Australian Journal of Crop Science AJCS

Aust J Crop Sci. 19(05):567-576 (2025) | https://doi.org/10.21475/ajcs.25.19.05.p324 ISSN:1835-2707

Using geospatial analysis to detect soil loss in pasture in the Brazilian savanna (Cerrado)

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Submitted: 24/01/2025

Revised: 10/03/2025

Accepted: 13/03/2025

Abstract: Well-managed pastures support watershed recharge by conserving soil, increasing organic matter, and enhancing water and nutrient retention, while also reducing erosion, nutrient leaching and surface run-off. This study used remote sensing to assess vegetation cover (Vc) in degraded pasture areas and examine its relationship with soil loss in the Brazilian savanna, employing vegetation indices and the Universal Soil Loss Equation (USLE). Given its socioeconomic importance, the Ribeirão Serra Negra Watershed in Piracanjuba, Goiás, Brazil was the focus of the research. Soil loss was estimated from freely available geographic data on climate, while soil class and relevance were assessed through a digital elevation model (DEM). The use of images from the Sentinel-2A orbital sensor alongside the Normalized Difference Vegetation Index (NDVI) also made it possible to quantify and classify Vc according to its condition. The findings reveal that pastures in this region exhibit varying levels of degradation, with intermediate degradation classes being most prevalent: 'moderately degraded' areas covered 3,919.25 hectares (ha) (56.87% of the total area), while 'severely degraded' areas accounted for 1,984.30 ha (28.79%). The most common index values ranged from 0.6 to 0.7, aligning with the higher prevalence of the moderately degraded class. Soil losses were considerable in these intermediate classes, affecting 5,683.19 ha (82.46%); the most frequent loss rate was estimated to lie between 20 and 40 Mg ha^{-1} year^{-1}, covering 4271.34 ha (61.98%). Higher Vc indices were more frequently observed in areas with lower soil losses, demonstrating a significant inverse correlation (-0.80, p-value ≤ 0.05) between these variables, with a determination coefficient (R^2) of 0.64.

Keywords: pastures, vegetation cover, USLE, soil conservation.
Abbreviations: DEM_digital elevation model; ESD_extremely severely degraded; LD_lightly degraded; MD_moderately degraded; NDVI_Normalized Difference Vegetation Index; SD_severely degraded; UD_undegraded; USLE_Universal Soil Loss Equation; Vc_vegetation cover.

Introduction

Pastures represent the most extensive land use in Brazil, covering 177 million hectares (ha) across all biomes. Studies suggest that approximately 109.7 million ha, or around 60% of these pasture areas, are degraded (Bolfe et al., 2024). Using land for agriculture and pasture can lead to soil loss, as the management practices often remove vegetation cover (Vc). Soil erosion is a geomorphological degradation process influenced by anthropogenic activities and wind action but primarily driven by rainfall erosivity and soil erodibility (Poesen, 2018).

Predictive models of soil loss are valuable tools for rural landowners and public managers, as they help identify areas with the highest erosive potential at both watershed and municipal scales (Polidoro et al., 2021). In this context, the Universal Soil Loss Equation (USLE) is one of the most widely used equations (Wischmeier; Smith, 1978).

The factors in the USLE serve as parameters that reflect the unique characteristics of the studied area and their impact on erosion. They include rainfall erosivity (R), soil erodibility (K), slope length (L) and steepness (S), land use and management (C), and conservation practices (P). The topography (relating to L and S) affects water velocity and thus the erosive potential. Land use and management relates to cover (C), which serves as a protective layer for the soil. Conservation practices (P) may either reduce or increase erosion, depending on how effectively they are implemented. Finally, the 'R' factor assesses amount and intensity of precipitation, while 'K' considers the soil's susceptibility to erosion, based on its physical properties (Alewell et al., 2019).

The most common soil conservation practices include: vegetative methods, which strategically utilise plants as tools for preservation; edaphic methods, which aim to improve soil function through enhanced fertility and structural conditions;

and mechanical methods, which employ artificial structures to slow water flow under various soil management practices (Lobato, 2019). The Normalized Difference Vegetation Index (NDVI) has been widely studied as a tool for identifying and monitoring degraded areas (Hopping et al., 2018).
According to the 2023 agricultural census, Brazil's cattle herd numbers came to approximately 238.6 million, making it the second-largest cattle producer globally. The state of Goiás ranks third nationally in cattle production (IBGE, 2023a). In Goiás, the municipality of Piracanjuba is the third-largest milk producer, with 83,500 milking cows out of a total herd of 190,000 (IBGE, 2023b).
Due to their socioeconomic importance, pasture areas require technological innovations for effective conservation assessment. Remote sensing and modelling are essential tools for monitoring these areas, allowing for analyses of erosive potential and vegetative health. This study, therefore, is aimed at assessing Vc in degraded pasture areas and examining its relationship with soil loss, employing vegetation indices and the USLE.

