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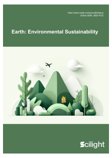

Article

A Framework Model to Assess Ecosystem Functioning in Agriculture Watersheds: The Case of Córrego Rico, Brazil

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Abstract: Sustainability is essential to Earth systems, but inadequate landscape planning makes it a challenge to modern societies. To help improving sustainable land use in watersheds, this study merged the so-called Conservation Use Potential (CUP) method with an Ecosystem Services (ES) accounting method. The compound CUP-ES method embeds a novel multifunctionality index, called Ecosystem Functioning Potential (EFP), which helps making sustainable land use actionable through Payment for Environmental Services (PES) schemes. The CUP and ES were assessed by a multicriteria analysis connecting a diversity of parameters, and regionalized using map algebra and zonal statistics in a Geographic Information System. The novelty of CUP-ES and EFP analyses rely on their ability to rank areas for practical interventions in the watershed: (a) land use conversions such as extensive reforestation or agroforestry systems; (b) landscape stabilization through erosion control; (c) conservationist soil management; and (d) PES to ensure the protection of natural capital and improve the supply of ecosystem services. The CUP-ES-EFP framework was applied to the Córrego Rico Watershed (CRW), located in the state of São Paulo, Brazil. The multicriteria analysis assigned different ratings and weights to soil use potential parameters (soil type, bedrock, terrain slope) as well as to provisioning (water resources) and supporting (soil carbon stock and biodiversity) ecosystem services. The key results showed that most sub-basins within the CRW correspond to moderately managed production systems (sugarcane), as they preserve ecosystem services notwithstanding the intensive use. Thus, they were recommended for conservationist soil management according to the CUP-ES interpretation. The spatial distribution of EFP suggested the implementation of PES in some areas, given their role as water resources suppliers. The main conclusion was that, the CUP-ES-EFP framework proved efficient for sustainable land use planning, being regarded as potential decision-making tool. In that context, sustainability of CRW could be reached through the balance of protected areas (the headwaters), seen as net suppliers of ES, and food production systems (the lower lands), mostly regarded as net ES consumers.

Keywords: land use policy; territorial management; watersheds; soil system; ecosystem functioning

1. Introduction

The soil is a fundamental resource for humankind, especially for production of food. In that context, many studies have sought to determine the capacity of soil for agricultural use, namely to implement a production system that minimizes soil degradation. As corollary, these studies also indicated the best way to manage an agricultural area without harming the soil's ecological functions [1,2]. In spite of these scientific efforts, the intensive use of soils and their deterioration persists in many regions worldwide. Thus, conservationist soil management, more than ever, emerges as critical global challenge of present time. Conservationist soil management means safeguarding the soil's physical, chemical and biological characteristics to maintain its natural fertility, ensure productivity, and at the same time protect the ecological function of landscapes over time [1].

A fundamental precursor of conservationist soil management is the assessment of soil's potential use (or natural use) through environmental variables [3]. The list of variables comprises physical, chemical and biological parameters. And the evaluation of soil use potential points to landscape compartments capable of being used for agriculture or livestock pasturing, or being protected and devoted to the preservation of natural capital and ecosystem functions [3–5]. Having detected the potential soil use in a region, the next step is to match actual and potential uses, especially if the former has degraded the soil. The rationale behind this footstep is that converting harmful actual uses to potential uses is sought to trigger the recovery of natural soil characteristics and bring back lost ecosystem services in the long term [6]. These include water provision, carbon sequestration and biodiversity [7,8]. Overall, assessing the potential soil use serves to identify the best way of using a soil unit in a sustainable manner [9,10].

Although the research on soil use potential exists, a large share of previous studies has linked it to soil fertility parameters, at the expense of other equally important physical and chemical factors. This bias tended to distort management practices hampering effective soil conservation [11]. In order to counteract this predisposition, Lepsch [1] launched a multicriteria classification of soil use potential for agricultural, forestry and grazing activities. The classification scheme was based on quantitative information about soil texture, depth, drainage, fertility, terrain slope, presence of obstacles, and susceptibility to erosion. The Lepsch method was later adopted in other studies [3,4]. Moreover, the early works of Lepsch inspired the development of conservationist soil management approaches, which advanced knowledge in this field. The Conservation Use Potential (CUP) is among the best to recall, because of its inherent capacity of allocating areas for production activities within a target region, while preserving others for aquifer recharge or erosion control [9,12]. Besides standing for conservationist soil management, the CUP emerged as oriented for landscape planning and should be especially considered in land use conversion proposals [13–15]. Currently, the CUP is an official land management tool of Minas Gerais state in Brazil (https://idesisema.meioambiente.mg.gov.br/, assessed on 21 November 2025). Other reliable approaches to conservationist soil management can be consulted in the works of Grass et al. [14] and Mucida et al. [16].

The CUP describes soil use potential for agriculture, livestock pasturing and forestry, while recognizing the ecosystemic role of watersheds, namely for aquifer recharge. However, in the CUP algorithm, the ecosystemic role of watersheds is deduced from proxies such as soil types, lithologic types and terrain slopes, instead of being assessed from ecosystem service accounting. For that reason, the CUP is incapable of validating ecosystem functioning. To bring this capacity into the model, the CUP would have to merge with an ecosystem services (ES) framework [17,18]. And to do that, the CUP-ES model would have to include indicators of ecosystem services such as stream base flow for aquifer recharge [5,6]. However, this integration has not been made so far being the reason of carrying out this work. Thus, the general purpose of this study was to develop a methodology that merges Conservation Use Potential (CUP) with Ecosystem Services (ES). The selected ES were provisioning (water) and supporting (soil carbon stock and biodiversity) services as they are relevant for crop and livestock production. The specific objectives were to: (a) describe the CUP in the studied area through relevant thematic maps (e.g., soil type, terrain slope); (b) define, evaluate and map three ecosystem services relevant for agriculture, namely water provision required for irrigation, carbon storage essential for production of stable organic matter, and biodiversity that is vital for nutrient cycling, improved pollination, natural pest control, and resilience of agricultural systems to climate change and other environmental stresses; (c) use a CUP versus ES diagram to verify the confluence between the potential and real ecosystemic statuses of watersheds within the studied area. This classification diagram allows comparing the potential conservation status of an expected land use defined on the basis of soil capability (the CUP; YY-axis), with the real conservation status of an actual land use assessed through the evaluated ecosystem services (the ES; XX-axis). In that context, confluent statuses plot along the diagram's main diagonal and divergent statuses above or below that line. Besides, the plot of watersheds off the main diagonal objectively discriminates disturbed ecosystem functioning (above the main diagonal) and improved ecosystem functioning (below the main diagonal), allowing selective and actionable land use management within the studied area. To our view, this is a landmark on sustainable land use planning of agricultural watersheds, comprehending enough novelty to justify publishing the current study; (d) define and map an aggregated index based on a weighted sum of CUP and ES, called EFP—Ecosystem's Functioning Potential of agricultural watersheds or, put another way, the ecosystem's functioning of watersheds predominantly used for agriculture and cattle grazing activities.

Having completed the coupling of CUP and ES, the CUP-ES model should be able to associate conservationist soil management practices to the corresponding effects on the selected ecosystem services (objective (c)). Put another way, the CUP-ES results are expected to monitor where the practices were effective because the services improved thereafter, or ineffective otherwise, in which case adjustments to land use or conservationist practices would be mandatory. In either case, the CUP-ES results would be an interesting decision-making tool in programs that remunerate farmers or local communities for adopting sustainable practices that harmonize food production with balanced ecosystemic functioning [18], frequently called PES—Payment for Ecosystem Services. In view of this potential, an additional goal of this study was to: (e) use the aggregated index derived from the CUP-ES model (the EFP) as basis to prioritize areas suited for the implementation of PES. It is worth recalling that merging the CUP and ES methodologies and embedding them into PES programs represents a methodological and practical innovation and therefore justifies the publication of this study. According to the works developed by [6,7,19,20], among others, the PES scheme is essential to encourage sustainable practices and economically recognize the environmental benefits that certain activities provide to society. Aligning CUP, ES accounting and PES schemes would make these programs more effective, ensuring that payments are associated with fundamental ecological production functions. Moreover, this alignment would boost water quality and quantity in watersheds through enhanced aquifer recharge, carbon stocks through improved sequestration, and biodiversity, ultimately generating sustainable watersheds.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Córrego Rico Watershed (CRW) located in the northeastern region of São Paulo state, Brazil (Figure 1). Comprising part of Jaboticabal, Taquaritinga, Monte Alto, Guariba and Santa Ernestina municipalities, it covers an area of approximately 571.6 km^2, with an altitude ranging from 754 to 498 m.

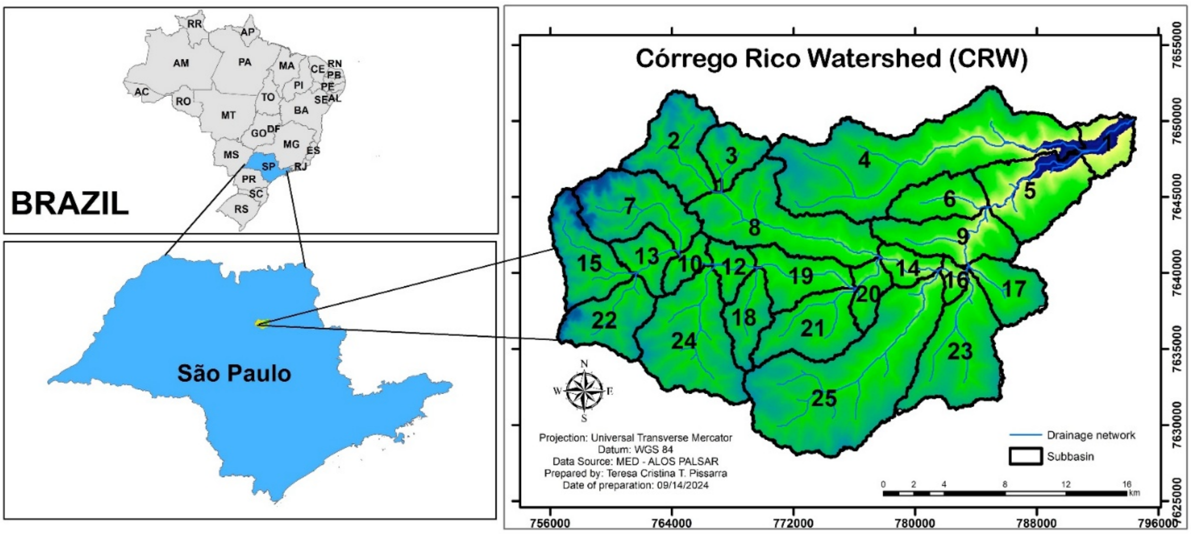

Figure 1. Location of Córrego Rico Watershed (CRW) and embedded catchments, in the state of São Paulo, Brazil.

The CRW is a tributary of Mogi Guaçu watershed located in the administrative region of Ribeirão Preto, as well as in the 9th Water Resources Management Unit of São Paulo state (UGRH-9). It also comprises a sector of Mogi Inferior-Médio economic-ecological compartment (https://sigrh.sp.gov.br, assessed on 3 December 2025). The area is of extreme economic importance because of its agricultural activities, being the key source of public water supply to the municipality of Jaboticabal with a 75% share. Recently, the region has faced recurring water stress problems in the course of low reservoir levels.

