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Integration vs. Segregation: Can Autochthonous Silvopastoral Systems Enhance Economic Viability and Ecological Functionality of the Brazilian Cerrado?

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INTEGRATION VS. SEGREGATION: CAN AUTOCHTHONOUS SILVOPASTORAL SYSTEMS ENHANCE ECONOMIC VIABILITY AND ECOLOGICAL FUNCTIONALITY OF THE BRAZILIAN CERRADO?

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ABSTRACT

The Brazilian Cerrado, a global biodiversity hotspot, faces severe threats from agricultural and livestock expansion. This study explores autochthonous silvopastoral systems (SPS) as a strategy to enhance ecosystem services (ES) in the Cerrado landscape. We mapped the potential for expanding SPS and compared the Potential for Conservationist Use (PCU) scenario to a Business-as-Usual (BaU) scenario in the Upper Pardo River basin, Brazil. Overall, soil and slope conditions are favorable, whereas low annual water yield limits productive land use in 23.9% of the land. Results confirm that SPS adoption in high-suitability land cover types – such as savanna formations, perennial crops, and forest plantations – is a viable strategy to enhance ES and promote sustainable land use. Under the BaU scenario, native vegetation covered 66.1% of the study area and 89.5% of total economic output (~USD 1.46 billion/year) was derived from ES provision. SPS expansion in the PCU scenario reduced native vegetation cover to 40.8%, yielding higher economic output (~USD 1.53 billion/year), with ES accounting for 81.2% of the total. These results demonstrate that SPS can enhance multifunctionality and economic output when targeted to suitable landscapes, underscoring the importance of spatial planning and supporting public policies, such as payment for ES.

Keywords: Agroforestry systems; Land degradation; Ecosystem services; Public policies.

1. INTRODUCTION

Land use/cover change and climate change are two critical planetary boundaries that have been surpassed, causing shifts in biomes across the globe (Sakschewski *et al.*, 2025). Among the affected ecosystems, savannas are experiencing significant losses in the spatial extent of their native vegetation and associated ecosystem services (ES) due to land degradation and conversion, making them more susceptible to climate change impacts while driving declines in biodiversity and ecosystem functioning on a global scale (Balima *et al.*, 2020; Leite-Filho *et al.*, 2024).

With 2 million km², the Brazilian Cerrado covers 22% of Brazil's territory, representing the largest Neotropical savanna globally (Durigan *et al.*, 2022). It is the world's species-richest savanna and a global biodiversity hotspot (Myers *et al.*, 2000; Borgiani *et al.*, 2022). It harbours over 12,000 plant species, of which 35% are endemic (Zappi *et al.*, 2015). It also plays a key role in climate mitigation as it stores up to 5.5 billion Mg of carbon (Lahsen, Bustamante and Dalla-Nora, 2016).

The Cerrado biome has been impacted by massive land use changes and intensification over the past century, primarily through the conversion of native vegetation into agriculture and pasture lands (Noojipady *et al.*, 2017). The original vegetation cover shrunk by almost 50% in the last three decades, resulting into deforestation rates higher than in any other part of Brazil (MapBiomas Project, 2023). As currently only 3% of the Cerrado is fully protected (CNUC/MMA, 2019), the viability of strict protection-based conservation models in the region is put into question sparking debate over the effectiveness of land-sparing versus land-sharing strategies in highly productive or contested landscapes (Pompeu et al. 2018). While land sparing typically relies on setting aside large, strictly conserved areas to offset intensive land use elsewhere (Duarte *et al*., 2016), land sharing is a strategy that aims to integrate biodiversity conservation within multifunctional, human-used landscapes (Borlaug 2002; Green et al. 2005). Though both strategies are essential and can be used as complementary strategies to protect biodiversity, ensure ecosystem services, and local people's livelihood (Scariot, 2013), land sharing has gained increasing relevance in the context of the Cerrado, where regional infrastructural and participative governance plays a strong role (Sales-Baptista & Ferraz-de-Oliveira, 2021).

Pastures cover 28% of the Cerrado landscape and produce 55% of all Brazilian cattle (Parente *et al.*, 2017). However, improper pasture management often leads to land degradation, reducing soil fertility and vegetation cover, resulting in the abandonment of degraded pastures (Hoffmann *et al.*, 2016). This abandonment drives further pasture

expansion into native vegetation areas to compensate for declining yields, a process that is often more economically attractive than investing in sustainable pasture management (Sales-Baptista and Ferraz-de-Oliveira, 2021), thereby perpetuating a cycle of degradation and expansion. Currently, 46% of the pasture lands in the Cerrado are degraded with low beef productivity (Pereira et al., 2018), highlighting the need for more sustainable landscape planning and management practices to reduce the environmental impacts of cattle production in the Cerrado.

Autochthonous silvopastoral systems (SPS) that integrate native trees of the natural Cerrado vegetation with livestock production emerge as a more sustainable alternative, which can better conserve biodiversity and maintain essential ES than current land management (Bruziguessi *et al.*, 2021). In the traditional communities of the Cerrado, SPS exemplify a culturally embedded form of land-sharing, in which ecological intensification and traditional knowledge support sustainable livestock production alongside biodiversity conservation (Lima *et al*., 2017; Lima *et al*., 2022). While SPS can help align conservation goals with productive use, restore degraded pastures and reduce pressure on the remaining native vegetation, the economic evidence concerning SPS remains mixed, with studies reporting contrasting results regarding their profitability and long-term viability under current market conditions (Plieninger and Huntsinger, 2018; Agethen et al., 2024).

In addition, further information gaps exist regarding the management of these systems, discouraging farmers from adopting SPS and restricting their broader implementation. Moreover, the spatial distribution, environmental potential, and capacity of these traditional systems to support sustainable land use have not yet been systematically analyzed, leaving significant gaps in understanding where SPS could be prioritized to promote conservation and sustainable management in the Cerrado. We assessed the potential for expanding SPS through mapping and identifying respective priority zones and determined the potential total economic output generated in a conservationist use (PCU) scenario and compared it to a Business-as-Usual (BaU) scenario.. Hence, our study involves estimating and mapping carbon storage, annual water yield, and habitat quality of different land uses, while also evaluating the potential for conservationist use (PCU) based on environmental attributes. Additionally, we estimate the economic outcomes of production activities and the value of ES provided under current land-use and the PCU scenarios. Our study aims to answer the following questions: i) Which characteristics make land most suitable for conservationist use through autochthonous SPS adoption?; ii) Where are the priority zones for land-

use/land-cover transition to SPS located?; and iii) What is the difference in economic output between the current land-use/land-cover (LULC) distribution and the PCU scenario?

2. MATERIAL AND METHODS

2.1. Study Site

This study took place in the *Alto Rio Pardo* (Upper Pardo River) basin, which includes the Pardo river headwaters and the São João do Paraíso sub-basin, in the northern region of the state of Minas Gerais, in the eastern part of the Cerrado biome, Brazil (Figure 1). It encompasses a total area of 809,848 hectares and includes seven municipalities (IBGE, 2019).

