producers and local communities for adopting sustainable practices. Thus fostering rural development and reducing environmental vulnerabilities, while contributing to environmental conservation and regional development (Simedo *et al*., 2020).

Each information plan inserts very important information into the model, considering the ES context. Among the selected criteria, particularly the density of

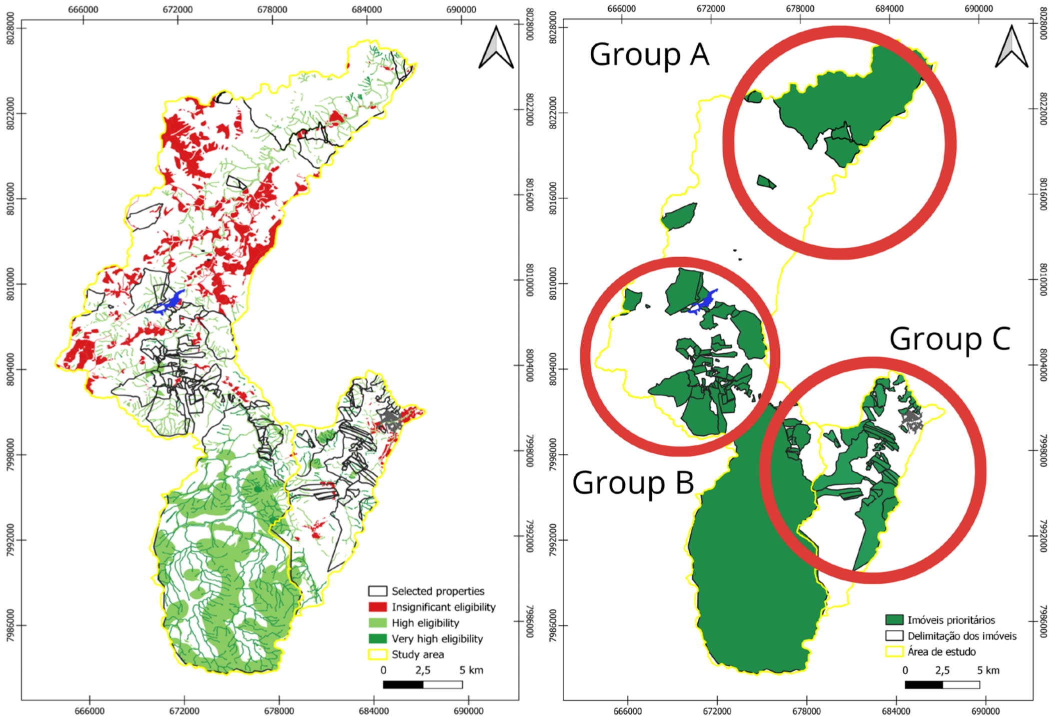

Figure 5: A) Rural Properties Eligible for PES. B) Priority Properties for PES are subdivided into A, B, and C Groups.

springs, the conservation status of riparian PPAs, and proximity to priority conservation areas, effectively highlight the critical zones for ES related to water provision. The prioritization of springs directly addresses the global challenge of water scarcity, which is especially relevant in dry sub-humid and semi-arid regions such as the study area (Bispo *et al.*, 2016; Hakim *et al.*, 2023). This approach aligns with SDG 6, "Clean Water and Sanitation," particularly Target 6.6, which calls for protecting and restoring water-related ecosystems, including forests, wetlands, rivers, and aquifers.

By emphasizing strategic areas for groundwater recharge and water quality maintenance, the study also converges with SDG 15, "Life on Land," especially Target 15.1, which aims to ensure the conservation and sustainable use of terrestrial and freshwater ecosystems (OECD, 2024). In this context, focusing on protecting springs and riparian PPAs enhances the effectiveness of water-oriented PES programs (Coelho *et al.*, 2021; Mamedes *et al.*, 2023), contributing simultaneously to water security, ecological integrity, and the achievement of global sustainability goals (Lima *et al.*, 2021).

It is essential to emphasize the importance of Permanent Preservation Areas (PPAs) in protecting riverbank ecosystems, as they prevent erosion, reduce sediment deposition in rivers, and preserve water quality (Verdonschot & Verdonschot, 2023). When these areas are anthropized, their environmental fragility may be intensified, causing them to fail in fulfilling their intended function (França *et al.*, 2022). The conservation status of spring directly influences both the quantity and quality of water production (Hakim *et al.*, 2023). Thus, areas with a higher density of springs, combined with the mapping of conserved and anthropized PPAs, are more suitable for water supply. This reinforces the importance of spring protection in this region, which is crucial for ensuring water availability (Silva, 2023).