2.2. Methodology

The methodology adopted to identify and prioritize areas that merge the CUP with provision and support ES was based on the mapping and interpretation of CUP parameters as well as classes of stream water flow, soil carbon stock and biodiversity in the CRW, being adapted from previous approaches of [1,3,4,8,9,12,13]. The methodological workflow was divided into four stages described in the next subsections and illustrated in Figure 2.

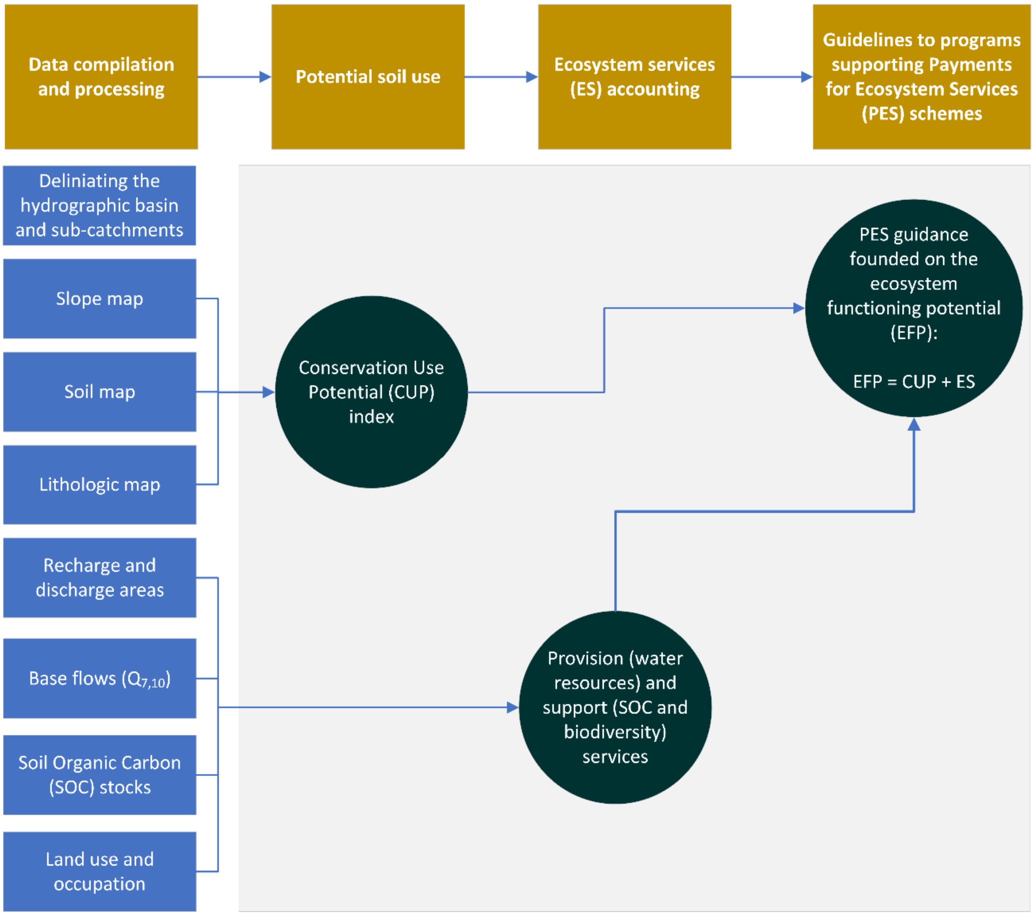

Figure 2. Methodological workflow implemented in the current study.

2.2.1. Delineating the Hydrographic Basin

The watershed's delineation process has identified the boundaries of Córrego Rico Watershed (CRW) and respective sub-basins. The delineation was performed using the Soil and Water Assessment Tool (ArcSWAT; https://swat.tamu.edu/software/arcswat/, assessed on 10 July 2025) hydrological model of Arnold et al. [21], which works in the ArcGis Geographic Information System (GIS) of ESRI (https://www.esri.com/, assessed on 10 July 2025). The geographical space of CRW was divided into 25 sub-basins as indicated in Figure 1.

The hydrologic regionalization process began with the acquisition of a spatial Digital Elevation Model (DEM), obtained from the ALOS Palsar website (https://search.asf.alaska.edu/#/, assessed on 10 July 2025) with a resolution of 12.5 m × 12.5 m. The DEM sinks were filled and then the direction and accumulation of water in the catchment was calculated. Finally, the sub-basins were delineated having the outlets and headwaters as topographic references. The outlets are the points of lowest elevation and the headwaters the points of highest elevation, which isolate the hydrological regions from each other. These outlet and headwater references were established by a threshold number (hydrologic resolution), in the course of which the sub-basins were delineated and their topography characterized for area and slope, among other morphometric parameters.

2.2.2. Conservation Use Potential (CUP)

The soil use potential in the CRW was assessed through the Conservation Use Potential (CUP) methodology, in keeping with the steps proposed by Costa et al. [3,4,6,9]:

$$\text{CUP} = (\text{slope} \times 0.50) + (\text{soil} \times 0.39) + (\text{lithology} \times 0.11) \quad (1)$$

The details of CUP method are beyond the scope of this study and can be consulted in the original publication of Costa et al. [3]. In brief, the slope parameter (the first appearing in Equation (1)) was used to define agricultural suitability. The soil parameter embedded information on drainage, fertility, texture, and effective depth. And the lithology parameter involved the characterization of bedrock's chemical and mineralogical composition in complement to denudation susceptibility. According to the authors of CUP method, the final weights obtained for the aforementioned components resemble empirical observations of sustainable land use in the state of Minas Gerais.

In the current study, the slope map was obtained through calculating the rate of elevation change for each cell in the DEM of CRW downloaded from the ALOS Palsar website. The slope was expressed as percentage and saved as raster format, where low slope values indicate flat to gently undulating terrain and high slope values point to steep areas, such as strongly undulating relief, hills, or mountains [4]. According to [9], the slope contributes with 50% to the CUP and describes surface runoff in the landscape, being associated with numerous potentialities and limitations regarding land use in the CRW. The base soil map was retrieved from [22] and coupled with the Soil Map of São Paulo state (https://redezee.datageo.ambiente.sp.gov.br/, assessed on 15 October 2025) produced at the scale of 1:100,000 to provide a better interpretation of soil attributes. As per Equation (1), the contribution of soils to the CUP is 39%, and relates to the degree of soil's natural fertility, water storage capacity, and resistance or vulnerability to erosion processes. The lithology map was compiled from studies about geology and mineral resources conducted at the 1:100,000 scale by the CPRM—Mineral Resources Research Company, downloaded from the https://geosgb.sgb.gov.br/geosgb/downloads.html website, assessed on 15 October 2025. Lithology contributes with 11% for the CUP and relates with resistance to denudation and the chemical and mineralogical composition of rocks. Having defined the slope, soil and lithology components, they were converted into dimensionless ratings, and then the ratings were applied in Equation (1) to calculate the CUP. The CUP scores were finally reclassified as classes of conservationist use management as follows [13]: Class 5—Very low (1–1.8); Class 4—Low (1.8–2.6); Class 3—Medium (2.6–3.4); Class 2—High (3.4–4.2); Class 1—Very High (4.2–5.0).

2.2.3. Ecosystem Services (ES)

A sustainable soil use has strong links to improved ecosystem services, such as enhanced water provision or life support through soil's carbon storage and biodiversity preservation in the landscape [23–26]. For the water provision services, two proxies were selected: recharge areas/spring sites and flow values in the CRW sub-basins. The recharge areas are crucial for maintaining the water cycle and its balance in terms of quantity and quality. They comprise the region where rainwater infiltrates the soil and replenishes underground aquifers, while spring areas are the places where this groundwater emerges on the surface forming the beginning of watercourses. Springs are considered the starting points of a river system and are important for maintaining stream flow in the basin. The location and quality of springs are decisive for water availability in the river basin and its provision to agriculture and livestock pasturing. The flow values (m^3/s) in the 25 sub-basins of CRW were represented by the $Q_{7,10}$ of [27], which describes the lowest discharge of a river in 7 consecutive days and a return period of 10 years, and represents a situation of low water availability. This index is frequently used to plan and manage water resources and assess the water production capacity of a drainage network and upstream area, because it represents an unfavorable condition in the watershed. The $Q_{7,10}$ values were calculated on the DAEE—Department of Water and Electric Energy portal (https://hidrologia.spaguas.sp.gov.br/, assessed on 5 May 2025). The support service was approached through soil carbon stocks and biodiversity. Soil carbon data were obtained from the MapBiomas 2 Soil Collection survey [28], which provides annual maps of soil organic carbon (SOC) stocks in Brazil, covering the period from 1985 to 2023 with a spatial resolution of 30 m processed to 12.5 m. The maps provide information on SOC stocks in the top 30 cm of soil profiles, expressed in tons per hectare (t/ha). The MapBiomas data are public and free and can be accessed via the https://brasil.mapbiomas.org/ portal, assessed on 9 June 2025. Biodiversity was deduced from the land use map also available in the MapBiomas portal (https://brasil.mapbiomas.org/metodo_ cobertura_e_uso/, assessed on 9 June 2025).

2.2.4. A Multicriteria Analysis to Merge CUP and ES Data

The values of CUP and ES were recast as dimensionless ratings, based on their relationship with soil fragility or supply of provision/support ecosystem services, respectively. In Table 1, the ratings of CUP are sorted in ascending order of soil fragility, while for the ES the sorting is in descending order of supply. For the CUP and the ES stream flow and soil carbon stock, the boundaries between the various classes were set by distributing the respective values found in the CRW using the Jenks natural breaks method. Setting the boundaries this way, the Reclassify tool of ArcGIS software was then used to convert the maps of CUP and ES into corresponding maps of ratings using the conversion values listed in Table 1. For the ES recharge/springs, the criterion used to set up the ratings was: the headwaters until the lower elevation limit where most springs bloom out the bedrock, were seen as recharge areas and given the highest rating of 7; the remaining space within the CRW was described as discharge zones and assigned the lowest rating of 5. Finally, for the ES biodiversity, the allocation of ratings was based on the role commonly played by various land uses, interpreted from an ecological value perspective:

- *High ecological value (Ratings 9–7)*

Class 1: Forest Formation (9)—Acts as primary biodiversity reservoir. Its multi-layered canopy provides diverse niches, supporting complex food webs and stabilizing the local microclimate and nutrient cycles.

Class 2: Floodplain (9)—These are critical ecotones (transition zones). They offer unique hydrological connectivity, acting as nurseries for aquatic species and providing essential resources for terrestrial fauna during dry periods.

Class 3: Perennial Crops (7)—Unlike the annual crops, these provide stable soil cover and long-term root structures. This perennial nature allows for the establishment of more resilient soil microbial communities and provides a semi-stable habitat for generalist species.

- *Moderate ecological value (Ratings 6–4)*

Class 4: Forestry (6)—While monocultures (like eucalyptus) lack native floral diversity, they provide vertical structure, carbon sequestration, and can act as biological corridors connecting more diverse forest patches.

