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Assessing and mapping ecosystem services in a tropical seasonal forest landscape

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A B S T R A C T

Ecosystem service surveys provide a basis for understanding how ecosystem functions and processes contribute to human well-being. In South America, forest ecosystems represent an important source of these services, although their spatial dynamics within the Caatinga (tropical dry forest) biome and its ecotone seasonal forests zones are still understudied. In this context, this research aimed to evaluate the ecosystem services provided by a tropical seasonal montane forest (TSMF) in Northeastern Brazil. The services were classified (CICES) and spatialized according to their relevance, based on data collected in situ and remote sensing data, analyzed in a Geographic Information System. The João do Vale mountain range vegetation cover provides "Provision" ecosystem services, with 91.45% of the study area providing "high relevant capacity" services for this class, and "Cultural" services, with 95.85% of the study area providing "very high relevant capacity" services, both directly and indirectly, through cultural relations with plant and fauna components. Regarding "Regulation and maintenance" services, a relationship between forest environments, declivity, and human activities was observed. The low slope areas covered by the TSFM present between 0 to 5 $t.ha^{-1}.year^{-1}$ of soil losses and occupy 15% of the study area, with the "very high relevant capacity" class assigned to these areas. At the other extreme, soil losses exceed 200 $t.ha^{-1}.year^{-1}$, reaching a maximum of 3,056.8 $t.ha^{-1}.year^{-1}$, were also observed. Finally, the ecosystem services in the study area were integrated, to characterize the way of life and relationships between local rural communities.

Keywords: Caatinga Biome; Ecosystem service; GIS; tropical mountain range vegetation; tropical seasonal montane forest.

Avaliação e mapeamento de serviços ecossistêmicos em uma paisagem de floresta tropical sazonal

R E S U M O

Os levantamentos de serviços ecossistêmicos oferecem bases para o entendimento de como funções e processos ecossistêmicos contribuem com seus benefícios para o bem-estar humano. Na América do Sul, os ecossistemas florestais representam uma importante fonte desses serviços, sendo pouco conhecida a dinâmica espacial destes serviços dentro do bioma Caatinga (tropical dry forest). Esta pesquisa teve como objetivo avaliar os serviços ecossistêmicos prestados por um ambiente de floresta tropical estacional montana (FTEM) na região Nordeste do Brasil. Os serviços foram classificados (CICES) e espacializados segundo sua relevância com base em de dados de sensoriamento remoto. A cobertura vegetal da Serra João do Vale presta serviços ecossistêmicos de "Provisão" (91,45% da área estuada presta serviços de "Alta capacidade relevante") e "Cultural" (95,85% prestam serviços de "Capacidade relevante muito alta"), direta e indiretamente, por meio das relações culturais com o componente vegetal e faunístico. Já para os serviços de "Regulação e manutenção" analisados, observou-se que há uma relação entre os ambientes florestais, declividade e atividades humanas. Foi constatado que as áreas pouco declivosas recobertas por FTEM apresentam entre 0 a 5 $t.ha^{-1}.ano^{-1}$ de perdas de solos e ocupam 15% da área de estudo. Para estas áreas foi atribuído à classe "Capacidade relevante muito alta". No outro extremo, foi registrada perda de solo que supera as 200 $t.ha^{-1}.ano^{-1}$, atingindo o máximo de 3.056,8 $t.ha^{-1}.ano^{-1}$. Por fim, os serviços obtidos para a área de estudo integram-se para caracterizar o modo de vida e as relações entre as comunidades rurais ali presentes.

Palavras-chave: Bioma Caatinga; Serviço do ecossistema; SIG; vegetação de serra tropical; floresta tropical sazonal montana.

Introduction

Ecosystem service (ES) surveys provide a basis for understanding how ecosystem functions and processes contribute to human well-being (e.g. Costanza et al., 1997). After the Millennium Ecosystem Assessment (MEA, 2005), a growing application of service surveys aiming to raise awareness on the conservation and intelligent use of natural ecosystem resources has been observed (e.g. Georgia et al., 2022; Chicago et al., 2022; Ma et al., 2022; Reale et al., 2022; Oliveira et al., 2023; Mamedes et al., 2023).

In a service survey context, cartographic representations have experienced increasing applications, due to their importance in landscape-integrated analyses, such as the production of studies associating ES to land use and occupation dynamics (e.g. Bao et al., 2023; Pilogallo and Scorza, 2022; Maes et al., 2016; González-García et al., 2022). In this regard, service surveys and analyses gain strength when assessing service spatializations and where they occur.

Important ES surveys have been carried out in South America (e.g. Mamedes et al., 2023, Oliveira et al., 2023; Niemeyer and Vale, 2022), although a gap concerning service spatial modeling knowledge in these environments is still evident. It is known that several ecological processes occurring in the Caatinga biome can trigger certain services, such as biomass production (e.g. Menezes et al., 2012; Jardim et al., 2023), the role of vegetation cover in erosion control (e.g. Santos et al., 2018) and the appropriation of these processes, as well as the use of wood/plant and wildlife resources, by rural communities.

Research on ecosystem services provided by seasonal montane tropical forests (SMTF) of crystalline massifs in the semi-arid region of Northeastern Brazil are scarce. Studies of the type on watersheds predominate (for example, Chaves et al., 2021; Oliveira et al., 2023), conservation units (for example, Val et al., 2022) and estuarine environments (for example, Costa et al., 2022). Therefore, inventories and assessments of the ecosystem services provided by seasonal montane tropical forests are urgent. Based on this scenario, our hypothesis is that SMTF provide relevant ES, even if they are undergoing processes of deforestation or ecological succession. The continued alteration of forest cover will seriously affect the continuity of the provision of ecosystem services.

In this context, this study aimed to evaluate the ES of the native vegetation remaining in the João do Vale mountain range (RN/PB). Services were spatialized and classified according to their relevance following the scale proposed by Burkhard et al. (2009).

Material and methods

Study area

The study area comprises approximately 278 km^2 and is located between the states of Rio Grande do Norte and Paraíba, in the Brazilian semiarid region (Figure 1). The João do Vale mountain range relief is characterized by steep slopes, slopes, and a small flat area on the top composed of sedimentary rocks belonging to the Martins Formation mountain range. Its geological composition consists, briefly, of igneous, metamorphic, and sedimentary rocks (Maia and Bezerra, 2019), with altitudes ranging between 200 and 754 meters and a local climate influenced by the Intertropical Convergence Zone (ITCZ), with the rainy season occurring during the first four months of the year. Different forest physiognomies cover the massif (Oliveira and Costa, 2023). Among the cited physiognomies, the tropical seasonal montane forest (TSMF) stands out (Figure 2).

