

ECOSYSTEM SERVICES AND THE TEMPORAL-SPATIAL DYNAMICS OF LAND USE IN THE PEDRAS RIVER BASIN, SOUTH OF BRAZIL

Pedro Almeida^{1*}, Leandro Redin Vestena¹

¹Universidade Estadual do Centro-Oeste (UNICENTRO), Ln. Élio A. Dalla Vecchia, Guarapuava, 85040-167, Brazil

*Corresponding author: 1912306@unicentro.edu.br

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ABSTRACT. Changes in land use in Brazil, particularly agricultural expansion, have significant impacts on ecosystems and their associated services. This study aimed to evaluate the temporal and spatial dynamics of ecosystem services (ES) in the Pedras River basin (PRB), the main water supply for Guarapuava, southern Brazil, between 2002, 2018 and 2023. The analysis was based on the Ecosystem Services Identification Matrix, integrating land use and land cover (LULC) maps and field observations of environmental and socioeconomic characteristics in the area. This approach allowed the classification and assessment of the potential supply of provisioning, regulating, and cultural ES in the basin. The findings between 2002 and 2018 revealed a general decline in most regulating and cultural services, with notable reductions in genetic resources, local climate regulation, air quality regulation services, and medicinal resources. Conversely, provisioning services related to food provision, energy provision, and soil quality regulation showed increases. Between 2018 and 2023, food provision, water quality regulation, soil quality, and pollination declined, along with decreases in cultural services. In contrast, the increase occurred in water supply, raw materials, genetic resources, ornamental resources (18.16%), and air quality and climate regulation services. Agricultural expansion resulted in a trade-off, increasing food provision while simultaneously degrading other ES. The study emphasizes that sustainable land management is necessary to preserve ecosystem functions and services, thereby preventing the degradation of their potential.

KEYWORDS: spatial analysis, sustainable management, agricultural expansion, trade-off dynamics

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INTRODUCTION

The PRB is the water supply area for the municipality of Guarapuava in the state of Paraná, Brazil. In the PRB, terrestrial ecosystems are associated with the Mixed Ombrophilous Forest (MOF) and aquatic ecosystems with river courses and lakes. They are directly related to land use and occupation since, for example, the removal of vegetation cover for cultivation alters hydrological and biological processes, affecting the balance of the ecosystem. In the PRB, anthropogenic activities cause the degradation of natural habitats, loss of biodiversity, and intensification of erosion processes that affect soil fertility and deteriorate water quality.

The expansion in recent years, mainly of agricultural activities involving soybean plantation, has been requiring new land for planting, causing significant changes in land use and cover to the detriment of areas with tree and shrub vegetation, which occupied 73.37% of the areas in the PRB in 2002 (Vestena et al. 2004). The use of agrochemicals, particularly glyphosate, is associated with intensive agriculture and has been detected in the water sourced from the PRB, often exceeding the safe tolerable limit set by the European Union (Bombardi 2017; Hess 2018; Aggio et al. 2021; Piassetta et al. 2021).

Other anthropogenic actions in the basin that are harmful to the ecosystem include the disposal and release of industrial effluents associated with agricultural activities

¹Aranha, A. and Rocha, L. (2019). "Coquetel" com 27 agrotóxicos foi achado na água de 1 em cada 4 municípios. *Repórter Brasil, Agência Pública*. Available at: <https://reporterbrasil.org.br/2019/04/coquetel-com-27-agrotoxicos-foi-achado-naagua-de-1-em-cada-4-municipios/> [Accessed 23 Jun. 2024].

(Santos and Kobiyama 2003; Teodoro and Santos 2009), intensive logging with the removal of tree vegetation and the intensification of erosion processes (Teodoro and Santos, 2009); the presence of sediment in the water of river courses from crops, roads, and paths (Cunha 2011; Cunha et al. 2013; Cunha et al. 2014; Cunha and Thomaz 2015).

Therefore, land use is a considerable human alteration to the earth's system that modifies the structure and functioning of ecosystems (Vitousek et al. 1997). This process directly threatens ecosystems' capacity to provide ES (Brito et al. 2016).

ES are increasingly used to analyze the interactions between humans and nature, as they represent the contributions of ecosystems to human well-being, resulting from the interaction of biotic and abiotic processes (Costanza et al. 1997; MEA 2005; Benabou et al. 2022). This research adopts the classification proposed by the Millennium Ecosystem Assessment (MEA), which comprises four types of services: provisioning, regulating, cultural, and supporting. As in Githiora-Murimi et al. (2022), supporting services, considered fundamental for the supply of other service categories, were excluded from the analysis to avoid double counting.

The increasing popularity of the concept of ES has led to the development of several assessments and mappings for different contexts and scales (Martínez-Harms and Balvanera 2012). In Brazil, the dissemination of the ES concept is connected to public policy strategies outlined in the National Policy for Payment for Environmental Services (PNPSA), which regulates mechanisms that promote the adoption of conservation-oriented agricultural practices, the restoration and preservation of natural permanent preservation and natural legal reserve areas, as well as the conservation of remnants of native vegetation (Brasil 2021).

In this context, watersheds are the territorial unit established by Brazilian legislation for the planning and management of water resources (Brasil 1997). Additionally,

watersheds or basins provide multiple ES by ensuring a reliable water supply. For this reason, they are frequently used as spatial units for the identification and mapping studies in ES thematic studies, as in the research of Chaves et al. (2021) in the Rio São José, Pernambuco; Hinata and Basso (2022) in the Rio Passo Fundo, Rio Grande do Sul; Sampaio and Bacani (2025) in the Rio Bebedouro, Mato Grosso do Sul; and Simões et al. (2022) in the Rio Paraíba do Sul, São Paulo.

