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RESEARCH

Assessment of the impact of conservation measures by modeling soil loss in Minas Gerais, Brazil

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Abstract Gullies are significant contributors to soil degradation in several regions of Brazil, including Minas Gerais, where erosion processes have caused soil loss. The characterization of erosion processes is crucial for the application of measures for recovering degraded areas and reducing erosion impacts. This study models soil loss with the use of InVEST software and assesses the impact of three different scenarios, namely (1) implementation of soil conservation practices and replacement of pasture areas for temporary agriculture, (2) reforestation of pasture areas, and (3) preservation of ciliary forests. Soil loss, sediment exportation, retention, and deposition for the present scenario (2019), as well as the three aforementioned hypothetical scenarios, were estimated. In the present scenario, the estimated mean annual soil loss was 2.75 t/ha year, with 1,449.54 t/year sediment exportation, 9,042.13 t/year retention, and 1,449.54 t/year deposition. The model predicted scenario 1 would result in 2.23 t/ha year mean annual soil loss, 1,300.59 t/year sediment exportation, 9,191.08 t/year retention, and 11,755.76 t/year deposition. Scenario 2 showed 1.92 t/ha year mean annual soil loss, 1,046.69 t/year sediment exportation, 9,444.98 t/year retention, and 10,229.77 t/year deposition, whereas the results for scenario 3 were 2.36 t/ha year, 616.65 t/year, 9,862.06 t/year, and 13,206.47 t/year, respectively. Reforestation and preservation of ciliary forests, along with soil conservation practices, were effective measures for reducing soil loss. Such findings are valuable for the management of areas degraded by erosion processes.

Keywords Erosion · Degraded areas · InVEST · Sediment exportation · Gully

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Introduction

Soil results from interactions among atmosphere, hydrosphere, and biosphere with lithosphere (White, 2006). Therefore, it is multifunctional and essential to maintain environmental quality of water, climate, and biodiversity, provide food and energy security,

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and support urbanization and infrastructure (Blanco & Lal, 2008; McBratney et al., 2014). Soil degradation occurs when quality losses are higher than resiliency capacity and the soil loses its environmental functionalities, due to anthropogenic processes (e.g., industrial, urban, and agricultural uses) or natural ones induced by human activities (e.g., erosion, mass movements, and subsidence) (Zuquette et al., 2013; Zuquette, 2015). Erosion processes indicate detachment of soil particles, transport by erosive agents, and deposition of sediment when the energy is not sufficient to sustain the sediments movement (Morgan, 2005). The removal of particles from eroded geological material corresponds to soil loss, whereas transported particles consist of exported sediments. The sediment retention occurs when the energy provided by the erosive agent is lower than normal forces and the particle does not move. If particles are already being transported and erosive agents' energy lowers, their movement stops, and they are deposited — corresponding to sediment deposition.

Accelerated soil erosion has on-site and off-site impacts to the environment, agronomy, ecology, economy, and society (Lal, 2001; Morgan, 2005; Blanco & Lal, 2008). Erosion directly contributes to removing fine sediments and thinning topsoil. Indirectly, erosive processes cause productivity reduction, lower soil fertility, alterations in soil, water, and biological dynamics, topographic changes, greenhouse gases emission, and desertification (Blanco & Lal, 2008; Rodrigues et al., 2015; Lal, 2020; Lal, 2022). The combination of eroded areas and land mismanagement results in losses of productive areas in rural areas (Bertoni & Lombardi Neto, 2010), strongly affecting small producers. Additionally, soil erosion impacts are in consonance with several UN Sustainable Development Goals, namely (2) zero hunger; (6) clean water and sanitation; (8) decent work and economic growth; (12) responsible consumption and production; (13) climate action; and (15) life in land.

In Brazil, along with equatorial, tropical, and subtropical climate regions, the dominant erosion type is water erosion or hydric erosion. It is controlled by the interaction of water intensity, volume, and velocity with the geological materials, subject to their properties, topography, and vegetation cover (Blanco & Lal, 2008). The concentration of superficial waterflow along with subterranean flow defines the formation of gullies (Poesen et al., 2003; Blanco & Lal, 2008; Rotta & Zuquette, 2015), in which the complexity requires an integrated study for assessments of the main conditioning properties and triggering erosion agents.

Areas intensely affected by erosion processes (e.g., the Palmital stream watershed in Nazareno and Conceição da Barra de Minas, Minas Gerais, Brazil) must be characterized for a proper comprehension of the attributes related to erodibility and erosivity interplay. The Palmital stream watershed region has faced erosion problems, motivating its study since 1996 (Bono et al., 1996), with gullies mapping and characterization of the area (Araújo, 2006; Araújo et al., 2018; Bono et al., 1996; Cassaro, 2015, 2018; Coelho et al., 2012; Ferreira, 2005; Ferreira & Ferreira, 2015; Ferreira et al., 2009, 2011, 2012; Gomide, 2009; Mello et al., 2012; Oliveira, 2015; Pereira et al., 2012, 2014; Real, 2019; Real et al., 2020a, 2020b; Sampaio, 2014; Sampaio et al., 2013, 2016, 2017; Silva, 2006; Silva et al., 2008a, 2008b; Soares, 2022). Both environmental properties and patterns of land use and land cover (LULC) are the main contributors to the development of numerous gullies in the area, which are interconnected by subsurface flow and watercourses (Real, 2019; Real et al., 2020a). Such an interconnectivity generates a cascade of self-feeding events, entailing conducive circumstances for the perpetuation of erosion processes, challenges for a successful gully restoration, and manifold repercussions of erosion, notably soil loss.

Since erosive feature development depends on both environmental conditions and triggering agents, changes of their dynamics will also change erosion evolution, for instance, if rainfall patterns are altered and concentrate in fewer days — leading to higher volume and velocity of water, as well as greater soil water content — erosion rate rises. INMET (2017) stated that there have been irregularities on rain distribution since 2013/2014 in Minas Gerais (Brazil), resulting in lower volumes of precipitation between January and February and worse hydric conditions of soil. Additionally, the South Atlantic Convergence Zone (SACZ) contributed to persistent and heavy rain episodes, which ranged between two to three times the monthly average (INMET, 2020; INMET, 2021). Soares (2022) compared gullies mapped in 2016 and 2019 satellite images and identified erosion progression in the Palmital stream watershed, due to erodible soil exposing in conjunction with change in rainfall patterns.

Models simplify reality to support predictions on a system's behavior considering specific conditions to its functioning (Morgan, 2005). The application of models is possible in various ways and purposes. For instance, modeling erosion can simulate resilience of soil, runoff, and soil loss rates. Then, it is easier to comprehend erosive processes; evaluate large-scale impacts to soil productivity and water quality; identify strategies to erosion control; and evaluate soil conservation practices performance to reducing erosive processes (Blanco & Lal, 2008; Morgan and Nearing, 2011; Soares, 2022). Modeling techniques that encompass various alternative scenarios must be adopted for a comprehensive assessment of the impacts of LULC changes on soil loss through gully erosion. The incorporation of those scenarios enables the derivation of quantitative and qualitative insights into the dynamics of sediment transport; hence, it facilitates decision-making among stakeholders regarding areas prone to erosion or those already degraded.