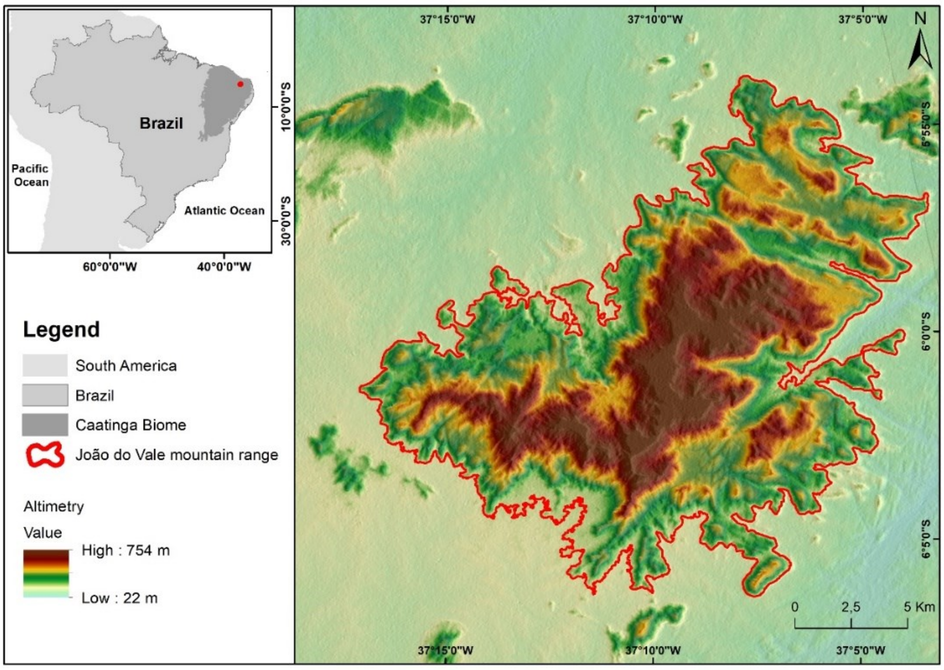


Figure 1: Location of the study area. Source: Elaborated by the authors.

Figure 2: Different Forest physiognomies. Source: Elaborated by the authors.

Methodological procedures

Land use and land cover classification and mapping were carried out with the aid of the InterIMAGE© software, v. 1.3. The input image comprised the panchromatic band of the CBERS 4 satellite (spatial resolution of 5 meters, orbit: 149, dot: 107 and date: 12/27/2017). Segmentation was performed using a CBERS 4 image composed of the R3G4B2 bands (spatial resolution of 10 meters, orbit: 149, point: 107, and date: 12/27/2018). The shade, geometry, and location of the groupings resulting from the segmentation were taken into account for classification purposes so that each area could be correctly classified into pre-established classes (arboreal Caatinga vegetation, shrub Caatinga vegetation, Water body, tropical seasonal montane forest (TSMF), Exposed soil/Housings/Rocks and Agricultural uses).

ES classifications were performed based on the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2013), as follows: 1) Provision services (food, wood and other resource provisions, etc.); 2) Regulation, and maintenance services (water and soil quality and area degradation regulation, among others.); 3) Cultural services (recreational, physical and mental health benefits, tourism, aesthetic landscape appreciation and other non-material benefits) (Haines-Young and Potschin, 2013).

The provision and cultural section services were validated, in situ, through the application of questionnaires applied based on the “key informant” or “snowball” method (Marshall, 1996), in which each interviewee indicated the next participant, and so on. Surveys of services through questionnaires were carried out in two stages: 1) Submission of the data collection protocol through a semi-structured questionnaire to the Ethics Committee of the Federal University of Rio Grande do Norte (CEP/UFRN); and 2) After the release of the protocol (CAAE: 98794918.5.0000.5537 and opinion number: 2.996.474). A total of 18 people were interviewed between December 2018 and January 2019, 07 women and 11 men, aged 40 and older, and residing in the area for over 20 years.

For the generation of the map of “Provision services” of the study area, the services listed by the interviewees were weighted. The same procedure was applied to the “Cultural Services” map. In both, map algebra was applied with the Weighted Overlay tool (figure 3 explains in detail how the calculation works), from ArcGIS Pro software (license n° 0cca8e7c4a620601a0e5423e82a3ab81). Figures 4 and 5 detail the quantification and weighting of information collected via questionnaire for the “Provision” and “Cultural” ecosystem services, respectively.

Input files and reclassification of classes

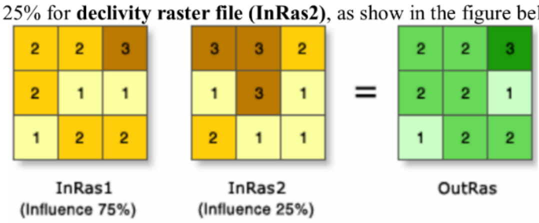
Land use and land	Reclassified values
Caatinga vegetation	3
Agricultural uses	2
Exposed soil	1

Each raster file had its values reclassified so that both are on the same scale of values. In this example, they have been reclassified from 1 to 3.

Declivity(°)	Reclassified values
>45°	3
20° - 45°	2
0° - 20°	1

Weighted Overlay Calculation

At the time of calculation, each raster received **a percentage of influence (weight)**, which added together should result in 100% (e.g. 75% for **land use and land cover (InRas1)** and 25% for **declivity raster file (InRas2)**, as show in the figure below).



For example, consider the top left cell of the illustration above. The calculation of the values for the two rasters is processed like this: (2 * 0.75) = 1.5 and (3 * 0.25) = 0.75. The sum of 1.5 and 0.75 is 2.25. Since weighted overlay output values are integers, the final value is rounded to 2 (**OutRas**).

Figure 03: Example of how weighted overlays are calculated with rasters. Source: Elaborated by the authors.

Weighted Overlay processing for "ES Provision"

For Cultural ES, weights were adopted using the following formulas:
Formula 01: $\mathbf{SE_{D.E.} = Class = 0.1 \times NC_{PSEC} \times 10}$

Where:
$\mathbf{SE_{D.E.}}$ = CICES table division specific ecosystem services
Classe = CICES table specific class
$\mathbf{NC_{PSEC}}$ = Number of classes providing the class-specific service from the CICES table
0.1 = Basic invariant value for all services
10 = Basic invariant value for all services

In cases where a Specific Division of the CICES table contained more than one specific Class, the following formula was used (Formula 02): $\mathbf{SE_{D.E.} = (Cla_A + Cla_B + Cla_C \ldots Cla_N) / NCla_S}$

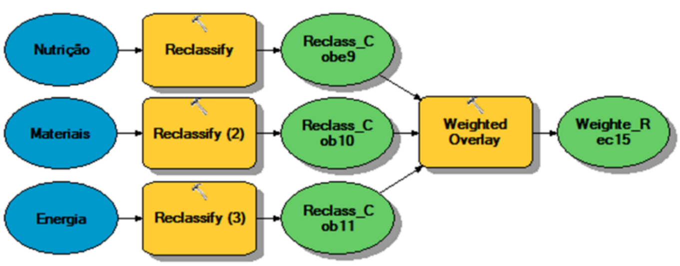
Where:
$\mathbf{Cla_N}$ = $0.1 \times NC_{PSEC} \times 10$
$\mathbf{(Cla_N)}$ = Values referring to each existing class in the Specific Division of the CICES table
$\mathbf{NCla_S}$ = Number of classes summed

Conditions: Whenever a calculation resulted in decimal (Formulas 01 and 02), the value was rounded down to the whole number below (for example, **3.54** rounded to **3**). In this first step, results greater than **5** were rounded to **5**.
These values were later inserted into a GIS environment, where each class received its value resulting from the calculations made using the formulas mentioned above. When overlapping, the values were reclassified to a scale of 1 to 6 (Value + 1; Example: 0 + 1 = 1). The Specific Divisions with the highest number of Classes were given greater weights. The file referring to **Nutrition** received a weight of **50%**, **Materials** had a weight of **25%**, and **Energy** had a weight of **25%**. The final results were framed in the scale proposed by Burkhard et al. (2009) (0 to 5).

