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New strategies to influence land use dynamic: spatial analysis and quantification

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FOREST ECOLOGY

ABSTRACT

Background: Land use plays a critical role in shaping human societies and environmental sustainability. This study investigates strategies influencing land use dynamics and their potential implications for territorial management and public policy development. We propose a new approach to identify three different land use strategies, and to quantify and analyze their spatial relevance. The study area, located in a Brazilian Biosphere Reserve, covers two watersheds with distinct ecosystems and socioeconomic contexts. We implemented the following steps: mapping land use, computing the potential for agricultural use, mapping restricted zones, and computing the strategies. We accessed public databases and performed spatial analyses using Google Earth Engine, Google Colab and QGIS software.

Results: One of the watersheds exhibits less anthropization and better environmental preservation. Consequently, it presents greater potential for implementing Payment for Environmental Services (PES) programs. The other watershed, with higher anthropization and agricultural intensity, requires more extensive restoration, especially in restricted areas.

Conclusion: These differences underscore the importance of tailoring land management strategies to specific socioeconomic and environmental characteristics, ensuring effective conservation and territorial management. The primary scientific novelty of this work lies in the methodological integration that transitions from traditional land-use diagnostics to a prescriptive spatial planning framework. Our study contributes to the UN's Sustainable Development Goals, particularly SDG 10 (Reduced Inequalities), SDG 15 (Life on Land), and SDG 13 (Climate Action).

Keywords: Anthropization; ecosystem services; natural cover; payment for environmental services; restoration.

HIGHLIGHTS

Importance of rational and integrated strategies to influence land use is explored.
Geospatial analysis supports better strategies for land use decision-making.
A new approach is proposed to identify and quantify strategies for sustainable land use practices.
Method maps areas for PES, forest restoration, and land retirement strategies.

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INTRODUCTION

Landscape changes resulting from land use change are considered one of the main drivers of global environmental change, with significant implications for ecosystem sustainability and human well-being (Ellis, 2021). Agricultural expansion, urbanization, and other anthropogenic activities have led to ecosystem degradation, resulting in biodiversity loss, habitat fragmentation, and increased vulnerability to climate change (Tolessa et al., 2017; Hald-Mortensen et al., 2023). This scenario highlights the need to develop integrated strategies to guide land use dynamics in a way that reconciles production and conservation goals (De Morais Júnior et al., 2024). However, there remains a considerable gap in the development of approaches that enable the design of effective interventions tailored to the particularities of complex and multifunctional landscapes.

Brazil has undergone major land use changes, with significant impacts across all its biomes (Curtis et al., 2018; Winkler et al., 2021; Caballero et al., 2022). The lack of effectively implemented public policies, combined with the growth of commodity production, are key factors driving the conversion of natural ecosystems (Azevedo et al., 2017; Maciel et al., 2020; Caballero et al., 2022). In this context, land use decision-making must consider the integration of multiple factors – such as edaphoclimatic and topographic characteristics, legal regulations, and socioeconomic conditions – which directly influence land suitability and its potential for different uses (McDowell et al., 2018; Moberg et al., 2021; AbdelRahman et al., 2022).

To mitigate the negative impacts of inappropriate land use and promote more sustainable landscapes, several strategies have been proposed and implemented to influence different flows in land use dynamics (Figure 1). Payment for Environmental Services (PES), for instance, aims to support landowners with compensation to preserve native vegetation and ecosystem services (Wunder, 2015; Wunder et al., 2020; Ruhl et al., 2021). Another approach is the promotion of land retirement or set-aside, which involves the voluntary withdrawal of land from less suitable productive uses, allowing for natural or assisted recovery and contributing to conservation (Hasan et al., 2020). Additionally, ecological restoration of illegally converted or abandoned areas is essential to recover biodiversity and ecosystem functions (Forzza et al., 2012; Ulloa et al., 2017; Gomes et al., 2020; Strassburg et al., 2020). Geospatial analysis, using tools such as remote sensing and Geographic Information Systems (GIS), has proven indispensable for land use mapping, agricultural suitability assessment, and the identification of restricted areas, providing the foundation for spatial planning (Nizeyimana & Opadeyi, 2020; Sperandio et al., 2025).