The soil system is connected to the four ecosystem services classes, namely: provisioning, regulatory, cultural, and supporting (MEA, 2005). Soil ecosystem services can be affected by compaction, contamination, erosive processes, fragmentation of vegetation, and reduction of soil fertility, biodiversity, and carbon stock (Prado et al., 2016). In this context, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software was developed to assess ecosystem services. The software has low to medium complexity regarding hardware requirements and data processing and is integrated to the Geographic Information System (GIS) environment (Cong et al., 2020). The software is open-source and free, which encompasses several models for ecosystem services, allowing the evaluation of relationships between supplies, services, and benefits (Azevedo, 2017; Natural Capital Project, 2021). The application of InVEST software is advantageous to compute biophysical and socioeconomic metrics both in high and low data volume (Hamel et al., 2015). Sediment delivery ratio (SDR), one of InVEST built-in models, enables analyses of soil loss and sediments dynamics in watersheds or subwatersheds under investigation, thus assisting public policies planning and recovery of degraded areas (Soares, 2022). SDR-InVEST model maps sediment generation and its transportation to watercourses considering sources (areas where erosion surpasses deposition) and sinks (areas of trapping and/or deposition of sediments) (Natural Capital Project, 2021). It has mapped areas more vulnerable to erosion processes (Bouguerra & Jebari, 2018; Bouguerra et al., 2021; Karunaratne et al., 2022; Meraj et al., 2022; Oleson et al., 2017; Ougougdal et al., 2020; Perera et al., 2020), compared temporal sequences or scenarios of LULC changes (Aneseyee et al., 2020; Bendito et al., 2023; Cunha et al., 2022; Gong et al., 2021; Guo et al., 2023; Kulsoontornrat & Ongsomwang, 2021; Liu et al., 2020; Marques et al., 2021; Matomela et al., 2022; Perovic et al., 2018; Rodrigues & Ferreira, 2021; Tamire et al., 2022; Zhou et al., 2019), and integrated the model with Geodetector (Guo et al., 2023; Matomela et al., 2022). In Brazil, institutions such as EMBRAPA (Brazilian Agricultural Research Corporation) and INPE (National Institute for Space Research) have collaborated with university researchers to testing InVEST (Bendito et al., 2023; Christo & Garrastazu, 2011; Guo et al., 2023; Horokoski et al., 2013; Hyslop et al., 2019, 2020; Weiser et al., 2012), especially SDR (Lemos et al., 2023; Rodrigues & Ferreira, 2021) and carbon (Cardoso et al., 2023; Castanhari et al., 2011) models. Therefore, the use of InVEST models enables geospatial interpretations of interactions among topography, erodibility, erosivity, and land use and land cover patterns, which is essential for the understanding of erosion consequences in a watershed. The simulation of alternatives scenarios through changes in parameters — such as LULC, erodibility, and erosivity — supports policymaking and area management, strengthening ecosystem services provided to population and amplifying sustainability (Soares, 2022). Synergistic and trade-off relationships between ecosystem services are associated with both natural environment and human activity (Zhao et al., 2022); therefore, alterations in land management will repercuss in the area.

This study evaluates soil loss in the Palmital stream watershed (Minas Gerais), where over 60 have been mapped, through InVEST application and considering the present scenario and three hypothetical ones. Regardless of being a case study of a Brazilian area, assessing more information about soil erosion and ecosystem services can support studies in similar areas — for instance, tropical regions — and compose a global context of erosion processes behavior, consequences, and recovering or minimizing impact techniques. Furthermore, exploring hypothetical scenarios provides an analysis especially useful considering climatic changes, an urgent issue that requires attention when planning LULC, studying conservation measures efficiency, and addressing degradation.

Materials and methods

Study area

The Palmital stream watershed (Fig. 1) is located in Nazareno and Conceição da Barra de Minas municipalities, in the south of Minas Gerais state, Brazil. It

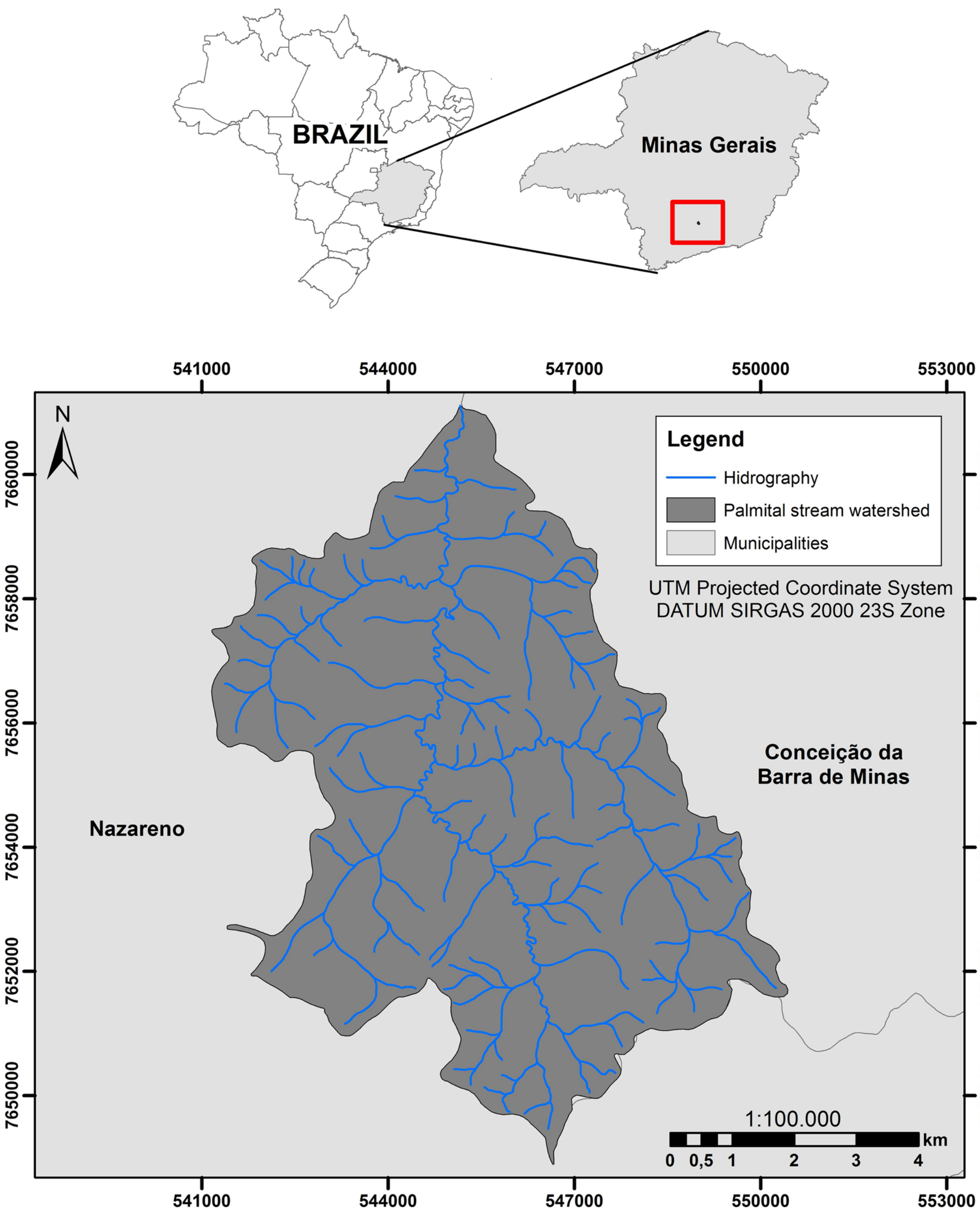

Fig. 1 Map of the Palmital stream watershed

comprises Beta de Baixo, Beta de Cima, Charuteiro, Forro, Fundo, Pitanga, Sapecado, Sítio, and Teixeira stream watersheds, with a 5866 ha total area. Soares (2022) identified 65 gullies in the watershed, corresponding to 404.48 ha of degraded area.

The climate is characterized by rainy summers and dry winters, with a 1,350 mm average annual rainfall and temperatures ranging from 8 °C to 28 °C (INMET, 2022). The rainy season goes from October to March, especially November to January. An irregular rainfall distribution has been reported since 2014, when lower volumes of precipitation were detected in January and February, resulting in heat waves that decrease soil hydric conditions, since the water absorbed by the soil evaporates before the typical period, impacting the crops growth (INMET, 2017). Moreover, climate changes associated with the South Atlantic Convergence Zone (SACZ) have caused intense and persistent rainstorms, twice to three times higher than the average rainfall (INMET, 2020; INMET, 2021).

The natural vegetation of Nazareno and Conceição da Barra de Minas is composed of Atlantic Rainforest and Brazilian Savannah (Cerrado) (IBGE, 2004) and has been switched for pastures and crops of soybeans, corn, and coffee, as well as urban areas.