Results and discussion

Rain intensity and soils in the erosive process

The R factor obtained for the rain gauge stations (Table 6) ranged from 9,537.72 to 14,392.08 MJ mm ha^{-1} h^{-1} $year^{-1}$ for the municipalities of Cristianópolis and Piracanjuba, respectively. According to Carvalho's (2008) classification of the R factor in the Ribeirão Serra Negra Watershed, all station records fell within the 'very strong' erosivity class. In this context, the R values have a significant influence on soil loss (Figure 2).
Anjos et al. (2020) reported similar findings for rainfall erosivity in municipalities across Goiás. According to the authors, these R values can lead to economic losses, including decreased productivity in agricultural areas due to soil layer removal and leaching of agricultural inputs. From environmental and social perspectives, they also contribute to sedimentation in water bodies, eutrophication, water contamination and increased flooding in human-modified areas.
Carvalho and Castro (2023) obtained R values greater than 10,000 MJ mm ha^{-1} h^{-1} $year^{-1}$ for the municipality of Piracanjuba; in addition, they highlighted that only 1.98% of the municipalities in Goiás present results equivalent to this class. To obtain this result, the authors used data from 88 rainfall stations in the state of Goiás from 1980 through to 2010. Rosa et al. (2022) confirm these high erosivity values for Piracanjuba, having evaluated the variability of soil loss in the municipalities of Goiás between the years 1985 and 2018. According to Rosa et al., the highest erosivity rates are continuously present in the central region of the state, while they vary year to year in other regions.
The predominant soil class in the watershed is Oxisols, covering 11,030.34 ha (99.35%), of which 6,820.25 ha (62.28%) are pasture areas. In contrast, the Inceptisols soil class is concentrated in southern areas, occupying 71.66 ha (0.65%) that are entirely classified as pasture, close to the epicentre of the 'very strong' erosivity values (Figure 2).
According to Carvalho's (2008) classification, Oxisols are characterised by low erodibility, as they are generally stable, well drained, highly permeable and porous, making them less prone to erosion. In contrast, Inceptisols exhibit high susceptibility to erosion, as they are less permeable and less developed (De Oliveira Rocha; Magri, 2022). For Beiniaich et al. (2023), Inceptisols are considered unstable when they are in landscapes with sharp relief and generally create chemically poor environments, making it difficult to sustain Vc.
Other studies indicate that the high erodibility of Inceptisols, linked to high erosivity values, favours soil loss. For Soares et al. (2024), compared to Oxisols, Inceptisols are more erodible due to the physical properties of the soil (notably its stoniness), which support lower levels of Vc, as well as its typical situation in the landscape. In the case of Inceptisols, rainwater intensifies soil loss due to the lack of Vc, worsening erosion processes in poorly managed pastures (Huang et al., 2017; Gibson et al., 2022).

Land use, management and topography in soil conservation

Table 7 shows that the 'pasture' class had the highest spatial representation, covering 6,891.91 ha in the study area (62.08%). This was followed by the 'agriculture' class, which occupied 2,500.84 ha (22.53%), encompassing areas dedicated to sugarcane, soybeans and other temporary crops (Mapbiomas, 2023). These agricultural practices exhibit high CP values, indicating land use management that significantly increases soil loss due to the removal of natural protective cover. In Brazil, these activities are the primary causes of soil loss, often due to inadequate planning and the absence of conservation practices (Bertoni and Lombardi Neto, 2010; Polidoro et al., 2021). The remaining land use and cover classes together comprised approximately 15% of the watershed (Figure 2).
Figure 2 illustrates that the most prevalent topographic factor classes in the watershed were 'low' (6,733.43 ha or 60.55%) and 'very low' (2,789.96 ha or 25.13%), indicating that much of the terrain has flat characteristics (Embrapa, 1979). These classes were particularly predominant in pasture areas, covering 6,011.30 ha (87.22%), characterised by flat terrain with good permeability and slow surface run-off, resulting in negligible susceptibility to erosion. Oxisols are well weathered and are often concentrated in flat reliefs. On the other hand, Inceptisols are rarely weathered and common on sloping surfaces (Castro et al., 2022).
The 'moderate' and 'moderately strong' classes represented 1,222.34 ha (11.01%) and 766.05 ha (0.69%), respectively. The LS results for the 'strong' class indicate a small area (2.63%), concentrated on slopes, such as the Serra Negra, located geographically at the centre of the watershed. According to Ribeiro de Jesuz and Ferreira (2022), the gentle and long slopes, along with the physical properties of Oxisols, facilitate water infiltration in these degraded pasture areas, thereby reducing surface run-off and minimising the need for soil conservation.
The implementation of conservation practices in pastures requires careful planning. Notably, Alves et al. (2022) showed increased surface erosion in both Oxisols and Inceptisols in terrain that has been terraced. In this study, it was observed