Nutrition	Valores reclassificados
Arboreal Caatinga	5
Shrub Caatinga	5
Water body	4
TSMF	5
Agricultural uses	4
Exposed soil	1

Materials	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	5
Water body	5
TSMF	5
Agricultural uses	1
Exposed soil	1

Energy	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	5
Water body	1
TSMF	5
Agricultural uses	5
Exposed soil	1



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 4: Calculation procedures for ES Provision. Source: Elaborated by the authors.

Weighted Overlay processing for "ES Cultural"

For Cultural ES, weights were adopted using the following formulas:

Formula 01: $\mathbf{SE_{D.E.} = Class = 0.1 \times NC_{PSEC} \times 10}$

Where:

$\mathbf{SE_{D.E.}}$ = CICES table division specific ecosystem services

Classe = CICES table specific class

$\mathbf{NC_{PSEC}}$ = Number of classes providing the class-specific service from the CICES table

0.1 = Basic invariant value for all services

10 = Basic invariant value for all services

In cases where a Specific Division of the CICES table contained more than one specific Class, the following formula was used (Formula 02): $\mathbf{SE_{D.E.} = (Cla_A + Cla_B + Cla_C \ldots Cla_N) / NCla_S}$

Where:

$\mathbf{Cla_N}$ = $0.1 \times NC_{PSEC} \times 10$

$\mathbf{(Cla_N)}$ = Values referring to each existing class in the Specific Division of the CICES table

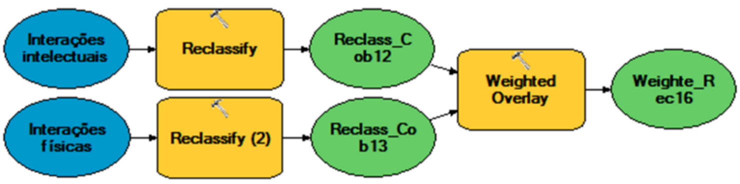
$\mathbf{NCla_S}$ = Number of classes summed

Conditions: Whenever a calculation resulted in decimal (Formulas 01 and 02), the value was rounded down to the whole number below (for example, **3.54** rounded to **3**). In this first step, results greater than **5** were rounded to **5**.

These values were later inserted into a GIS environment, where each class received its value resulting from the calculations made using the formulas mentioned above. When overlapping, the values were reclassified to a scale of 1 to 6 (Value + 1; Example: 0 + 1 = 1). The Specific Divisions with the highest number of Classes were given greater weights. The file referring to **Intellectual Interactions** received a weight of **40%** and **Physical Interactions** had **60%**. The final results were framed in the scale proposed by Burkhard et al. (2009) (0 to 5).

Intellectual Interactions	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	5
Water body	1
TSMF	5
Agricultural uses	5
Exposed soil	1

Physical Interactions	Reclassified values
Arboreal Caatinga	6
Shrub Caatinga	6
Water body	6
TSMF	6
Agricultural uses	6
Exposed soil	5



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 5 Calculation procedures for ES Cultural. Source: Elaborated by the authors.

With the aid of ArcGIS Pro, service mapping was carried out by interpolating the number of services identified in a certain area with the vector file (polygon format) of the mapped land cover units. To this end, the GIS attribute table was altered in each mapped unit, including columns and the total values of each identified service division ("Nutrition", "Materials" and "Energy", for health service provision, and "Intellectual and symbolic interactions with the ecosystem" and "Physical and intellectual interactions with the ecosystem" for cultural services).

After this stage, each unit was classified concerning ES provisions, where total values were grouped into six classes, ranked from 0 to 5, as follows: No relevant capacity - 0; Relevant low capacity - 1; Relevant capacity - 2; Average relevant capacity - 3; Relevant high capacity - 4; Very high relevant capacity - 5 (Burkhard et al., 2009).

The map production procedures of the "Regulation and maintenance services" services used orbital images from the ALOS radar/PALSAR sensor, with a spatial resolution of 12.5 meters (Date: 10/30/2012, Absolute Orbit: 26270, Angle: 34.3 ° and Date: 01/16/2011, Absolute Orbit: 26518, Angle: 34.3 °).

To generate the "Flow Mediation" map with emphasis on the "Mass Flow" group of the studied mountain environment, a "weight" was assigned to each layer (uses and coverings: 60%; slope: 40%)(Figure 6). To generate the "Flow Mediation" map with emphasis on the "Liquid flow" group, a drainage scenario of the study area was generated, with a 30m buffer . This size was justified by the radius of the Permanent Preservation Area (APPs) of each drain, taking into account the criteria described in Brazilian Federal Law Nº. 12.651/2012. During modeling, altimetry and use and cover classes were used. Subsequently, the map was generated using the Weighted Overlay tool, with each layer being assigned a "weight" (use and cover: 35%; altimetry: 40%; slope: 25%) (figure 7 details the process).

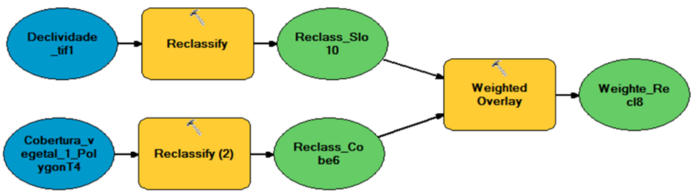
Weighted Overlay processing for "ES Flow Mediation"

The values of each layer were reclassified so that they were on the same scale of values (from 1 to 6). Each file was sliced into 06 classes, and each class received a value according to its importance. The file referring to **land use and land cover** received a **weight** of **60%**, while the **declivity raster file** had **40%**. The resulting raster was reclassified with values between 0 and 5 and then analyzed according to the matrix proposed by Burkhard et al. (2009).

Land use and land cover	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	4
Water body	2
TSMF	6
Agricultural uses	3
Exposed soil	1

Declivity (°)	Reclassified values
0 - 7.72°	1
7.73° - 13.95°	2
13.96° - 20.20°	3
20.21° - 27.03°	4
27.04° - 35.64°	5
35.65° - 75.72°	6

Reclassified values	Values according to Burkhard et al. (2009).
1	0
2	1
3	2
4	3
5	4
6	5



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 6: Calculation procedures for the ES Mediation of Flows. Source: Elaborated by the authors.