Class 5: Pasture (5)—Though simplified, pastures maintain permeable soil and herbaceous cover. If managed well, they support soil carbon storage and provide foraging grounds for various birds and small mammals.

Class 6: Mosaic of Agriculture/Pasture (4)—The high frequency of human disturbance and landscape fragmentation limits specialist species. The ecological value is hampered by the "edge effect" and inconsistent habitat availability.

- *Low ecological value (Ratings 3–1)*

Class 7: Temporary Crops/Sugarcane (3)—Characterized by frequent resetting of the ecosystem through harvesting. Intensive chemical inputs and low plant diversity create an unreceptive environment for most native wildlife and beneficial insects.

Class 8: Urban Infrastructure (2)—Represents a barrier to ecological flow. Soil impermeability prevents water infiltration, while light and noise pollution further degrade any remaining biological function.

Class 9: Non-vegetated areas (1)—These are areas of minimal ecological functionality. Without vegetation to protect the soil, these areas suffer from high erosion, lack of primary production, and extreme temperature fluctuations, offering very limited habitat value.

Table 1. Allocation of ratings to the CUP and ES variables to form the CUP-ES ecosystem function model. For every variable, ranking class 1 represents the largest score allocated to the variable and ranking *n* the lowest score. For example, ranking class 1 of CUP represents the regions where productive use is prioritized whereas ranking class 5 of soil carbon stock represents regions where this stock is the lowest. When forming the CUP-ES model, the ratings are allocated in reverse order of ranking, with exception of CUP because larger CUP scores are linked to productive instead of ecological functions in the watershed. The number classes of each variable as well as their characterization, is represented in the legends of corresponding distribution maps presented in the results section.

Ranking Class	CUP	Recharge/Springs	Stream Flow ($Q_{7,10}$)	Soil Carbon Stock	Land Use/Biodiversity
1	4	7	7	9	9
2	5	5	6	7	9
3	6		5	5	7
4	7		4	3	6
5	8		3	1	5
6					4
7					3
8					2
9					1

2.2.5. Analytical Hierarchy Process

Having defined and implemented the rating process, the importance of each parameter (CUP and ES) in the multicriteria framework was set up by a multidisciplinary panel composed of professionals from the fields of agricultural, biological, exact, and human sciences. Subsequently, the adopted importances were checked for consistency by the well-known Analytic Hierarchy Process (AHP) of Saaty [29–31]. The details on the application of AHP to the current study are presented in the Appendix A. In brief, the weights assigned by the experts were used to reconstruct the pairwise comparison matrix based on Saaty's scale. Then, the priority vector was derived from the normalized pairwise comparison matrix using the eigenvector method. The maximum eigenvalue was $\lambda\text{max} = 5.26$, which resulted in a consistency ratio $CR = 0.058$. Being less than 0.1, this ratio indicates acceptable consistency of judgments according to the AHP criteria. Thus, the weights proposed by the expert panel were accepted and are depicted in Table 2.

Table 2. Weighting of CUP and Ecosystem Services (ES; represented by ES1 to ES4) to form the CUP-ES multicriteria model and calculate the EFP index (Equation (2a,b)). The weight of ES (0.6) is the sum of weights assigned to ES1, ES2, ES3 and ES4.

CUP-ES Parameter	Weight
CUP	0.40
ES, with individual weights indicated below for each ES1 to ES4.	0.60
ES1 (Recharge/Springs)	0.10
ES2 (Stream flow ($Q_{7,10}$))	0.05
ES3 (Soil organic carbon)	0.20
ES4 (Land use/Biodiversity)	0.25

2.2.6. Ecosystem Functioning

In order to detect and map areas that simultaneously indicate protection of natural capital through CUP (e.g., recharge) and improved ES, the multiparameter index EFP—Ecosystem Functioning Potential was defined and calculated as follows:

$$EFP = 0.4 \times CUP + 0.6 \times ES \tag{2a}$$

with

$$ES = 0.10 \times ES1(\text{Recharge/Springs}) + 0.05 \times ES2(\text{Stream flow } (Q_{7,10})) + 0.20 \times ES3(\text{Soil organic carbon}) + 0.25 \times ES4(\text{Land use/Biodiversity}) \tag{2b}$$

Equation (2a) reveals that the CUP contributes with 40% and the assemblage of ES with the remaining 60%, while the individual ecosystem services (ES1 to ES4; Equation (2b)) contribute as indicated in Table 2.

The EFP index varies between a minimum of 2.7 and a maximum of 8.3, considering all possible combinations of ratings listed in Table 1 and weights depicted in Table 2. The calculation of individual ES and EFP are detailed in the Supplementary Materials. Under undisturbed ecosystem functioning, the larger EFP scores are allocated to regions where the CUP is low, representing steep hillslopes and regions of thin (fragile) soil cover, and where the supply of ecosystem services is the largest such as headwaters with SOC-rich soils and resilient streams or springs. The lowest EFP scores, on the other hand, are regions where agriculture and livestock pasturing are practiced (intensively) in flat or smoothly undulated landscapes covered by thick (resilient) soils, which are net consumers of ecosystem services (e.g., water, SOC, biodiversity). Finally, in between these two end-members there are hybrid regions of average EFP where agricultural and cattle grazing activities are mixed with natural landscapes, generally called transitional landscapes. This framing of EFP is represented in Figure 3 by the green cells located along the main diagonal of that CUP-ES diagram.

The status of undisturbed functioning described in the previous paragraph may not hold for every sub-basin of a watershed, in which case that catchment will be represented by a cell in the off-diagonal of Figure 3. Two scenarios can occur: (1) Disturbed ecosystem functioning, usually linked to average-low EFP scores and represented in Figure 3 by the yellow and red cells. Disturbed functioning in agricultural watersheds may occur in the course of inadequate occupation of fragile landscapes, deforestation, poorly managed agriculture, or livestock pasturing in marginal landscapes, among other causes. When the disturbance occurs, the supply of ecosystem services tend to drop and may even trigger disservices, such as amplified soil erosion accompanied by stream water pollution; landslides and damages derived therefrom; floods and their social and economic impacts; pests and invasive species that impact crop productivity; amidst other harmful consequences to the ecosystem; (2) Improved ecosystem functioning, frequently associated to average-high EFP scores and represented in Figure 3 by the bluish cells. This scenario is generally related to conservationist soil management practiced to smaller or larger extents where food production systems are implemented.

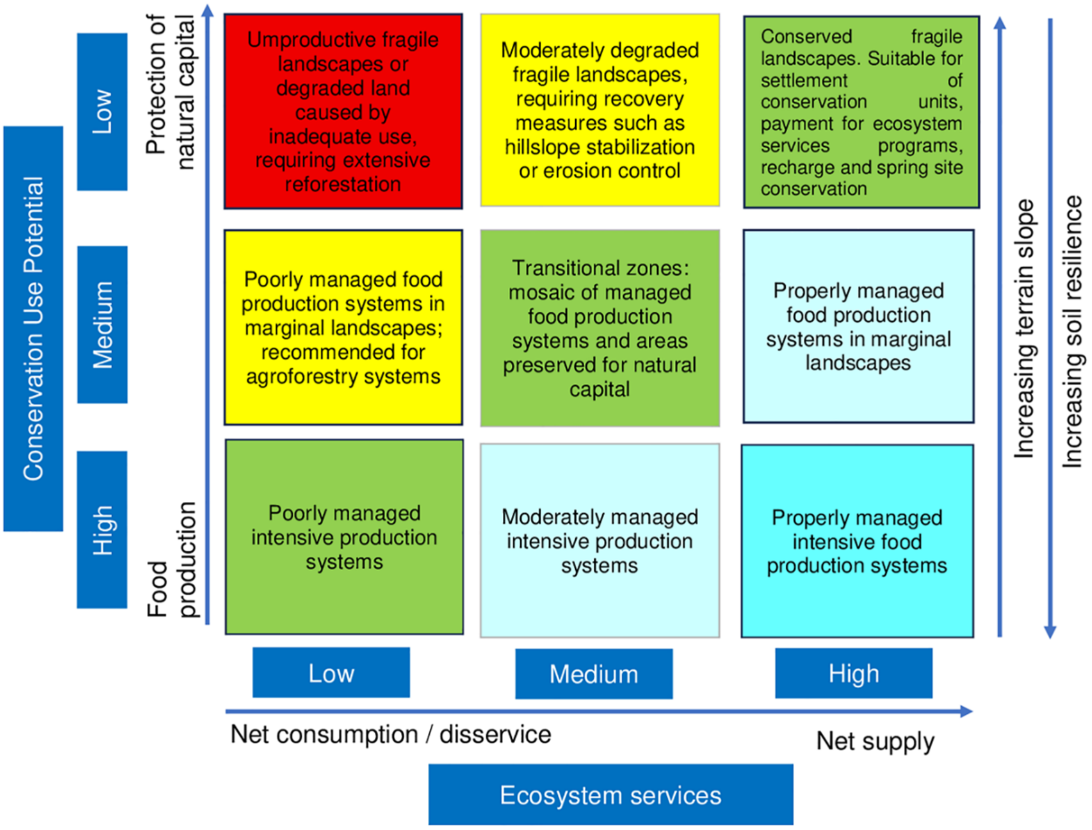

Figure 3. Framework model to assess the ecosystem functioning of agricultural watersheds, based on the combined assessment of CUP and ES (CUP-ES model).

According to the CUP-ES model rationale illustrated in Figure 3 and described above, areas of large EFP contribute significantly to maintain the ecological functioning of landscapes and should be protected for that role, and hence prioritized for integration in officially designated conservation units, be financially supported through PES programs; amid other protection mechanisms. On the other hand, the aforementioned areas of low or average-high EFP scores should be monitored for conservationist soil management so they can improve their ratios of ecosystem supply/ecosystem consumption. Finally, the above cited areas of average-low EFP scores should be targeted for recovery measures or even land use conversions, including the implementation of agroforestry systems or extensive reforestation. Taken together, the framework model used to access the ecosystem functioning of agricultural watersheds, portrayed in Figure 3, allows aggregating the EFP scores into five classes, as described in Table 3.

Table 3. Characterization of ecosystem functioning in agricultural watersheds and its relationship to five EFP classes.