This research aimed to evaluate the temporal and spatial dynamics of ES potential in the PRB, specifically focusing on the years 2002, 2018, and 2023, through the qualitative mapping of potential ES.

MATERIALS AND METHODS

Study area

The PRB has been a water source area for Guarapuava since July 1st, 1974. The basin has an area of 330.42 km² and is located between the coordinates 25°17'55" S 51°16'10" W and 25°28'0" S 51°26'15" W (Fig. 1). The Pedras River is a tributary of the Jordão River, a right-bank tributary of the Iguaçu River, which flows into the Paraná River.

Methodological procedures

The methodological framework for this study was structured in steps, as illustrated in the flowchart (Fig. 2): 1) acquisition and organization of LULC mapping supplemented by field surveys; 2) identification of relevant ES in the area; 3) scoring the ES potential from each LULC type using a matrix; and 4) mapping the ES potential for three periods, 2002, 2018, and 2023.

Research in the field of ES can be either valuation studies, which assign monetary values to ES in various land cover types (Costanza et al. 1997), or socio-cultural studies with methods that can evaluate social values of ES and link them to land cover maps (Iniesta-Arandia et al. 2014).

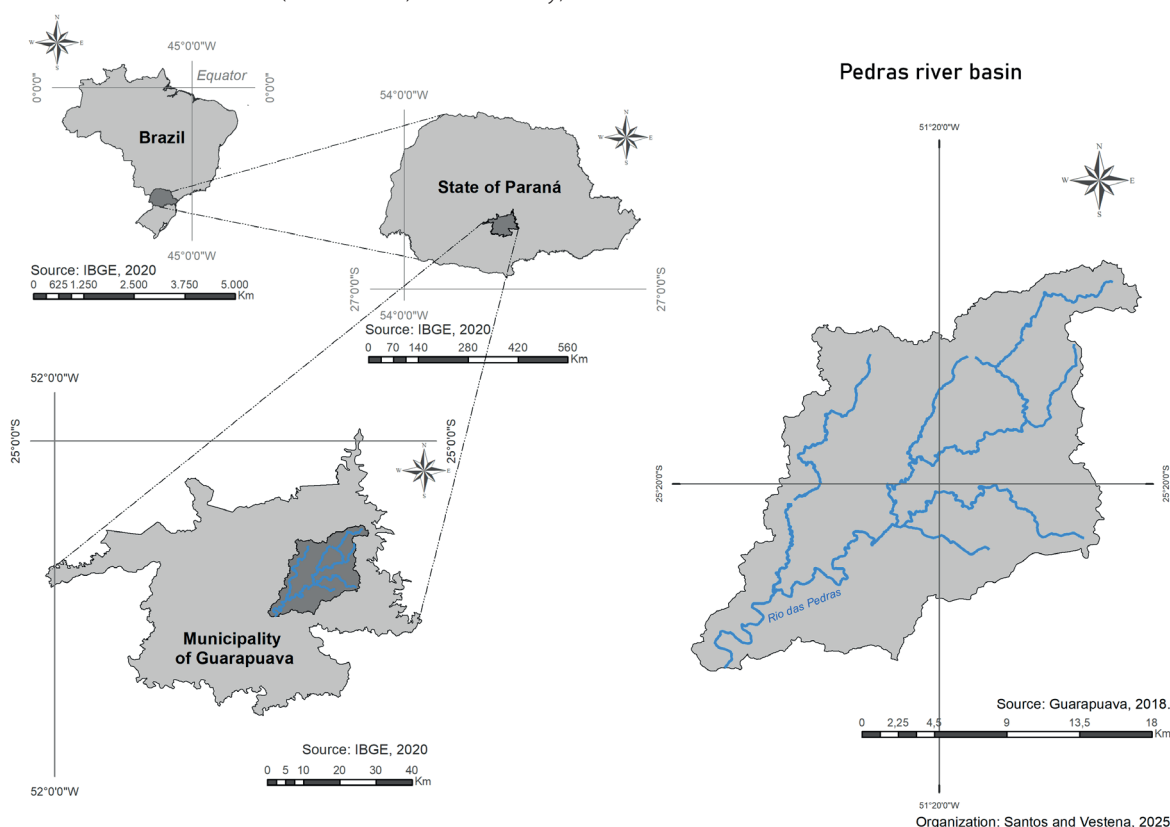


Fig. 1. Study area: the PRB

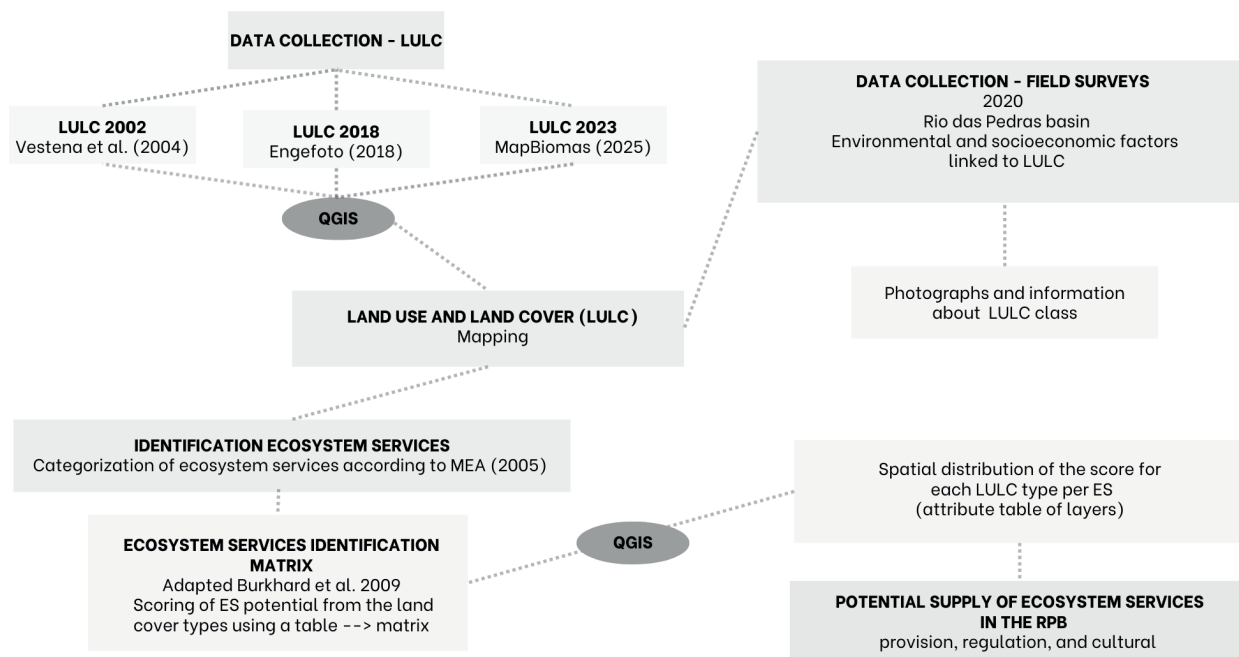


Fig. 2. Methodological flowchart

This study adopted the matrix model developed by Burkhard et al. (2009; 2017), as applied in studies such as Githiora-Murimi et al. (2022) in Kenya and Sohel et al. (2015) in Bangladesh. In this model, the LULC is used as a proxy for ES supply and scored in a table using information from multiple sources combined with a judgment of scores, and the resulting table quantifies the capacity of each class of use to provide ES (Burkhard et al., 2009).

LULC for 2002 (Fig. 3a) were mapped by Vestena et al. (2004), based on a visual interpretation of orthophotos at 1:30,000 scale from an aerial survey conducted in September 2002 (Engefoto; Guarapuava 2003). LULC mapping for 2018 (Fig. 3b) was generated through supervised automatic interpretation and classification of orthorectified images acquired between January and June 2018 by Engefoto (Engefoto; Guarapuava 2018). The classification, symbols, and colors used in the maps are in accordance with the Technical Manual of Land Use of the Brazilian Institute of Geography and Statistics (IBGE, 2013). LULC mapping