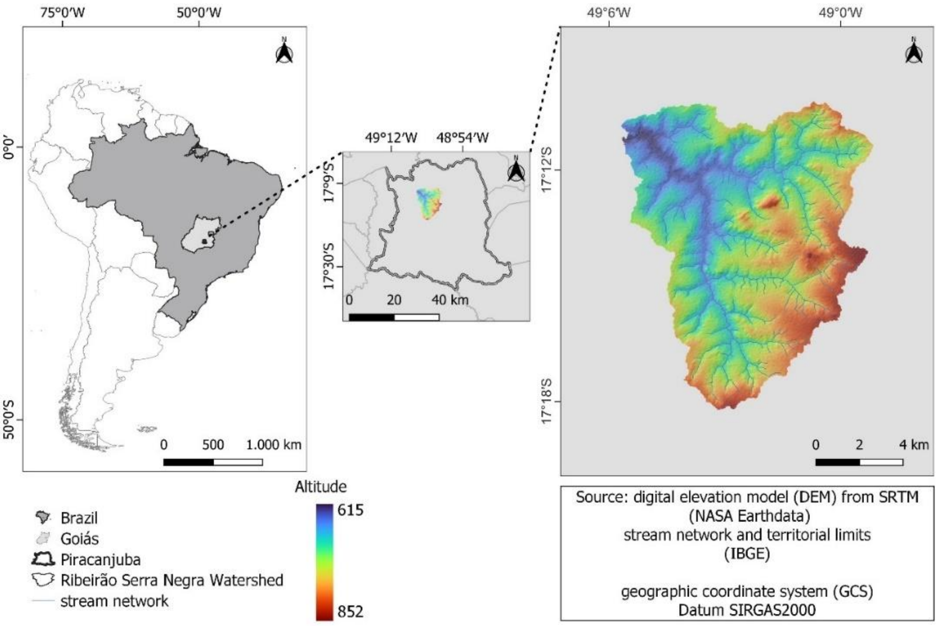

Fig 1. Geographic location of the Ribeirão Serra Negra Watershed in the municipality of Piracanjuba, Goiás.

Table 1. Rain gauge stations, adapted from SIC (2006).

Station	Municipality	Data period	Time (years)	Average monthly precipitation (mm)
12	Bela Vista de Goiás	1977 to 2001	24	129
31	Cristianópolis	1977 to 2001	24	116
33	Cromínia	1979 to 2001	22	126
61	Piracanjuba	1969 to 2001	32	172

Table 2. K factor of soil classes in the watershed in Piracanjuba, Goiás, Brazil, adapted from Cerri et al. (2001).

Soil class	K factor (Mg h MJ^{-1} mm^{-1})
Oxisols	0.0156
Inceptisols	0.0508

Table 3. CP values for the watershed in Piracanjuba, Goiás, Brazil, adapted from Stein et al. (1987).

Land use and cover class	CP factor
Agriculture	0.2
Water body	0
Forest formation	0.00004
Non-forest natural formation	0.01
Other non-vegetated area	1
Pasture	0.1
Forest plantation	0.0001

Table 4. Soil loss classes and their estimated values, adapted from Carvalho (2008).

Soil loss class	Loss estimate (Mg ha^{-1} $year^{-1}$)
None to moderate	<15
Moderate	15–50
Moderate to strong	50–120
Strong to very strong	>120

that soil particle transportation is worsened by the erodibility of the soil, steep and short slopes and the lack of sizing between terraces. Furthermore, according to Almeida et al. (2019), one of the main factors that promotes erosion processes is the accumulation of rainwater. Almeida et al. (2019) believed that mapping critical points of erosion by identifying the flow of rainwater on the ground is essential to mitigate soil loss.