Although knowledge about land use challenges and management strategies has advanced, there is still a notable lack of integrated approaches (Reed et al., 2020). Specifically, there is a shortage of methodologies that systematically consider current land use, agricultural potential, and environmental legal restrictions to simultaneously identify and spatially quantify where different interventions – such as PES, land retirement, or restoration – would be most appropriate. The effectiveness of spatial planning and the efficient allocation of resources are compromised when multiple factors and landscape heterogeneity are not considered simultaneously – a limitation that single-criterion approaches often fail to overcome (Margules and Pressey, 2000).

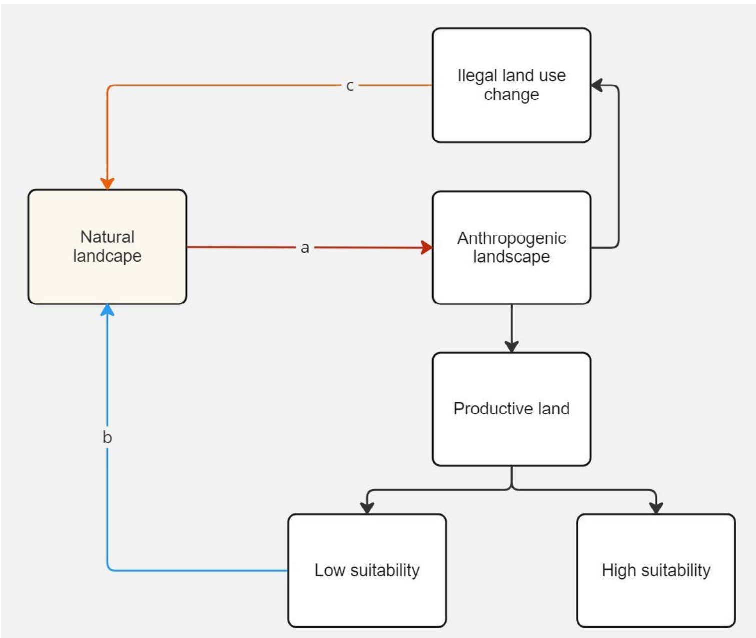

Figure 1: Land use change dynamics. Flow 'a' indicates land use change from a natural form to a anthropogenic landscape; 'b' indicates the land retirement and restoration; 'c' indicates the legal obligation to restore.

In our study area, these methodological gaps are especially critical. The region is marked by land-use conflicts, pressure on water resources, climate-related impacts, and the presence of mining and hydropower projects (De Magalhães Júnior et al., 2019; Ribeiro et al., 2026). Additionally, intensive agricultural and livestock activities exert significant pressure on the Atlantic Forest, particularly in riparian zones (Fernandes et al., 2025; Ferreira et al., 2021). This complex combination of socioeconomic and environmental drivers reinforces the need for approaches capable of jointly assessing multiple territorial dimensions to inform decision-making.

In response to this challenge, this study proposes a new methodological approach to identify, spatially quantify, and analyze the territorial relevance of three distinct strategies aimed at influencing land use dynamics: Payment for Environmental Services (PES), land retirement, and restoration of restricted zones. Our main objective is to demonstrate how this integrated approach, applied to two watersheds with distinct socioeconomic and biophysical contexts within a Brazilian Biosphere Reserve, can generate crucial information for the development of more effective and targeted public policies and land management practices. We hypothesize that the biophysical characteristics and differing levels of anthropogenic pressure between the watersheds will result in distinct spatial allocations of the strategies, underscoring the need for customized planning approaches for effective conservation and sustainable land management.

MATERIAL AND METHODS

Our methodology was applied in the Águas Vertentes Environmental Protected Area (EPA), Brazil (Figure 2). A EPA permits private properties inside its boundaries and aims to influence land use by promoting a sustainable landscapea sustainable landscape (Brasil, 2000). It is a mountainous region, with a temperate Cwa climate, according to Koppen-Geiger (Beck et al., 2023). The vegetation is formed by a mosaic of semidecidual forest and savannah, associated with a transition zone between two biomes: Cerrado (Brazilian Savanah) and Atlantic Forest (Ombrophilous forest) (Schaefer et al., 2016; Myers et al. 2000). The region is considered a hotspot grouping 15% of the vascular flora in less than 1% of the Brazilian territory (Fernandes et al., 2018; Neves et al., 2018; Silveira et al., 2016). It also has a unique social, historic, hydrological, and biodiversity relevance (Echternacht et al., 2011; Scalco and Souza, 2018).