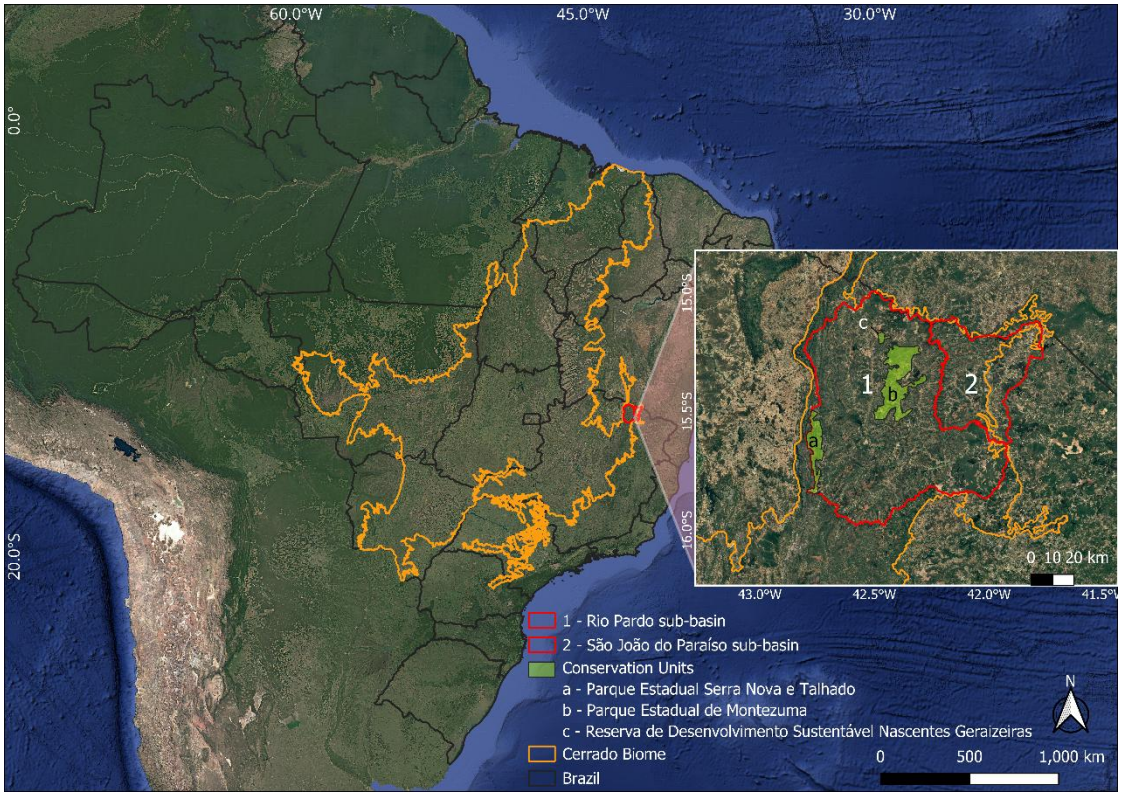


Figure 1: Study area encompassing the *Alto Rio Pardo* River basin, including Pardo River headwaters and São João do Paraiso sub-basin in the northern region Minas Gerais, Brazil.

The region is characterized by Cerrado plant physiognomies, including Cerrado *stricto sensu*, Seasonal Deciduous Forest (montane and submontane), and Vereda (palm swamps). In addition, some areas of Caatinga and transition zones between Cerrado and Caatinga also occur (Carvalho et al., 2009).

155 The predominant climate in the study area is semi-humid tropical with patches of semi-
156 arid conditions, featuring two defined seasons: a wet season and a dry season (Bethonico,
157 2009). The average annual temperature is 24°C, approximately 20.4°C in the coldest months
158 (June and July) and 25.5°C in the hottest month (October) (Lopes dos Santos *et al.*, 2021).
159 The predominant soils are Cambisols, Ferralsols, and Arenosols, with the presence of
160 Acrisols and Plinthosols (dos Santos *et al.*, 2011). The topography is a mix of mountainous
161 areas and flat plains, with plateaus, valleys, and hills. The altitude ranges from 500 to 1,000
162 meters a.s.l. The heterogeneous topography determines land use, water availability, and
163 agricultural practices, and contributes to the high levels of plant endemism.

164 ### *2.2. Data source*

165 #### *2.2.1. Soil and topography variables*

166 The soil class data for Minas Gerais were obtained at a scale of 1:650,000 (UFV *et al.*,
167 2010). This dataset provides a spatial representation of soil types across the state as defined
168 by the Brazilian Soil Classification System (Santos *et al.*, 2018). Drainage, texture, effective
169 depth, and fertility data were obtained from soil classification literature (Costa *et al.*, 2022).
170 Slope data was retrieved from the Shuttle Radar Topography Mission (SRTM) elevation
171 model and categorized as: flat (0 to 3%), gently sloping to undulating (3 to 8%), undulating
172 to rolling (8 to 20%), rolling to moderately steep (20 to 45%), and steep (> 45%) (Mucida
173 *et al.*, 2023).

174

175 #### *2.2.2. Land-use/Land-cover classification*

176 The 2022 LULC classification provided by MapBiomas Collection 8 (MapBiomas
177 Project, 2023) was used to map and estimate carbon stocks, annual water yield, and habitat
178 quality in the study area. The LULC map presented 13 classes in the region (Figure 2) and
179 constituted the BaU reference scenario against which the PCU map was compared to
180 identify priority zones for SPS adoption.

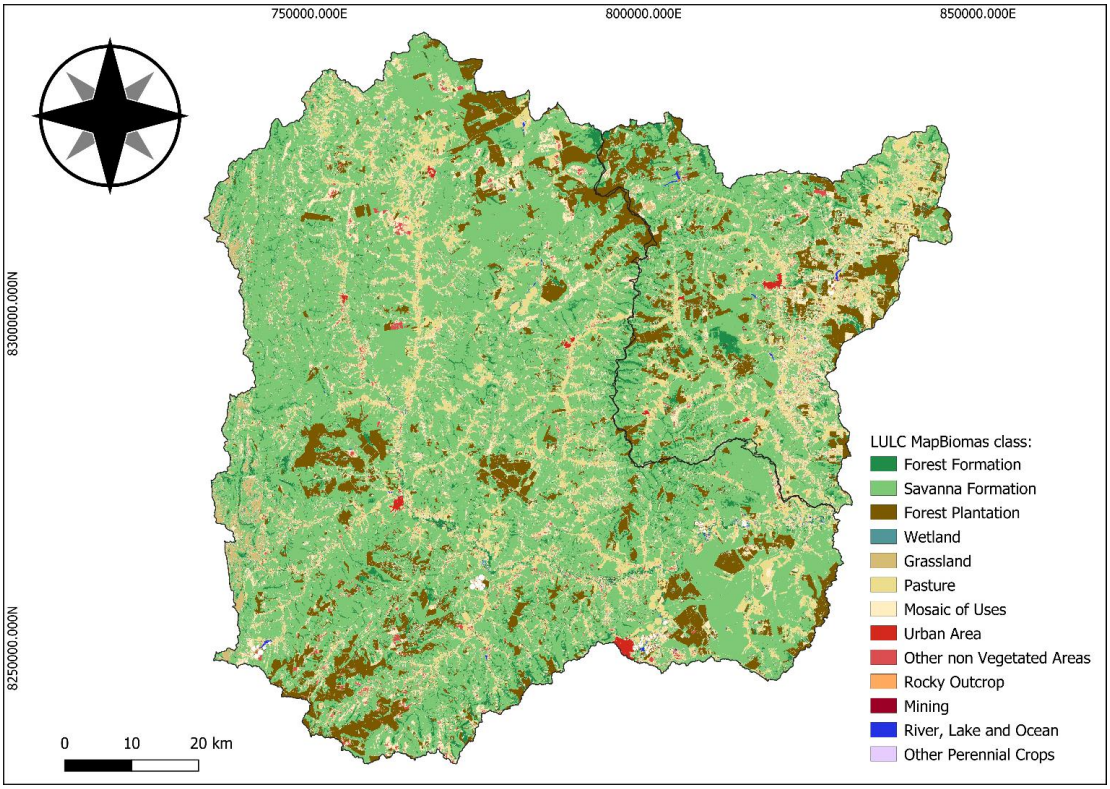


Figure 2: Mapbiomas Land-Use and Land-Cover (LULC) Collection 8 classification of the Upper Rio Pardo basin, Brazil, for 2022.

2.2.3. Carbon storage

Carbon storage was assessed using LULC maps and carbon density per LULC class, including aboveground biomass. The above-ground biomass was estimated as the product of absorbed photosynthetic active radiation (APAR, Mj/m²/day) (Monteith, 1972) and light use efficiency (LUE) (Field, Randerson and Malmström, 1995). The relationship between these factors is presented in Online Resource 1 (ESM 1).

2.2.4. Annual water yield

The water yield index is defined as the net amount of water flowing off from each pixel in the landscape per year (Villamizar, Pineda and Carrillo, 2019). The annual water yield map was produced through the InVEST software, which estimates the quantity and value of water used from each watershed (Online Resource 1). First, it calculates runoff for each pixel based on precipitation minus evapotranspiration. Second, the model estimates the surface water available in each area, accounting for all land uses and land cover types. Finally, it estimates the value of water reaching the reservoir.

As the model considers all LULC classes, it is necessary to provide biophysical coefficients for each class (see coefficients in Table 1). First, a binary value of 1 must be

assigned for vegetated LULC and 0 for all other LULC. Then, for vegetated LULC, root depth and crop evapotranspiration coefficient (Kc) were obtained from studies with similar LULC classes (Yang *et al.*, 2019).