Elevations in Nazareno range from 1140 to 839 m, with strong relief in the gully region (Horta et al., 2009), and from approximately 1091 to 897 m in the watershed. The geology is represented by Cassiterita Orthogneiss, Nazareno Formation, and Represa dos Camargos Metadiorite (Soares, 2022), paleoproterozoic units with an elongated shape in the ENE-WSW direction (Ávila et al., 2019). The Lenheiro shear zone and greenstone belts are at its southern limits (Ávila et al., 2003).

Red-yellow Oxisol, red Oxisol, and Cambisols are the typical soil types in the area (Ferreira, 2005; Horta, 2006; Horta et al., 2005, 2009). Oxisols are dystrophic and clayey, with high levels of sesquioxides and aluminum oxides and lower levels of silica and organic matter. Cambisols are dystrophic and alic shallow soils with superficial encrusting and low permeability (Horta, 2006; Horta et al., 2009). In comparison with Oxisols, they are more erodible, due to slower drainage, stoniness, fewer vegetal cover, and relief and slope characteristics (Ferreira, 2005). In the watershed, Oxisols are on top of Cambisols and their removal leads to soil exposition to weathering and erosion (Sampaio, 2014).

SDR-InVEST framework

SDR-InVEST model, a built-in package that map sediment sources and delivery to the sinks (where sediment deposits), provides information to better understand the service of sediment retention in a catchment. The model maps and quantifies soil loss and sediment exportation, retention, and deposition of a given watershed. Additionally, it is possible to simulate alternative or hypothetical scenarios through the alteration of attributes — particularly those more susceptible to changes with time, namely LULC, conservation practices, and climate (Soares, 2022). The capacity of mapping, quantifying, and predicting soil erosion and sediment exportation, retention, and deposition contributes to better decision on land management. When comparing InVEST to other similar modeling software, there are several differences regarding methodology and algorithms, as well as data requirements and processing time. Due to the simpler nature of input and processing, InVEST is a better alternative to promptly assessing current state and scenarios of areas with limited amount of data. As limitations, InVEST may not accurately represent tropical climate, which should be validated with more research in tropical regions. The model's validation will be possible with time and comparisons between modeled results and reality results.

The module computes the amount of annual soil loss from each pixel of the digital elevation model (DEM) and then computes the proportion of soil loss that reaches the stream (Natural Capital Project, 2021). The model is based on Revised Universal Soil Loss Equation (RUSLE), which can be applied to greater areas, as watersheds (Silva, 2008; Wischmeier & Smith, 1965). The RUSLE formula is show in Eq. 1, where $usle$ = annual soil loss (tons/ha/year); R = rainfall erosivity (MJ mm/(ha h)); K = soil erodibility (ton ha h/(MJ ha mm)); LS = slope length-gradient factor (unitless); C = crop-management factor (unitless); P = support practice factor (unitless).

$$usle = R \times K \times LS \times C \times P \tag{1}$$

The LS factor is calculated by InVEST, according to the method for a two-dimensional surface, proposed by Desmet and Govers (1996), as shown in Eq. 2, where S = slope factor for grid cell calculated as a function of slope radians θ (Eqs. 3 and 4); $A_{i\text{-}in}$ = contributing area at the inlet of a grid cell which is computed from the multiple-flow direction method (m^2); D = grid cell linear dimension (m); x_i = mean of aspect weighted by proportional outflow from grid cell i determined by a multiple-flow direction algorithm (Eq. 5); and m = RUSLE length exponent factor (Eqs. 6 to 11), which is capped to 333 m to avoid overestimation in heterogeneous landscapes (Natural Capital Project, 2021).

$$LS = S \times \frac{\left(A_{i-in} + D^2\right)^{m+1} - A_{i-in}^{m+1}}{D^{m+2} \times x_i^m \times (22.13)^m} \tag{2}$$

$$S = 10.8 \times \sin(\theta) + 0.03 \text{ where } \theta < 9\% \tag{3}$$

$$S = 16.8 \times \sin(\theta) - 0.50 \text{ where } \theta \geq 9\% \tag{4}$$

$$\sum\nolimits_{d\in\{0,7\}} \frac{P_i(d)}{x_d} \text{ where } \theta \geq 9\% \tag{5}$$

$$m = 0.2 \text{ for slope } \leq 1\% \tag{6}$$

$$m = 0.3 \text{ for } 1\% < \text{slope} \leq 3.5\% \tag{7}$$

$$m = 0.4 \text{ for } 3.5 < \text{slope} \leq 5\% \tag{8}$$

$$m = 0.5 \text{ for } 5\% < \text{slope} \leq 9\% \tag{9}$$

$$m = \frac{\beta}{1+\beta} \text{ where } \beta = \frac{\frac{\sin\theta}{0.0986}}{3\sin\theta^{0.8} + 0.56} \text{ for slope} \geq 9\% \tag{10}$$

The connectivity index (IC) is computed for each pixel, as a function of the area upslope of each pixel (D_{up}) and the flow path between the pixel and the nearest stream (D_{dn}), as represented in Eq. 11. Therefore, upslope is related to the transport, and downslope is corresponding to retention (Natural Capital Project, 2021).

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \tag{11}$$

The upslope and downslope components are defined by mathematical relations shown in Eqs. 12 and 13, respectively, where $\overline{C}$ = average C factor of the upslope contributing area; $\overline{S}$ = average slope gradient of the upslope contributing area (m/m); A = upslope contributing area (m^2); d_i = length of the flow path along the ith cell according to the steepest downslope direction (m); C_i = C factor of the ith cell; and S_i = slope factor of the ith cell. C_i and S_i minimum and maximum limits are 0.005 m/m and 1 m/m, respectively, to avoid infinite values (Natural Capital Project, 2021).

$$D_{up} = \overline{CS}\sqrt{A} \tag{12}$$

$$D_{dn} = \sum_i \frac{d_i}{C_i S_i} \tag{13}$$

The proportion of sediment that reach the stream corresponds to the sediment delivery ratio and is calculated as shown in Eq. 14, where SDR_{i} = SDR ratio for a pixel i; SDR_{max} = maximum theoretical SDR, set to an average value of 0.8; IC_0 and k = calibration parameters that define the shape of the SDR-IC relationship.

$$SDR_i = \frac{SDR_{max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)} \tag{14}$$

The amount of sediment eroded from a given pixel that reaches the stream, sediment export, is given by Eq. 15. The sediment deposition consists of the amount of sediment deposited on the landscape downstream from the source, which do not reach the stream, given by Eq. 16.

$$E_i = usle_i \times SDR_i \tag{15}$$

$$E\prime_i = usle_i\left(1 - SDR_i\right) \tag{16}$$

Modeling process

The models for each scenario were generated in InVEST 3.9.0 software, following the sequence of processes as shown in Fig. 2, that is, data gathering and processing, calibration, data input, and modeling. Raster (TIF) and shapefile (SHP) data were processed in ArcMap 10.4. Matrix data were converted