Furthermore, aboveground carbon has proven to be an important metric, strengthening the case for PES by linking local conservation efforts to the global carbon credit market (Costa *et al.*, 2023; Marco *et al.*, 2023). This dual benefit, environmental conservation and economic development (Lima *et al.*, 2020), demonstrates how PES can be strategically employed as a public policy instrument in regions dependent on provisioning and cultural ecosystem services (Silva, 2025). Carbon credit programs that encourage forest protection and the maintenance of native vegetation have a positive impact on combating climate change (Rosendo & Rosa, 2012; Marco *et al.*, 2023). They can also foster better payment conditions for PES areas by combining environmental conservation with local economic development and strengthening cultural services tied to the social dimension (Oliveira *et al.*, 2024).

We identified a trend of selected properties being located near protected areas, reinforcing the role of these areas in the formation of ecological corridors (Morandi *et al.*, 2020; Isola *et al.*, 2022), which are crucial for maintaining biodiversity and can be applied to any fragmented landscape globally (Queiroz-Stein & Siegel, 2023). However, it is important to note that this trend may be detrimental to the selection process, as it highlights only the areas prioritized by this criterion. Buffer zones emphasize the importance of the proximity of properties to priority conservation areas, expanding the coverage of protected lands. Nevertheless, these distance buffers may introduce a bias toward areas