Table 1: Input parameters for Land-use and Land-cover (LULC) classes, including vegetation status, root depth, and crop evapotranspiration coefficients (Kc)

LULC Code	LULC Description	Vegetated (1 or 0)	Max Root Depth (mm)	Kc
0	unknown	0	0	0
3	Forest	1	8,000	0.8
4	Savanna	1	6,000	0.7
11	Wetland	0	1,000	1
12	Grassland	1	200	0.5
29	Rocky outcrop	0	100	0.2
15	Pasture	1	200	0.45
36	Perennial crops	1	7,000	1
21	Mosaic of uses	1	2,000	0.6
9	Silviculture	1	7,000	1
25	Non vegetated area	0	0	0.2
24	Urban area	0	0	0.3
30	Mining	0	0	0.2
33	Water body	0	0	1

2.2.5. Habitat quality

Habitat quality refers to the ecosystem's capacity to support the survival and reproduction of different species considering levels of disturbance and potential anthropogenic threats (Gomes *et al.*, 2020). We assessed habitat quality for all native vegetation classes in the LULC map, including wetlands, grasslands, forest and savanna formations, considering them the most viable habitats for most species. Four main threats were considered: agriculture, silviculture areas (mainly *Eucalyptus* spp.), urban areas, and paved roads (Table 2). We expect that as the distance from the threat increases, its impact on the habitat decreases.

Table 2: Characteristics of anthropogenic threats and their relative impact weights within the Upper Rio Pardo Basin, Brazil. Adapted from Zhang et al., 2022.

Threat	Max distance (km)	Weight	Decay
Agriculture	8	0.8	linear
Paved roads	10	0.7	linear

Urban areas	11	0.9	exponential
Silviculture areas	8	1	linear

Habitat quality was mapped and estimated using the InVEST software (Sharp *et al.*, 2018). The analysis is based on the relative impact of threats, the distance between habitats, the location of threats, and the habitat's vulnerability to threats (Online Resource 1), as shown in Table 3.

Table 3: Habitat suitability of different landscape types and sensitivity of LULC types to each threat for the Upper Pardo River, Brazil. Adapted from Yan et al., 2018; Zhang et al., 2022.

LULC class	**Habitat Suitability**	**Sensitivity to Threat Factors**			
		Agriculture	**Paved Road**	**Urban Area**	**Eucalyptus**
unknown	0	0	0	0	0
Forest	1	0.7	1	0.6	0.8
Savanna	1	0.7	1	0.8	0.8
Wetland	1	0.7	0.5	0.7	1
Grassland	1	0.7	1	0.6	0.8
Rocky outcrop	0	0	0	0	0
Pasture	0	0	0	0	0
Perennial crops	0	0	0	0	0
Mosaic of uses	0	0	0	0	0
Forest plantation	0	0	0	0	0
Non vegetaded area	0	0	0	0	0
Urban area	0	0	0	0	0
Mining	0	0	0	0	0
Water body	0	0	0	0	0

Subsequently, an impact map is generated by integrating the impact zones and the identified land-use types posing threats. The output map represents habitat quality using a relative metric ranging between 0 and 1, with low values in high-impact zones and high values in low-impact zones.

2.2.6. Production datasets and Ecosystem Services values

Economic data for agriculture, livestock, collection of non-timber forest products (NTFP), and forest production were obtained from the IBGE platform for 2022. For Agriculture, the PAM (Municipal Agricultural Production) dataset was used to estimate economic output per hectare for various crop types, representing the gross production value

241 at the municipal level (IBGE, 2023b). For livestock, the PPM (Municipal Livestock
242 Production) dataset provided the economic value of livestock activities (IBGE, 2023a). For
243 NTFP collection and Forestry, the PEVS (Plant Extraction and Forestry Production) dataset
244 was used to estimate the economic contribution of both native and planted forests, including
245 timber and NTFPs (IBGE, 2023c).

246 ES values were derived from the Ecosystem Service Valuation Database (Brander *et al.*,
247 2024) which offers globally standardized monetary estimates based on land cover types.
248 The database synthesized >9,000 empirical value estimates from >1,300 peer-reviewed
249 studies, covering a broad range of provisioning, regulating, habitat, and cultural services,
250 and is widely used in ecosystem valuation research (Brander *et al.*, 2024). The specific
251 values used from both the production datasets and ES valuation database are detailed in
252 Online Resource 2 (ESM 2).

253 ### *2.3. Data analysis*

254 #### *2.3.1. Biophysical parameters & multi-criteria evaluation*

255 To compute the PCU scenario, a script based on Costa et al. (2017) was implemented
256 in Google Earth Engine[1]. Unlike the original approach, the PCU was calculated from six
257 variables: soil class, terrain slope, distance to natural protected areas, annual water yield,
258 habitat quality, and carbon stock. All layers were resampled to a 30-meter spatial resolution
259 in Google Earth Engine to ensure scale consistency. Each layer was scored from 0 (low
260 potential) to 5 (high potential) for agricultural/livestock activities. Quantitative variables
261 (distance to natural conservation areas, annual water yield, habitat quality, carbon storage)
262 were normalized to a 0-5 range through the min max scaling method (Mazziotta and Pareto,
263 2022), while soil classes and slope were reclassified according to their suitability for
264 agricultural/livestock use (Online Resource 3).

265 Distance to natural conservation areas served as a proxy for native vegetation and
266 habitat connectivity (Gomes *et al.*, 2020). In the study region, two protected areas are
267 particularly relevant: *Serra Nova* State Park in the western portion of the basin and the
268 *Nascentes Geraizeiras* Sustainable Development Reserve in the central-north. Areas closer
269 to these units, where ecological sensitivity is higher, were assigned lower suitability scores
270 (closer to 0). Carbon storage in this study indicates the quantity of carbon stored in the
271 above-ground biomass. Areas with higher carbon storage received scores closer to 0,
272 reflecting their unsuitability for agricultural expansion, since land clearance in such areas

[1] Available at https://code.earthengine.google.com/76a7d9abc9109a6de575fe155ac7dee9

would release significant carbon emissions. Conversely, areas with higher annual water yield received scores closer to 5, as water availability enhances agricultural and grazing suitability. For habitat quality, a proxy for biodiversity and land sensitivity, areas of high habitat quality received lower PCU scores to prioritize conservation and guide agricultural expansion toward human-modified landscapes.

The scored layers were then integrated using the Analytic Hierarchy Process (AHP), where the variables are evaluated via a pairwise comparison matrix according to their agricultural suitability (Saaty, 2008). Seven experts ranked the relative importance of the six variables to populate the matrix. The normalized layer weights were validated using Saaty's (2008) consistency ratio (CR), refining the matrix whenever the CR exceeded 0.1. The AHP helped index the potential for conservationist use in the area for further analysis of priority zones for autochthonous SPS, based on the region's environmental and land-use/cover attributes. All six variables had their layers combined, considering their weights assessed by the AHP, as shown in the following equation:

$$PCU = \sum_{n=1}^{i}(n * w_i) \quad (7)$$

where *PCU* = Potential for Conservationist Use; *n* = environmental variables (soil class, slope, distance to natural conservation areas, carbon storage, annual water yield, and habitat quality); w_i = weights obtained in the AHP operation.

2.3.2. PCU classification

The thresholds for PCU classification were defined based on data distribution rather than arbitrary decisions, ensuring that variability in the data was accounted for. Percentile values were used to classify the data into three different classes (Table 4). This allowed the inclusion of autochthonous SPS as an intermediate class between conservation practices and conventional agricultural/livestock production, reflecting its dual role in income generation and the provision of regulating ES. Therefore, SPS with native tree species are considered as suitable for conservationist use to a certain degree, while maintaining productive factors (Röhrig, Hassler and Roesler, 2020; Bruziguessi *et al.*, 2021).

Table 4: PCU classification thresholds and description considering the percentile values for the Upper Pardo River basin, Brazil.

Percentile (%)	PCU score	Class	Land Description
0 - 40	0 - 2.38	Conservation	Largely undisturbed areas with high conservation value and sensitivity

41 - 60	2.39 - 2.53	SPS	Managed semi-natural mosaics with moderate human influence and resource use
61 - 100	2.54 - 5	Conventional agriculture/livestock	Intensively exploited and transformed landscapes

304

305 ***2.3.3. Priority zones for SPS expansion***

306 To determine the priority zones for SPS expansion, the PCU map was overlayed with
307 the municipality boundaries map (IBGE, 2019). The municipalities included in the region
308 of interest were those with an area of more than 30% within the watersheds of the Pardo
309 and São João do Paraíso Rivers. The resulting map was overlayed with the 2022 LULC
310 classification map to produce the land-use assessment. The priority zones were then defined
311 based on the area of specific LULC classes that overlapped with the SPS recommendation,
312 prioritizing those classes that represent the greatest spatial opportunity for SPS while
313 adhering to natural and legal limitations.