According to Schwamback et al. (2024), poorly managed pastures on sandy soils and high slopes result in greater surface run-off than land that is planted with crops – Schwamback et al. used sugar cane for the purposes of their study. When comparing degraded pasture with native Vc, the authors found that surface run-off in degraded pasture areas was twenty times greater; meanwhile, in areas planted with sugar cane, it was five times greater. Under these conditions, mechanical

Table 5. Vegetation cover classification in different pasture conditions.

Classification	Vc
Undegraded (UD)	Vc > 90%
Lightly degraded (LD)	90 ≥ Vc >75%
Moderately degraded (MD)	75 ≥ Vc > 60%
Severely degraded (SD)	60 ≥ Vc > 30%
Extremely severely degraded (ESD)	Vc ≤ 30%

Source: Gao et al. (2006).

Table 6. Rain gauge stations of municipalities surrounding the watershed and annual average soil erosivity values.

Rain gauge station	R factor (MJ mm ha^{-1} h^{-1} $year^{-1}$)
Bela Vista de Goiás	10,573.48
Cristianópolis	9,537.72
Cromínia	10,628.12
Piracanjuba	14,392.08

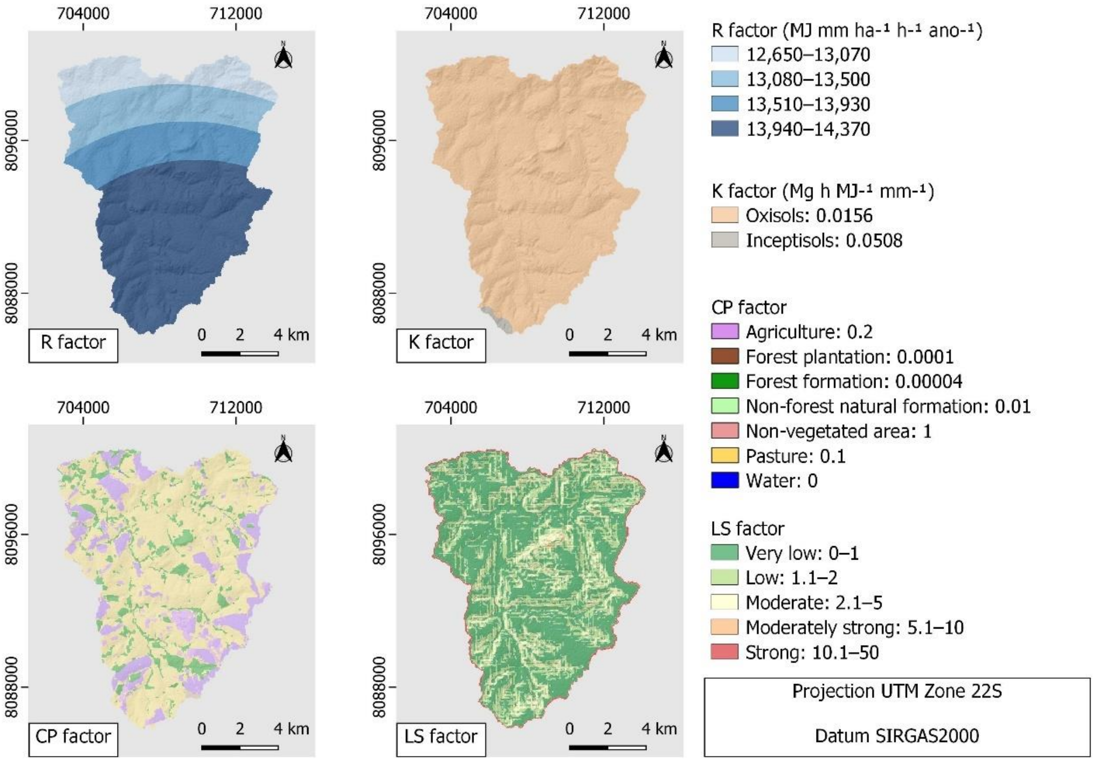

Fig 2. Erosivity factor (R); erodibility factor (K); land use, management and conservation practices factor (CP); slope length and steepness factor (LS) of the watershed in Piracanjuba, Goiás, Brazil.

procedures should be avoided due to the physical structure of the soil and efforts should be made to improve Vc (Cunha et al., 2022; Alves et al., 2023).