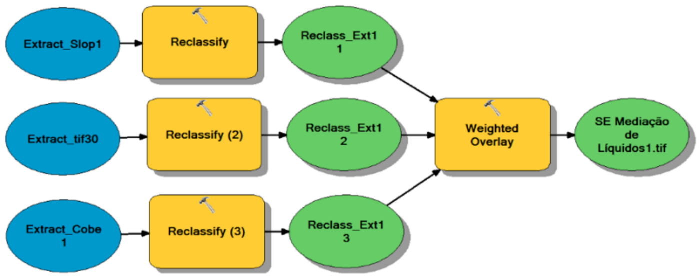
Weighted Overlay processing for "ES Liquid flow"

The values of each layer were reclassified so that they were on the same scale of values (from 1 to 6). Each file was sliced into 06 classes, and each class received a value according to its importance. The file referring to **land use and land cover** received a **weight** of **35%**, **altimetry** had a **weight** of **40%**, while the **declivity raster file** had a **weight** of **25%**. The resulting raster was reclassified with values between 0 and 5 and then analyzed according to the matrix proposed by Burkhard et al. (2009).

Land use and land cover	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	4
Water body	2
TSMF	6
Agricultural uses	3
Exposed soil	1

Declivity (°)	Reclassified values
0 - 5.76°	6
75.76° - 10.64°	5
10.64° - 15.97°	4
15.97° - 21.74°	3
21.74° - 29.28°	2
29.28° - 56.57°	1

Altimetry (meters)	Reclassified values
170 - 250	6
250 - 325	5
325 - 408	4
408 - 502	3
502 - 610	2
610 - 738	1



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 7: Calculation procedures for ES Mediation of Liquids. Source: Elaborated by the authors.

The "Waste Mediation Services" results with an emphasis on the "Mediation per Ecosystem" group were acquired through the weighted overlap of the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988) corresponding to two moments regarding local annual precipitation (rainy season and dry season), as well as land use and cover types. The spectral bands used for the SAVI calculation were obtained from the Sentinel-2A satellite, with a spatial resolution of 10 meters. The dates for each period were as follows: for the rainy period - date: 04/21/2018, tile number: T24MYU and MSI sensor; and for the dry period - date: 11/17/2018, tile number: T24MYU and MSI sensor). Pre-processing was performed in a GIS environment, using the Semi-Automatic Correction plugin of the QGIS software, v. 3.0 (Essen/GNU - General Public License ©) (QGIS Team, 2015).

Specialized bibliography (e.g. Menezes et al., 2012; Andrade et al., 2020) contributed to the decision to attribute greater weight to the rainy season, due to the significant increase in the biomass produced by Caatinga vegetation at this time of year. Thus, weights were distributed as follows: uses and coverage: 50%; SAVI rainy season: 30% and SAVI (dry season): 20% (Figure 8).

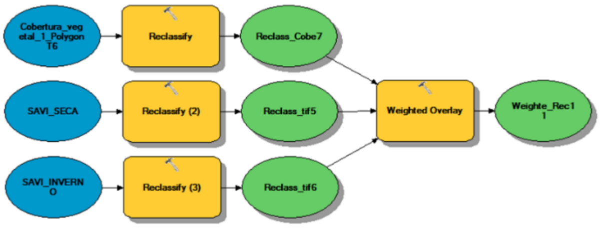
Weighted Overlay processing for "ES Mediation by Ecosystem"

The values of each layer were reclassified so that they were on the same scale of values (from 1 to 6). Each file was sliced into 06 classes, and each class received a value according to its importance. The file referring to **land use and land cover** received a **weight** of **50%**, **SAVI dry season** had a weight of **20%**, and **SAVI rainy season** had a weight of **30%**. The resulting raster was reclassified with values between 0 and 5 and then analyzed according to the matrix proposed by Burkhard et al. (2009).

Land use and land cover	Reclassified values
Arboreal Caatinga	5
Shrub Caatinga	4
Water body	2
TSMF	6
Agricultural uses	3
Exposed soil	1

Dry season	Reclassified values
-0.06 - 0.12	1
0.12 - 0.15	2
0.15 - 0.18	3
0.18 - 0.23	4
0.23 - 0.30	5
0.30 - 0.35	6

Rainy season	Reclassified values
-0.07 - 0.22	1
0.22 - 0.29	2
0.29 - 0.34	3
0.34 - 0.39	4
0.39 - 0.43	5
0.43– 0.61	6



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 8: Calculation procedures for ES Mediation by Ecosystem. Source: Elaborated by the authors.

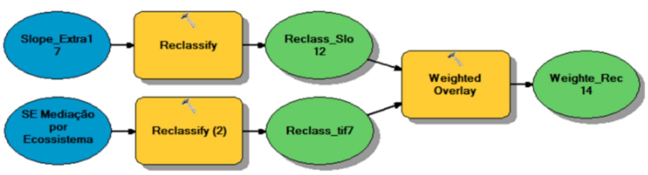
For the "Maintenance of physical, chemical and biological conditions" service map with emphasis on the "Soil Formation" group, files referring to the declivity of the study area, biomass production (overlapping ES Ecosystem Mediation), and forms of land use and coverage were overlapped in weighted form. The weights of each raster were: ES mediation per Ecosystem at 60% and slope at 40% (for more details, see figure 9).

Weighted Overlay processing for "ES Soil Formation"

For this study, the values of each layer were reclassified so that they were on the same scale of values (from 1 to 6). Each file was sliced into 06 classes, and each class received a value according to its importance. The file referring to the **ES Mediation by ecosystem** received a **weight** of **60%**, while the **declivity raster file** received **40%**. The resulting raster was reclassified with values between 0 and 5 and then analyzed according to the matrix proposed by Burkhard et al. (2009).

ES Mediation by ecosystem	Reclassified
No relevant capacity	1
Relevant low capacity	2
Relevant capacity	3
Average relevant capacity	4
Relevant high capacity	5
Very high relevant capacity	6

Declivity(°)	Reclassified values
0 - 7.72°	6
7.73° - 13.95°	5
13.96° - 20.20°	4
20.21° - 27.03°	3
27.04° - 35.64°	2
35.65° - 75.72°	1



When performing the calculation, a **model** was set up (figure on the side), which outlines in a simplified way the processing of the **weighted overlay**.

Figure 9: Calculation procedures for ES Soil Formation. Source: Elaborated by the authors.