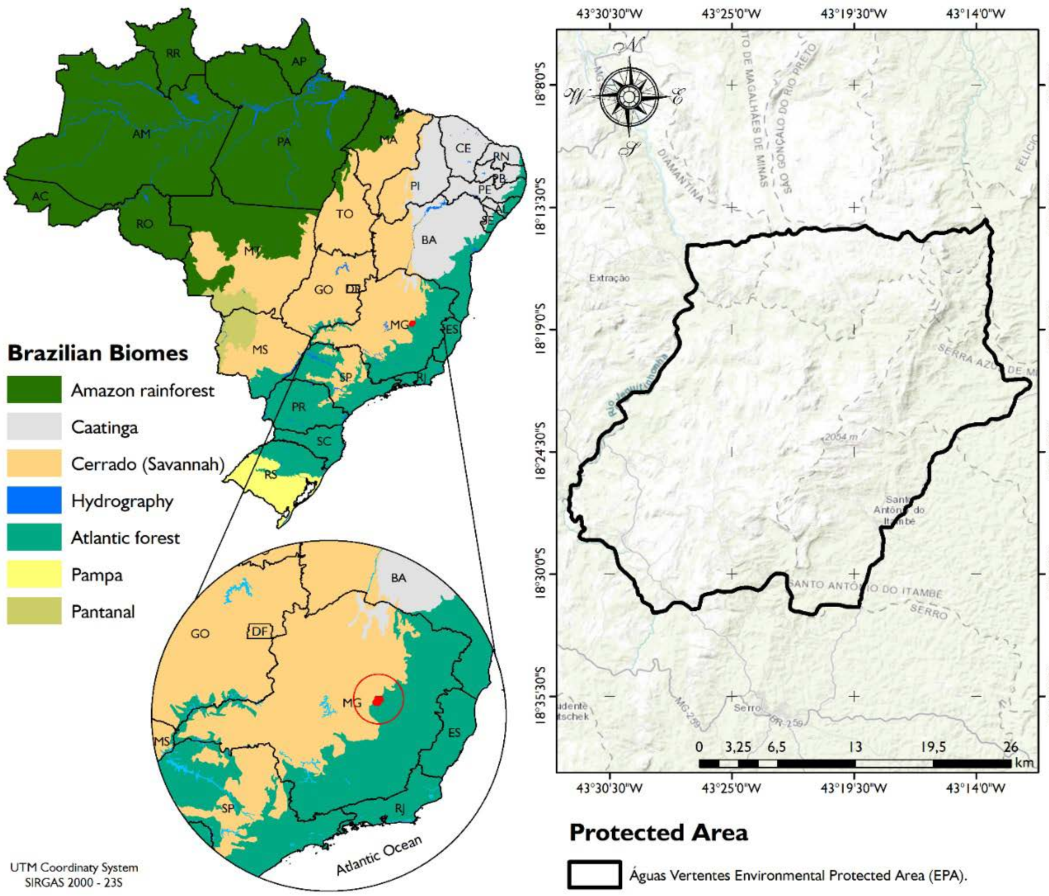

Figure 2: Location of the Águas Vertentes Environmental Protected Areas within the context of the state of Minas Gerais and Brazilian biomes.

Situated in the Espinhaço Range Biosphere Reserve (ERBR) in southeastern Brazil, this area was recognized by UNESCO in 2005 as a biodiversity hotspot. It plays a crucial role in balancing conservation efforts with social development. The EPA has a total area of 76,285.50 ha, serving as the water catchment for two important national rivers. The northwest portion belongs to the Jequitinhonha River, where the strong climatic constraint (Fernandes 2016; Domingues et al., 2012) allows a subsistence agriculture (Scalco and De Souza, 2018). The southeast portion belongs to Doce River, which has a stronger agricultural potential, where the low-tech production system for livestock and dairy farming dominates (Schettini et al., 2020).

The analysis followed a five-step process: 1) mapping the land use; 2) computing the land potencial for agriculture use; 3) mapping the restricted zones related to the watercourses; 4) overlapping the layers; 5) identifying and computing the strategies. Land use and cover were accessed through the MapBiomas database, which uses cloud processing and automated classifiers operated from the Google Earth Engine platform to generate annual maps for Brazil (MapBiomas Project, 2024). We grouped the original MapBiomas classes into six: natural cover (including rocky outcrops), agriculture, pasture (including the mosaic of uses class), silviculture, urban areas, and other uses (including inland waters and mining).