Soil loss in degraded pastures

The soil loss scenarios were similar in both the watershed and pasture areas (Table 8). The 'moderate' soil loss class was the most prevalent, covering 7,767.25 ha (69.96%) in the watershed and 5,683.19 ha (82.46%) in pasture areas. The 'moderate to strong' class was the second most prevalent, covering 1,385.76 ha (12.48%) in the watershed and 996.22 ha (14.45%) in pasture areas.

The 'none to moderate' and 'strong to very strong' soil loss classes covered the least extensive areas, encompassing 130.15 ha (1.89%) and 82.35 ha (1.19%), respectively. Figure 3 illustrates the spatial distribution of soil loss classes and Vc within pasture areas. The highest concentration of soil loss was observed in pastures located in the southern part of the watershed, attributed to high erosivity values and the presence of Inceptisols (Figure 2). Areas covered by Inceptisols tend to have lower Vc values due to the soil's physical properties: Inceptisols' high porosity and permeability allow rapid percolation of water to the deeper layers, leaving the surface dry and therefore hindering plant growth (Gomes et al., 2017; Gibson et al., 2022).

Pasture Vc in the watershed showed varying degrees of degradation and soil loss, with no non-degraded pastures observed. The predominant Vc classes were 'moderately degraded' (MD) and 'severely degraded' (SD), covering 3,919.25 ha (56.87%) and 1,984.30 ha (28.79%), respectively. The 'lightly degraded' (LD) class accounted for 823.50 ha (11.95%), while

Table 7. Extent of land use and land cover classes associated with CP values in the watershed in Piracanjuba, Goiás, Brazil.

Land use and cover class	CP factor	Area (ha)	(%)
Agriculture	0.2	2,500.84	22.53
Water body	0	4.70	0.04
Forest formation	0.00004	1,665.19	15
Non-forest natural formation	0.01	13.68	0.12
Other non-vegetated area	1	22	0.20
Pasture	0.1	6,891.91	62.08
Forest plantation	0.0001	3.79	0.03

Table 8. Occurrence of soil loss classes in the watershed and its pasture areas, located in the municipality of Piracanjuba, Goiás, Brazil.

Soil loss class	Watershed (ha)	%	Pasture`(ha)	%
None to moderate	1,677.68	15.11	130.15	1.89
Moderate	7,767.25	69.96	5,683.19	82.46
Moderate to strong	1,385.76	12.48	996.22	14.45
Strong to very strong	271.42	2.44	82.35	1.19

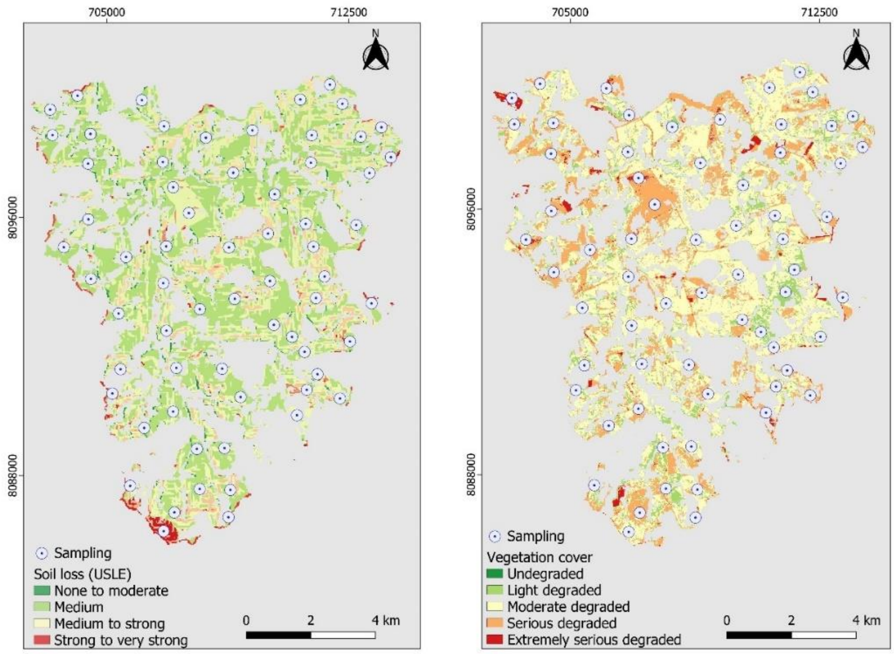

Fig 3. Spatial variation of soil loss classes and vegetation cover under different pasture conditions in the watershed in Piracanjuba, Goiás, Brazil.