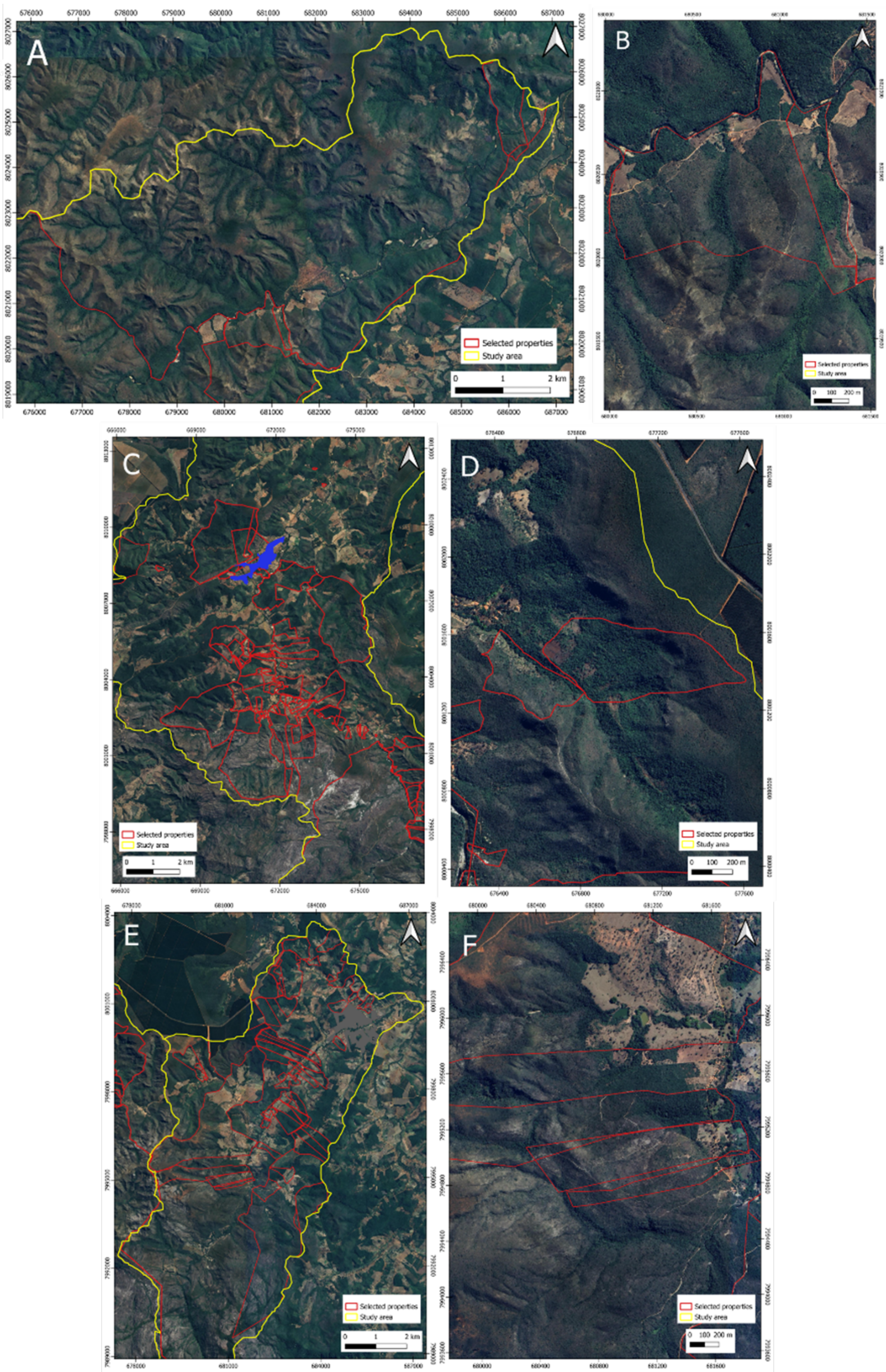

Figure 6: A) Priority properties for PES (Group A). B) Exploratory analysis of priority properties for PES (Group A). C) Priority properties for PES (Group B). D) Exploratory analysis of priority properties for PES (Group B). E) Priority properties for PES (Group C). F) Exploratory analysis of priority properties for PES (Group C).

closer to priority conservation zones, and their use must be carefully structured to avoid skewed selection.

The high capacity for ES supply, identified through expert consultation, can be justified by the area's high conservation level of approximately 87% (Gorgens *et al*., 2021; Mucida *et al*., 2022). Mapping ES based on land use allows for more realistic estimations. Especially when conducted at a local scale and with the participation of experts familiar with the study area (Burkhard *et al*., 2009; Martínez-Harms & Balvanera, 2012; Jacobs *et al*., 2015). Unlike anthropized classes, forest and Cerrado classes showed higher ES supply due to their conservation status and local importance, making the estimates more reliable. Degraded land, bare soil, agricultural, and silvicultural areas are considered anthropized (Enescu *et al*., 2025). However, areas that produce products indirectly useful to humans, such as food and timber, mainly due to the legal context for PES, tend to provide higher ES supply than degraded or bare soil areas, which have lower potential (Ekka *et al*., 2023).

Study area eligibility

The results indicated an average potential for PES across the analyzed sub-basins, with the eligibility classes "very low" and "medium" accounting for the largest percentages, each approximately 26–27%. Although the study area exhibits a high level of conservation, which favors the provision of ES (Gorgens *et al*., 2021; Mucida *et al*., 2022), this factor did not directly influence PES eligibility. Insignificant eligibility was distributed in anthropized areas located far from the state park, its buffer zone, and the main course of the Preto River. The weighing of these information layers may be influencing this outcome, prioritizing areas closer to the protected area and priority conservation zones.

In studies of this nature, it is important to ensure that the criteria do not favor a specific location, even if the spatial configuration may lead to such outcomes. For example, degraded areas near a protected area may achieve higher eligibility than another degraded area farther away. As evidenced by the northern portion of the eligibility map, which showed lower weights than the southern portion. It is up to managers to analyze each case and apply the necessary adjustments.

We can observe from the exploratory analysis of established groups, especially in areas classified as having low eligibility, that they have a lower supply of SE (Derak *et al*., 2023). This makes them ineligible for PSE. It is up to the manager to instruct the owner to encourage the recovery of this area so that it can return to offering SE and become eligible for PES. The 'insignificant', 'very low', and 'low' eligibility classes represent 52.89%, which may be related to the limited number of priority conservation areas considered in the information layer.

Currently, there are only two classes of priority areas, one within the protected area and another along the Preto River, which highlights the difficulty of mapping cultural SE (Jones *et al*., 2021; Yang *et al*., 2022; Santos, *et al*.; 2026). It would be necessary to establish additional priority areas, considering various local cultural contexts raised through expert consultation. But the lack of cultural mapping does not change the fact that anthropized areas offer ES. These are important for highlighting priority areas for restoration. Despite the high conservation index, it is still necessary to raise awareness of PES implementation to make this index practically relevant.

Another issue identified in the analysis was errors in the CAR through the SICAR, which show inconsistencies in property boundaries and area overlaps in more than 4% of registered properties (Furumo *et al*., 2024). This serves as a warning for public policy involving this registry. A lack of regularization and validation of data allows landowners to use areas that, according to the CA), should be conserved. Exploratory analysis enabled the identification of properties with the greatest need for regularization and the establishment of PES priorities. This step is essential for validating results in public policy, as it helps assess and confirm the suitability of the selected area, including its potential and limitations. The methodology serves as a support tool for managers in selecting priority areas for PES and the properties associated with them.