314

315 ***2.3.4. Business as usual vs PCU economic performance***

316 To evaluate the economic implications of land-use transitions, two scenarios were
317 developed: Business as Usual (BaU) and Potential for Conservationist Use (PCU); based
318 on land-use/cover (LULC) classifications from MapBiomas and the results of the PCU
319 spatial analysis. Economic performance under each scenario was estimated on a per-hectare
320 basis by combining production data (IBGE – PAM, PPM, PEVS) and ES values (ESVD)
321 with class specific adaptations applied across the scenarios (Table 5). In the BaU scenario,
322 the original MapBiomas LULC raster was reclassified into four aggregated land cover
323 classes based on economic and ecological functions. Economic output was calculated at the
324 pixel level using raster-based operations, with the final values representing the combined
325 contribution of production and ES valuation per pixel, expressed in USD. Per-hectare
326 economic values were derived from the area-weighted contribution of each original
327 MapBiomas LULC class to the new aggregated classes and incorporated into the raster
328 dataset. This process ensured that each pixel in the reclassified LULC received a
329 corresponding economic output value.

330 Table 5: Production, ecosystem service, and total economic output values per hectare
331 across Land-use and Land-cover (LULC) classes under the BaU scenario, and PCU classes
332 under the PCU scenario, for the Upper Pardo River basin, Brazil.

LULC MapBiomas class	LULC Re-Class	PCU Class	Production value (USD/ha)	Ecosystem Service value (USD/ha)	Total Economic output (USD/ha)

Forest Formation, Savanna Formation, Wetlands, Grasslands	Native Vegetation	Class 1 – Conservation	14.7	2089.2	2104.0
-	-	Class 2 – Silvopastoral Systems	359.1	1872.0	2231.1
Pasture, Mosaic of Uses, Perennial Crop, Forest Plantations	Agricultural/Livestock Land-Cover	Class 3 – Conventional Agriculture/Livestock	711.1	773.5	1484.6
Urban Area, Other Non-Vegetated Areas, Rocky Outcrop, Mining	Non-Ecosystem Service Providing Land-Covers	-	0	0	0
River, Lake, and Ocean	Water Bodies	Class 4 – Water body	0	36407.0	36407.0

In the PCU scenario, per-hectare values were assigned based on the specific classification of each land-cover category. For the SPS class, the value was calculated by combining simultaneous PPM/PAM production data with PEVS ecosystem service contributions, reflecting the integrated nature of SPS (Online Resource 2). Zonal statistics were applied to extract aggregated economic values for each land cover class, which were then used to compare economic performance under both BaU and PCU scenarios.

3. RESULTS

3.1. Biophysical parameters of the landscape in the study area

Predominant Ferralsols and Acrisols in the north and east portions of the Upper Pardo River basin show high scores and potential for autochthonous SPS (Figure 3a). Low scores were often associated with Arenosols and rocky outcrops, primarily found in the western portion of the study area. Conversely, the flattest reliefs are concentrated in the eastern part (Figure 3b), indicating similar topographical and soil characteristics within these areas, where matching scores reflect geomorphological features and suitability for agricultural/livestock production.

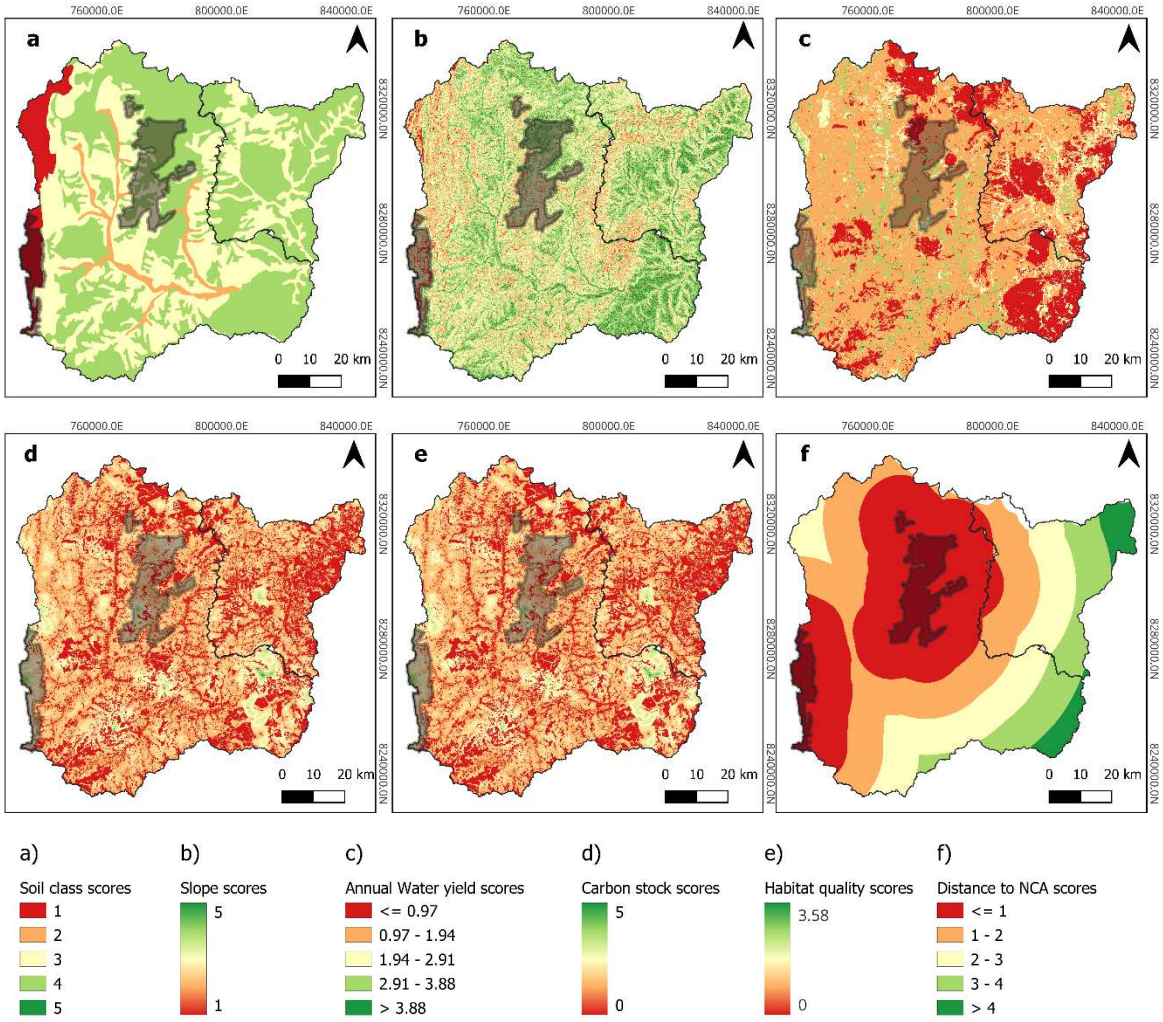


Figure 3: Score values for the six variable layers used in the Upper Pardo River basin, Brazil: a) soil classes, b) terrain slope, c) annual water yield, d) carbon stock, e) habitat quality, f) distance to natural conservation areas.

The eastern and northern parts of the study area showed low annual water yield. In contrast, areas with higher water availability are mainly associated with streamlines and riparian forests (Figure 3c). The carbon stock map did not identify specific high-carbon areas and showed sparse land plots with the lowest carbon stock values (Figure 3d). Habitat quality (max: 3.58) is lower in the eastern part of the study area, favoring agricultural or livestock production, while the central-western area is more suitable for SPS (Figure 3e). Protected areas demonstrating high conservation value are present in the central, northern, and western regions of the map, while production suitability progressively increases eastward (Figure 3f).

3.2. PCU in the Rio Pardo and São João do Paraíso watersheds

In the present study, the AHP evaluated the criteria relative to their agricultural and livestock production potential. The pairwise comparison matrix (Online Resource 4) yielded individual parameter weights with a CR of 0.034.

After combining the slope, soil class, habitat quality, annual water yield, carbon stock, and distance to natural conservation areas (Figure 4) to create the PCU map, the region showed an average PCU score of 2.52, ranging from 1.00 to 4.28 (Figure 5).