To complement the ES Soil Formation data, soil losses in the study area occurring by laminar erosion were estimated in a GIS environment, employing the Universal Soil Loss Equation - USLE (Wischmeier and Smith, 1978). USLE was obtained using equation 01 proposed by Wischmeier and Smith (1978):

$$A = R.K.LS.C.P \quad (01)$$

Where A is soil loss per unit area over time ($t.ha^{-1}.ano^{-1}$); R is the index of erosion caused by rain ($MJ.mm.ha^{-1}.year^{-1}$); K is the soil erodibility factor ($t.ha^{-1}.ano^{-1}$); LS is the topographic factor, that is, the ratio of soil losses between a slope and a slope length for the same soil and degree of slope (dimensionless); C is the soil cover and management factor (dimensionless); P is the conservation practices factor (dimensionless).

The R factor is the capacity of rain to cause soil erosion. To determine this parameter, rainfall data provided by the National Water Agency (ANA) were obtained for the Augusto Severo rainfall station and equation 02 proposed by was used Bertoni and Lombardi Neto (1985):

$$R = \sum_{i=1}^{12} 89{,}823.\left(\frac{pm^2}{pa}\right)^{0.759} \quad (02)$$

Where R is the rainfall erosivity ($MJ.mm.ha^{-1}.ano^{-1}$); pm is the average monthly precipitation (mm); and pa is the total annual precipitation (mm).

The K factor represents the susceptibility of a soil to erosion and was obtained from the literature, as shown in Table 1.

Table 1 - K factor for each type of soil.

Soil type	Area (ha)	Area (%)	Factor K	Source
Alfisols (Luvissolo Crômico)	6.727	70	0.032	Silva et al. (2012)
Entisols (Neossolo Litólico Eutrófico)	2.950	30	0.036	Farinasso et al. (2006)

Source: Elaborated by the authors.

Each value of the K factor was associated with its soil spot in the watershed in a GIS environment. The soil map used was produced by EMBRAPA on a scale of 1:5.000.000 (the only mapping done for the study area).

The LS factor consists of the ability that the length and slope of the slopes have to influence the rate of erosion caused by rainwater. The greater the length of the ramp and the greater its slope, the greater the erosion.

The LS factor was obtained by processing the ALOS PALSAR-FBS images in a GIS environment with a spatial resolution of 12.5 m. The calculation of the LS factor was based on equation 03 adopted by Zhang et al. (2009) in the ArcMusle extension:

$$LS = \left(\frac{V.\Delta}{22{,}13}\right)^{0.4}.\left(\frac{\sin\theta}{0.0896}\right)^{1{,}3} \quad (3)$$

Where V means the accumulated flux of each cell; Δ the size of each cell in the image given in meters; ϴ the slope angle in degrees.

The C factor represents the relationship between soil loss values in land cultivated under certain conditions and the corresponding losses in land that is uncovered and cultivated (Carvalho, 2008). For its determination, it is necessary to know the use and occupation of the soil in the analyzed area.

Factor C values were obtained from studies by Farinasso et al. (2006) and Borges (2009) with soil covers similar to those existing in the study area. Table 2 presents the C factor values for each type of land use and cover.

Tabela 2 – Fator C para cada classe de uso e ocupação do solo.

Land use land cover	Area (ha)	Area (%)	Factor C	Source
Arboreal Caatinga	1.603	12	0.013	Farinasso et al (2006)
Shrub Caatinga	8.053	60	0.013	Farinasso et al (2006)
Tropical Seasonal Montane Forest (TSMF)	2.007	15	0.00004	Borges (2009)
Exposed soil/Housings/Rocks	208	2	1	Borges (2009)
Agricultural uses	1.595	12	0.2	Borges (2009)

Fonte Source: Elaborated by the authors.

The *P* factor represents the use of practices that provide greater protection to the soil in terms of its loss in occupied areas. According to Bertoni and Lombardi Neto (1985), the values of the P factor vary from 1 to 0.1 according to the conservationist practice used. The more efficient the practice adopted, the lower the value of the *P* factor.

Due to lack of information on conservation practices for the study area, the value of 1 was assigned, as also performed in the studies by Irvem et al. (2007) and Silva et al. (2012).

Soil loss estimates were then applied as a proxy for the Soil Erosion ES. The qualitative analysis of soil losses in the study area was performed based on the classification adopted by Irvem et al. (2007) and Silva et al. (2012) (Table 3). These values were subsequently reclassified into each ES class, according to Burkhard et al. (2009).

Table 3: Soil loss estimates and classification.

Soil losses ($t.ha^{-1}.ano^{-1}$)	**Classification**	**Burkhard et al. (2009)**
<5	Very low	Very high relevant capacity
5 – 12	Low	Relevant high capacity
12 – 50	Moderate	Average relevant capacity
50 – 100	Strong	Relevant capacity
100 – 200	Very strong	Relevant low capacity
>200	Extremely strong	No relevant capacity

Sources: Irvem et al. (2007), Silva et al. (2012), and Burkhard et al. (2009).

Results and discussion

According to the sample analyzed herein, the João do Vale mountain range vegetation cover provides both direct and indirect "Provision" ES through the plant and fauna component. Plant resources comprise fruit and/or seed food items, such as the catolé coconut (*Syagrus oleracea* (Mart.) Becc./Arecaceae fruits), bush passion fruit (*Passiflora cincinnata* Mast./Passifloraceae), umbú (*Phytolacca dioica* L./Phytolaccaceae fruits) and mucunã seeds (*Dioclea grandiflora* Mart. ex Benth./Fabaceae). In addition, the local herbaceous layer is useful for feeding cattle and goat herds. Caatinga fruits and seeds and the use of the local herbaceous layer to feed animal herds are mainly observed in rural semiarid region communities, thus comprising widely provided ES.

The local fauna is also used for feeding, consisting mainly of mammals (e.g. *Euphractus sexcinctus* Linnaeus/Chlamyphoridae; *Dasypus novemcinctus* L./Dasypodidae; *Conepatus semistriatus* Boddaert/Mephitidae; *Cavia aperea* Erxleben/Caviidae; *Tamandua tetradactyla* Linnaeus/Myrmecophagidae) and some birds (e.g. *Crypturellus tataupa* Temminck/Tinamidae; *Zenaida auriculata* DesMurs/Columbidae; *Patagioenas picazuro* Temminck/Columbidae), while honey extraction is also carried out (e.g. Trigona spinipes Fabricius and Apis spp./Apidae). The listed animals are mostly obtained from hunting, which is locally prohibited but widely applied in the semiarid for food purposes (e.g. Alves et al., 2016; Barbosa et al., 2022; Marques et al., 2022).

In addition to food purposes, the woody resources of both the Caatinga and TSMF vegetation are used to construct fences, gates, roof support, rafters, and slats, with the following species being the most noteworthy: *Myracrodruon urundeuva* Allemão/Anacardiaceae; *Myroxylon peruiferum* L.f./Fabaceae; *Copernicia prunifera* (Mill.) H.E.Moore/Arecaceae; *Croton sonderianus* Müll. Arg./Euphorbiaceae; *Copaifera duckei* Dwyer/Fabaceae; *Amburana cearenses* (Allemão) A.C. Sm./Fabaceae; *Syagrus oleracea* (Mart.) Becc./Arecaceae and *Mimosa tenuiflora* Benth./Fabaceae).