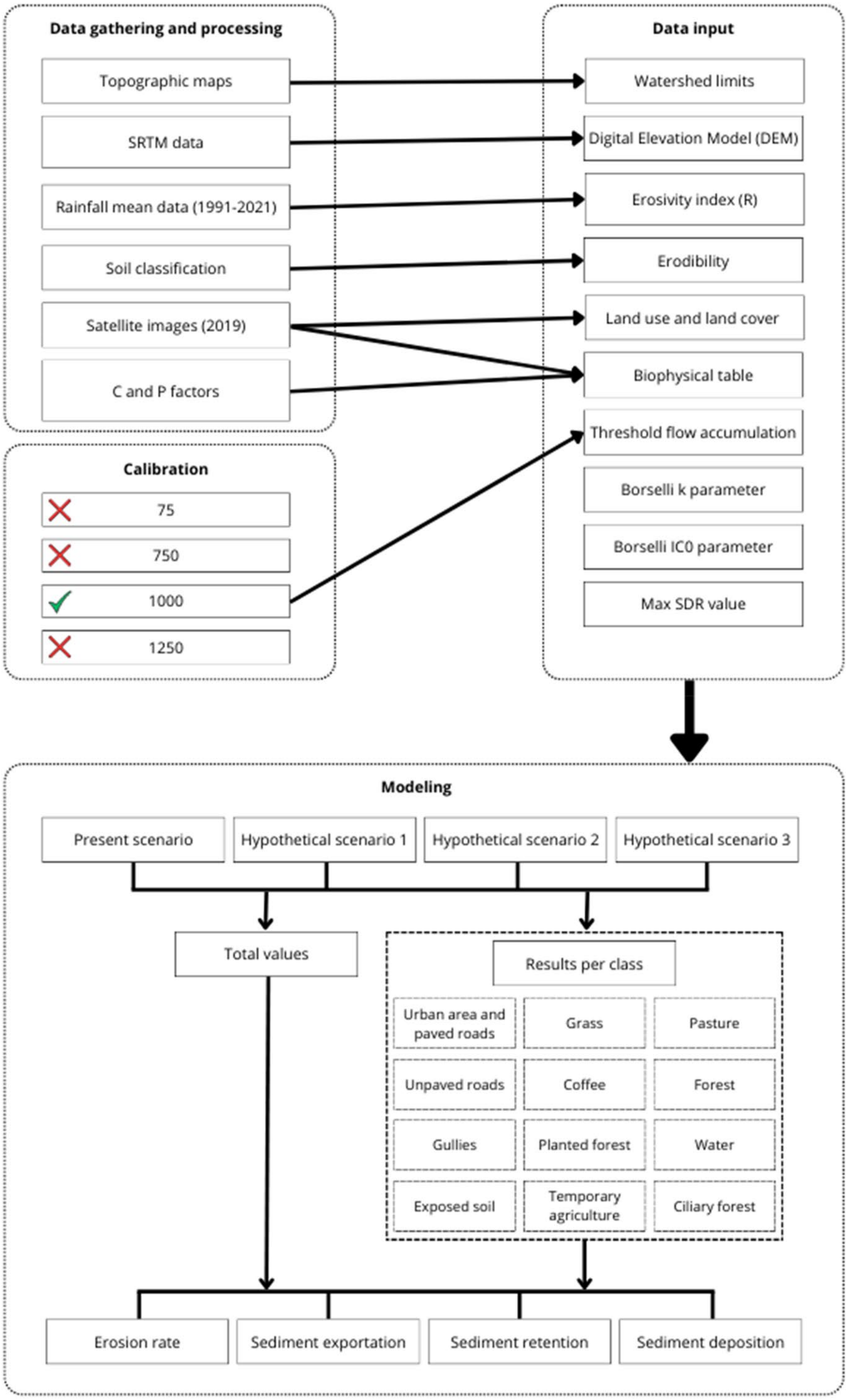

Fig. 2 Flowchart of applied methodology

from raster files to TIF format and vector data were inserted as a shapefile file. The biophysical table was a CSV file.

The default values from InVEST SDR model were applied to threshold flow accumulation, Borselli k parameter, Borselli IC0 parameter, and max SDR value (1000, 2, 0.5, and 0.8, respectively).

The watershed limits were based on Nazareno (SF-23-X-C-I-2) (IBGE, 1975a) and Itutinga (SF-23-X-C-I-4) (IBGE, 1975b) topographic maps, on a 1:50,000 scale, from Brazilian Institute of Geography and Statistics (IBGE). DEM was generated as a raster file in ArcMap with "Raster Interpolation" and "Hydrology – Fill" tools.

The rainfall erosivity index (R) was generated from the interpolation of rainfall mean data of Lavras and São João del Rei (Minas Gerais, Brazil) weather stations, from 1991 to 2021. The point format shapefile classes were weather station name, latitude, longitude, mean rainfall, and years considered in the mean rainfall calculation. Coordinates were converted from WGS 1984 datum to SIRGAS 2000 23S Zone datum, and the geoprocessing environment included the following municipalities: Nazareno, Conceição da Barra de Minas, Lavras, São João del Rei, Bom Sucesso, Carrancas, Ibituruna, Ijaci, Itumirim, Itutinga, Ritápolis, and São Tiago. The interpolation was performed by the inverse distance weighted (IDW) interpolation tool from spatial analysis package, which assumes a decrease in the variable being mapped considering its distance from its sampled location, therefore determining cell values using a linearly weighted combination of a set of sample points through a function of inverse distance (as informed in ArcGIS 10.4 software documentation). IDW interpolation of erosivity is given by Eq. 17, where Z_i = rainfall erosivity or erosivity interpolated at the point i (MJ mm/ha/h); d_{ij} = distance between the points i and j; Z_j = rainfall erosivity or erosivity density calculated at the point j (MJ mm/ha/h); and n = number of neighboring points used in interpolation (Teixeira et al., 2022).

$$Z_i = \frac{\sum_{j=1}^{n=30}\left(\frac{Z_j}{d_{ij}^2}\right)}{\sum_{j=1}^{n=30}\left(\frac{1}{d_{ij}^2}\right)} \tag{17}$$

The soil erodibility raster was based on a soil survey conducted by Federal University of Viçosa (UFV), Technological Center Foundation from Minas Gerais (CETEC), Federal University of Lavras (UFLA), and State Foundation of the Environment from Minas Gerais (FEAM-MG), on a 1:100,000 scale (UFV, 2010). The units considered were rock exposition, red-yellow Oxisol, red Oxisol, and Cambisols. Soil erodibility values were obtained from the literature (Table 1).

LULC characteristics of a given area influence erosive processes development due to its role in protecting or exposing the geologic material and in changing conditions for infiltration and runoff dynamics. According to Blanco and Lal (2008), vegetation cover may intercept, absorb, and reduce energy from raindrops. An exposed soil is more likely to erode, since it lacks a physical barrier to water's erosive energy (Soares, 2022). Changes in LULC may accelerate natural erosion, especially due to soil mismanagement, deforestation, unpaved roads without a drainage system, overgrazing, over farming, and inadequate practices (Poesen et al., 2003; Real, 2019; Valentin et al., 2005).

Land use and land cover data were obtained from 29 satellite images from July 1, 2019 (Maxar Technologies), obtained from Google Earth PRO, providing free data with great quality regarding to resolution. Real (2019) and Soares (2022) mapped LULC from 2016 images, and it was needed to update data using more recent images, especially considering climate changes in the area as reported in INMET (2017, 2020, 2021). Visual representation of the satellite images of the watershed is given in Supplementary Material.

The LULC map had bare soil, gully, unpaved road, urban area and paved road, grass, coffee, temporary agriculture, pasture, planted forest, forest, and water as classes. The LULC features were saved in a shapefile (polygon format) after the polygons had been clipped. Therefore, only the elements in the

Table 1 Soil erodibility values in the Palmital stream watershed

Soil classification	Erodibility (Mg ha/MJ/mm)	Sources
Red Oxisol	0.0100	Silva (1997 apud Beskow et al., 2009)
Red-yellow Oxisol	0.0032	Silva et al. (2009)
Cambisol	0.0355	Silva et al. (2009)

watershed were considered. The LULC map for scenario 3 showed a 30-m buffer from the rivers, corresponding to the permanent preserved area (ciliary forest). Consequently, the shapefiles were converted to a raster file by "Polygon to Raster" and then to TIF by "Export Data".

The biophysical table (Table 2) provides information on LULC classification, respective c (land use and management) and p (conservation practices) factors, and sources.

The model was calibrated through a comparison of the resultant "Stream" raster with a shapefile of the study area's hydrography and different values of "Threshold Flow Accumulation," namely 75, 750, 1000, and 1250 were tested. Those values were arbitrarily chosen to observe the adjustment of the outcome, and the best adjustment indicated greater calibration of the model. As observed in Figs. 3 and 4, the better adjustment was made when a threshold flow accumulation of 1000 was applied. Therefore, it was used in all scenarios.