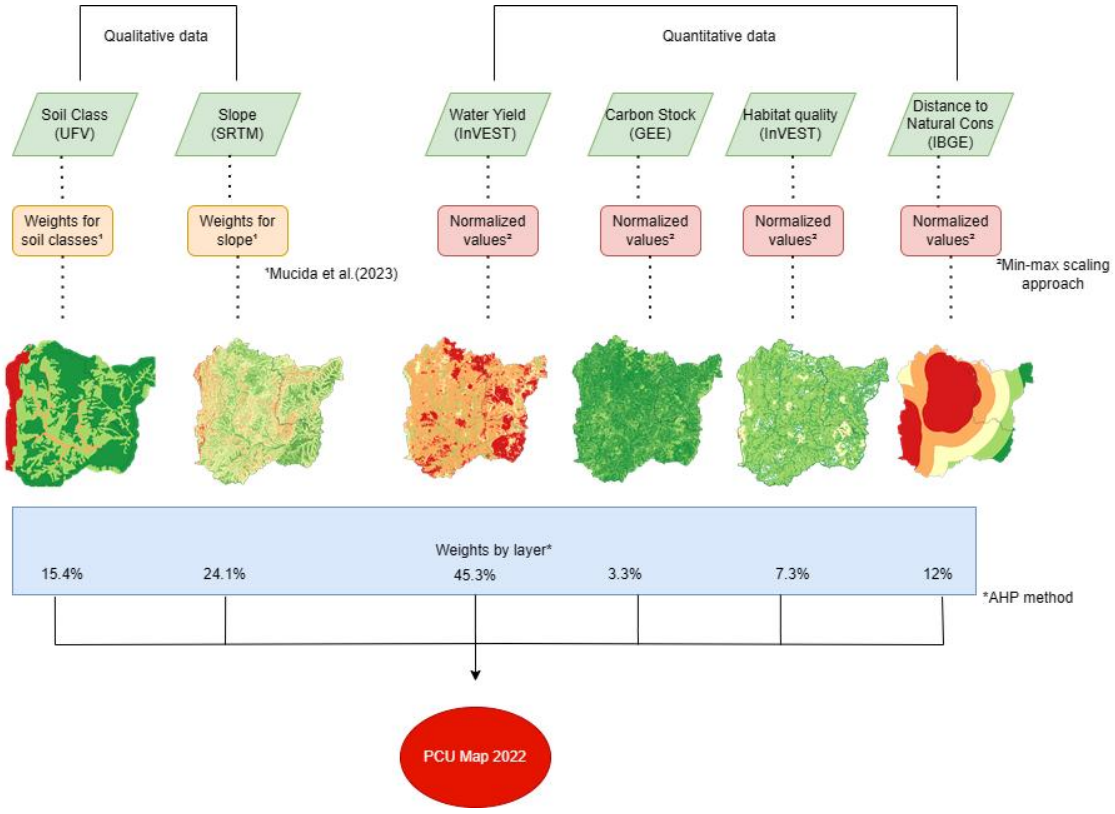


Figure 4: Methodology used to produce the PCU map for the Upper Pardo River basin, Brazil. Adapted from Mucida et al. (2023).

The highest PCU score (>4.2) ocurred in small regions to the south, heavily influenced by the annual water-yield distribution. The annual water yield is the primary factor in the PCU spatial distribution, followed by slope (45.3% and 24.1%, respectively). High PCU values were also observed in the eastern part of the map, where favorable slope conditions prevail. In contrast, the lowest PCU score (≤1.8) was observed mainly in two areas: the extreme western portion of the Upper Pardo River watershed and along the division with the São João sub-basin. In the west, low scores are associated with steep slopes and rocky outcrops, which limit land-use suitability. Along the watershed division, however, low

scores result from the dissection of sandstone plateaus and the prevalence of steep escarpments, which also restrict productive uses. Additionally, the presence of a natural protected area in the western sector (*Serra Nova* State Park) further reinforces conservation as the primary land-use option in the zone. On the other hand, medium PCU score regions are often associated with higher water scores in riparian forests and water bodies, which present moderate restrictions to the use of natural resources and were classified as potential sites for autochthonous SPS.

3.3. Municipal divisions – PCU and autochthonous SPS land use

Considering the seven municipalities of the Upper Pardo River basin (Figure 5), the PCU results showed that 20.9% (~170,000.00 ha) of land has adequate potential for autochthonous SPS.

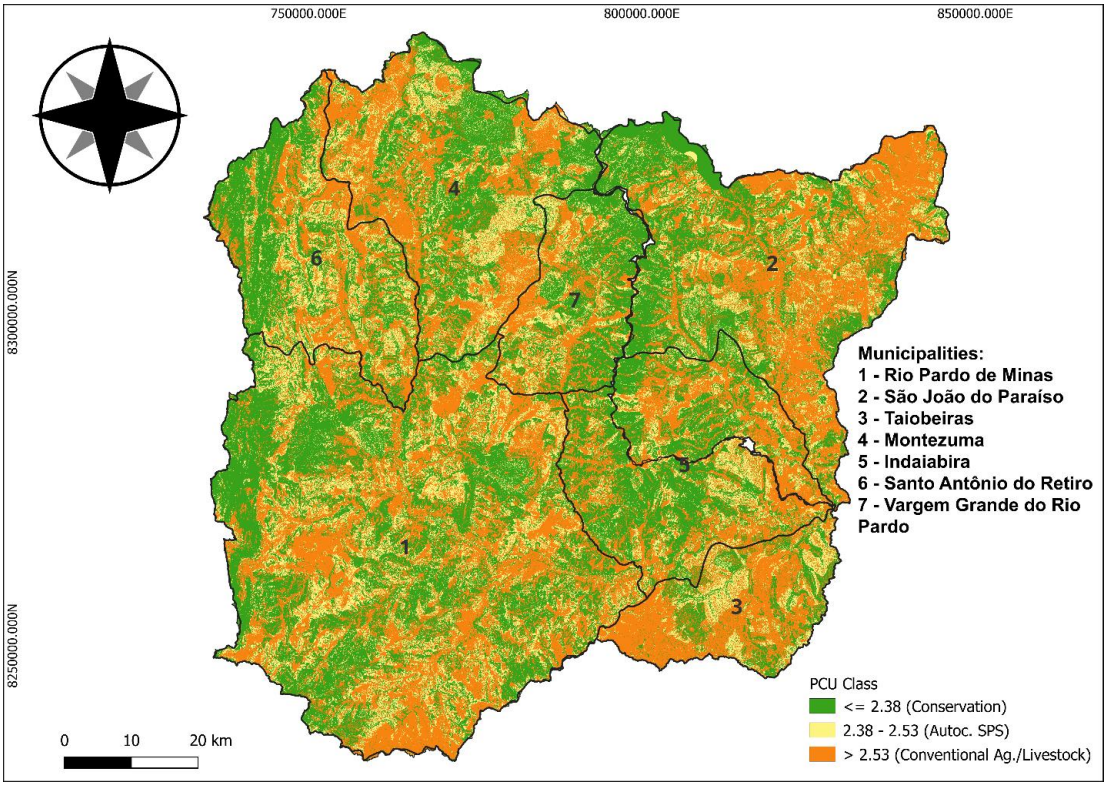


Figure 5: PCU generated from the combined layers: soil classes, terrain slope, annual water yield, carbon stock, habitat quality, distance to natural protected areas with municipality divisions in the Upper Pardo River basin, Brazil, where *Autoc.SPS*: Autochthonous silvopastoral system; *Conventional Ag./Livestock*: Conventional Agriculture and livestock production systems.

Across all municipalities, suitability for SPS represents the smallest share of potential land use, ranging from 18.5% to 22.5% (Table 6). In contrast, conservation (24.1% to

405 46.3%) and conventional agriculture/livestock (32.9% to 54.5%) alternate as the dominant
406 suitable land uses across municipalities. Taiobeiras shows the highest PCU average (2.6) as
407 well as the largest portion of land suitable for agriculture/livestock (54.5%), while Santo
408 Antônio do Retiro had the lowest PCU average (2.45), which reflected in the largest share
409 of suitable land for SPS (22.5%) and the second largest share for conservation (44.2%).
410
411 Table 6: Average PCU scores and classification of land potential for three different uses
412 for each municipality in the Upper Pardo River basin, Brazil.
413

Municipality	**PCU average score**	**Suitable % of land cover**		
		Conservation (%)	Autoc. SPS (%)	Conventional Ag/Livestock (%)
Montezuma	2.5	37.8	22.2	40.0
Rio Pardo de Minas	2.5	40.3	21.8	37.9
Santo Antônio do Retiro	2.4	44.2	22.5	33.3
Taiobeiras	2.6	24.1	21.3	54.5
Vargem Grande do Rio Pardo	2.5	46.3	20.8	32.9
São João do Paraíso	2.6	36.1	18.5	45.3
Indaiabira	2.5	44.0	19.0	37.0