To assess the land suitability for agriculture uses, we considered three official databases: lithology, soil class, and terrain slope (Costa et al., 2017). Lithology was available on the scale of 1:1,000,000 and downloaded from http://www.portalgeologia.com.br/ (accessed on 12/05/2020); the soil map was available on a scale of 1:650,000 and downloaded from https://www.dps.ufv.br/?page_id=742 (accessed on 12/05/2020). The soil classes followed the Brazilian Soil Classification System (Santos et al., 2018). The slope was computed from the elevation model obtained by the Shuttle Radar Topography Mission (SRTM), distributed by NASA JPL in a resolution of 1 arc-second (approximately 30m). Each layer was associated with a score between 1 and 5, and the land suitability for agriculture was computed with weighting slope by 50%, soil class by 39%, and lithology by 11%, and summing them up. Score below 2.6 indicates low potential for agriculture (Costa et al., 2017).

We considered as restricted areas the surrounding springs and perennial watercourses, and areas with protected status, as state parks. The layers were downloaded from the state environmental agency at http://idesisema.meioambiente.mg.gov.br/ (accessed on 11/03/2024). We delimit buffer zones for restricted areas of watercourses, we followed the standards established by the Brazilian environmental law (Brasil, 2012).

Based on the three produced datasets, we identified and spatially quantified three strategies that could influence land use: a) areas suitable for receive payments under environmental services framework (i.e. areas with natural coverage, not included in restricted zones); b) areas for land retirement (i.e. used lands in not suitable areas, not included in restricted zones); c) restricted zones which are under agricultural use. Each land use strategy was quantified using the raster calculator tool.

To propose land use change strategies, it is essential that we know the peculiarities of each region, since this type of action has the potential to generate direct impacts on the local socioeconomic reality. To analyze whether our approach would spatially differ in the contexts of the two studied watersheds, we performed a comparison using a Pearson's chi-squared test, at a 5% significance level, to determine whether there is a statistically significant difference between the frequencies in the contingency table. Spatial data processing was performed using Colab, Google Earth Engine and QGIS software, version 3.32.3 'Lima'.

RESULTS

The main productive activity developed in the study area is pasture, occupying 17.03% of the area (12,988.041 ha), practically the entire anthropized area (Figure 3). In the northern/northwest part, the pasture activity occupies 6,321.81 ha (12.15% of the watershed). In the southern/southeastern region, two economic activities stand out: pasture and silviculture, occupying 27.50% (6,666.23 ha) and 1.65% (400.46 ha) respectively of the watershed. The region does not have significant urbanized areas.

The study area has 82% of natural coverage. The most relevant natural covers categories were forest (28.50%), savanna formation (27.21%), and rocky outcrop (23.63%). The north/northwest watershed is more preserved than the south/southeast one, with natural coverage of 87.42% and 70.68% respectively. Excluding the restricted zones from natural coverage, the protected area has a total of 45,866.20 ha (60.12%) with potential for benefit a PES strategy program. The north/northwest watershed has 36,107.20 ha that would benefit from a PES strategy (69.38% of the watershed area). The south/southeast watershed has 9,759.00 ha that would benefit from a PES strategy (40.26% of the watershed area) (Figure 4a).

The entire area has a low or very low agricultural potential in 76.66% (58,482.43 ha) of the land (Figure 3b). On which, 13.69% (8,004.84 ha) are currently occupied by some agroforestry activity. Areas with low aptitude, used for agricultural activities, have a high risk related to both economic and environmental activity. The north/northwest watershed has a lower percentage of anthropization in areas with low or very low agricultural potential (9.36%) compared to the south/southeast watershed (23.78%). These areas, excluding the restricted zones, would benefit from a retirement strategy (Figure 4b).

Approximately 18,886.26 ha (24.76%) of the study area is classified as a restricted zone. On which, 2,054.86 ha of these areas (10.88 %) shows signs of anthropic activities. The north/northwest watershed has 1,063.88 ha (10.15%) of restrict zones anthropized, while the south/southeast watershed has 990.98 ha (11.80%) (Figure 4c). These are areas that would benefit from a natural vegetation restoration incentive strategy.

When we look exclusively at the restricted areas related to watercourses, we notice a greater discrepancy. The southeast basin shows the banks of the watercourses being much more anthropized, with 898.87 ha (23.48%)

compared to the northwest basin with 702.39 ha (9.77%). However, when we refer to the restricted areas belonging to the category of strictly protected areas, we notice that those located in the northwest basin exhibit a greater degree of anthropization (9.04%) than the areas in the southeast basin (2.89%).