Gully development in the watershed is especially related to areas of pasture and temporary agriculture, as observed in previous research (Cassaro, 2015, 2018; Real, 2019; Real et al., 2020a, 2020b; Sampaio, 2014; Sampaio et al., 2016, 2017); therefore, it was necessary to evaluate if changes in those LULC classes would have major implications in erosion process, assessed through soil loss and sediment transport information. Pastures are predominant in the watershed and generally are associated with mismanagement and land degradation due to poor vegetation covering, soil compaction by cattle, and lower maintenance. Following a tendency of substitution of pasture areas for temporary agriculture, observed between 2016 and 2019, due to the rise of grains prices (Soares, 2022), it was chosen to model a scenario (scenario 1) that followed this trend, along with conservation practices, which would also have positive impacts to minimizing erosion. A more optimistic scenario (scenario 2) simulated the replacement of pastures for planted forests, testing reforestation as an extreme measure to contain erosion. Finally, scenario 3 modeled the successful preservation of ciliary forests (areas up to 30 m from the watercourses), according to Law nº 12,651/2012 (Brasil, 2012), which is already legally required but not effectively adopted. Then, those scenarios support a comparative analysis of LULC influence to soil loss in the area, mostly related to soil vulnerability to erosive agents and deflagrant agents.

All scenarios modeled had the same input data, except for LULC raster and biophysical table. LULC classes and c and p factors were the categories and values defined for 2019 for the present scenario. Alterations were made in LULC classes and in c and p factors (defined in biophysical tables for the hypothetical scenarios in function of the criteria adopted).

Individual results for each LULC class were obtained from biophysical tables specific for the

Table 2 Biophysical table of LULC classes in the Palmital stream watershed

Description	Code	C factor	P factor	Sources
Urban area and paved roads	1	0.8500	1	Marques et al. (2003)
Unpaved roads	2	0.1500	1	Azevedo (2017)
Gullies	3	1.0000	1	Mota e Silva et al. (2021)
Bare soil	4	1.0000	1	Mota e Silva et al. (2021)
Grass	5	0.0130	1	Azevedo (2017)
Coffee	6	0.1350	1 or 0.5*	Cerri (1999)
Planted forest	7	0.0080	1	Silva et al. (2011)
Temporary agriculture	8	0.2900	1 or 0.5*	Beskow et al. (2009)
Pasture	9	0.2000	1	Marques et al. (2003)
Forest	10	0.0004	1	Bertoni and Lombardi Neto (1990 apud CERRI, 1999)
Water	11	0.0000	1	Bertoni and Lombardi Neto (1990 apud CERRI, 1999)
Ciliary forest	12	0.0008	1	Tavares (2001)

*p factor = 1 in the present scenario and 2 and 3 hypothetical ones; p factor = 0.5 in hypothetical scenario 1

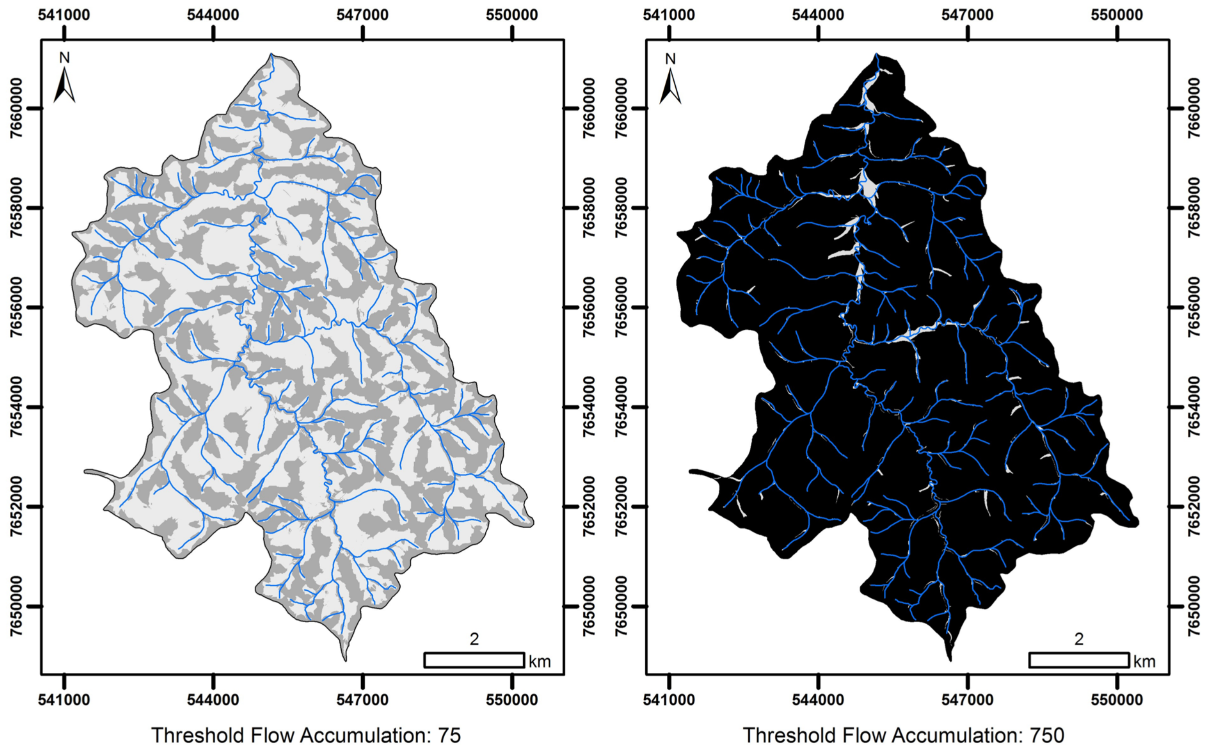

Fig. 3 Calibration of InVEST model through a comparison of threshold flow accumulation values of 75 and 750 with stream vector data

scenario class. The process was repeated ten times (for all classes, except water, whose c and p factors were zero) for the present scenario and for hypothetical scenarios 1 and 2 and eleven times (with the addition of ciliary forest) for hypothetical scenario 3.

Results and discussion

Base maps

The attributes required for modeling were processed and their maps are shown below: topography (DEM) (Fig. 5), erodibility of the soil (Fig. 6), rainfall averages (Fig. 7), LULC from 2019 (Fig. 8), and LULC considering a 30-m buffer from water courses as preservation areas (Fig. 9). It is highlighted that there are two rasters for LULC since hypothetical scenario 3 includes ideal areas of ciliary forests, which are not compatible with reality observations in 2019 images. Also, erosivity data is represented as mean annual rainfall, which was the raw data input to assess erosivity in the watershed.

Present scenario

The model results for land use and cover mapped in 2019, denominated as present scenario, are shown in Table 3.

Forests, grass fields, and planted forests showed the lowest erosion rates, since vegetation protects from raindrops impacting the soil. Their c factor and soil loss results are the lowest in the area. The highest mean erosion is associated with gullies and bare soil, since their c factor is 1, suggesting higher exposure to rainsplash and overland flow. Sediment mobilization surpasses deposition in gullies because the particles are removed from the area.