414 Where *Autoc*. *SPS*: Autochthonous silvopastoral systems; *Conventional Ag/Livestock*:
415 Conventional agriculture and livestock production systems.
416
417 ***3.4. LULC and priority zones for autochthonous SPS land use***
418 Land-use data from Mapbiomas (2022) overlayed with the PCU map indicate that
419 Savanna formations (26.29%), Perennial Crop areas (25.17%), and Forest Plantations
420 (20.96%) provide the highest potential for conversion into autochthonous SPS land use
421 (Figure 6; Online Resource 5). With over 500,000 ha, the Savanna formations are the most
422 prevalent and extensive LULC class in the region (Figure 2). This vast area presents a
423 significant opportunity for sustainable practices and can impact the overall land-use
424 strategy, thus a high priority for autochthonous SPS. By converting those savanna areas into
425 autochthonous SPS that are (a) not suitable for conventional agriculture/livestock
426 production, and simultaneously, (b) already influenced by human use and of low
427 conservation value, the land use in the Cerrado could be intensified in a sustainable way,
428 without compromising the provision of ES.
429

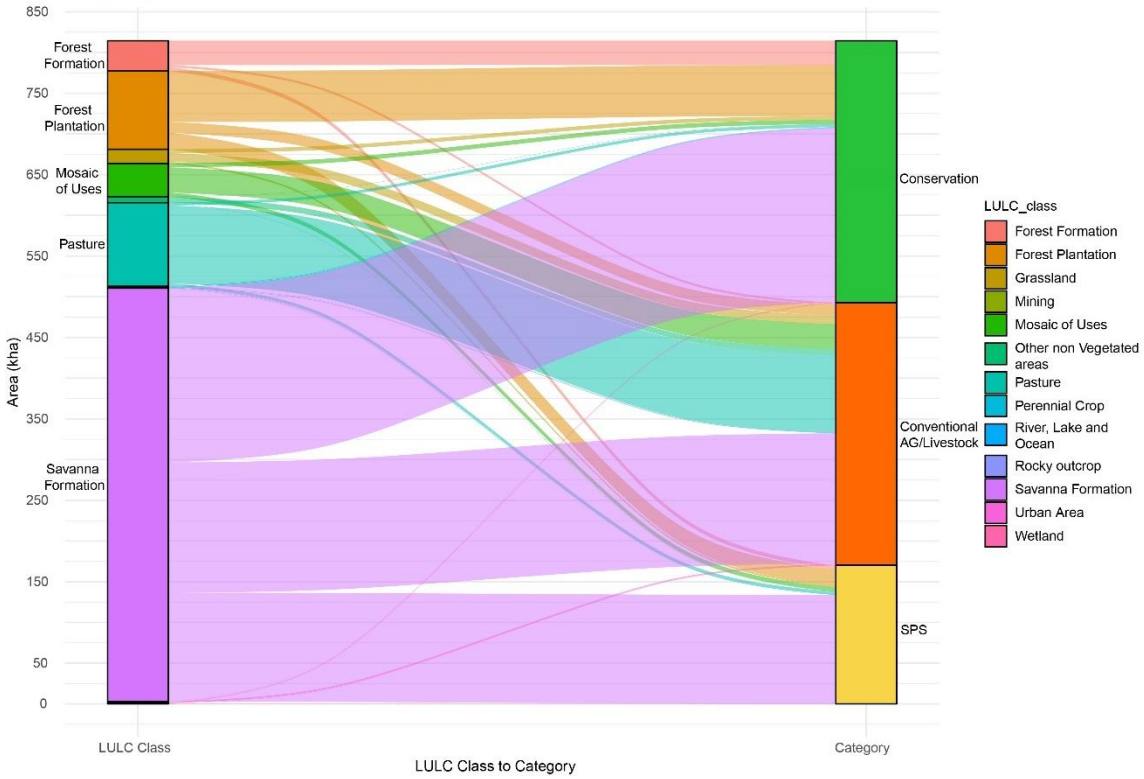


Figure 6: Sankey diagram of each current LULC class transition to the recommended PCU category for the Upper Pardo River basin, Brazil. The left column (*LULC Class*) represents current Land-Use classes from Mapbiomas; the Right column (*Category*) represents the PCU Land-Use recommendation, where *SPS*: Autochthonous silvopastoral systems; *Conventional AG/Livestock*: Conventional agriculture and livestock production systems.

Savanna formations, Perennial Crops, and Forest Plantations combined represent approximately 154,000 ha of potential land for autochthonous SPS practices. Forest formations showed moderate potential for further autochthonous SPS implementation, with 12.7% of their 37,193 ha suitable for SPS. Conversely, 92.8% of the pastures and 61.5% of the grassland areas are highly suitable for conventional agriculture/livestock. While only 3.6% of pastureland has potential for autochthonous SPS, grasslands show a moderate potential for more sustainable systems, with 11.0% suitable for autochthonous SPS.

3.5. Business as Usual (BaU) vs PCU-based economic performance

The total estimated economic output for the BaU scenario was approximately 1.46 billion USD, while the PCU scenario resulted in a slightly higher total of 1.53 billion USD (Online Resource 6). In the BaU scenario, ES accounted for approximately 89.5% of the

total value (1.31 billion USD), while production activities accounted for only 10.5% (153 million USD). The reclassified Native Vegetation class represented the largest land cover category, covering 66.08% of the area and contributing 77.7% of the total economic output through combined production and ES values (Figure 7). The Agricultural/Livestock Land-Cover class followed, occupying 25.12% of the area and accounting for 20.80% of the total value. The remaining classes accounted for minor shares in both area and output.

In the PCU scenario, changes in land distribution and function were introduced. The Conservation class – analogous to the Native Vegetation class in the BaU scenario – remained the dominant land cover type but decreased in extent to 40.76%. A notable shift occurred with the introduction of the SPS class, which replaced portions of previous agricultural areas and Native Vegetation (Figure 6). SPS covered 18.45% of the area and generated approximately 314 million USD, contributing 20.51% to the total economic output. Meanwhile, the Conventional Agriculture/Livestock class expanded substantially, occupying 39.81% of the area - closely matching the Conservation class - and contributed 33.54% to the total economic output. Approximately 40% of this class´s value came from production, with the remaining 60% attributed to ecosystem services.

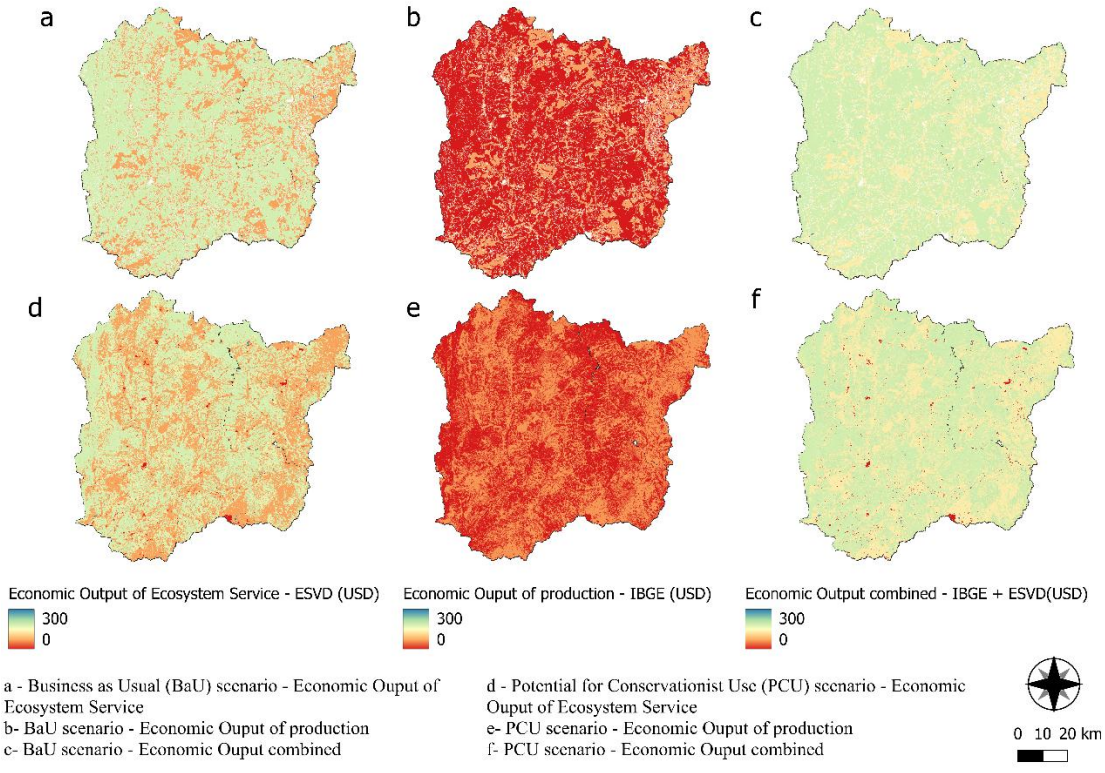


Figure 7: Spatial distribution of economic output (USD) under BaU and PCU scenarios, separated into ES provision, production, and combined total economic value for the Upper Pardo River basin, Brazil.