Eligibility of PES for rural properties

In practice, eligibility combines both the technical criteria for selecting rural properties suitable for PES and the requirements that prospective beneficiaries must meet to participate in the initiative. Ninety (90) small properties eligible for PES were selected, with economies based on family farming (IBGE, 2017). This highlights the importance of PES programs as incentives for family development and for raising awareness of the sustainable use of environmental resources. Managers should work collaboratively with property owners, identifying areas of concern and aiming not only to protect the environment but also to promote the socioeconomic development of families that depend on ecosystem services for their livelihoods.

During field visits, it was evident from owners' reports that they use ecosystem services in their daily lives and understand how the degradation of these environments can affect their availability, underscoring the need for conscious, sustainable use. The methodology's criteria may favor or disadvantage properties depending on their size, due to the scale of the available spatial data (Koldasbayeva *et al*., 2024). Therefore, it is the responsibility of decision-makers to analyze the information and contextualize it with the local reality, details of which may not be fully captured by geographic data (Magdalena *et al*., 2023).

Analyzing the results, a proximity relationship is observed between the selected properties and priority conservation areas, which favors higher eligibility in this region. This underscores the importance of protected areas for the formation of potential ecological corridors (Morandi *et al*., 2020). The protection of forest remnants within properties is crucial, particularly for water resources (Coelho, 2021), yet the proximity bias may obscure the reality of other properties. The model also highlights ineligible areas, which can be explored in future research aimed at indicating areas to be recovered to resume the provision of ES.

Environmental degradation compromises the capacity of ecosystems to provide ES by altering essential ecological functions (Derak *et al*., 2023). In this context, the recovery of degraded areas constitutes an ecological restoration action so that functions can operate properly again. Thus, it becomes characterized as an environmental service, contributing to restoring the integrity of the ecosystem and ensuring the continued provision of ES to society (Ekka *et al*., 2023; Wang *et al*., 2026).

In the selected properties, economic activities such as forestry, pasture, or agricultural cultivation provide primary benefits to local populations (timber and food production). These land uses are permitted if they comply with the Brazilian Forest Code (Brasil, 2012), and land use capability must also be considered (Taveira *et al*., 2021; Mucida *et al*., 2023). PES can, therefore, serve as a tool to raise awareness about the conscious use of resources and land in properties with degraded areas. This happens because degraded areas do not act in erosion prevention, nor in carbon sequestration. In some cases, they lose their stock and cease to be eligible for PES (Ekka *et al*., 2023).

The selection of properties in extreme conditions, such as those with almost completely exposed soil or, conversely, with almost intact vegetation, requires field validation. Satellite images assist in the validation of the proposed model, which may still present flaws despite its great potential. However, it is difficult to avoid the automatic selection of properties with this configuration. This highlights that MCDA has limitations and depends on the perspective of the professional in the field, but it also contributes to decision-making in PES analyses (Zhang *et al*., 2013; Langemeyer *et al*., 2016). O modelo agrega maior rigor científico e metodológico, contribuindo para uma alocação mais eficiente e justa dos PES. Assim, promove a conservação dos recursos naturais, considera o desenvolvimento socioeconômico e integra a perspectiva do gestor (Vilela, 2023).

CONCLUSION

The criteria defined for MCDA contributed to the identification of priority properties for the implementation of a PES program. The mapping of ES proved to be an important support for the study. The methodological approach proposed in this work showed good results, highlighting more and less eligible areas for PES, identifying priority properties for the implementation of a potential mechanism. Being also possible to identify ineligible regions that can be explored in future works for subsequent indication for restoration.

The use of public and official geospatial data contributes to replicability in any study area. Being necessary adaptations for application, according to the local cultural reality. The exploratory analysis of eligibility, based on the boundaries of rural properties, allowed for the selection of the most suitable properties for PES, as well as the identification of owners based on CAR data. The recognition of rural landowners who protect important areas for the provision of ES is an important factor in the dissemination of good environmental practices, contributing to minimizing environmental pressure on native areas.

The methodology meets the initial objective of the work, but it is not immune to some limitations. The prioritization of areas within locations with conservation priority was identified, and some factors influence it, such as the scale of spatial data, the difficulty of mapping cultural ES, and the definition of new priority areas for conservation. The areas with low eligibility serve as a starting point for future studies aimed at restoring the provision of ES.

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DATA AVAILABILITY:

The datasets supporting the conclusions are included in the article.

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Analysis: GRA; LCJF; DPM; JDS; MSM; RCS; CSJD; LMR; HVS; CVGR
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