The LULC classes with the most significant soil loss rates in the study area were gullies (5,117.03 t/year), pasture (5,052.51 t/year), temporary agriculture (3,116.27 t/year), and exposed soil (2,407.10 t/year). Soil loss tolerance values were 5.60 t/ha year for

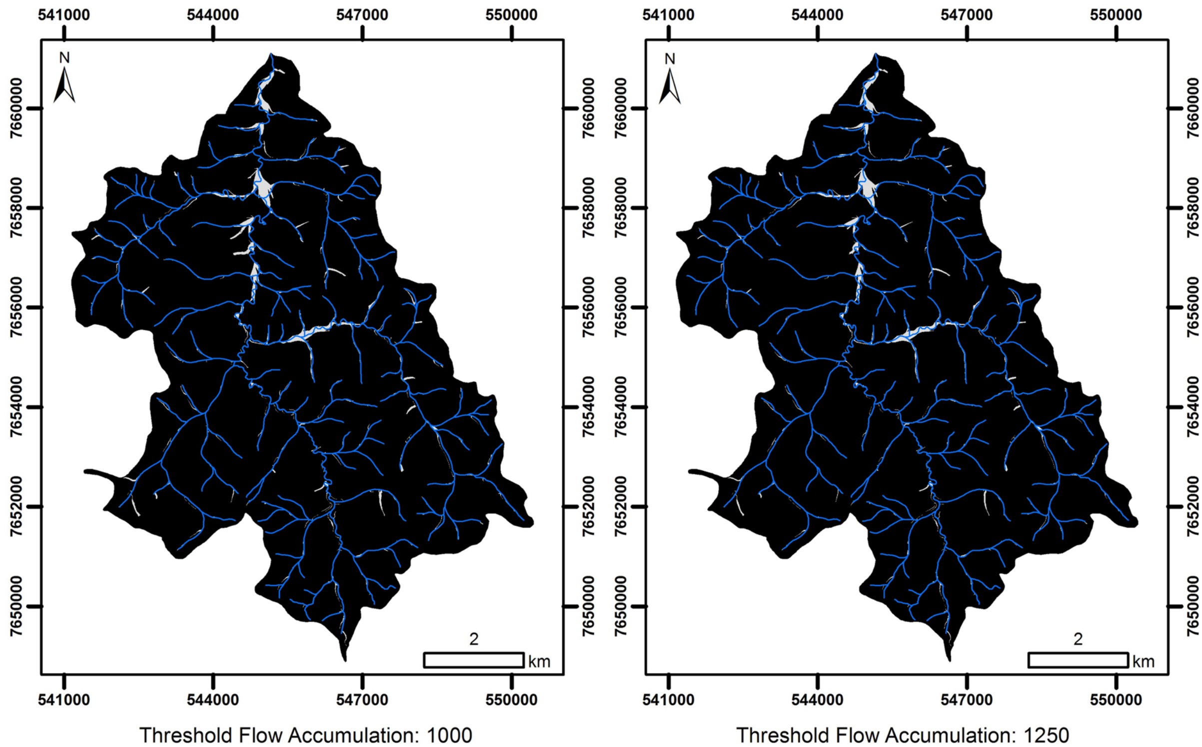

Fig. 4 Calibration of InVEST model through a comparison of threshold flow accumulation values of 1000 and 1250 with stream vector data

Cambisols (Silva et al., 2009) and 10 to 12 t/ha year for red-yellow latosols (Sparovek &Jong Van Lier, 1997; Silva et al., 2005; Silva et al., 2008a, 2008b; Ferreira et al., 2021). Average rates of 13.34 t/ha year for gullies and 10.89 t/ha year for exposed soil, which are above tolerance, justify the need for conservation of degraded and exposed soil.

Pasture and temporary agriculture were identified as the dominant LULC classes, occupying 39.28% and 20.44% of the watershed, respectively, and pasture areas were associated with erosive soils known as Cambisols. Real (2019) had observed a modest variation in pastures areas, which corresponded to 51% of the watershed in 2022, 38% in 2007, 42% in 2014, and 46% in 2016. Comparing with 2019 mapping, the pastures total area was reduced. However, gullies mapping indicated the progression of erosion, evidenced by the enlargement of features and new gullies arise (Soares, 2022).

Inadequate management practices in pastures resulted in increased vulnerability to water erosion, intensified by soil compaction from cattle movement, thus hindering water infiltration and promoting overland flow (Cassaro, 2015, 2018; Ferreira & Ferreira, 2015; Real, 2019; Sampaio, 2014; Sampaio et al., 2016; Soares, 2022). The large extent of pastures in the watershed were selected as target areas for a potential replacement with temporary agriculture or reforestation, as explored in hypothetical scenarios 1 and 2, respectively. It was also modeled on a hypothesis that considered the preservation of ciliary forests (hypothetical scenario 3). Temporary agriculture, comprising mainly corn and soybean crops, represents an alternative form of land use instead of pastures. However, its erosion potential, characterized by a higher c factor compared to permanent agricultural activities such as seedling planting, requires the implementation of conservation practices to mitigating soil loss. Notably, when pasture areas were replaced by temporary agriculture and conservation practices were implemented in both temporary agriculture and coffee crop areas in hypothetical scenario 1, temporary agriculture constituted 59.72% of the total land area, as described below.

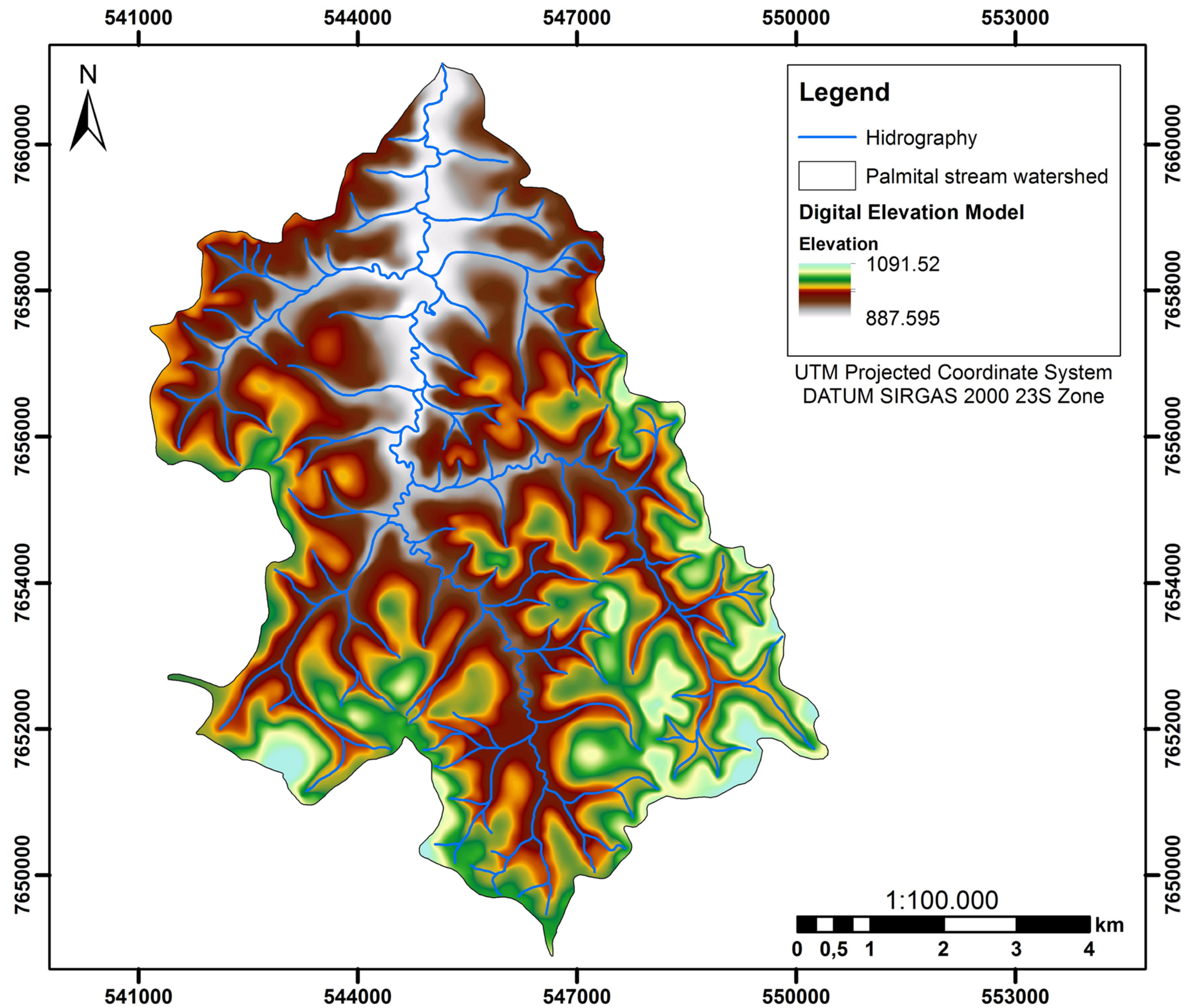

Fig. 5 Map of topography of the Palmital stream watershed

Hypothetical scenario 1: implementation of soil conservation practices and temporary crops

The first hypothesis considered the application of soil conservation practices, represented as p factor (changed from 1 to 0.5), on temporary agriculture (dominantly soybeans and corn) and coffee crops. The replacement of all pasture areas for temporary agriculture, which shows lower potential for erosion, according to results from the present scenario, was modeled, leading to a change in the c factor of pastures, responsible for the second greater total mean erosion — gullies are the first. Table 4 shows the results for hypothetical scenario 1.