4. DISCUSSION

4.1. PCU in the Rio Pardo and São João do Paraíso watersheds

The region's average PCU score (2.52) and range (1.00 – 4.28) suggest a diverse landscape with varying suitability for conservation and agricultural use.. Regions with low PCU scores indicate areas of high conservation value, underscoring the need for targeted research into ecosystem threats and the subsequent development of management and conservation plans (França *et al.*, 2022). PCU classification-based land use planning strategies are expected to promote agricultural practices in areas of suitability (indicated by high PCU scores), while in areas with medium PCU scores, public policies and interventions are required to encourage land uses that integrate production and conservation objectives, including autochthonous SPS.

Regarding the environmental factors, annual water yield is expected to be a driver of farmers' decisions in a water-scarce region such as the Cerrado (D'Odorico *et al.*, 2020; Silva *et al.*, 2021) and, as determined through the AHP, contributes 45.3% to the PCU classification in this study. The region's annual water yield distribution shows a predominance of low scores (625-854 mm/yr), which poses a major challenge for conventional rural production systems and directly affects the smallholder farmers and local communities and their livelihoods. In addition, water availability in the region is further constrained by intensive agriculture and eucalyptus plantations with water demands exceeding annual rainfall(Leite, *et al.*, 2025). These land uses should be restricted to areas where water consumption does not exceed hydrological limits. Furthermore, transitioning from water-intensive land uses into SPS can also improve the quantity, quality, and distribution of water resources, thereby increasing overall landscape productivity (Martinkoski *et al.*, 2017). Because farmers perceive water availability as a key determinant of yields in the region (Silva *et al.*, 2021), visible on-farm improvements in water supply resulting from SPS adoption can strengthen the broader uptake of these systems. Moreover, the establishment of SPS in deforested areas near urban centers also represents an opportunity to restore degraded lands and enhance water services near settlement areas, addressing both environmental and socioeconomic challenges.

Slope (24.1% of the PCU weight) plays a crucial role in determining land suitability for various uses (Chatterjee and Murali Krishna, 2019). The reclassified slope scores in the region are generally high, particularly on the expansive flat plateaus, which are highly favorable for agriculture/livestock and SPS activities. Lower reclassified slope scores are often associated with mountain ranges and lowland valleys along incised drainage lines.

504 These areas, often used by *Geraizeiros* communities for housing, forage cultivation, and
505 livestock grazing, present practical limitations for intensive mechanized farming. Thus,
506 these areas receive lower PCU scores, indicating reduced suitability for intensive land use
507 (Fitzsimons and Michael, 2017). Yet such challenging topographies may still hold
508 potential for alternative land management practices like conservation or autochthonous
509 SPS (Pinheiro and Nair, 2018).

510 Soil classes and the distance to natural conservation areas also played important roles
511 in the PCU classification (15.4% and 12% respectively). The lowest PCU scores were
512 observed in the rocky outcrop zones in the western portion of the map, which coincide with
513 natural conservation areas (Figure 5). Due to environmental conditions favorable for
514 endemic animal and plant species, these areas are of high ecological importance and
515 conservation value, where conservation-oriented management is preferable to prevent
516 further habitat losss at both the local watershed scale and within the broader context of the
517 Cerrado biome. On the other hand, the vast presence of Ferralsols and Acrisols with high
518 fertility and structural stability provides favorable conditions for conventional
519 agricultural/livestock and autochthonous agrosilvopastoral practices (Moterle *et al.*, 2019).
520 Furthermore, while Arenosols are characterized by low natural fertility, their occurrence
521 on flat terrain facilitates mechanization and high-input management, necessary to
522 overcome these soil limitations. This same topographic suitability for mechanization
523 suggests these landscapes can also be candidates for intensification through autochthonous
524 SPS while still maintaining the original vegetation structure.

525 Natural protected areas are key to maintaining water resources and biodiversity in the
526 region, while providing sustainable livelihoods for traditional communities. Many of these,
527 such as the *Geraizeiros*, have long managed the landscape through extractivism and low-
528 input farming, including the development of autochthonous SPS adapted to local ecological
529 conditions. Brazil's National System of Nature Conservation Units (BRASIL, 2000)
530 differentiates between strict protection areas, which prohibit direct resource use, and
531 sustainable-use categories that accommodate agroecological management. Accordingly,
532 while productive activities are prohibited within the boundaries of the *Serra Nova e Talhado*
533 and *Montezuma* State Parks, their surrounding buffer zones are key targets for
534 autochthonous SPS to shield core headwaters. Conversely, within the *Nascente Geraizeiras*
535 Sustainable Development Reserve, SPS can be directly deployed to strengthen the cultural
536 and economic resilience of local communities. Together, this coordinated landscape
537 framework highlight opportunities where autochthonous SPS in authorized zones can

complement biodiversity conservation goals and enhance ecosystem services without compromising rural livelihoods.

Finally, carbon stock (3.3%) and habitat quality (7.3%) were the least influential dimensions for the PCU classification. High-carbon-stock areas generally showed lower PCU scores, in line with their role in climate change mitigation. However, in the case of forest plantations (e.g., eucalyptus), this carbon storage is often temporary and lacks the functional complexity and the diverse ES inherent to native Cerrado ecosystems (Bispo et al., 2023).To avoid overvaluing these simplified landscapes, carbon stock exerts a restricted influence on the PCU classification (Hua *et al.*, 2022). Eucalyptus plantations in the study area, similar to other monocultures, do not only reduce biodiversity but, in light of historically low precipitation values and the spread of large-scale afforestation projects, also reduce water yields and severely endanger the water balance security in the region (Bustamante *et al.*, 2019; Leite and Fujaco, 2010). Meanwhile, the carbon map also highlights areas where land-use practices could be optimized for carbon sequestration. Implementing SPS in low-carbon stock areas offers potential to improve soil health and increase carbon sequestration, contributing to climate change mitigation efforts (Fornara *et al.,* 2018). Habitat quality, with a maximum weighted value of only 3.58 in this study, reflected in a medium PCU score range of 2.38 – 2.53. This relatively low value helped identify areas most suitable for autochthonous SPS, as these systems are expected to prioritize land rehabilitation while maintaining productivity and income for local communities. Increasing the share of SPS within current agricultural and livestock areas can further enhance habitat quality, supporting biodiversity and environmental services while promoting socioeconomic benefits.

4.2. Municipal-Level Suitability and Opportunities for SPS Adoption

Municipal divisions in the region showed high overall agricultural and livestock suitability, as well as SPS potential. These results emphasize the need to improve land-use programs at the municipal level to further successful adoption of autochthonous SPS (Mucida *et al.*, 2023). Santo Antônio do Retiro, Montezuma, and Rio Pardo de Minas show strong potential for the adoption or expansion of autochthonous SPS. In contrast, the municipalities in the north-western portion of the region, due to their better road conditions and connection to bigger cities, benefit more from development strategies focused on market-driven intensification and value-added agricultural processing such as regional agro-industrial processing hubs (Lupinetti-Cunha *et al.*, 2022).

The PCU results suggest a stratified management strategy based on municipal characteristics. Within this framework, municipalities with high conservation potential, such as Vargem Grande do Rio Pardo (46.3%), Santo Antônio do Retiro (44.2%) and Indaiabira (44.0%), should prioritize land sparing (strict conservation) in low PCU-score zones. In addition, land sharing through autochthonous SPS should be targeted in the surrounding matrix or "buffer" areas. This spatial separation ensures that high-value ecological fragments are strictly protected, while the adjacent lands provide a functional transition that maintains economic viability and provides ES (Röhrig, Hassler and Roesler, 2020; Sales-Baptista and Ferraz-de-Oliveira, 2021).