'extremely severely degraded' (ESD) land encompassed 164.87 ha (2.39%). The Vc results and data obtained through the USLE showed similar patterns, with intermediate class values appearing most frequently.

Overall, the soil loss and Vc results presented the second-best scenario, according to the classifications (Gao et al. 2006; Carvalho, 2008). Despite the highest density of degraded pastures occurring in the northern portion of the river basin, these areas have the lowest occurrence of critical soil loss areas, due to lower erosivity, erodibility and slope steepness values. Figure 4 illustrates the frequency distribution of soil loss estimates and Vc index values.

The most frequent soil loss rate was estimated to lie between 20 and 40 Mg ha^{-1} year^{-1}, covering 4,271.34 ha (61.98%). These data reiterate the predominance of soil loss within the 'moderate' class. For Vc, the most common index values ranged from 0.6 to 0.7, consistent with the predominance of the MD class. The least frequent results occurred at values below 0.3 and above 0.8. According to Mayel et al. (2021), decline in pasture productivity and biological degradation are mainly associated with soil deterioration. In this process, the proportion of bare soil (without vegetation) in the pasture area increases, which facilitates erosion and the loss of organic matter and nutrients from the soil (Embrapa, 2017; Bolfe et al., 2024).

Figure 5 illustrates the relationship between Vc values in pastures and soil loss. An inverse (-0.80) and significant (p-value ≤ 0.05) correlation was observed between the variables, indicating that as Vc values increase, soil losses decrease. The coefficient of determination (R^2) was 0.64, suggesting that a substantial portion of data variation (64%) is explained by the relationship between these two variables.

This relationship was similarly observed by Donavam and Monaghan (2021), who identified significant losses in soil physical properties using a predictive model in high-density grazing areas. According to Donavam and Monaghan, the primary drivers of exacerbated soil losses were inadequate Vc and the absence of conservation practices. Additionally,

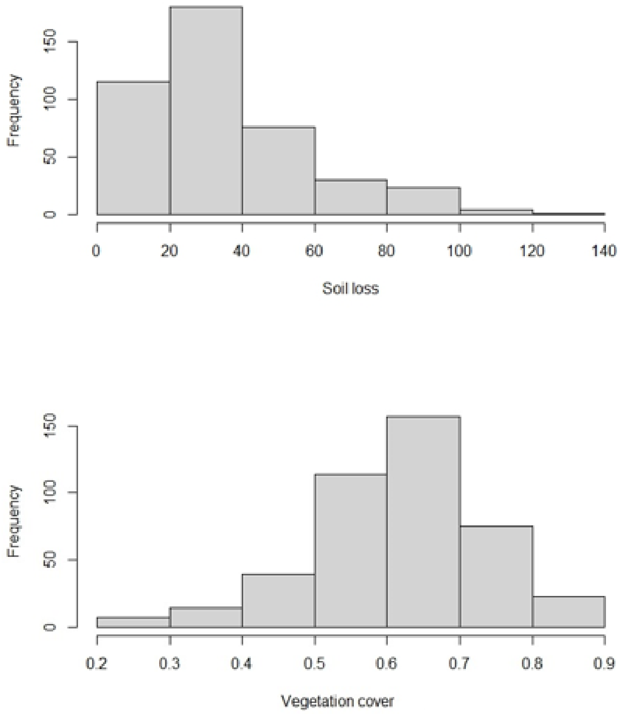

Fig 4. Spatial variation of soil loss classes and vegetation cover under different pasture conditions in the watershed in Piracanjuba, Goiás, Brazil.