ID	EFP	Description
A	6.14–8.2	Fragile landscapes with evident conservation of natural capital. This is ideal for setting up conservation areas and payment-for-ecosystem-services programmes, as well as protecting recharge areas and spring sites.
B	5.26–6.13	Areas used for agriculture and cattle grazing activities, occupying low to moderate slope landscapes, with moderately to improved implementation of soil conservation practices. Recommended for monitoring of ecosystem services under the implementation of conservationist soil management
C	4.69–5.25	Managed food production systems mixed with areas preserved for natural capital that together make up a mosaic of transitional zones. Adequate for monitoring the ecosystem services following the implementation of agroforestry systems
D	4.24–4.68	Unproductive and fragile landscapes, or degraded land caused by poor management, requiring extensive reforestation. Moderately degraded landscapes that require recovery measures such as hillslope stabilization and erosion control. Marginal landscapes with poorly managed food production systems that are recommended for agroforestry.
E	2.7–4.23	Intensive food production systems, practiced in low slope areas covered by resilient soils. Recommended for monitoring of ecosystem services to ensure long-term crop productivity and food security. Also recommended for implementation of conservationist soil management if the services drop in spite of soil's natural resilience

2.2.7. Sensitivity Analysis

In order to check the robustness of EFP modeling relative to the AHP weights, a sensitivity analysis was carried out following the "dynamic" and "one-at-a-time" scenarios [32]. The "dynamic" scenario involved moving the CUP weight represented in Equation (2a) from 10% less (0.36) to 10% more (0.44) the value proposed by the expert panel (0.4), while the weight of ES moved from 0.64 to 0.56 because the sum of CUP and ES weights must stay constant and equal to 1. The "one-at-a-time" scenario involved allocating the weight variation obtained from the "dynamic" scenario to a specific ecosystem service, one at-a-time, moving from ES1, ES2, ES3 and finally ES4 (Equation (2b)). Thus, while simulating the weight variation of ESy ($1 \le y \le 4$), the x% change assigned to the ES in Equation (2a) ($-0.1 \le x \le 0.1$) was allocated to the ESy in Equation 2b. The simulation runs considered a 2% step variation to the ES, meaning that 10 simulations were carried out for each ESy, with a grand total of 40 simulations. The calculation details are presented as Supplementary Materials.

3. Results

CUP-ES Model

In the Córrego Rico Watershed (CRW), the following soil units were identified according to [22]: oxisols (also called latosols) and acrisols (also termed argisols). The corresponding soil map is shown in Figure 4. The two soil types present significant differences that affect agricultural use, management and conservation practices. Oxisols are well-drained, generally deep, reddish or yellowish soils, characteristic of humid tropical regions. They have low natural fertility due to the leaching of nutrients [33]. Therefore, regular fertilization is often necessary to keep agricultural productivity. They also have a clayey to loamy texture, which ensures good water retention but can hinder drainage in more compacted areas. In addition, the oxisols tend to have low pH values and are therefore acidic soils, which may require correction with limestone. They also have a good granular and porous structure, which facilitates water infiltration, but can also make the soil susceptible to erosion when poorly managed, especially in sloping areas. Acrisols, on the other hand, are clayey soils with a well-developed textural B horizon. Like the oxisols, the acrisols generally have low natural fertility, requiring correction with organic and chemical fertilizers. They have physical limitations in the textural B horizon, being more susceptible to erosion processes, especially in areas with more rugged terrain.

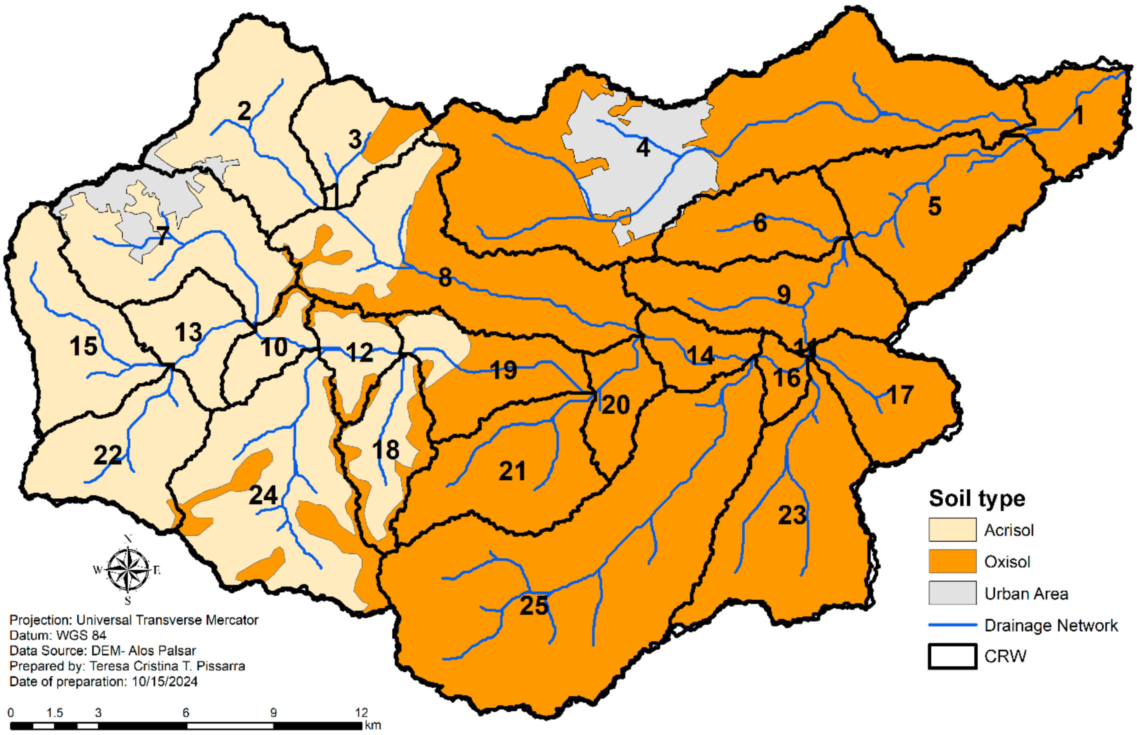

Figure 4. Soil units of Córrego Rico Watershed. Adapted from [22].

As regards suitability for agricultural use, the oxisols are good for farming when well managed. Management practices to contain the erosion process are crucial, especially in areas with steep slopes. The use of techniques such as no-till farming and terracing systems can help preventing soil and water loss. Due to their good water retention, oxisols are more suitable for areas that receive regular rainfall. However, in areas with intensive rainfall or steep slopes, erosion can be a problem. The use of drainage systems and soil cover is recommended to prevent nutrient loss. Acrisols, on the other hand, are good quality soils for agriculture, but tend to be more compacted, which can reduce water infiltration and root growth. To improve agricultural use, liming may be necessary to correct soil acidity and aeration. Cover cropping and crop rotation can improve soil structure and reduce compaction. In acrisols, compaction of B textural horizon can reduce water percolation, increasing the risk of waterlogging in areas with low slopes. The implementation of drainage systems and soil management practices such as the use of adapted agricultural machinery to prevent compaction is essential. Although compaction is a concern, soil structure can be restored through practices such as the use of organic matter, namely compost and manure, and minimum tillage, which helps preventing the formation of compacted layers. These are areas that require conservation practices such as no-till farming, the use of ground cover, agroforestry systems, or the conservation of natural vegetation to prevent degradation and improve soil quality.

The slope map of CRW is illustrated in Figure 5. The figure exposes gradients greater than 20% in the western region, mainly in the sub-basins 2, 3, 7, 10, 12, 13, 15, 18, 22 and 24. The comparison of Figure 4 (soil map) and Figure 5 (slope map) reveals that the oxisols are predominantly located in the flatter or gently undulated areas from the eastern region, with low to medium slopes (0 to 8%). The most representative sub-basins from this sector are the 1, 4, 5, 6, 9, 14, 16, 17, 20, 23 and 25, as well as part of sub-basins 8 and 19. The acrisols were observed in both the gently undulated terrain (3–20%) and in areas with steeper slopes (values above 20%), such as the sub-basins 2, 3, 7, 10, 12, 13, 15, 18 and 22, as well as parts of sub-basins 8, 19 and 24.

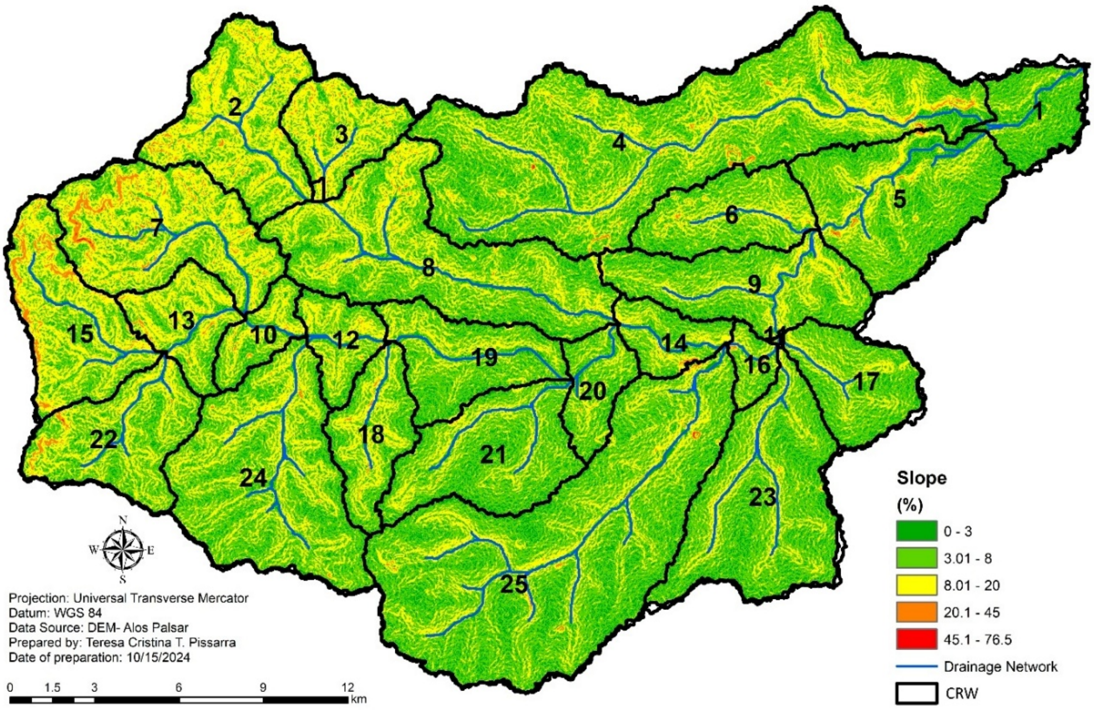

Figure 5. Slope map of Córrego Rico Watershed.

The lithology of CRW generally consists of sandstones consolidated with limestone cement, belonging to the Bauru Group (Upper Cretaceous), conglomerates, and basic effusive rocks of Serra Geral Formation, according to the Brazilian Geological and Geographical Institute (1963) (Figure 6). In the CRW, the Bauru Group comprises the Marília and Vale do Rio do Peixe formations. The Marília Formation is characterized by friable sandstones, claystones and conglomerates, with yellowish to reddish coloring. It represents ancient continental environments, such as deserts and alluvial plains. It is significant for paleontological studies, given the presence of dinosaur fossils, and for hydrogeology, as it can present good aquifer conditions. The Vale do Rio do Peixe Formation is composed predominantly of sandstones, siltstones and claystones, with sedimentary structures that indicate deposition in fluvial and lacustrine environments. It varies in color from yellowish to pinkish, and their sediments may contain fossils. It is relevant from a hydrogeological and geomorphological point of view, with potential for the formation of local aquifers. The Serra Geral basaltic sequence in the CRW is represented by the Pitanga Formation, being related to volcanic eruptions of Cretaceous period. It is composed of igneous rocks (basalts and andesites), with a massive or vesicular structure, rich in ferromagnesian minerals. Due to its geological nature, it can play an important role in the control of groundwater recharge and storage, in addition to influencing the fertility of soils formed from the weathering of basalt. In the drainage network, all the aforementioned rocks are covered by alluvial deposits from the Quaternary period, being generally composed of unconsolidated sediments such as sand, silt, clay, and gravel. They are formed by the action of rivers and watercourses, accumulating in riverbeds and floodplains. These deposits are important because they store groundwater in unconfined aquifers, are fertile for agriculture, and influence current geomorphological processes (https://www.sgb.gov.br/, assessed on 15 October 2025).