The land use and occupation strategies exhibit statistically distinct spatial configurations comparing both watersheds (chi-square = 1,837.2638 $p < 0.00001$, significant for $p < 0.5$). The PES strategy would benefit larger areas in the north/northwest region of the protected area, with the potential to influence land use and occupation in 69.38% of the area. Due to the higher level of anthropization, land retirement and land restoration strategies would benefit larger areas in the south/southeast watershed (occupying 13.43% and 4.09% of the area, respectively) (Table 1).

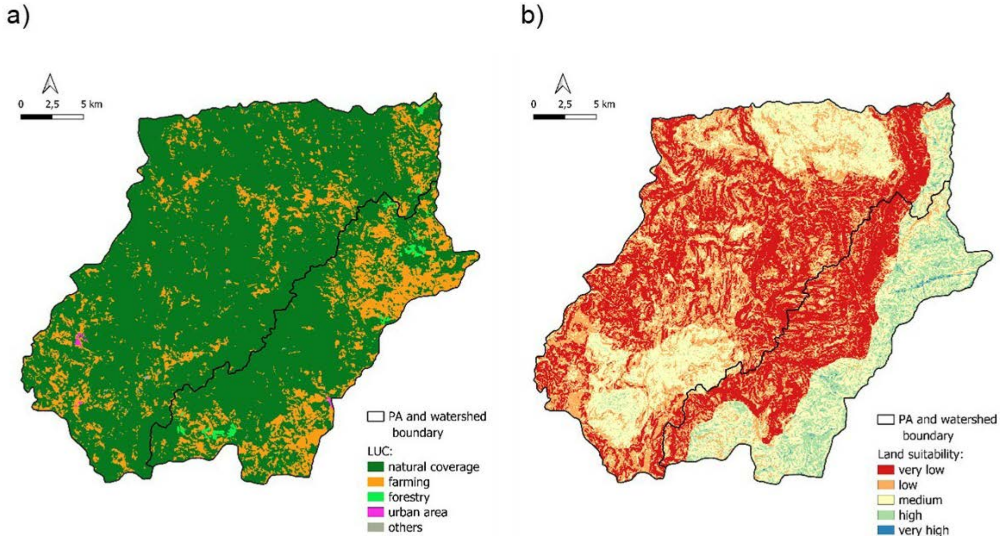

Figure 3: Panel a) indicating the current land use; Panel b) exhibiting the land potential for agricultural use (including livestock farming and silviculture).

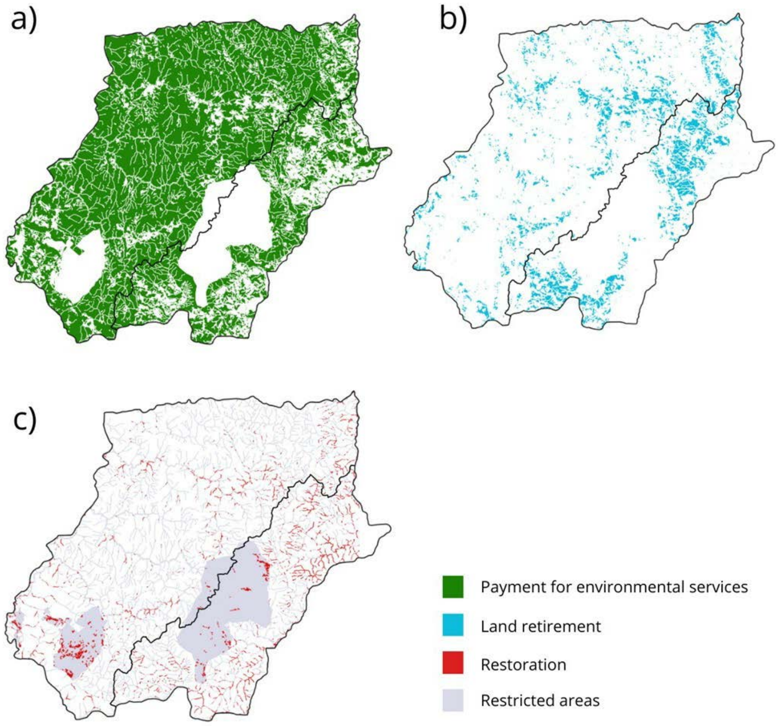

Figure 4: Selected study area showing a) natural landscapes, with natural cover, suitable for payment for environment services, b) areas with low potential for agriculture use, suitable for retirement. c) land use over Restricted zones, suitable for restoration.