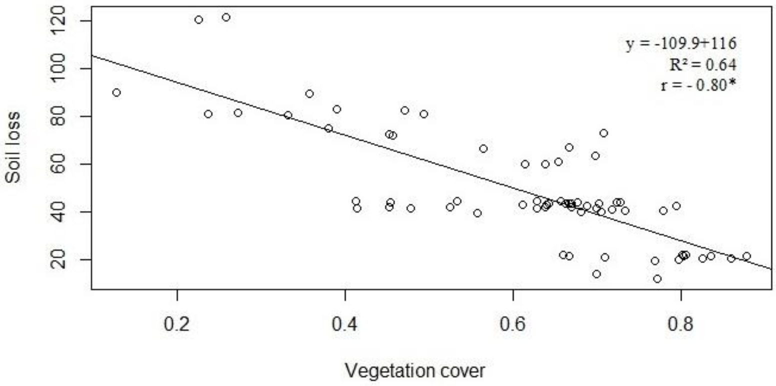

Fig 5. Relationship between the vegetation cover index and estimated soil loss (Mg ha^{-1} year^{-1}), using a simple linear regression model for pasture areas in the watershed in Piracanjuba, Goiás, Brazil.

Serrano et al. (2023), using NDVI, noted the impact of soil compaction from cattle trampling on pasture conditions and suggested that the vegetation index is a powerful tool for monitoring these areas.

For Löbmann et al. (2020), degraded pastures with inefficient Vc enable soil compaction due to trampling, causing hydraulic conductivity and infiltration rates through sealing. This ultimately leads to an increase in surface area and erosive potential. Similarly, Blanco and Rattan (2023) found that soil compaction from cattle trampling exacerbates water erosion in pasture areas and impedes Vc development. In addition to inadequate management, De Andrade et al. (2020) suggest that climatic phenomena contribute to prolonged drought periods and elevated wildfire risks, directly affecting the vegetative vigour of pastures.

Zhang et al. (2022) indicate that effective Vc on the soil surface decreases susceptibility to rainfall-induced erosion. This is because vegetation intercepts rainfall, reducing the impact of raindrops, and helps maintain soil aggregate structures, preventing pore blockage and surface sealing. Vc and its residues also serve as barriers to excessive run-off, thereby reducing both the volume and velocity of surface flow (Pruski, 2009).

Materials and methods

Study area

The Ribeirão Serra Negra Watershed is located in the municipality of Piracanjuba, in the microregion of Meia Ponte, which is itself in the mesoregion of Southern Goiás in the Brazilian Cerrado. It falls between the geographic coordinates 17°10’55”S, 49°03’07”W and 17°18’12”S, 49°05’38”W and covers approximately 11,100 ha (Figure 1). According to the Köppen-Geiger classification, the climate is classified as Aw (tropical humid), with average annual precipitation of 1,600 mm (Alvares et al., 2013).

USLE predictive model

To estimate soil loss due to sheet erosion, the USLE predictive model was employed. This estimation accounts for both anthropogenic and natural factors that contribute to soil loss, including soil properties, topographic variables, and land use and management practices. The equation is expressed as:

$A = R \times K \times L \times S \times C \times P$ (1)

Where: 'A' represents the average annual soil loss (Mg ha^{-1} year^{-1}); 'R' is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}); 'K' characterises the soil erodibility factor (Mg h MJ^{-1} mm^{-1}); 'L' denotes the slope length factor, based on slope length values in metres (dimensionless); 'S' is the slope gradient factor, based on slope percentage values (dimensionless); 'C' represents the land use and management factor (dimensionless); and 'P' represents the conservation practices factor (dimensionless).

R factor: rainfall erosivity

The R factor was developed by interpolating data from four meteorological stations near the watershed, located in the cities of Bela Vista, Cristianópolis, Cromínia and Piracanjuba. Data from these stations were obtained from a historical series provided by the Goiás State Superintendency of Geology and Mining (SIC, 2006), covering the period from 1969 to 2001 (Table 1).
Drawing on these data, an equation by Morais et al. (1991) was then employed to determine the monthly average of the erosion index (EI_{30}):

$EI_{30} = 36.849 \times (\frac{M_x^2}{P})^{1.0852}$ (2)

Where: 'EI_{30}' represents the monthly average erosion index (MJ mm ha^{-1} h^{-1} year^{-1}); 'Mx' denotes the monthly average rainfall (mm); and 'P' is the annual average rainfall (mm).
The monthly EI_{30} values were summed to obtain the annual average estimate of the R factor for each rain gauge station:

$R = \sum_{i=1}^{12} (EI_{30})_i$ (3)

K factor: soil erodibility

The K factor was derived from a soil map provided by the Institute of Technical Assistance and Rural Extension (EMATER) at a 1:250,000 scale, using the third level of the Brazilian Soil Classification System and its equivalence to Soil Taxonomy (Santos et al., 2018). The adopted values are presented in Table 2 (Cerri et al., 2001).