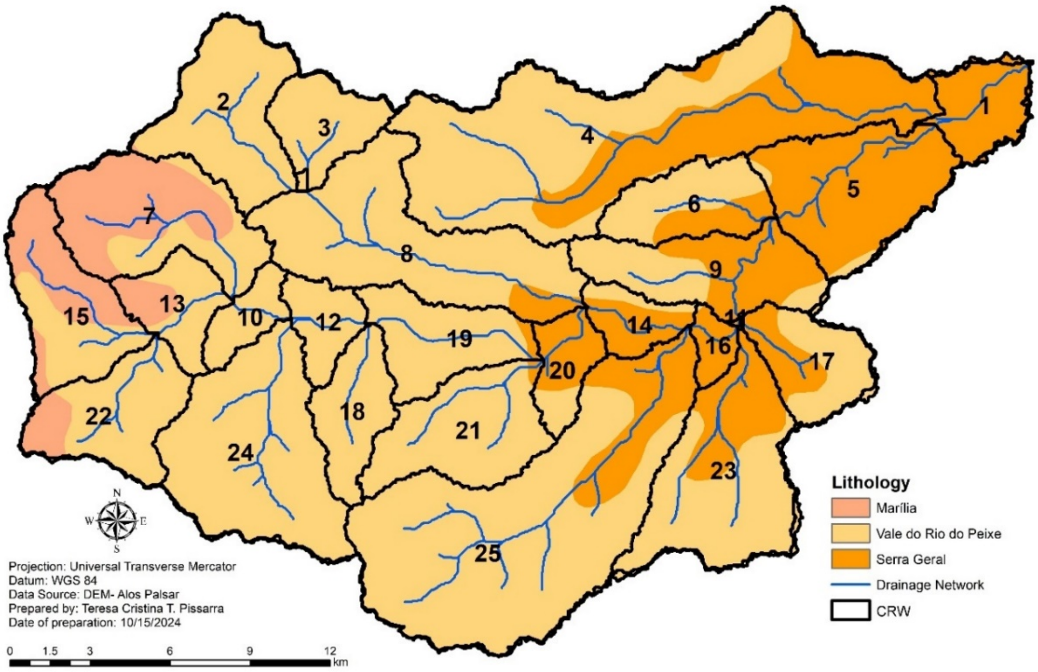

Figure 6. Geological map (lithology) of Córrego Rico Watershed. Adapted from the Brazilian Geological Institute (https://www.sgb.gov.br/, assessed on 15 October 2025).

The Conservation Use Potential (CUP) of CRW is shown in Figure 7. The highest values indicate areas that are naturally more likely to support production activities, i.e., they have a greater ecosystem carrying capacity for land use and are more resilient to agricultural activities. In the CRW, the CUP classes ranged from 0.6 (very low) to 5.0 (very high). The CUP map visually categorized areas in the basin according to their suitability or priority for conservation efforts, with color gradients indicating different levels of CUP values, namely from red (low) to blue (high). The blue regions are more capable of supporting anthropogenic activities and have greater adaptability and capacity to recover from environmental damages caused in the course of implementing the activity. As the CUP classes indicate the natural capacity of soil to support plant, forest, animal, and other anthropogenic activities in the CRW, these activities must be managed considering soil management and conservation practices in order to present the lowest risk of degradation. Regions with the lowest CUP values (red areas) exhibit a higher degree of natural fragility. The class of 0.6–1.8 represents areas with the lowest potential for conservationist use, where the greatest limitations on use occur due to the predominance of acrisols and the more rugged terrain and steep slopes, generally located in the headwaters of CRW. The class of 1.8–3.4 (low-medium) was considered to have an intermediate CUP value. The regions covered by this class could benefit from targeted restoration or more sustainable soil use and conservation practices. The class of 3.4 to 4.2 had the highest CUP in the region where oxisols predominate, which are less prone to erosion processes and allow greater water infiltration according to the studies of Costa et al. [9].

The mapping of ecosystem services, as approached by the SOC, water provision and biodiversity (land use and occupation), are illustrated in Figures 8 to 10. There seems to be a relationship between lower SOC values and the presence of streams and streamlets (Figure 8), suggesting the occurrence of SOC loss through rill erosion. Conversely, the largest SOC values are distributed across the hillslopes, suggesting that sheet erosion is less effective in removing organic carbon from the soil. Figure 9a illustrates the $Q_{7,10}$ and Figure 9b the recharge/discharge areas. The resilience of streamflow ($Q_{7,10}$) is larger in the hydrologic regions from the left and right margins of CRW (dark blue areas) than along the mainstream and headwaters. As expected, the headwaters are the place indicated for recharge in Figure 9b, while the discharge from the underground system occurs from the central part to the outlet of CRW. The biodiversity in the CRW (Figure 10) is very low because the watershed is mostly used for sugarcane production (area = 74.2%; Table 4), or used as mosaic of agriculture and pasture (area = 12.43%). The higher biodiversity occurs in the areas of forest formation, but they represent solely 5.61% of CRW. The spatial distribution of ecosystem functioning potential (EFP) can be observed in Figure 11. It can be considered that, in areas where the CUP values were very high to high (Figure 7), there is a high suitability to develop production activities. However, there was a relatively low net supply of ecosystem services, which indicates a highly modified environment with intensive activities and mostly moderate conservationist management.

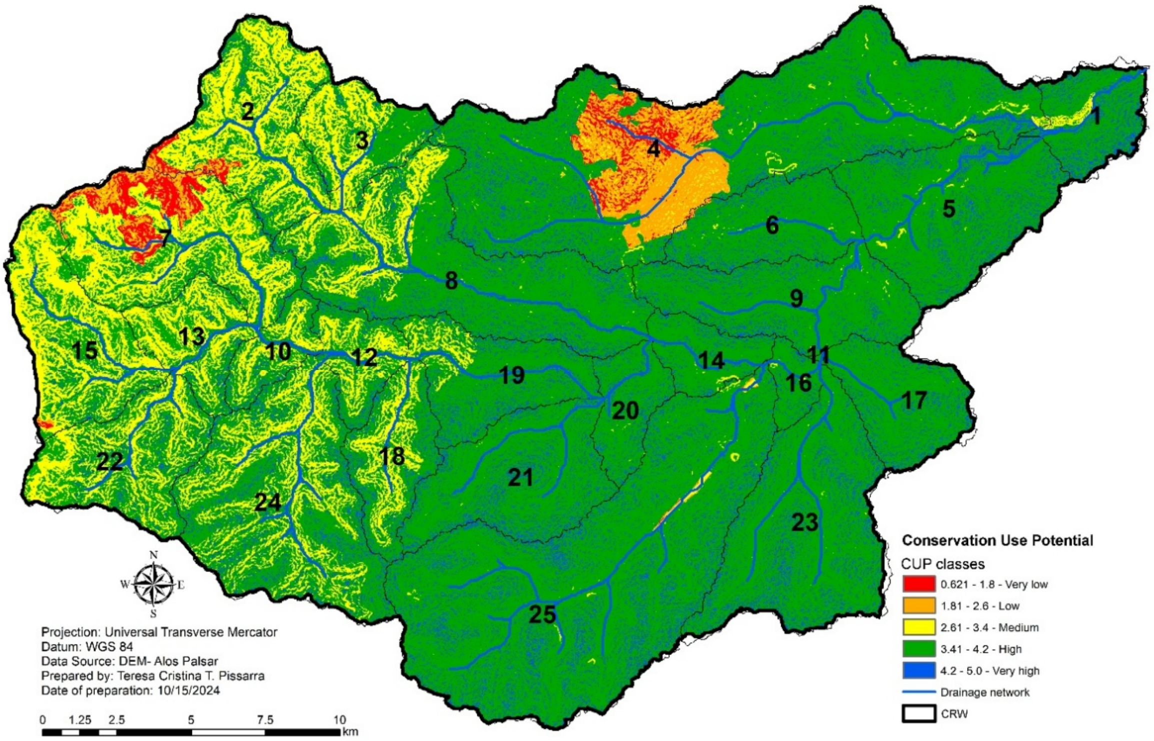

Figure 7. Conservation Use Potential (CUP) of Córrego Rico Watershed.

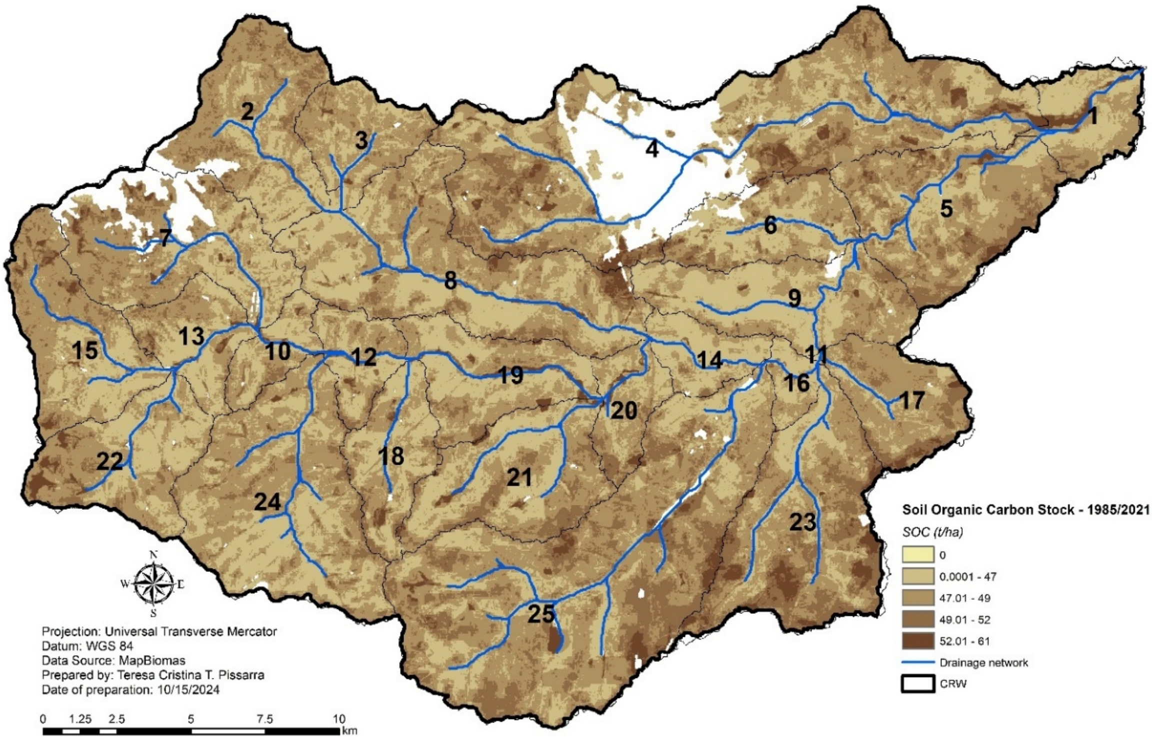

Figure 8. Soil Organic Carbon stock (SOC) in the Córrego Rico Watershed in the 1985–2021 period. Source: MapBiomas (https://brasil.mapbiomas.org/ assessed on 9 June 2025), Brazil.