Results for mean erosion per area showed higher values for gullies, exposed soils, urban areas, and paved roads. Despite the lower mean erosion per area values for temporary agriculture, the total mean erosion sums 5,221.20 t/ha year due to their extensive area of 3,493 ha. However, a comparison of the sum obtained for the present scenario, i.e., 8,168.78 ha/year, revealed almost 3,000 t of soil would be preserved each year.

The application of conservation practices such as terraces reduces slope degree and length, lowering runoff energy, and increases water infiltration and organic matter content (Chen et al., 2021; Deng et al., 2021; Wen et al., 2021; Cerretelli, 2023).

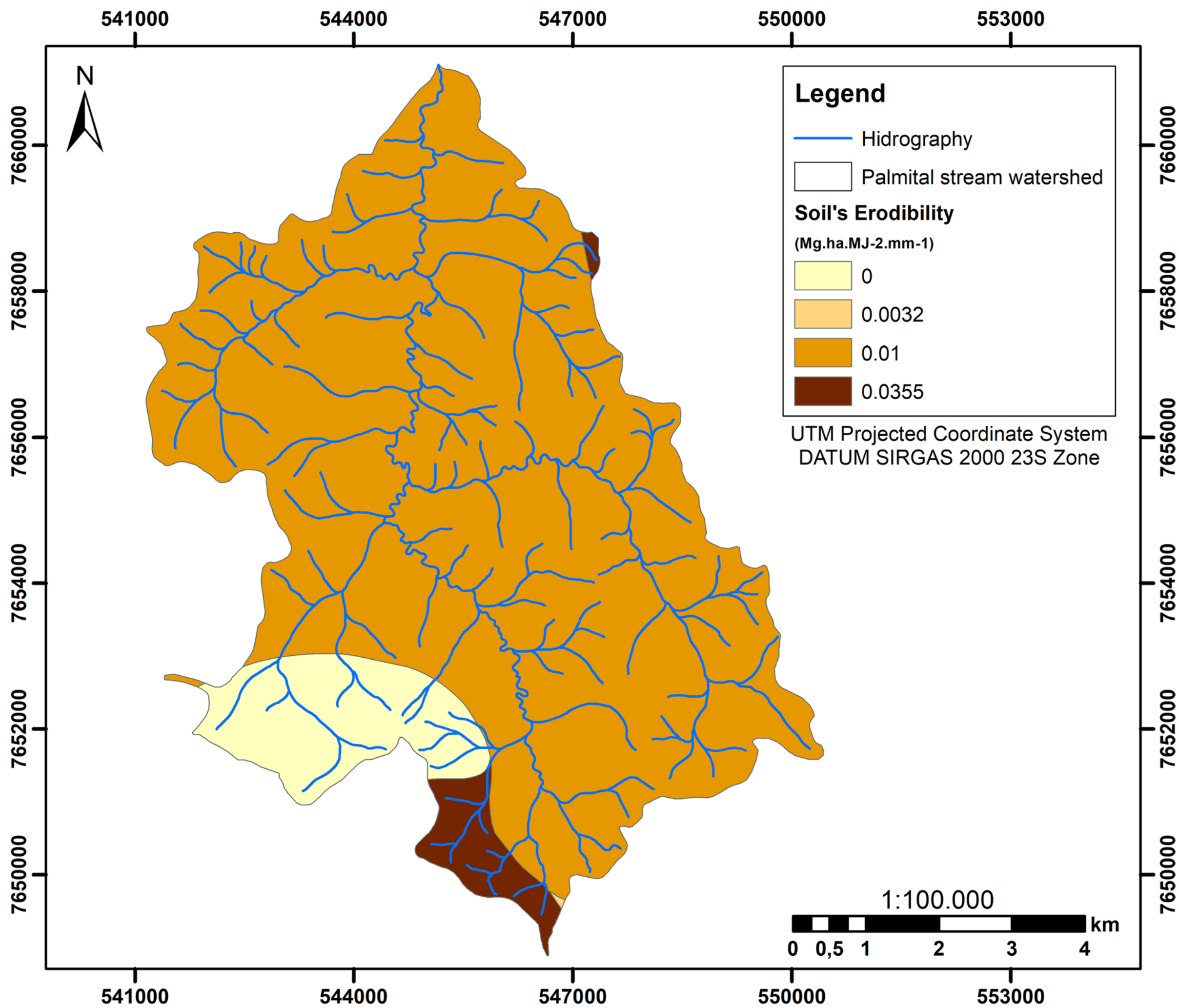

Fig. 6 Map of erodibility of the Palmital stream watershed

Therefore, favorable conditions to erosion progressing are reduced, which is positive to containing loss of productive areas. As stated by Lal (2019), one of the basic principles of sustainable management of agroecosystem soils is to maintain a permanent cover and protection to the soil. So, permaculture would be better than temporary agriculture to avoid erosion, but comparing the latter with pastures, and considering the influence of economic advantages to producers, temporary agriculture is more viable. Then, the replacement of pastures and application of conservation practices in temporary agriculture and coffee crops (planting on contour lines) modeling showed a reduction on soil loss from 2.61 to 1.30 t/ha year and from 0.92 to 0.46 t/ha year, respectively, i.e., mean erosion per area would be cut in half.

Hypothetical scenario 2: reforestation of pasture areas

The second hypothesis modeled the replacement of all pasture areas, which are the major source of erosion from the watershed, for planted forests. It would represent a more extreme measure for the preservation of potentially productive land, avoiding soil erosion due to vegetation cover. The results are shown in Table 5.