Bark, resin, and oil extractions for medicinal uses are also highlighted (e.g. *Mimosa tenuiflora* Benth./Fabaceae; *Amburana cearenses* (Allemão) A.C. Sm./Fabaceae; *Myroxylon peruiferum* L. f./Fabaceae) and common throughout the semiarid region (e.g. Almeida et al., 2022; Laurentino et al., 2022). Finally, the woody component of the vegetation formations from the João do Vale mountain range can also be applied in an energy context (e.g. *Croton sonderianus* Müll. Arg./Euphorbiaceae; *Copaifera duckei* Dwyer/Fabaceae; *Mimosa tenuiflora* Benth./Fabaceae), mainly for “wood stove” uses, as mentioned in specialized bibliography (e.g. Ramos et al., 2008; Lima et al., 2016).

Concerning “Cultural” ES, mythical/superstitious/symbolic elements associated with plant formations are observed, such as the legend of “Comadre Fulozinha” (one of the variations of the Caipora legend, a Tupi-Guarani mythological entity, which is represented by an indigenous woman who confronts hunters in the Caatinga to defend the local fauna), as well as plant and animal components (the use of seeds and insect cocoons as elements used to curb certain feelings, such as envy, popularly known as the "evil eye"). From a sacred/religious point of view, uses include Christian religious aspects, where certain plants are used on specific religious dates (e.g. *Copaifera duckei*, *Syagrus oleracea* e *Phytolacca dioica* L.). Mountain ecosystems physical and experience interactions, such as sports trails, academic research, and environmental education support, are also noted.

Concerning Provision service spatialization (Figure 10), all of the evaluated vegetation covers provided ES, mainly in the "High relevant capacity" category, representing 91.45% of the study area (255.12 km^2) (Table 4). Regarding Cultural services, 95.85% (267.39 km^2) of the study area provides "Very high relevant capacity" ES (Table 2).

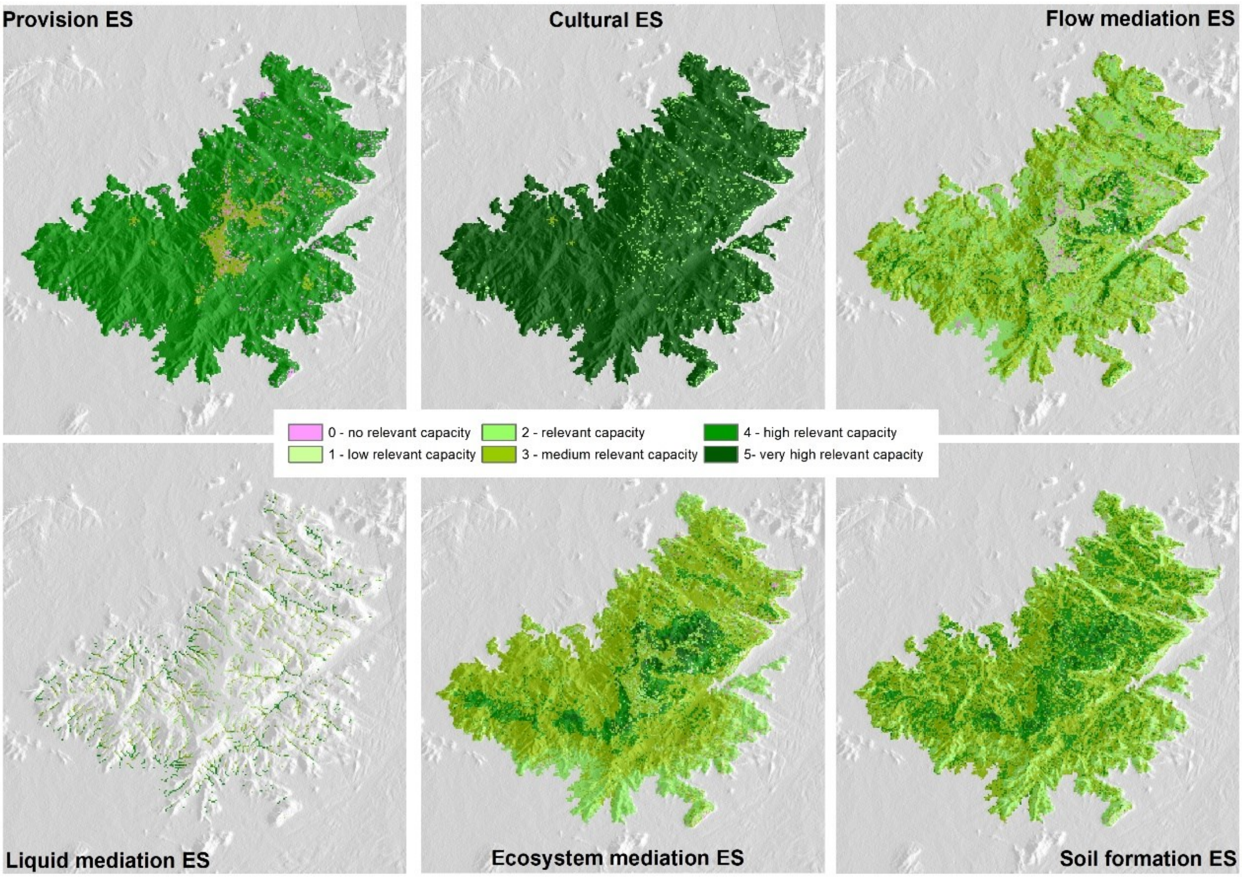


Figure 10: Ecosystem service spatialization. Source: Elaborated by the authors.

Table 4: Areas exhibiting relevant Ecosystem Service levels.

Section	Burkhard et al. (2009)	Km^2	%
Provision	No relevant capacity	11.52	4.13
	Average relevant capacity	12.35	4.43
	Relevant high capacity	255.12	91.45
	Total	**278.98**	**100.00**
Cultural	Relevant capacity	11.14	4.00

	Average relevant capacity	0.43	0.15
	Very high relevant capacity	267.39	95.85
	Total	**278.97**	**100.00**

Source: Elaborated by the authors.

Regarding the biotic and abiotic interactions in diverse Brazilian semiarid region environments, the Caatinga vegetation cover plays an important role in mass flow regulation and maintenance, and its conservation state is directly associated with soil erosion. In the study area, the evaluated ecosystems cover sloping areas and escarpments, where morphogenesis is predominant (Maia and Bezerra, 2019), with a naturally higher incidence of mass flows. In this context, the presence of a vegetation cover in more sloped environments results in "Mass Flow Mediation" ES (Figure 2). In this service group, a higher relevance of the "Average relevant capacity" (48.85%/135.93 km^2) was observed, followed by "Relevant capacity" (33.25%/92.53 km^2) (Table 5). The "High Relevant Capacity" (10.28%) and "Very High Relevant Capacity" (0.68%) categories were distributed mainly in sloped areas covered by seasonal mountainous rainforests and arboreal Caatinga vegetation.