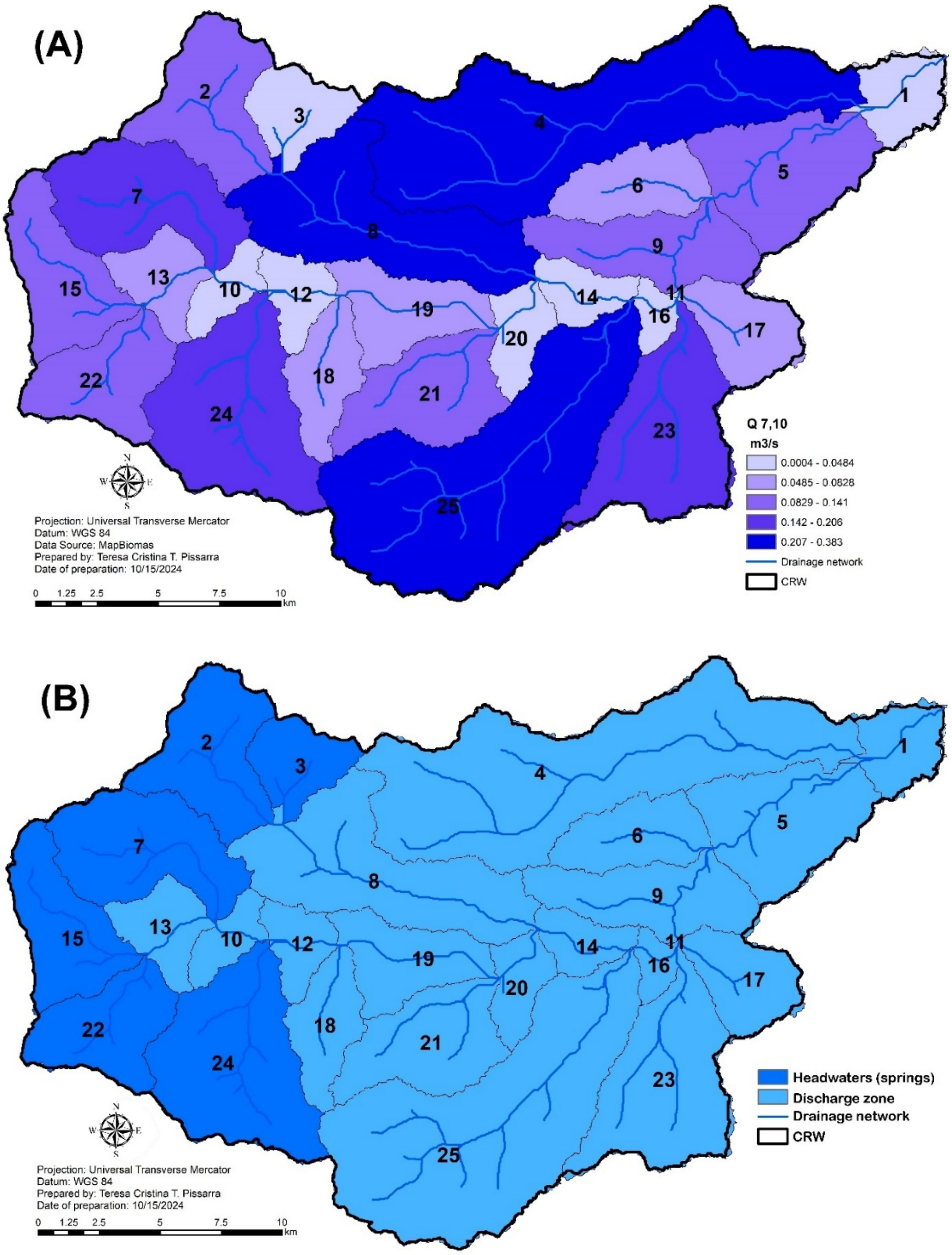

Figure 9. (**a**) Stream flow ($Q_{7,10}$) and (**b**) recharge/discharge areas in the Córrego Rico Watershed.

Table 4. Area and percentage of land use/occupation in the Córrego Rico Watershed.

Land Use/Occupation	Area (km^2)	Percentage (%)
Forest formation	32.05	5.61
Forestry	1.21	0.21
Floodplain	2.13	0.37
Pasture	11.03	1.93
Temporary crops (sugarcane)	424.19	74.20
Mosaic of agriculture and pasture	71.04	12.43
Urban infrastructure	26.80	4.69
Non-vegetated areas	1.69	0.29
Aquaculture	0.00	0.00
Drainage Network	1.34	0.23
Perennial Crops	0.16	0.03
Total	571.66	100.00

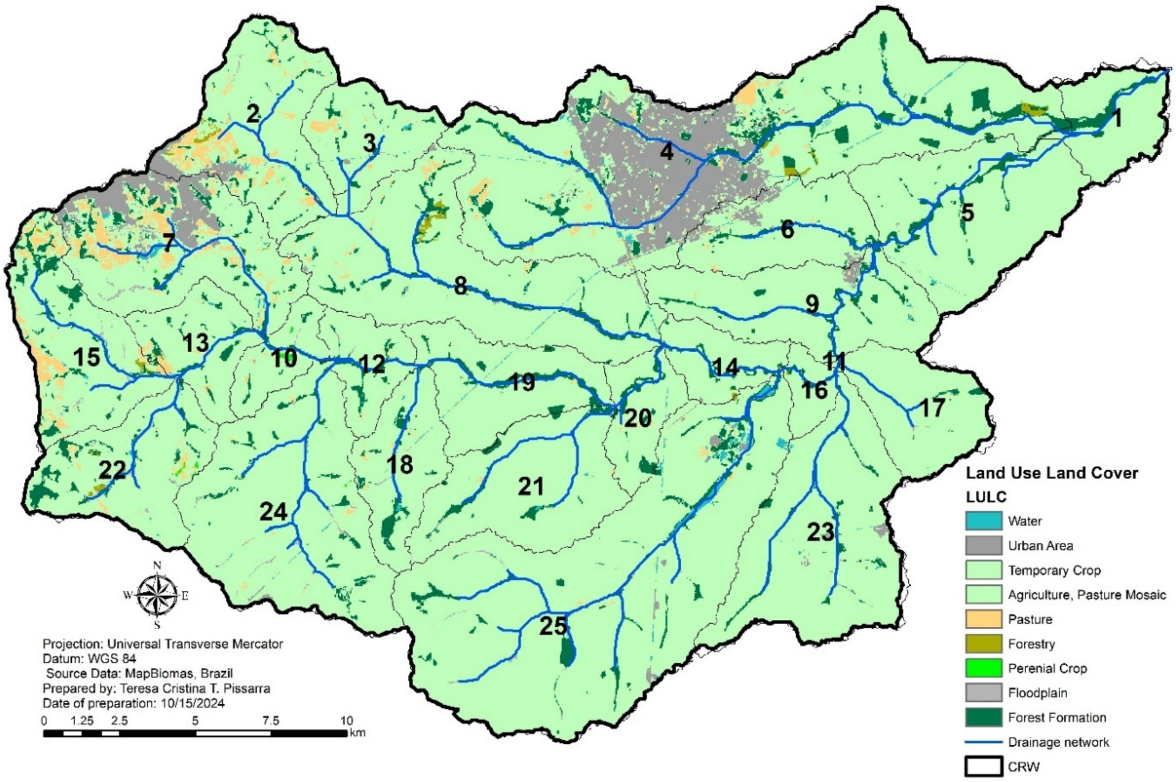

Figure 10. Biodiversity (land use/occupation) in the Córrego Rico Watershed.

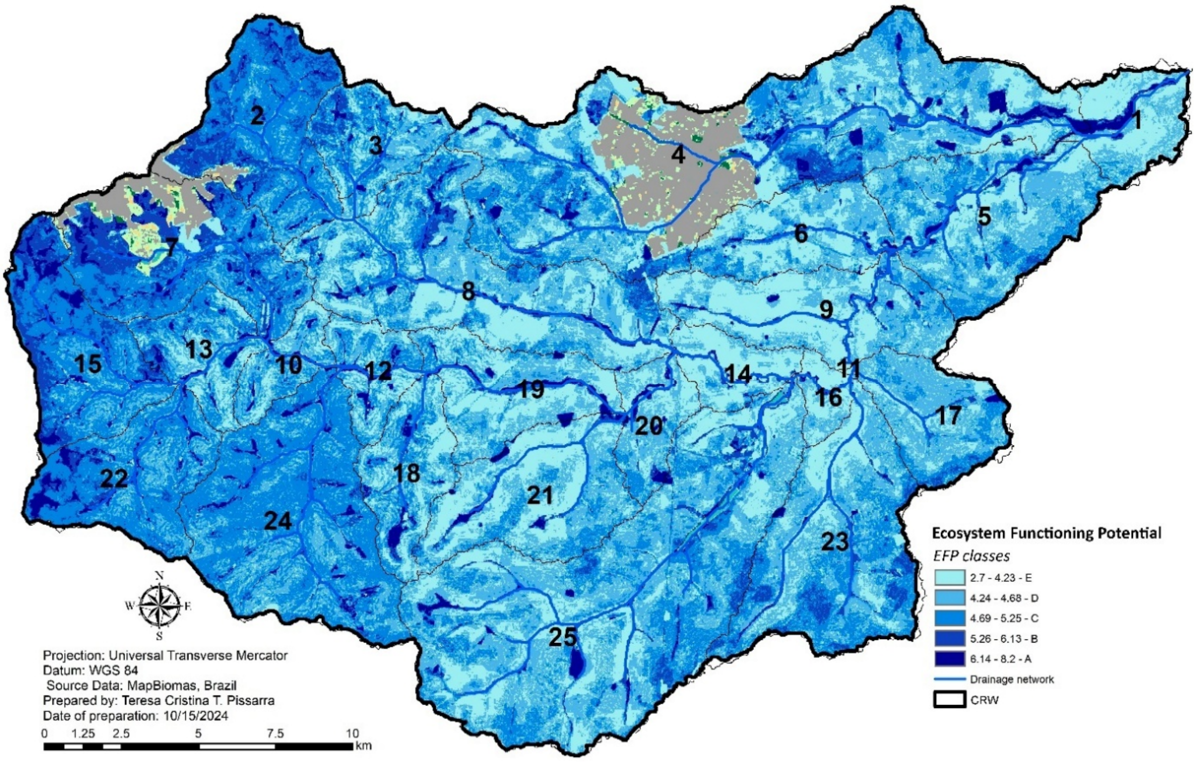

Figure 11. Ecosystem Functioning Potential (EFP) in the Córrego Rico Watershed. The legend identifies classes of EFP in keeping with the descriptions of Table 3.