for 2023 (Fig. 3c) was mapped by MapBiomias at a 1:30,000 scale from collection 9, using annual satellite images (Landsat, Sentinel, and MODIS) processed in Google Earth Engine. The method is based on pixel-by-pixel supervised classification using the Random Forest algorithm, calibrated with reference samples and time series of spectral indices. The process includes mosaicking, temporal filtering, accuracy validation, and thematic integration steps (MapBiomias 2025). In addition, we made a reclassification to merge and simplify similar classes of farming uses (temporary and perennial crops).

Field surveys conducted in 2020 aimed to identify environmental and socioeconomic characteristics associated with different LULC classes of the PRB. This information was crucial for validating LULC classification and informing the ES scoring process.

Ecosystem service scores were tailored to the specific classification detail of the 2002, 2018, and 2023 LULC datasets to mitigate discrepancies in data sources. This approach involved underestimating potential values where necessary to prevent the overrepresentation of functions, thereby respecting the internal variability of each class over time. The assessment of ES was performed based on functionally equivalent LULC groups, using LULC as proxies for ES provision, as proposed by Burkhard et al. (2009; 2017).

The qualitative mapping of LULC provides an important basis for identifying ES using the Ecosystem Services Identification Matrix. The matrix structure with an X and Y axis was constructed for each year analyzed, linking the LULC classes mapped in the area (Y axis) with the ES (X axis), which were categorized into provisioning, regulating, and cultural services, following the MEA (2005) framework.

Once the matrix was built, each ES was assigned a score representing its potential supply, classified on a scale from 0 to 5. A value on the scale of "0" represents no relevant potential for ES in a given use class, "1" very low potential, "2" low potential, "3" medium potential, "4" high potential, and "5" maximum potential for providing ES (Burkhard and Maes 2017).

Scores were assigned based on field survey observations, like in Githiora-Murimi et al. (2022), and a synthesis of information from academic literature and government data about the characteristics of the PRB, described in IBGE, 2002; Vestena et al. 2004; Donatti et al. 2004; Vestena e Thomaz 2006; IBGE 2018; Paraná 2019; Favaro et al. 2020.