LS factor: slope length and steepness

The LS factor was derived from a digital elevation model (DEM) provided by the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 30 m. To determine slope length (L), the equation developed by Desmet and Govers (1996) was applied.

$L = \frac{(A+D^2)^{m+1} - A^{m+1}}{\alpha^m \times D^{m+2} \times 22{,}1^m}$ (4)

Where: 'A' represents the contributing area or accumulated flow for a cell (m^2); 'D' is the cell or pixel size (m); 'L' denotes the slope length factor of a cell (dimensionless); 'α' is a coefficient based on the cell grid's flow direction; and 'm' is a coefficient determined by the cell grid's slope.

To calculate the slope length factor (S), the equation proposed by McCool et al. (1989) was applied, as shown below:

$S = \begin{cases} 10.8 sin\theta + 0.03 \ (S < 9\%) \\ 16.8 sin\theta - 0.50 \ (S \geq 9\%) \end{cases}$ (5)

The LS values were classified according to the categories proposed by Fornelos and Neves (2007), divided into six classes: 'very low' (0–1), 'low' (1.1–2), 'moderate' (2.1–5), 'moderately strong' (5.1–10), 'strong' (10.1–50) and 'very strong' (> 50).

CP factor: land use and management (C) and conservation practices (P)

The CP factor represents the integration of the land use and management factor (C) with the conservation practices factor (P). Geographic data on land use and soil cover for the year 2022, with a spatial resolution of 30 m, were sourced from the 9th collection of Mapbiomas (2023). The CP factor values were determined based on the potential outlined by Stein et. al. (1987).

A factor: estimated annual soil loss
Based on the values obtained for the A factor, the data were adapted to the soil loss classification system by Carvalho (2008), which divides soil loss into four classes ranging from 'none to moderate' to 'strong to very strong' (Table 4).

Vc under pasture conditions
Orbital images from the Sentinel-2A sensor were obtained through the Copernicus Programme, provided by the European Space Agency (ESA, 2022). Acquisition dates were standardised to the first half of May, July and October 2022, periods during which pastures display higher vegetative vigour, plus there are generally clear skies and fewer occurrences of wildfire. Climate data were sourced from the National Rice and Beans Research Centre (EMBRAPA, 2022).
The images included two MSIL2A coverages, T22KGF and T22KGG. The multispectral bands used were red (B04) and near-infrared (B08), each with a spatial resolution of 10 metres. During pre-processing, the data were georeferenced and underwent atmospheric correction using the dark object subtraction method (DOS1).
To evaluate pasture vegetative activity during the selected periods, the NDVI was applied to the pre-processed satellite images, following the method proposed by Rouse et al. (1974) (Equation 6):

$$NDVI = NIR - Red/NIR + Red \quad (6)$$

Where: 'NDVI' stands for the Normalized Difference Vegetation Index; 'Red' represents the red spectral band; and 'NIR' denotes the near-infrared spectral band.
Based on the data extracted from NDVI pixels, Vc was estimated. The Vc values were calculated as follows (Equation 7):

$$Vc = (NDVI - NDVIs/NDVIv - NDVIs) \times 100\% \quad (7)$$

Where: 'Vc' represents vegetation cover; NDVI is the annual average NDVI value; NDVIs is the lowest NDVI value found among exposed soil pixels; and NDVIv is the highest NDVI value found among vegetation pixels.

The annual Vc values (Equation 7) were reclassified according to Gao et al. (2006) into five distinct classes of pasture Vc (Table 5).

Statistical analysis
Based on a sample of 65 spatially distributed observations, the relationship between the observations (USLE and Vc) was assessed. The data were analysed using the Pearson correlation and simple linear regression.

Conclusions

The 'moderate' soil loss class was predominant in pasture areas, covering 5,683.19 ha (82.46%), with the most frequent loss rate estimated to lie between 20 and 40 Mg ha^{-1} year^{-1}. Areas with the greatest erosive potential were located in the southern part of the watershed, characterised by Vc conditions ranging from MD to SD, as well as high erosivity and erodibility values. The MD Vc class was predominant, covering 3,919.25 ha (56.87%); however, the Vc results indicated that all pastures exhibited some level of degradation. Higher Vc indices were more frequently observed in areas with lower soil losses, showing a significant inverse correlation (-0.80, p-value ≤ 0.05) between the variables, with a determination coefficient (R^2) of 0.64.

Conflict of interest

The authors declare no conflict of interest.

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