4. Discussion

4.1. The CUP-ES Model and Its Role in Assessing Ecosystem Functioning

The sectors of low CUP within the CRW, namely the rural regions represented in yellow in Figure 7, are environmentally fragile, because steep slopes as well as soils and lithologies prone to erosion and denudation, are predominant. The presence of low CUP regions in a watershed point to sectors that naturally cannot support intensive use without serious risks of land degradation. In these areas, soil must be safeguarded for ecological functions and exempted from the food production function. According to [34], the unifunctional focus of humans on biomass production in agricultural systems has resulted in rapid soil degradation. In the sequel, like a boomerang, land degradation became a key threat to food security [35]. However, the condition of low CUP does not necessarily reveal an area with a high capacity for ecosystem regulation. Areas with very low CUP, when well conserved, can indeed supply abundant provision and support services, but if they are degraded, they cannot. Thus, the combined use of CUP and ES allows to detect whether the potential use is being respected in the target area, as indicated by the CUP, and simultaneously the protection of natural capital is being practiced leading to improved ES values (Figure 3). In the CRW, the CUP-ES analysis was based on average data of CUP and ES estimated for the 25 sub-basins (Table 5), being illustrated in Figure 12. The results show a predominance of sub-basins falling in the field of "*Moderately managed intensive production systems*", with sub-basins 2 and 7 located in the headwaters being placed in the so-called "*Transitional zones*", which is consistent with the reality. The joint assessment of sustainable management, soil quality and ecosystem services has been the topic of various recent studies [36–40], but this study provides a map (Figure 11) and a classification diagram (Figure 12) where the combination of those three components is spatially highlighted and interpreted, respectively, serving as tool to act where they are not confluent resulting in land degradation, meaning as decision-making tool. According to the works of Costa et al. [3,4], the CUP indicates the susceptibility of a soil so a better condition for use is offered, allowing the planning and implementation of production activities. However, for greater sustainability of food production systems, it is necessary to protect some areas for ecological productivity. By integrating the CUP with the ES, the analysis allowed the identification of priority areas where ES can provide the greatest ecological and socioeconomic benefits [16,41] in a rural watershed with high agriculture and livestock activity such as the CRW.

Table 5. Average CUP and ES ratings in the CRW considering the 25 sub-basins in separate.

Sub-Basin	AREA (m^2)	PUC	Rating PUC	Rating Recharge/Springs	$Q_{7,10}$ (m^3/s)	Rating $Q_{7,10}$	SOC (t/ha)	Rating SOC	Rating Biodiversity	EFP
1	10,386,406	4.2	5	5	0.04	3	48.2	5	4	4.6
2	24,712,969	3.4	6	7	0.08	5	48.2	5	4	5.2
3	11,856,875	3.5	5	7	0.04	3	48.2	5	3	4.7
4	82,819,531	3.6	5	5	0.30	7	48.4	5	3	4.7
5	28,455,469	4.1	5	5	0.10	5	48.5	5	3	4.6
6	15,318,125	3.9	5	5	0.07	4	48.0	5	3	4.5
7	28,988,906	3.1	6	7	0.14	6	48.4	5	4	5.3
8	42,350,000	3.8	5	5	0.21	7	48.1	5	3	4.7
9	22,362,500	4.0	5	5	0.11	5	47.7	5	3	4.6
10	6,598,906	3.6	5	5	0.03	3	48.0	5	4	4.6
11	116,406	4.0	5	5	0.00	3	47.4	5	4	4.6
12	8,072,344	3.6	5	5	0.03	3	48.1	5	4	4.6
13	10,966,406	3.5	5	5	0.05	4	47.9	5	4	4.6
14	7,649,844	4.0	5	5	0.03	3	47.2	5	3	4.5
15	21,125,938	3.4	5	7	0.10	5	48.3	5	4	5.0
16	3,790,938	4.1	5	5	0.01	3	47.6	5	3	4.5
17	13,969,063	4.0	5	5	0.07	4	48.8	5	3	4.5
18	13,020,313	3.7	5	5	0.06	4	48.1	5	4	4.6
19	16,898,594	3.9	5	5	0.08	4	48.1	5	4	4.6
20	8,329,688	4.1	5	5	0.04	3	48.4	5	4	4.6
21	23,056,094	4.0	5	5	0.11	5	48.4	5	3	4.6
22	19,797,031	3.6	5	7	0.10	5	48.2	5	4	4.9
23	33,476,719	4.0	5	5	0.17	6	49.2	7	3	5.0
24	39,977,656	3.7	5	7	0.20	6	47.9	5	3	4.8
25	77,961,250	4.0	5	5	0.38	7	48.8	5	3	4.7

The CUP-ES approach leverages informed decision-making for environmental planning, besides releasing the diagnostic presented in Figure 12. In the CRW, the most suitable areas for the preservation of ecosystem services were identified by the highest IFP scores in Figure 11, and should be designated priority areas to integrate programs supporting Payment for Environmental Services (PES) schemes. These areas comprised zones of high ecological value, such as the sub-basins 2, 3, 7, 15, 22 and 24 of Figure 1. These sub-basins are located in the headwaters of CRW and their preservation is mandatory to counteract the environmental impacts on ecosystems derived from the agricultural and cattle grazing activities prioritized in the lower lands, while enabling sustainability or at least neutrality in the entire watershed. It is worth recalling that headwater areas are sectors of a watershed where natural vegetation cover and biodiversity is usually greater, carbon dioxide (CO_2) sequestration is enhanced which helps regulating the climate [42,43], and the conditions for infiltration and aquifer recharge are ideal [44]. Besides, natural vegetation acts as a barrier against the impact of raindrops and the velocity of surface runoff, consequently reducing the intensity of erosion and flooding [45,46]. Finally, as increased biodiversity naturally regulates populations of harmful organisms and keeps ecosystems balanced, populations become healthier and pollinators, such as bees and butterflies, can be more effective.

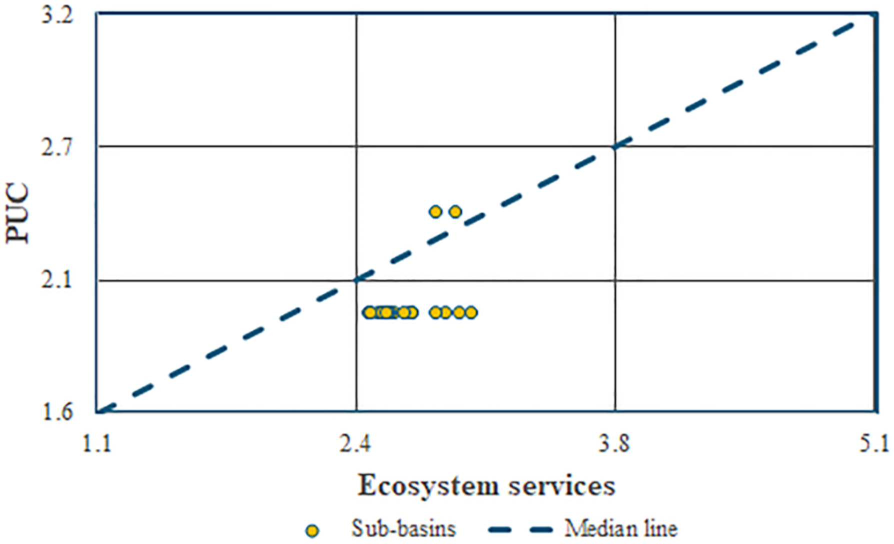

Figure 12. Classification of CRW sub-basins based on the CUP-ES analysis. Most sub-basins fall in the “moderately managed intensive production systems” (cf. Figure 3), whereas sub-basins 2 and 7 fall in the so-called “transitional zones” composed of productive systems and areas where the natural capital is preserved. The median line generally discriminates areas with disturbed ecosystem functioning (above the line) and improved ecosystem functioning (below the line), whereas the cells crossed by the line are assumed to be in normal ecosystem functioning.

4.2. The EFP Support to the Implementation of PES Schemes

The objective of Payment for Ecosystem Services (PES) schemes is to reward landowners or users who adopt practices that preserve or enhance ecosystem services. As such, Figure 11 provides a scientific basis for identifying priority zones for the implementation of PES (the class A areas), justifying financial incentives to landowners in areas with high EFP to maintain or enhance ecosystem functions. The rewarding must be limited on time and checked periodically for efficacy through monitoring of ES. In this regard, the development and spatialization of a potential soil multifunctionality index for agriculture on a regional scale, as proposed by [47], reinforced the importance of continuous monitoring of ES using annually updated spatial data, to check PES schemes for liability and to justify rewarding continuity. Constanza et al. [48], on the other hand, estimated the global value of ES to range from US$ 125 to US$ 145 trillion per year, highlighting that natural capital protection is essential for the economy and human well-being, supporting this way the implementation of PES programs. Thus, recognizing the economic value of ES is a crucial step towards including them in decision-making and public policies, especially through Payment for Environmental Services (PES) programmes.

The purpose of assigning monetary value to ES is to raise awareness in society about our dependence on these services and their preservation. Targeted conservation policies can allocate PES funds to areas with greater ecological value such as the class A regions portrayed in Figure 11, while restoration strategies should focus on degraded areas (class E regions). It is therefore recommended to integrate the valuation of ES into the zoning of CUP, an already official conservationist soil management tool in the Minas Gerais state, highlighting priority areas for recovery (e.g., land use conversions), properly managed agriculture and cattle grazing activities, conservation of natural capital, based on the EFP map. In the CRW, the CUP methodology was applied in conjunction with ES. The CUP-ES model made it possible to identify and prioritize areas with relevant environmental functions, considering natural attributes such as soil, slope and lithology, which favor water regulation, carbon storage, and biodiversity conservation. The spatialization EFP served as strategic tool for territorial planning, supporting decision-making in rural areas with a focus on sustainability and the mitigation of environmental degradation. It does merit the aforementioned integration in the CUP zoning, officially. In PES contexts, the EFP contributes to justifying and implementing more effective environmental policies by identifying areas of greater ecological and economic return within rural properties. In the CRW, for example, the headwaters facing west and located at the higher elevations were recognized as priorities for conservation actions, maximizing environmental benefits (clean water) to beneficiaries living at the Jaboticabal municipality [8]. These measures strengthen the resilience of CRW as whole, besides promoting climate change adaptation to water scarcity in the long term.

The accretion of ES into food production systems is a corollary of assessing ecosystem functioning through the EFP index, because the index looks at production systems and ES simultaneously and through the same lens. According to what has been described in Table 3 about the EFP classes, services such as water supply, climate regulation and biological pest control are urged to merge with agricultural and agroforestry systems, becoming strategic assets in rural production. This recognition also justifies the implementation of PES programs, as well as ecological certifications, or any public policy that rewards sustainable production practices. In the context of EFP realization, farmers are expected to begin managing the ES as an essential part of their production system, adopting conservation practices that protect biodiversity, soil fertility, and water resources. One example is the agroforestry system [49,50], in which supporting and regulating ES are integrated into production, reinforcing the property's ecological efficiency and economic sustainability [51]. According to various authors, the success of a PES scheme is associated with the creation of sustainable production chains [52], where products originating from the maintenance of ES, such as clean water, agroecological foods, or carbon credits, generate market value. To this end, the State must act to formulate public policies and financial instruments, promoting access to rural credit with equitable conditions for small and large producers [53]. These incentives can transform protected areas into sustainable production units, where environmental conservation is rewarded economically.