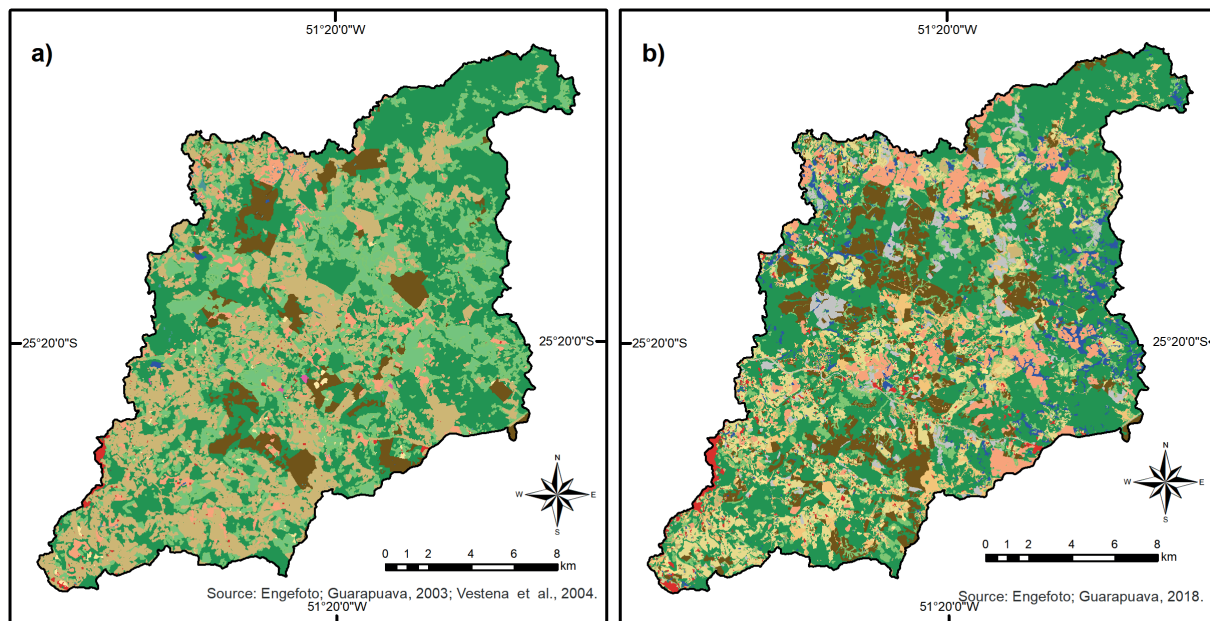
The spatial mapping of ES potential for provisioning, regulating, and cultural services was performed in QGIS. As proposed by Burkhard et al. (2012), the matrix scores were integrated into the LULC vector maps by joining them to the attribute table of each LULC polygon. For each period, 2002, 2018, and 2023, a new field was created for each individual ES, and the corresponding score (0-5) was assigned to each LULC class. This resulted in a set of maps illustrating the spatial distribution of the ES potential in the PRB for the three years.

RESULTS AND DISCUSSION

Ecosystem properties define the potential for providing ES (Bastian et al. 2012). The potential for ES can be obtained using different indicators, which can be ecological, social, and economic (Zhen and Routray 2003). These indicators were used to weight the potential values for ES.

The matrix with the estimated values of the relationship between land use, land cover, and potential ES in 2002, 2018, and 2023 is summarized in Tables 1, 2, and 3.

The scores established from the matrix were spatialized to generate summary maps for the years 2002, 2018, and 2023, representing the spatio-temporal dynamics of ES potential in the study area (Fig. 4).

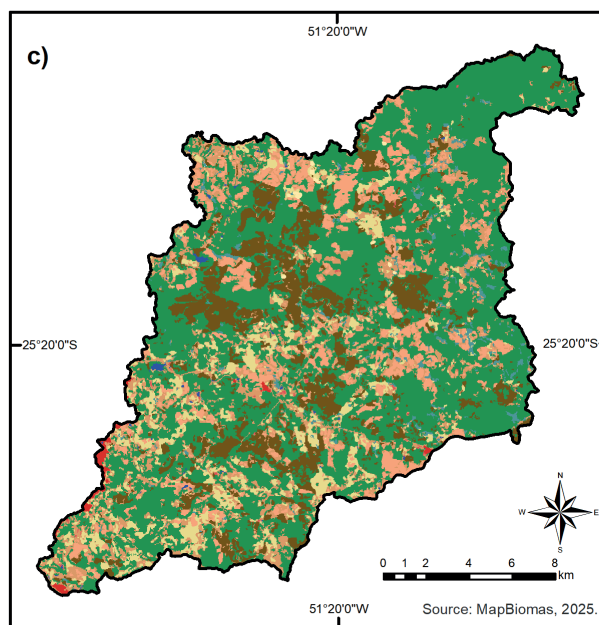


Legend:

- Forest
- Capoeira
- Reforestation/forestation
- Grassland
- Traditional agriculture
- Mechanized agriculture
- Mining
- Industrial area
- Urban/built-up area
- Urban/built-up area
- Garbage dump
- Water bodies
- Flooded/wetland area

Legend:

- Forest
- Capoeira
- Reforestation
- Shrubby Grassland
- Open Grassland
- Traditional agriculture
- Mechanized agriculture
- Cultivated pasture
- Native pasture
- Exposed soil
- Urbanized areas
- Water bodies/Flooded/wetland area



Legend:

- Forest Formation
- Forest Plantation
- Perennial Crops
- Temporary Crop
- Pasture
- Mosaic of Uses
- Other non-Vegetated Areas
- Urban Area
- Wetland
- River, Lake

Organization: Santos and Vestena, 2025

Fig. 3. LULC mapping of the PRB for (a) 2002, (b) 2018 and (c) 2023

Table 1. Matrix of ES by LULC classes (2002)

LULC*	Ecosystem Services															
	Provisioning							Regulation					Cultural			
	Food	Water Supply	Raw Materials	Genetic resources	Medicinal resources	Ornamental resources	Energy	Air quality regulation	Local climate regulation	Water quality regulation	Soil quality regulation	Pollination	Recreation and leisure	Educational value	Inspiration for art and design	Tourism
U1	4	5	4	5	5	5	4	5	5	5	5	5	4	5	5	4
U2	5	0	0	3	0	0	0	2	1	1	0	1	1	1	0	1
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	5	0	4	4	0	0	0	0	0	0	1	2	0	5	1	0
U5	0	4	0	4	4	0	0	4	4	4	4	5	3	4	3	0
U6	5	5	0	0	0	0	4	5	5	5	5	0	5	5	5	5
U7	0	0	0	0	0	5	0	0	0	0	0	0	0	5	0	0
U8	0	5	0	0	0	0	0	5	5	5	5	2	0	4	0	0
U9	5	0	0	4	4	0	0	4	4	4	4	5	4	5	0	5
U10	3	3	5	0	0	0	5	3	2	1	1	2	0	5	0	0
U11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Not relevant potential
 Low potential
 High potential
 Very low potential
 Medium potential
 Maximum potential

*Land uses: U1 Forest; U2 Grassland; U3 Urban/built-up area; U4 Mechanized agriculture; U5 Capoeira¹; U6 Water bodies; U7 Mining; U8 Flooded/wetland area; U9 Traditional agriculture; U10 Reforestation/forestation; U11 Industrial area; U12 Garbage dump. Organization: Authors (2021).