Conversely, municipalities with a high proportion of land suitable for conventional agriculture and livestock, most notably Taiobeiras (54.5%) and São João do Paraíso (45.3%), should be prioritized for agricultural intensification. By optimizing productivity in these high PCU-score regions, the agricultural demand can be concentrated, effectively "sparing" the more ecologically fragile municipalities from further expansion pressure (Green et al., 2005). This approach moves beyond a one-size-fits-all model, strategically allocating land sparing and sharing across the landscape to balance the region's diverse ecological and economic needs.

4.3. LULC and priority zones for autochthonous SPS land use

Overlaying the calculated PCU scores with the current LULC map (MapBiomas Project, 2023) indicated the degree of conflict between the current and PCU-based land use. This enables the definition of priority zones for SPS integration and the development of public policies for conservation and the supply of ecosystem services (Grêt-Regamey *et al.*, 2017). The conversion of degraded areas into SPS can increase landscape heterogeneity and functional connectivity, directly benefiting agricultural systems (Allan *et al*., 2015). Moreover, the PCU index supports a hybrid zoning approach – highlighting areas that can be spared for protection and those where low-ecological-impact land use is feasible.

Over 150,000 hectares across savanna formations, perennial crops, and forest plantations areas show high potential for SPS use. These land cover types typically exist as managed semi-natural mosaics, which are fragmented landscapes where native vegetation is interspersed with agriculture and forestry. Because these areas maintain a moderate degree of ecological structure while already supporting human resource use, they represent the primary priority zones for the expansion of autochthonous SPS that do not

require total land conversion. The viability of SPS in these priority zones is further enhanced by the existing regulatory framework, as autochthonous SPS offers a strategic pathway for legal compliance. Under the Brazilian Native Vegetation Protection Law (Law 12.651/2012), rural properties are required to maintain a Legal Reserve (*Reserva Legal)*, which mandates that, in the case of the Cerrado biome, at least 20% of the property area needs to be dedicated to preservation or sustainable use of native vegetation such as autochthonous SPS (BRASIL, 2012). Because of these environmental attributes and regulatory restrictions, these areas are considered as the primary priority zones with high potential for adoption or expansion of the autochthonous SPS.

Despite the advances of environmental zoning methods to enhance territorial planning, the intensification of autochthonous SPS in the region remains underexplored (Ribeiro *et al.*, 2025). Incorporating socioeconomic variables in environmental zoning models, such as land tenure, family income, and education level, is essential to align zoning results with the farmers' realities. By accounting for these socioeconomic dimensions, environmental zoning methods can move beyond biophysical suitability to identify areas where landowners possess the legal stability and financial capacity required for the long-term investment that SPS demands, thus, further improving adoption and intensification Furthermore, payment for environmental services (PES) schemes can provide important incentives to increase the environmental performance of agriculture, livestock and forestry activities. This improvement in performance is linked to production diversification, where farmers through autochthonous SPS restore soil health, improve water infiltration, and increase carbon sequestration compared to conventional monocultures. By providing the necessary financial leverage to support these transitions. PES schemes make such systems economically viable, thus making it more attractive for farmers to diversify their production systems (Zapata, Robalino and Solarte, 2015).

One potentially promising strategy to valorize the ES provided by autochthonous SPS is to commercialize the non-timber forest products (NTFPs) produced in these systems. Studies show that autochthonous SPS have high potential for NTFP development with approximately 250 native species identified for use in food, medicine, culture, and construction (Orioli *et al.,* 2025). While farmers in some regions indeed generate considerable income from NTFP commercialization, the lack of adequate technical support and management strategies, the heterogeneity of products, trader profiles, and volumes currently provide only limited economic incentives overall to scale NTFP production (Ribeiro *et al.,* 2025; de Mello *et al*., 2023). By identifying biophysically suitable and

strategically important priority zones for SPS and NTFP production, this study aims to enable and strengthen targeted public policies and municipal strategies to promote integrated land use in the Brazilian Cerrado.

4.4. BaU vs PCU potential economic contributions

The economic outputs of the BaU and PCU scenarios highlight the trade-offs between land use options in terms of ES provision. The BaU scenario represents a sparing-oriented land use approach, in which the reclassified native vegetation land cover class remains intact on 69.7% of the land surface while 29.9% of the land are dedicated to intensive agricultural and livestock production with only limited provision of ES. The fact that almost 90% of the total economic value generated originates from ES in the BaU scenario highlights the significance of the provisioning, regulating, supporting and cultural services rendered by the various types of Cerrado formations compared to the overall productive capacity of the landscape.

In contrast, the PCU scenario introduces the adoption of autochthonous SPS as a land-sharing element, which aims to enable the coexistence of agricultural production and ES provision within the same production unit. Under our scenario assumptions this integration of agricultural production and ES provision leads to a net gain in total economic output compared to BaU, despite the reduction in total native vegetation cover to 40.8%. In comparison with conventional agriculture/livestock production, autochthonous SPS deliver much higher amounts of ES per hectare (89% of the ES value of native vegetation), while maintaining a robust production value (>50% of the value for agriculture/livestock production). This suggests that autochthonous SPS as an instrument of responsible land sharing – when strategically pursued – can enhance both economic viability and ecological functionality of land use in the Cerrado (Sales-Baptista & Ferraz-de-Oliveira, 2021).

. However, because the expansion of autochthonous SPS in the PCU scenario also comes at the expense of native vegetation, SPS adoption should prioritize already cleared, moderately restricted, or degraded lands such as abandoned pastures, rather than native savanna remnants, particularly in a region where water-related ES constitute one of the most critical societal needs.

The PCU scenario, by design, highlights areas that are potentially suitable for agricultural activities based on physical and environmental factors, rather than reflecting strategic land-use recommendations. With our methodology emphasizing the conservation value of current land use types, e.g. by integrating distance to NCA and habitat quality

scores, the scenario results could be interpreted as a conservative illustration of the potential impacts of unregulated land use change in the Cerrado. The sharp increase in area under conventional agriculture/livestock in the PCU scenario vis-à-vis BaU, therefore, also underscores the urgent need for proactive land use planning and related policy measures aimed at incentivizing sustainable land use practices and preventing the unchecked conversion of high-value native vegetation areas in the Cerrado.

Suitable instruments may include land use zoning that designates areas of high conservation value as off-limits to conversion, PES schemes that reward landholders for maintaining or restoring native vegetation, and targeted support for the adoption of practices such as autochthonous SPS on degraded lands. These strategies could help align agricultural development with ES provision, minimizing trade-offs and promoting win-win outcomes where feasible (Zapata, Robalino and Solarte, 2015; Zabala, Pascual and García-Barrios, 2017).

Finally, we acknowledge that the valuation of ecosystem services remains a complex and evolving field (Mandle *et al.*, 2020). In this study, we used generalized global average values to illustrate the potential magnitude of economic contributions from different land-use types. While this approach offers a useful means of comparison, it is important to acknowledge that local ecological conditions, socioeconomic contexts, and cultural values can lead to significant variation in the actual ES benefits and values provided (Schmidt, Manceur and Seppelt, 2016). Moreover, the PCU scenario represents a potential suitability-based projection rather than a normative recommendation for future land use. Its value lies in zoning areas that may be at risk of conversion under prevailing economic pressures. In this context, the ES trade-offs – especially those related to water regulation – carry particular weight. While ES can appear conceptually abstract, their effects on water availability are directly tangible to local communities, who already experience the consequences of reduced water infiltration and seasonal scarcity across the region. By quantifying the potential ES trade-offs associated with such changes, the analysis provides an important evidence base for guiding proactive policy and land management decisions that prioritize long-term ecological and economic suitability.

5. CONCLUSION

Identifying priority zones for the expansion of autochthonous silvopastoral systems (SPS) supports a strategic approach to land sharing in the Cerrado. Our analyses demonstrate that the adoption of autochthonous SPS in high-suitability areas can optimize

land use and promote sustainable land management. Our findings indicate strong potential for autochthonous SPS across the region, with suitability relatively evenly distributed among municipalities. Analysis of current land use in relation to these priority zones shows that savanna formations, perennial crops, and forest plantations are high-suitability areas for autochthonous SPS adoption. Despite their biophysical suitability, savanna formations hold high ecological value and are already under pressure in the Cerrado. Therefore, SPS expansion should be strategically directed toward moderately degraded areas where integrating trees and livestock production can enhance water retention and the provision of further ES, while providing animal, timber and NTFP products. Land sharing, through an integrated conservation-through-use approach, thus aligns conservation objectives with agriculture and livestock production. Promoting sustainable land use through autochthonous SPS can ensure the long-term security of local and regional water supplies, carbon sequestration, and biodiversity, strengthen ecosystem resilience and deliver socioeconomic benefits to local communities in the Cerrado.

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