Table 1: Strategies to influence land use dynamics in each study watershed.

Strategies	Northwest watershed (ha)	% of the watershed	Southeast watershed (ha)	% of the watershed	Total (ha)	% of the total area
PES	36,107.20	69.38	9,759.00	40.26	45,866.20	60.12
Land retirement	3,680.06	7.07	3,254.81	13.43	6,934.87	9.09
Land restoration	1,063.88	2.04	990.98	4.09	2,054.86	2.69

DISCUSSION

This study spatially quantified three strategies that aim to influence changes in land use. Each strategy can affect the land use dynamics in a different way. The PES strategy can increase the value of natural land cover, reducing the economic attractiveness for the land use change. The second strategy promotes retirement of land by discouraging economic activities in areas with low suitability. The third strategy encourages the restoration of restricted zones that is currently under agrosilviculture use. Quantification and valuation of these strategies help guide decision-making processes regarding land use, reconciling public and private interests (Goldstein et al., 2012; Mucida et al., 2023; Sperandio et al., 2025).

Our study area illustrates the challenge of developing effective public policies for land use and occupation within a single and large protected area, which encompasses watersheds with distinct characteristics. While in one part (north/northwest) of the protected area, much of the watershed remains preserved, in another (south/southeast) anthropic activities are consolidated. The south/southeast watershed has a higher degree of anthropization, including areas with low and very low potential.

The north/northwest watershed has a strong organization around traditional communities, often related to extractivism of natural resources (Scalco and De Souza, 2018). This region is marked by a high number of small rural properties (family farms), but large properties occupy the majority of the watershed land area (eucalyptus plantations and mining) (da Silva et at., 2021;). There are conflicts originating from a historical and political process of territorial occupation (Trojbicz, 2025). In the southern basin, there is a greater diversity of rural properties, smallholdings are still the most common, but the landscape is increasingly shaped by large-scale land uses such as eucalyptus plantations and pasture (de Oliveira et al., 2019; Salomão et al., 2022; Temponi et al., 2018).

The north/northwest watershed has a greater environmental fragility (Domingues et al., 2012; Fernandes 2016; França et al., 2020), currently resulting in a lower level of anthropization. Promoting land use allocation based on its aptitude is crucial for the development of land use strategies, especially in environments with strong environmental constraints (Li et al., 2021). Avoiding the use of low aptitude lands, we reduce environmental degradation, land abandonment, and underutilization of natural resources (Seyedmohammadi and Navidi, 2022; Subedi et al, 2022), reducing uncontrolled occupation.

In parallel, conserving high-value ecosystems represents a proactive strategy that can be enhanced through PES programs. While information about large preserved areas is essential for planning PES initiatives, it does not automatically translate into higher recommendations or payment values. Rather, PES programs are typically linked to the risk of land conversion or to the provision of high-value ecosystem services, such as water supply and biodiversity hotspots (Chen et al., 2020; Rigonato et al., 2023; De Mendonça et al., 2025;). A PES program focused on biodiversity conservation and water production, involving local families, would not only enhance property values, but would also keep families connected to the land and strengthen community ties (Schettini et al., 2021; Aza et al., 2021).

There are several gaps and significant challenges for the implementation of PES programs. The main one is to ensure not only local socioeconomic improvements, but also ensure the program to be economically viable. Additionally, it is crucial to ensure that PES programs are effective in environmental conservation and ecosystem service provision. Although managers make the final decisions, one strategy does not exclude the others. PES actions achieve greater effectiveness when integrated with complementary approaches (Aza et al., 2021), particularly those incorporating sustainable land-use practices and the active involvement of local stakeholders (Ola et al., 2019).

An effective engagement of local communities in the design, implementation, and monitoring of programs is crucial to ensure their support and active participation. The assurance of long-term sustainability of these programs requires developing adequate funding mechanisms and robust monitoring and evaluation systems. Complementing PES programs with initiatives that promote sustainable agricultural systems is essential to holistically address socioeconomic challenges and foster positive change in local communities (Calle, 2020; Sangha et al., 2024).