¹Note: "Capoeira" is a Brazilian Portuguese term for secondary vegetation that grows after the suppression of primary forest, typically characterized by shrubs and young trees.

Table 2. Matrix of ES by LULC classes (2018)

LULC*	Ecosystem Services															
	Provisioning							Regulation					Cultural			
	Food	Water Supply	Raw Materials	Genetic resources	Medicinal resources	Ornamental resources	Energy	Air quality regulation	Local climate regulation	Water quality regulation	Soil quality regulation	Pollination	Recreation and leisure	Educational value	Inspiration for art and design	Tourism
U1	4	5	4	5	5	5	4	5	5	5	5	5	4	5	5	4
U2	0	0	0	0	0	0	0	0	0	2	1	1	0	1	0	0
U3	0	3	0	0	0	0	0	0	0	3	3	4	0	1	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	5	0	5	5	1	0	0	0	0	0	1	2	0	5	1	0
U6	5	0	0	5	5	0	5	3	3	4	3	5	4	5	2	5
U7	0	4	0	4	4	0	0	4	4	4	4	5	3	4	3	0
U8	5	0	0	0	0	0	0	0	0	1	1	1	0	4	0	0
U9	5	1	0	0	0	0	0	0	0	4	3	2	0	3	0	0
U10	3	0	5	0	0	0	5	4	4	3	3	4	0	5	1	0
U11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U12	1	5	0	0	1	0	0	5	5	5	5	3	0	4	0	0

Not relevant potential
 Low potential
 High potential
 Very low potential
 Medium potential
 Maximum potential

*Land uses: U1 Forest; U2 Open Grassland; U3 Shrubby Grassland; U4 Urbanized areas; U5 Mechanized agriculture; U6 Traditional agriculture; U7 Capoeira¹; U8 Cultivated pasture; U9 Native pasture; U10 Reforestation; U11 Exposed soil; U12 Flooded/wetland area. Organization: Authors (2021).

¹Note: "Capoeira" is a Brazilian Portuguese term for secondary vegetation that grows after the suppression of primary forest, typically characterized by shrubs and young trees.

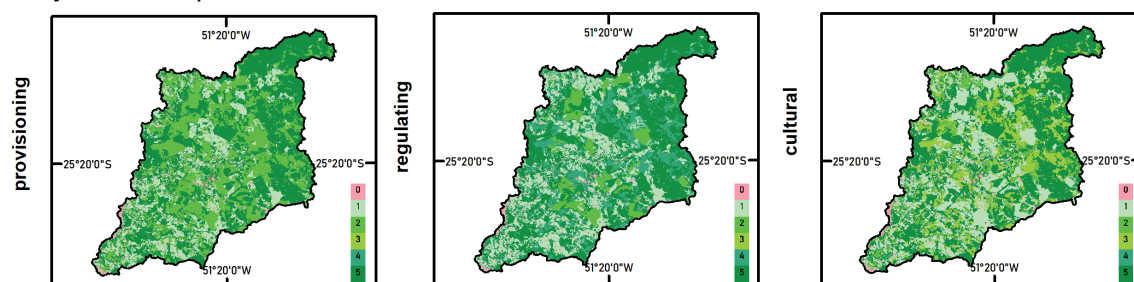
Table 3. Matrix of ES by LULC classes (2023)

LULC*	Ecosystem Services															
	Provisioning							Regulation					Cultural			
	Food	Water Supply	Raw Materials	Genetic resources	Medicinal resources	Ornamental resources	Energy	Air quality regulation	Local climate regulation	Water quality regulation	Soil quality regulation	Pollination	Recreation and leisure	Educational value	Inspiration for art and design	Tourism
U1	4	5	5	5	5	5	4	5	5	5	5	5	4	5	5	4
U2	2	2	3	0	0	1	4	2	2	0	0	0	0	4	0	0
U3	0	3	0	3	1	0	0	2	2	2	2	2	0	1	0	0
U4	0	0	3	0	0	4	0	0	0	0	0	0	0	0	0	0
U5	4	0	3	2	0	0	0	0	0	1	0	0	0	1	0	0
U6	4	0	3	2	4	0	4	2	2	2	2	3	4	4	4	4
U7	4	0	3	2	0	0	0	0	0	0	0	1	0	4	0	0
U8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U9	4	5	0	5	0	0	4	4	4	4	4	0	4	4	4	4
U10	0	4	0	0	0	0	0	4	4	4	4	0	0	4	0	0

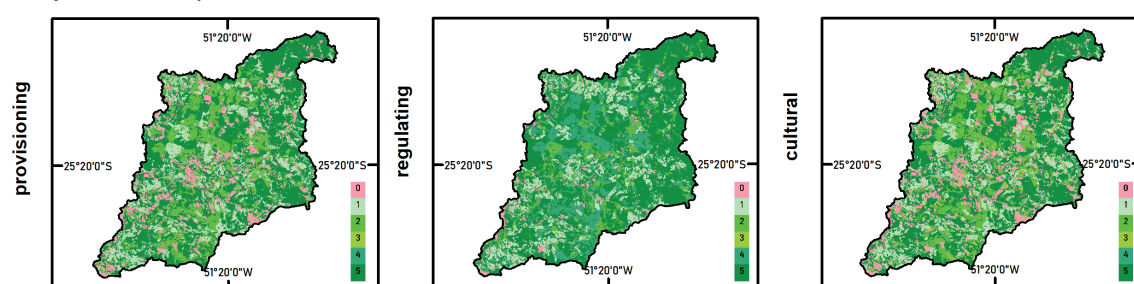
■ Not relevant potential
 ■ Low potential
 ■ High potential
■ Very low potential
 ■ Medium potential
 ■ Maximum potential

*Land uses: U1 Forest formation; U2 Forest plantation; U3 Mosaic of uses; U4 Other non-vegetated Areas; U5 Pasture; U6 Perennial Crop; U7 Temporary Crop; U8 Urban Area; U9 River and lakes; U10 Wetland. Organization: Authors (2025).