Table 5: Relevant ecosystem service areas provided by vegetation cover.

Group	Burkhard et al. (2009)	Km^2	%
Mass flow mediation	No relevant capacity	6.45	2.32
	Relevant low capacity	12.85	4.62
	Relevant capacity	92.53	33.25
	Average relevant capacity	135.93	48.85
	Relevant high capacity	28.62	10.28
	Very high relevant capacity	1.89	0.68
	Total	**278.29**	**100.00**
Liquid mediation	No relevant capacity	0.01	0.04
	Relevant low capacity	0.43	2.07
	Relevant capacity	4.11	19.97
	Average relevant capacity	9.01	43.74
	Relevant high capacity	6.98	33.88
	Very high relevant capacity	0.06	0.31
	Total	**20.61**	**100.00**
Ecosystem mediation	No relevant capacity	3.35	1.20
	Relevant low capacity	7.07	2.54
	Relevant capacity	57.31	20.57
	Average relevant capacity	168.33	60.42
	Relevant high capacity	34.38	12.34
	Very high relevant capacity	8.14	2.92
	Total	**278.59**	**100.00**
Soil formation	No relevant capacity	4.13	1.48

Relevant low capacity	6.41	2.30
Relevant capacity	55.16	19.78
Average relevant capacity	147.94	53.05
Relevant high capacity	61.13	21.92
Very high relevant capacity	4.13	1.48
Total	**278.89**	**100.00**

Source: Elaborated by the authors.

The "Liquid mediation" ES (Figure 10) is performed, mainly, by the vegetation located in the first-order drains present at the João do Vale mountain range, comprising 20.61 km^2 (Table 5). The results of the weighted overlap indicated the predominance of services between the "Average relevant capacity" (43.74%/9.01 km^2) and "High relevant capacity" (33.88%/6.98 km^2) classes. In addition, riparian forest removal was observed, resulting in increased erosion and environmental degradation effects. In the semiarid region, the presence/absence of vegetation cover leads to significant impacts on the water dynamics of drains or hydrographic basins. At the studied mountain range, the higher the slope and the sparser the vegetation cover, the lower the infiltration, and thus, the lower its classification level importance.

The vegetation index weighted overlap from different rainfall periods alongside land use and land cover assessments enabled the classification of biomass production services and carbon sequestration inferences ("Mediation by Ecosystem" ES, Figure 10). Considerable areas presented this type of service provision, with importance levels ranging from "Relevant capacity" (20.57%/57.31 km^2) to "Average relevant capacity" (60.42% / 168.33 km^2) (Table 5). The predominance of these categories can be explained by the overlapping of shrub Caatinga vegetation ecosystems and low photosynthetic activity values compared to those observed at the TSMF.

The highest importance levels for the "Mediation by Ecosystem" ES (High relevant capacity and Very high relevant capacity) are distributed according to the TSMF location, which is responsible for the highest photosynthetic activity values, even during drought periods. Carbon sequestration processes, cycling, and biomass production in Caatinga ecosystems are more active during the rainy season, when intense photosynthetic activity and biomass production are noted (e.g. Menezes et al., 2012; Jardim et al., 2023), with litter production occurring soon after the end of the rainy season. It should be noted that vegetation cover suppression impairs the provision of this type of service (Araújo Filho et al., 2018; Brasil et al., 2022; Guerreiro et al., 2022).

Semi-arid environment ecosystems act forcefully both in pedogenesis processes, when present, and in erosion processes, when absent (e.g. Medeiros and Araújo, 2014). In the study area, ecosystems provide "Soil Formation" ES (Figure 10), predominantly in the "Average relevant capacity" (53.05%/147.94 km^2) to "Relevant high capacity" (21.92%/61.13 km^2) classes, denoting the singular importance of vegetation cover. This importance pattern is explained by the overlapping of biomass production ecosystems superimposed to medium to gentle slopes since these characteristics amplify weathering and biomass decomposition processes.

The opposite was observed for the steepest slopes, was the lowest importance in providing this type of service were recorded. However, the vegetation formations that cover these slopes perform important "Flow Mediation" services, preventing/delaying soil and colluvium dissection.

To complement the Soil Formation ES results, the USLE was calculated to assess soil loss. A total of 45% of the study area exhibits soil losses between 12 and 50 t.ha^{-1}.year^{-1} (Table 6). The average soil loss is 15.91 t.ha^{-1}.year^{-1}, being considered as moderate according to the classification adopted by Irvem et al. (2007) and Silva et al. (2012). The low slope areas covered by the TSMF present between 0 and 5 t. ha^{-1}.year^{-1} of soil losses and occupy 15% of the study area (Table 7). The "Very high relevant capacity" class applying the ES classification developed by Burkhard (2009) was assigned to these areas.

Table 6: Soil loss area percentages for the study area.

Soil loss ($t.ha^{-1}.year^{-1}$)	Classification	Area (%)
<5	Very low	27
5 – 12	Low	24
12 – 50	Moderate	45
50 – 100	Strong	2
100 – 200	Very strong	1
>200	Extremely strong	1

Source: Elaborated by the authors.

Table 7: Soil losses per use and cover class.

Use and cover	Area (km^2)	Area (%)	Soil loss ($t.ha^{-1}.year^{-1}$)		Classification
			Means	Standard deviation	
Arboreal Caatinga	39	12	16.35	12.26	Moderate
Shrub Caatinga	190	60	5.51	10.35	Low
Tropical Seasonal Montane Forest (TSMF)	22	15	0.21	5.34	Very low
Exposed soil/housing /rock	14,7	2	420.79	421.25	Extremely strong
Agricultural uses	12	12	81.68	119.09	Strong

Source: Elaborated by the authors.

At the other extreme, a registered soil loss exceeding 200 $t.ha^{-1}.year^{-1}$, was observed, reaching a maximum of 3,056.8 $t.ha^{-1}.year^{-1}$. Areas with soil losses greater than 200 $t.ha^{-1}.year^{-1}$, in only 1% of the study area, are associated with exposed soil or agricultural areas located on slopes.

In general, the studied mountain environment presents losses mostly between 0 and 50 $t.ha^{-1}.year^{-1}$ (96% of the study area), and the ES classification used in this study indicates that ecosystems provide erosion control services ranging from “Very high relevant capacity” to “Average relevant capacity” (Figure 11).