The valuation of ES can be carried out using different metrics [54,55], such as volume of water kept in the watershed (m^3/year), area of native vegetation preserved (ha), carbon dioxide sequestered in the soil and vegetation (tCO_2/year), and erosion reduction (tons of soil loss avoided). Monetization can resort to different methods [56,57], namely avoided cost (e.g., savings in water treatment), market price (e.g., carbon credits), or willingness to pay (estimated by research). Thus, the realization of CUP-ES and EFP in the CRW or elsewhere is well grounded by the literature, justifying its legal recognition and integration in public policies and management plans as soil conservation tool. The PES model also requires a clear definition of beneficiaries and service providers [58]. Beneficiaries (e.g., companies, municipalities, consumers) must financially compensate providers (e.g., farmers, local rural communities) with contracts that stipulate value, frequency, monitoring criteria, and conditions for service continuity. The use of technologies such as remote sensing and GIS is essential to ensure map, assess and monitor the services provided and its continuity in the long term [59]. In the CRW, farmers who respect legally-protected areas, preserve riparian forests, and adopt sustainable practices already receive annual payments per hectare, according to the improvement in the quality and quantity of water supplied to urban areas, namely the municipality of Jaboticabal [8]. Schemes like the one ongoing in the CRW give visibility and real value to the invisible benefits of nature, integrating environmental conservation into the rural economy and land management. Furthermore, the coexistence of agribusiness and agroecology is both possible and necessary [60,61]. While agribusiness contributes significantly to the trade balance and technological advancement in the field, agroecology strengthens short supply chains, promotes sustainable practices, and values cultural and biological diversity. Both approaches play a crucial role in rural development, income generation, and food security.

As final note, it is essential that small producers have equitable access to public policies, credit lines, and technical assistance, with fair conditions such as differentiated interest rates. The democratization of access to credit and environmental incentives, such as the PES, contributes to reducing inequalities and ensuring that families can remain in the countryside with dignity. The official recognition of CUP-ES analysis (Figures 3 and 12) as well as the EFP index (Figure 11) as powerful tools for integrating the valuation of ecosystem services into the territorial management carried out by the CUP, would contribute to expand equity among players in the agribusiness and agroecology sectors, promoting ecological, economic, and social sustainability in watersheds. The current application of PES in the CRW, grounded on the EFP, demonstrates its potential to guide public policies and transform environmental conservation into a long-term productive strategy.

4.3. Sensitivity Analysis of EFP

The average EFP values of CRW calculated for the 40 simulation runs are presented in Table 6, while the details of each run and sub-basin are provided as Supplementary Materials. The results suggest small sensitivity of EFP to changes in the weights of CUP and the various ES (Equation (2a,b)). For example, moving SOC weight from 0.24 to 0.16, meaning ±20% from the value proposed by the expert panel (see the "Sensitivity Analysis_SOC"

Sheet in the Supplementary materials), barely changed the EFP. The largest response came from the ES4 (Land use/Biodiversity), which moved the average EFP from 4.64 when the CUP weight is reduced by 10% to 4.76 when the CUP weight is increased by 10% (see the values under the heading ES4 in Table 6), meaning that from one edge to the other the EFP variation is solely 2.7%. Overall, the impact of changing the weights resulted in a variation of EFP from a minimum of 4.64 and a maximum of 4.76. Comparing this range with the meaning of EFP as defined in Table 3, it is clear that the CRW fits Class C of ecosystem functioning ("Managed food production systems mixed with areas preserved for natural capital that together make up a mosaic of transitional zones. Adequate for monitoring the ecosystem services following the implementation of agroforestry systems"), with the exception of scenarios where the weight of CUP is 0.9–0.94 the value proposed by the expert panel, in which case the basin moves (degrades) to Class D ("Unproductive and fragile landscapes, or degraded land caused by poor management, requiring extensive reforestation. Moderately degraded landscapes that require recovery measures such as hillslope stabilization and erosion control. Marginal landscapes with poorly managed food production systems that are recommended for agroforestry"). In view of these results, it is reliably considering that the discussion of CUP-ES model and especially of EFP index, presented in the previous sections, is robust.

Table 6. Sensitivity analysis of AHP weights and corresponding impact on the average EFP scores of CRW. The ES1 to ES4 represent Recharge/Springs, Stream flow (Q7,10), Soil organic Carbon and Land use/Biodiversity, respectively. The heatmap colors highlight the gradients of ES (from the lowest value represented in red color to the highest represented in green color) and corresponding percent variation (from the lowest value represented in red color to the highest represented in blue color).

Parameter	ES1	ES2	ES3	ES4	Min	Max	Var(%)
0.9CUP	4.72	4.68	4.70	4.64	4.64	4.72	1.69
0.92CUP	4.71	4.68	4.70	4.65	4.65	4.71	1.35
0.94CUP	4.71	4.69	4.70	4.66	4.66	4.71	1.01
0.96CUP	4.71	4.69	4.70	4.68	4.68	4.71	0.67
0.98CUP	4.70	4.70	4.70	4.69	4.69	4.70	0.33
1.00CUP	4.70	4.70	4.70	4.70	4.70	4.70	0.00
1.02CUP	4.70	4.71	4.70	4.71	4.70	4.71	0.33
1.04CUP	4.69	4.71	4.70	4.73	4.69	4.73	0.67
1.06CUP	4.69	4.71	4.70	4.74	4.69	4.74	1.00
1.08CUP	4.69	4.72	4.70	4.75	4.69	4.75	1.34
1.10CUP	4.69	4.72	4.70	4.76	4.69	4.76	1.68
Min	4.69	4.68	4.70	4.64			
Max	4.72	4.72	4.70	4.76			
Var(%)	0.7	1.0	0.0	2.7			

5. Conclusions

The assessment of ecosystem functioning in the Córrego Rico Watershed (CRW), comprising the planning of sustainable food production, landscape recovery or conservation, conservationist soil management and ecosystem service valuation, proved efficient when the Conservation Use Potential (CUP) classes were aligned with provisioning Ecosystem Services (ES) such as water supply, as well as supporting services like soil and biodiversity conservation. Moreover, the CUP-ES approach, summarized as aggregated Ecosystem Functioning Potential (EFP), proved strategic to support policies for implementing food production systems (crop, forest, cattle) and environmental conservation actions under the umbrella of Sustainability. Key outcomes from this study showed that an integrated analysis such as the CUP-ES/EFP allows the identification of specific territories where compatibility between land use and ecosystem services supply can be maximized, strengthening the scientific basis for the implementation of Payment for Environmental Services (PES) schemes. This possibility promotes more efficient and targeted territorial planning, capable of guiding investments in conservation and encouraging sustainable practices among landowners and users, ensuring the maintenance of ecosystem functions in the river basin essential to the well-being of all those living there.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2605081343348545/EESUS-26010171-Supplementary-Materials.xlsx. The Supplementary Materials comprise an Excel file with details on the calculation of EFP index and corresponding sensitivity analysis of embedded weights (Equation (2a,b)).

Author Contributions

T.C.T.P.: conceptualization, methodology, investigation, writing—original draft preparation; A.M.C.: data curation, software, visualization; L.F.S.F.: formal analysis, validation, writing—reviewing and editing; F.A.L.P.: methodology, investigation, data curation, software, writing—reviewing and editing, visualization; A.M.daC.: resources, supervision, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The base data will be available on request. The study does not incorporate statistical assessments.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. The Analytical Hierarchy Process to Determine the Contribution (Weights) of CUP and ES to the EFP

A.1. Analytical Framework

The Ecosystem Functioning Potential (EFP) was quantified using a multi-criteria decision analysis (MCDA) approach based on the Analytic Hierarchy Process (AHP), originally proposed by Thomas L. Saaty [29–31]. The AHP was selected because of its ability to systematically integrate biophysical variables and ecosystem service indicators into a hierarchical and consistent weighting structure.

The EFP index combines Conservative Use Potential (CUP) and Ecosystem Services (ES), following (Equation (A1)):

$$EFP = (0.40 \cdot CUP) + (0.10 \cdot R) + (0.05 \cdot F) + (0.20 \cdot C) + (0.25 \cdot LU) \quad \text{(A1)}$$

where R = water recharge, F = streamflow (Q7,10), C = soil organic carbon, LU = land use/biodiversity.

This formulation reflects expert-based weighting derived from a multidisciplinary panel.

A.2. Hierarchical Structure

The AHP model was structured into three levels:

Level 1: Goal—Ecosystem Functioning Potential (EFP)

Level 2: Criteria—CUP (0.40), water recharge (0.10), streamflow (0.05), soil organic carbon (0.20), land use/biodiversity (0.25)

Level 3: Sub-criteria—(3a) CUP decomposition—soil, lithology, slope, with soil represented by drainage, depth, texture, fertility; lithology represented by nutrient supply, denudation resistance, geochemical proxy; and slope represented by five slope classes (0–3%, 3–8%, 8–20%, 20–45%, >45%); (3b) Ecosystem services—recharge (infiltration, permeability, topography), flow (baseflow, runoff regulation), carbon (organic matter, management, depth), land use (categorical classes reflecting ecological integrity)

A.3. Pairwise Comparison Matrix

Although the final weights were defined a priori (Equation (A1)), a pairwise comparison matrix was reconstructed to ensure methodological transparency and allow consistency verification. Each matrix element a_{ij} expresses the relative importance between criteria $i$and j, following Saaty's fundamental scale (1–9):

$$a_{ij} \approx \frac{w_i}{w_j} \tag{A2}$$

where w_i and w_j are the predefined weights. The resulting matrix A is:

$$A = \begin{bmatrix} 1 & 4 & 7 & 2 & 2 \\ 1/4 & 1 & 2 & 1/3 & 1/2 \\ 1/7 & 1/2 & 1 & 1/4 & 1/5 \\ 1/2 & 3 & 4 & 1 & 1 \\ 1/2 & 2 & 5 & 1 & 1 \end{bmatrix} \tag{A3}$$

A.4. Eigenvector Derivation of Weights

The priority vector wwas computed using the eigenvector method, which consists of:

(i) Column normalization:

$$a_{ij}^{norm} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{A4}$$

(ii) Row averaging:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}^{norm} \tag{A5}$$

The resulting weight vector was:

$$\mathrm{w} = \begin{bmatrix} 0.406 \\ 0.097 \\ 0.052 \\ 0.227 \\ 0.218 \end{bmatrix} \tag{A6}$$

which closely reproduces the original weighting scheme (Equation (A1)).

A.5. Consistency Analysis

The consistency of judgments was evaluated using the maximum eigenvalue λ_{max}, obtained as:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(A\mathrm{w})_i}{w_i} \tag{A7}$$

The Consistency Index (CI) is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{A8}$$

The Consistency Ratio (CR) is:

$$CR = \frac{CI}{RI} \tag{A9}$$

where RI is the Random Index (Saaty).

For this study:

- $\lambda_{max} = 5.26$
- $CI = 0.065$
- $RI = 1.12$(for $n = 5$)
- $CR = 0.058$

Since $CR < 0.10$, the matrix is considered consistent.

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