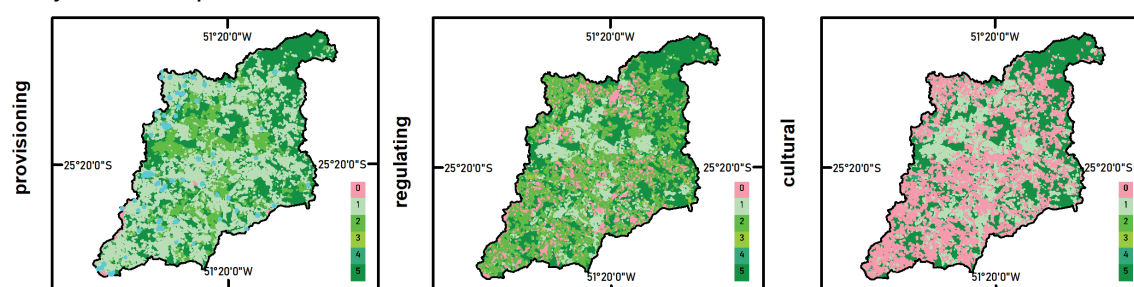
Ecosystem services potential in 2002



Ecosystem services potential in 2018



Ecosystem services potential in 2023



Organization: Santos and Vestena, 2025.

Fig. 4. Spatial distribution of ES potential (provisioning, regulating, and cultural) in the PRB for the years 2002, 2018 and 2023

The evolution of the dynamics of ES in the PRB in 2002 and 2018 (Table 3) showed significant decreases, especially in ES of genetic resources provision (-30.37) and medicinal resources (-3.86); the ES of air quality regulation (-22.16), local climate regulation (-22.16), water (-2.46) and pollination (-8.32); and decreases in all classes of cultural ES. It is noteworthy that there was a significant increase in the ES of soil quality regulation (14.27), and in the provision of food (6.04) and energy (5.24). Between 2018 and 2023 (Table 3), there was a decrease in the ES of food provision (-2.82), water quality regulation (-12.23), soil quality regulation (-11.40), and pollination (-13.36), as well as reductions in the cultural ES of inspiration for art and design (-17.12) and recreation and leisure (-1.02). In contrast, there was a significant increase in the ES of water supply (16.13), raw and other materials (17.67), genetic resources (24.86), ornamental resources (18.16), air quality regulation (13.82), and local climate regulation (13.82).

The increase in the potential for ES of *provision of food* in 2002 and 2018 is related to the increase in areas where animal husbandry, cultivation, and forest areas occur. Although the decrease in the potential for food provision in 2023 can be attributed to land use shifts, for instance, in several portions of the basin, traditional and diversified agricultural areas typically associated with higher food provision potential were replaced by mechanized monocultures or temporarily converted to other production systems. The production of commodities (soy, wheat and corn) in a mechanized agricultural area is part of a low-cost food system that does not promote food security and provides low monetary compensation for rural workers (Pereira et al. 2020).

It is important to emphasize that in animal husbandry and intensive agricultural production, there is a conflict situation or *trade-off* with regulatory services because in these areas there is the use of pesticides, chemical

Table 4. Dynamics of ES in the PRB (%) between 2002–2018 and 2018–2023

ES	ES class	Area (ha)* 2002	Percentage of total area of PRB 2002 (%) **	Area (ha) 2018*	Percentage of total PRB area in 2018 (%)**	Change in potential area 2002 – 2018 (%)	Area (ha)* 2023	Percentage of total PRB area in 2023 (%)**	Change in potential area 2018 – 2023 (%)
Provisioning	Food	263,58	79,7	283,53	85.81	6.04	274.19	82.99	-2.82
	Water supply	219.96	66.5	223.34	67.60	1.02	276.63	83.73	16.13
	Raw materials and other materials	203.86	61.7	215.35	65.18	3.48	273.74	82.85	17.67
	Genetic resources	295.5	89.4	195.17	59.07	-30.37	277.31	83.93	24.86
	Medicinal resources	219.47	66.4	206.71	62.56	-3.86	224.92	68.08	5.52
	Ornamental resources	157.14	47.5	162.16	49.08	1.52	222.17	67.24	18.16
	Energy	184.5	55.8	201.8	61.08	5.24	222.73	67.41	6.33
Regulation	Air quality regulation	304.29	92.1	231.08	69.94	-22.16	276.74	83.76	13.82
	Local climate regulation	304.29	92.1	231.08	69.94	-22.16	276.74	83.76	13.82
	Water quality regulation	304.29	92.1	296.16	89.64	-2.46	255.75	77.41	-12.23
	Soil quality regulation	249.01	75.3	296.16	89.64	14.27	258.51	78.24	-11.4
	Pollination	323.65	97.9	296.16	89.64	-8.32	252.03	76.28	-13.36
Cultural	Recreation and Leisure	276.14	83.5	180.76	54.71	-28.87	177.39	53.69	-1.02
	Educational values	325.07	98.3	296.16	89.64	-8.32	328.20	99.33	9.69
	Inspiration for art and design	238.56	72.20	233.95	70.81	-1.40	177.39	53.69	-17.12
	Tourism	216.83	65.63	163.02	49.34	-16.29	177.39	53.69	4.35

Note: *Area in hectares corresponding to the sum of the land use and cover classes relative to the potential for ES. **Percentage of ES concerning the total area of the PRB (330.42 ha).

fertilizers, and antibiotics, which leads to possible long-term declines in human well-being due to the alteration of the functioning or balance of the ecosystem (Foley et al. 2005). It is necessary to analyze strategies to reduce these conflicting situations in agricultural production.