In addition to PES, some authors have advocated retirement of areas with low or very low aptitude (Lomba et al., 2020; 2015; Ayambire and Pittman, 2021). This strategy removes low-potential land from the market, promoting change in land use through restoration of natural coverage. According to (Van Leeuwen et al., 2019), simply abandoning the land can lead to degradation, highlighting the importance of associating retirement programs with restoration programs. Despite the undeniable environmental benefits, adopting this strategy can present significant financial and social costs that may vary from case to case (Iftekhar and Polyakov, 2021; Richardson and Davidson, 2021; Chen et al., 2022).

The retirement strategy is particularly relevant in regions with low to very low potential areas and high levels of anthropization. Land use reflects both productive potential and market demands. Environmental factors such as terrain slope, soil type, altitude, climatic variables, and hydrological conditions are significant indicators of changes in land use as they denote the productive potential (Mitsuda and Ito, 2011). The expansion of agricultural frontiers is associated with the need for new productive areas and the expectation of improving local economic conditions. Consequently, there is an increase in pressure on low-suitability areas, leading to their occupation (Garcia and Ballester, 2016).

Areas with lower agricultural potential tend to generate higher production costs and lower economic returns due to biophysical and logistical constraints (Barakat et al., 2025). Limited access to capital also reduces productivity and increases costs (Sadowski et al., 2024), as farmers require more inputs, soil improvements, and face naturally lower productivity. These conditions demonstrate the need for targeted policies that strengthen environmental resilience and support landowners in areas where agriculture is constrained not only by environmental factors but also by technology, public policies, market integration, and social organization (Medina et al., 2015; Barakat et al., 2025).

The study site is still maintaining most of its restricted zones preserved. Conservation of watercourse margins is essential to provide environmental services such as soil protection, biodiversity preservation, and regulation of the hydrological cycle (Riis et al., 2020). The provision of these services can be affected by the dynamics of land use dynamics. Our work allows the identification of priority areas for vegetative restoration, providing information for the formulation of public policies to promote environmental adequacy.

The south/southeast watershed exhibits a higher degree of anthropization in restricted zones, which will require a more intensive restoration process. These efforts involve significant costs, but there is a great disparity in the estimates (Schimetka et al., 2024), which vary according to the method (natural regeneration, planting of seedlings or seeds), the ecosystem, and the type of land use (Adas et al., 2020; Lucchesi et al., 2024).

It is crucial to increase funding for scientific and technological research to assess the effectiveness of restoration (DA Silva et al., 2017). Additionally, strengthening partnerships between environmental agencies, research centers, non-governmental organizations, and landowners is necessary to make land use policies tangible and effective (Silva et al., 2017; Liu et al., 2023).

Notwithstanding these important considerations, the present findings should be interpreted in light of certain methodological limitations. This study acknowledges limitations regarding data granularity and temporal scope. Specifically, the resolution of the land-use layer may be too coarse to detect distinct activities in smaller areas, while the lack of data on farm property sizes within the methodology could lead to an overestimation of the strategies' potential impact. Furthermore, the absence of a temporal analysis prevents the identification of future land-use change trends, which could otherwise provide additional insights for strategy prioritization.

CONCLUSION

Strategic land-use planning requires integrating land potential with local realities. This new approach clearly identifies priority areas for restoration and provides a practical tool for targeting PES planning. Crafting more efficient land use strategies should consider the dynamics and specific characteristics of each locality. This approach, combined with strengthening existing public policies, has the potential to further enhance the appreciation of natural resources and promote the adoption of more sustainable agricultural practices.

The primary scientific novelty of this work lies in the methodological integration that transitions from traditional land-use diagnostics to a prescriptive spatial planning framework. Unlike single-criterion approaches, this study establishes a simultaneous nexus between legal restrictions, biophysical agricultural aptitude, and current anthropogenic pressure. This allows for the precise spatial differentiation of three complementary intervention strategies: PES, Land Retirement, and Restoration, within the same landscape. Consequently, this approach provides a replicable tool for decision-makers to maximize resource allocation efficiency by tailoring territorial management policies according to the specific socio-environmental aptitude of different watersheds.

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AUTHORSHIP CONTRIBUTION

Project Idea: JAC; EBG

Funding: JAC; EBG

Database: JAC; EBG

Processing: JAC; EBG

Analysis: JAC; EBG

Writing: JAC; MLA; HVS; DPM; IMP; RCS; MSM; CCM; EBG; LCJF

Review: JAC; MLA; HVS; DPM; IMP; RCS; MSM; CCM; EBG; LCJF

DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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