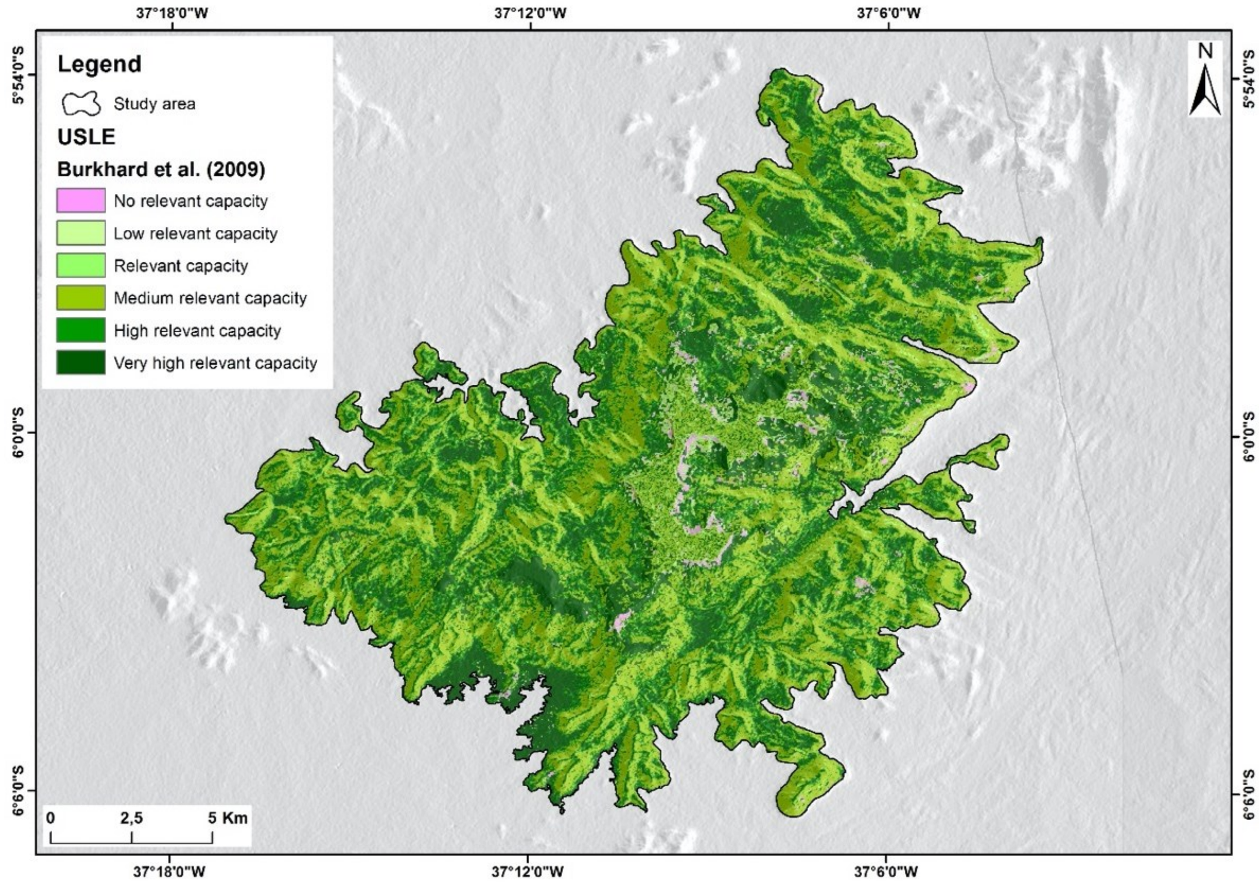


Figure 11: Ecosystem service spatialization to control soil erosion.
Source: Elaborated by the authors.

Studies applying USLE to mountainous environments in the Brazilian semiarid region are scarce, as a predominance of hydrographic basin assessments is noted (e.g. Medeiros and Araújo, 2014; Oliveira et al., 2023). Batista (2015) indicated that the minimum soil loss rates for mountainous environments with rainfall above 1,000 mm, characterizing humid mountain ranges, such as the Baturité mountain range (Ceará State, Brazil), are higher than the maximum values recorded for mountainous environments similar to the present study area, as well as for other dry mountain environments.

The relationship between soil loss and rainfall in the semiarid is also clear, where increased rainfall results in increased soil loss rates (e.g. Guerreiro et al., 2022). This is due to the phenotypic characteristics of the local vegetation, which has few leaves at the beginning of the rainy season, facilitating erosion. Thus, the denser and more arboreal the physiognomy, the better its Soil Erosion Control ES performance.

Data surveys for assessing ecosystem service provisions focusing on qualitative data are best acquired using semi-structured interviews. Studies using data surveys through semi-structured interviews (e.g. Kovács et al., 2015; Chicago et al., 2022) have been successfully applied to both trade-off discussions (e.g. Kovács et al., 2015) and assessments on how to guide the weighting of important elements in ES assessments (e.g. Inkoom et al., 2018). Although previous studies achieved their objectives and obtained important results for each theme, none of the aforementioned studies have addressed the cultural ES sphere, as the present research was willing to do.

Concerning services analyzed using weighted overlays, we emphasize that semi-structured interviews are required to measure the weights applied for each variable to obtain spatial result robustness, as noted by Inkoom et al. (2018). Nevertheless, the simple models used in the present research tend to exhibit robust results (Bagstad et al., 2018; Rotich et al., 2022).

Service surveys and analyses have also undergone more integrated approaches, taking into account both interactions between services and the main landscape conditions (e.g. Chicago et al., 2022; Georgia et al., 2022; González-García et al., 2023; Bao et al., 2023). In this context, the results obtained in the present study are the consequence of an integrated analysis of intrinsic landscape variables (e.g. Flow Mediation ES and Liquid Flow ES), as well as of the relationship between services (e.g. Soil Formation ES).

Despite advances concerning services and landscape relationship analyses, attention has been drawn to the difficulty in which the results of these surveys have to be absorbed by planners and decision-makers (Portman, 2013). This lies in the need to simplify relationships noted between services and landscape and between the services themselves (Portman, 2013), which can be complex from both a theoretical point of view (e.g. Bastian et al., 2015) and in cartographic representations (e.g. Inkoom et al., 2018; Rotich et al., 2022; Pilogallo and Scorza, 2022). In an attempt to overcome this fact, semi-structured interviews were conducted with people displaying social and local protagonism, such as local leaders and teachers, as recommended by Kovács et al. (2015).

Conclusions

The mapped and evaluated services allow us to consider that the hypothesis of this work is consistent with the results obtained. From the realization of the object of this work, we consider that the maintenance of the provision of services will depend on conservation actions for the study area, which does not have any conservation unit.

The methods applied herein used to obtain information concerning “Provision” and “Cultural” services were proven efficient since the information was locally acquired from residents who depend both directly and indirectly on plant and fauna components for their survival/livelihood, as well as for symbolic/cultural religious interactions.

The methods used to obtain "Regulation and maintenance" services were proven effective for both classification and spatial modeling. It should be noted, however, that many services were not obtained due to a lack of weighted overlap data.

Finally, the identified services were integrated to characterize the way of life and the relationships between local rural communities. Such relationships can be harmonious, comprising entertainment and scientific knowledge production, for example, or antagonistic, like hunting and collecting animal and plant resources. In addition, the intensity of these relationships can both expand certain services, i.e. environmental education acting on the awareness of predatory hunting, while quelling others, such as deforestation through soil formation and/or flow mediation suppression.

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