The effects of intensive agriculture, which is constantly expanding, are harmful to human well-being and to the *food supply* in the future. In Brazil, it is already possible to see some of the effects of climate change on agriculture, such as reduced productivity due mainly to rising temperatures and extreme weather events such as precipitation and droughts, which are occurring with increasing intensity and frequency (Jägermeyr et al. 2021; IPCC 2021).

Traditional and subsistence agriculture, as well as organic food production practices, have decreased in the PRB. This decline is driven by public policies that mandate pesticide use as a condition for accessing agricultural credit (Favaro et al. 2020). In addition, squatters and owners of small properties face problems such as land concentration and conflicts over land, possession, use, and ownership through resistance and confrontation (CPT 2018).

Despite this, traditional agriculture has the greatest potential for *food supply*, as it is responsible for approximately 1/5 of the planet's food production. Traditional farmers interact directly with the benefits generated by the ecosystem and are aware of the importance of biodiversity, the preservation of springs and hillsides, Permanent Preservation Areas, and Legal Reserves, as they are more directly connected to the land and the causes and consequences of actions in ecosystems.

Agrosystems in general, when combined with agroecology, can provide sustainable food production, allowing for a synergistic relationship between other ES. Sustainable land management practices can help reconcile agricultural production with the maintenance of ES.

In the Brazilian context, sustainable land management practices have emerged, for example, integrated Crop–Livestock–Forestry (ICLF), no-till farming, and crop rotation. In the integrated ICLF systems, the productive arrangements combine agriculture, livestock, and forestry through intercropping, rotation, or succession. These systems optimize land use, enhance soil and water conservation, promote biodiversity, and contribute to carbon sequestration, being widely implemented in degraded and non-degraded pasturelands (Balbino et al. 2012; Skorupa and Manzatto 2019; Leite et al. 2023; Marchão et al. 2024). The no-till farming practice is based on permanent soil cover, absence of plowing, and diversification of cropping systems, including cover crops. It reduces erosion, improves soil quality, and increases resilience to climatic variability (Mello and Van Raij 2006), is integrated with the crop rotation, enhances physical, chemical, and biological soil conditions, diversifies production, and reduces both climatic and market risks (Franchini et al. 2011).

In forested areas, the potential food supply does not affect the other ESs due to the synergy between them, with food being extracted in a controlled manner, as is the case with the harvesting, sale, transportation, and storage of ripe pine nuts, which takes place with the permission of the IAT (Instituto Água e Terra – is the Water and Land Institute of Paraná State).²

The increase in areas with vegetation cover, which favors the *water supply*, directly helps regulate the river regime and water quality. However, the importance of sustainable practices in cultivated areas stands out, as they

have vegetation cover and, even temporarily, can cause trade-offs with the ES.

The supply of *raw materials and other materials* has increased due to the expansion of reforestation/afforestation and forest areas, which largely provide this type of ES. As well as the potential for *energy supply*, which is primarily associated with vegetation. However, in these areas, there is a conflicting situation or trade-off, since intensive logging can affect the ES that regulates soil, air, and water quality due to the impacts of removing and transporting materials. Even if the structure of the forest is not altered by the exploitation of raw materials such as wood, there is degradation in the forest productivity, biomass, and biodiversity, as well as the introduction of pests and pathogens (Folley et al. 2005).

Despite the expansion of forest areas, the increase in 2023 in the ES of the *supply of genetic* and medicinal resources is linked to the total vegetated area and to the diversification of land-cover types that contribute to these functions. Early-successional mosaics, such as capoeira, can temporarily elevate the availability of genetic resources. In addition, the persistence of small patches of traditional agriculture and secondary vegetation maintains species used for medicinal purposes that tend to disappear under intensive mechanized agriculture. Thus, even with reductions in some capoeira areas, the structural diversification of the landscape and the presence of regenerating vegetation contributed to the increase in the potential supply of genetic and medicinal resources.

The *soil quality regulation* ES increased between 2002 and 2018 but declined in 2023. This shift is linked to the expansion of mechanized agriculture and pasturelands, introducing trade-off dynamics. While vegetation in these areas offers some protection against precipitation-driven erosion, other practices, such as intensive machinery use and animal trampling, accelerate soil disaggregation and erosion processes, ultimately reducing the system's regulating capacity.

The *local climate regulation* service had a decrease related to agricultural expansion in the PRB, reiterating that these activities are highly degrading and lead to a decrease in synergy between ES, mainly due to soil and water pollution, loss of biodiversity, soil erosion, decrease in carbon stocks, deforestation, and forest fragmentation (Vestena and Thomaz 2006; Pessoa et al. 2020; Polidoro et al. 2020; Kumi et al. 2021). Despite the overall degradation pressures, the *climate regulation service* shows an increase in 2023 due to the role of regenerating vegetation and soil-based carbon recovery processes. Even though capoeira areas were reduced compared to previous years, the remaining secondary vegetation patches, and the increase in forest formations continued to accumulate biomass and organic matter.

Vegetation and soil are responsible for most of the carbon storage and organic matter stocks, which contribute to climate regulation (Machado 2005; Uzeda 2020). The degrading activities' expansion reduces vegetation cover and increases impervious areas, affecting the regional climate through changes in net radiation and energy flow in the soil (which make up the energy balance in the interaction between soil and atmosphere) and the water balance (Foley et al. 2005).

In the years mapped, capoeira areas were reduced to a large extent and were replaced by mechanized agriculture. This fact makes it important to protect secondary

²IAT libera colheita e venda do pinhão em todo o Paraná, mas com exigência de maturação. Agência Estadual de notícias. Available at: <https://www.aen.pr.gov.br/Noticia/IAT-libera-colheita-e-venda-do-pinhao-em-todo-o-Parana-mas-com-exigencia-de-maturacao> [Accessed 10 Apr. 2024].

vegetation, as it is resilient, easily regenerates, mitigates climate change, and conserves biodiversity. In some cases, it sequesters around eleven times more carbon than vegetation in advanced stages of regeneration and preservation and provides other ES such as the provision of water, energy, and raw materials. It can also contribute to restoring ecosystems and improving environmental conditions (Poorter et al. 2016; 2021).

Air quality regulation has also seen a significant decrease due to changes in land use related to anthropogenic activities, which, through various sources of pollution such as dust particles and other particulate matter, nitrous oxide emission from the use of agrochemicals (inorganic fertilizers), methane emissions from livestock, pollution from pesticide spraying, the burning of biomass, and the emission of polluting gases from vehicles, alter atmospheric conditions and consequently air quality (Folley et al. 2005; Miller Junior 2011). The 2023 mapping shows an increase in *air quality regulation* in ES, driven by localized gains in vegetation cover, particularly the expansion of forest formations and young secondary vegetation. Although these improvements do not fully counterbalance pollution sources, they generate a measurable enhancement in air quality regulation relative to previous years.

Water quality regulation is related to forest ecosystems, such as natural and planted forests and riparian forests (Rares and Brandimarte 2014). The reduction of this regulatory ES necessitates attention to preserving areas with vegetation cover, which must be distributed along the entire length of the watershed to maintain its functions, primarily in regulating biogeochemical cycles, water and nutrient flow, reducing erosion, and purifying water (Tundisi and Matsumura-Tundisi 2010; Adas et al. 2020). Water quality is degraded depending on the dynamics of land use. Furthermore, the expansion of intensive agriculture tends to increase erosion and sediment load and release nutrients and pesticides into groundwater, streams, and rivers (Folley et al. 2005). It is noteworthy that the water that supplies the municipality of Guarapuava comes from the PRB and has been contaminated by pesticides (Aggio et al. 2021; Piasseta et al. 2021).

The decline observed in *water quality regulation* in 2023 is associated with a different pattern of land use and vegetation structure. Although the area of forest formations and mosaic land-use classes increased, these mosaics consist of agro-pastoral and peri-urban mixtures where pastures, croplands, and fallow fields are interspersed with secondary vegetation at early successional stages. These transitional environments lack the structural complexity, continuous canopy cover, and well-developed root systems characteristic of mature forests, which are essential for filtering sediments, retaining nutrients, stabilizing soils, and regulating biogeochemical processes (Cui et al. 2020).

The *soil quality regulation* ES increased between 2002 and 2018 concerning the other regulating ES because of the increase in areas with vegetation cover. However, the 2023 mapping shows that the soil regulation has decreased, so the apparent increase in vegetated area does not translate into improved regulating functions. Instead, the replacement or fragmentation of mature forests exacerbated by agricultural pressures in surrounding transitional zones reduces the landscape's capacity to control erosion (Cui et al. 2020). In addition, the ongoing expansion of the PRB and the degrading potential of

agroforestry or agricultural activities that do not incorporate soil conservation practices further intensify this decline (Miller Junior 2011).

The results indicated a decrease in *pollination potential*, mainly related to the replacement of native vegetation in areas by intense agriculture, which leads to a decline in *natural habitats* for pollinators, the increased use of pesticides, a decrease in floral resources, an increase in monocultures, and the intensive use of soil and water (Imperatriz-Fonseca 2004).

Pollinators are essential components for the functioning of ecosystems, and consequently, human food depends on pollination, so it is important to adopt the controlled use of agrochemicals and pesticides, land preparation practices that protect the nests of bees that occur in the soil, the maintenance of native vegetation edges, and living fences, and the reduced use of herbicides because some species of ruderal plants also provide resources for pollinators (Imperatriz-Fonseca 2004; FAO 2004).

The increase in educational values and tourism is attributed to a qualitative, rather than quantitative, shift in land-use practices within the basin. Although the areas historically associated with these cultural activities, such as traditional agriculture, declined, this loss was counterbalanced by the growth of environmental education initiatives, outreach programs, and revitalization projects. Consequently, the cultural tourism ES was either maintained or, in certain areas, expanded, supported by the diversification of rural recreational practices.

CONCLUSIONS

This study demonstrates that LULC changes in the PRB between 2002, 2018 and 2023 are directly associated with shifts in ES potential. While the expansion of anthropogenic activities, including mechanized agriculture and increased provisioning services (such as food and energy), these gains occurred alongside critical trade-offs, such as intensified soil erosion, forest fragmentation, and biodiversity loss. These dynamics in the PRB indicate that increases in vegetated areas are insufficient to ensure the integrity of ecosystem functions.

The matrix-based approach used in this study relies on LULC classes as proxies for ES potential. To account for discrepancies between LULC mappings, ES scores were assigned relative to each specific year, considering their respective scales and levels of generalization. Consequently, the results represent relative potentials that, while year-specific, allow for an evaluation of temporal and spatial trends. Thus, the observed changes reflect both land-use dynamics and the inherent specificities of the datasets used.

Our findings emphasize the need to implement integrated strategies and multi-level governance to promote sustainable land management. Future research should prioritize harmonized LULC classifications, integrate quantitative biophysical indicators with socio-economic data, and incorporate participatory approaches to better capture ES demand and access. We recommend developing monitoring protocols integrated into constantly updated databases to facilitate ES valuation. Such an approach would enable long-term management decisions on land use and ecosystems to safeguard human well-being for current and future generations. ■

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