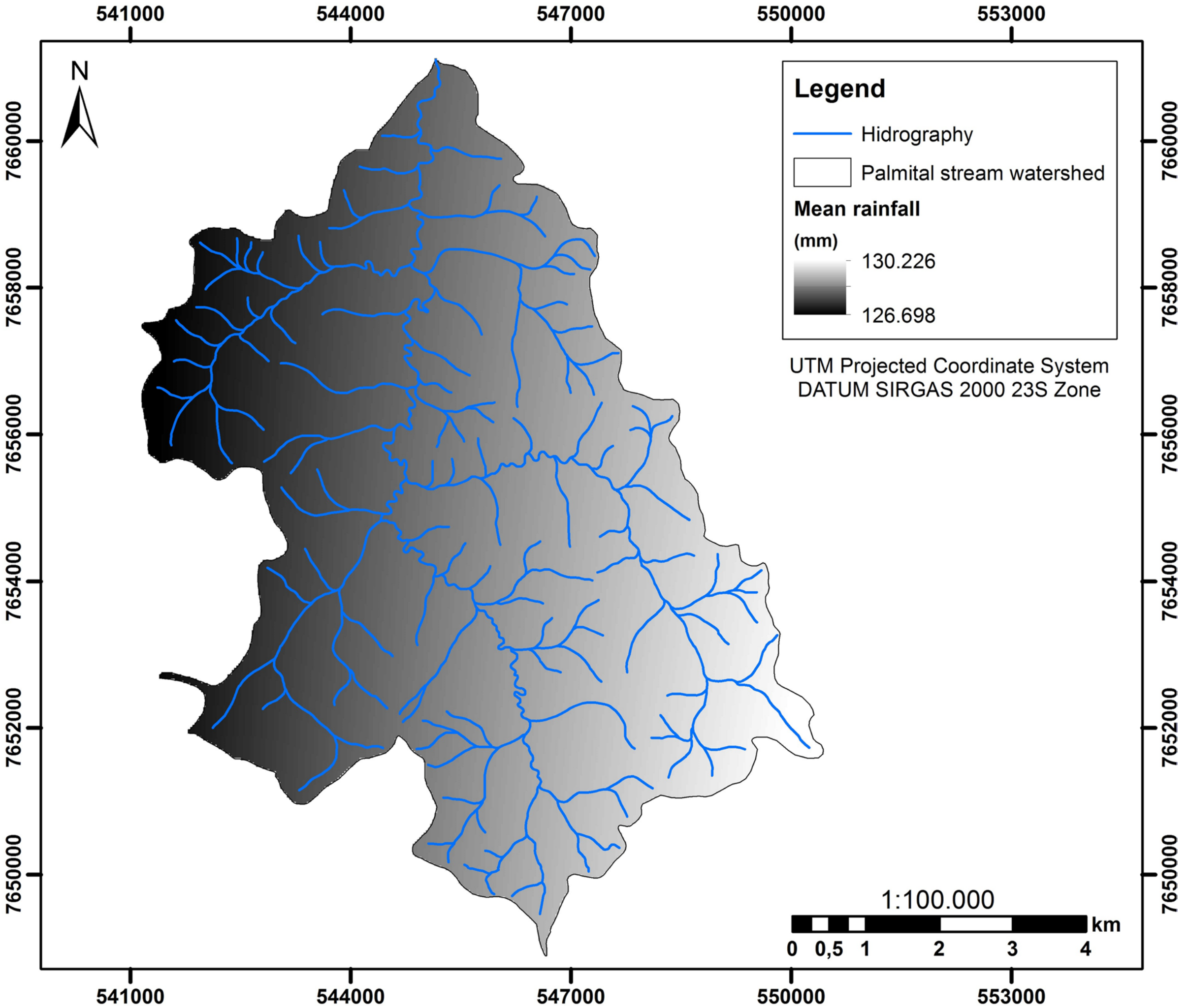

Fig. 7 Map of mean rainfall used to calculate erosivity of the Palmital stream watershed

Pastures can induce erosive processes, since they are generally associated with inadequate soil management, overgrazing, and soil degradation due to modifications in soil properties and nutrients and organic matter loss (Antoneli et al., 2018). The circumstances in the Palmital stream watershed are aggravated by the major presence of Cambisols in pasture areas, which combine the high erodibility of the soil with the poor management of land, favoring soil erosion. Studies have suggested positive impacts of reforestation and implementation of agroforestry practices in grazing systems (Gibson et al., 2022; Huang et al., 2017; Korkanç, 2014; Madern, 2012). The replacement of areas prone to erosion for conservation and reforestation ones is an alternative to decrease surface runoff (Korkanç, 2018; Lense et al., 2022a, 2022b; Smith et al., 2015; Tiwari et al., 2019) and splash erosion, due to permanent soil cover (Lense et al., 2022a, 2022b), therefore reducing soil loss.

The reforestation of pasture areas reduced their mean erosion from 2.29 t/ha year to 0.09 t/ha year and sediment exportation from 223.04 t/year to 3.73 t/year. Therefore, reforested areas would have lower values than temporary agriculture (2.61 t/ha year mean erosion and 142.21 t/year sediment exportation) and coffee crops (0.92 t/ha year mean erosion and 7.49 t/year sediment exportation).

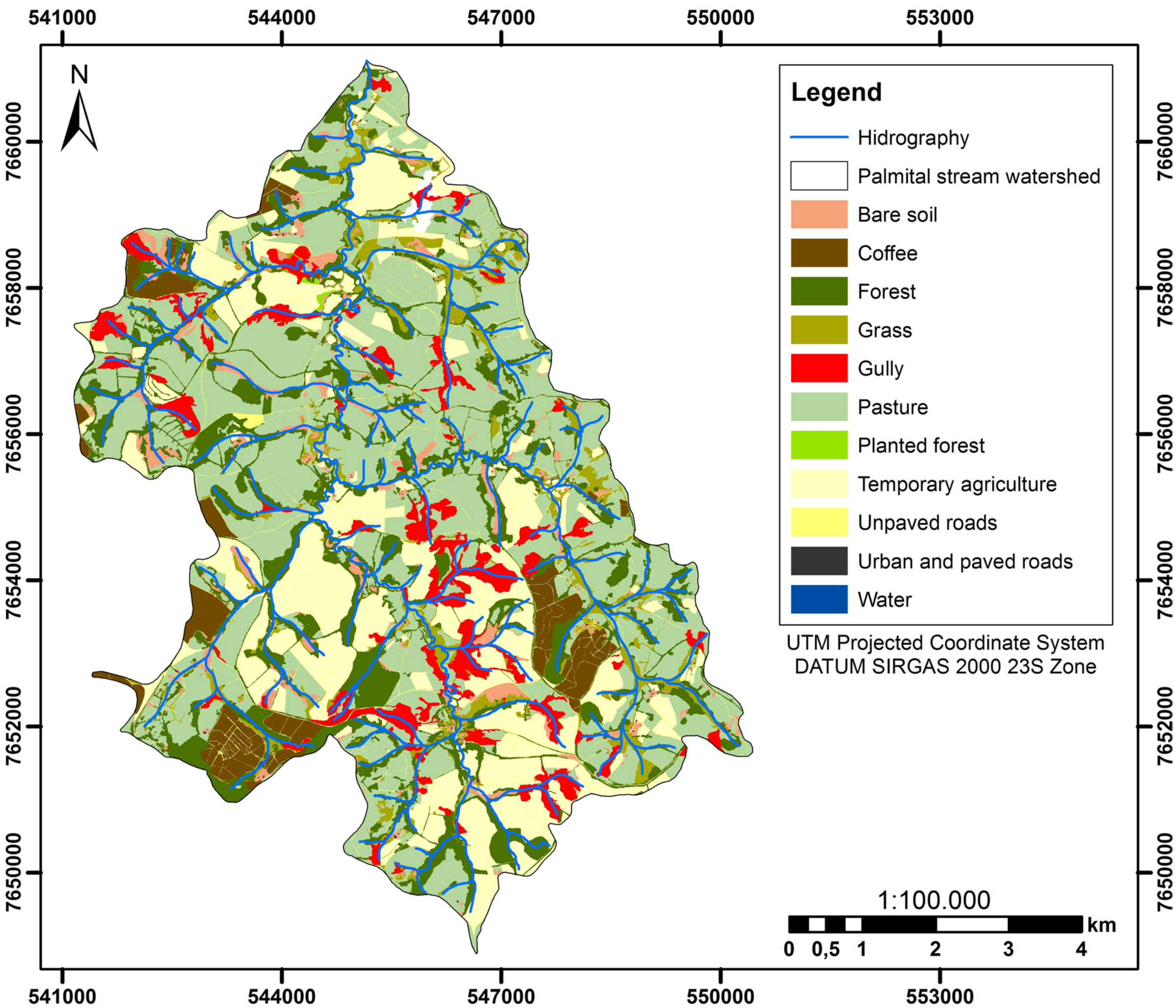

Fig. 8 Map of land use and land cover of the Palmital stream watershed from 2019

A comparison of the results from the hypothesis with the present scenario revealed soil loss, sediment exportation, and deposition would be reduced by approximately 30%, and the sediment retention would increase by 4%. Consequently, reforestation would reduce impacts of pasture on the watershed by modifying the dynamics of erosion processes.

Hypothetical scenario 3: preservation of ciliary forests

The third hypothesis simulated the full preservation of ciliary forests, represented by a 30-m buffer from water courses, as established by Law no. 12,651/2012 (Brasil, 2012), which is not decently implemented. This measure is intended to conserve water courses and protect soil from erosion agents, notably water (rainfall, runoff, and fluvial).

Although other LULC classes did not have their p and c factor modified, parts of their areas were replaced with ciliary forests, affecting values of total mean erosion, sediment exportation, retention, and deposition. The major changes were identified in grass, exposed soil, forest, and gullies, which showed area losses of 40, 35, 26, and 25%, respectively. Considering that exposed soils and gullies have higher soil loss potential, a reduction in their areas is remarkably. However, as a disclaimer, the preservation of ciliary

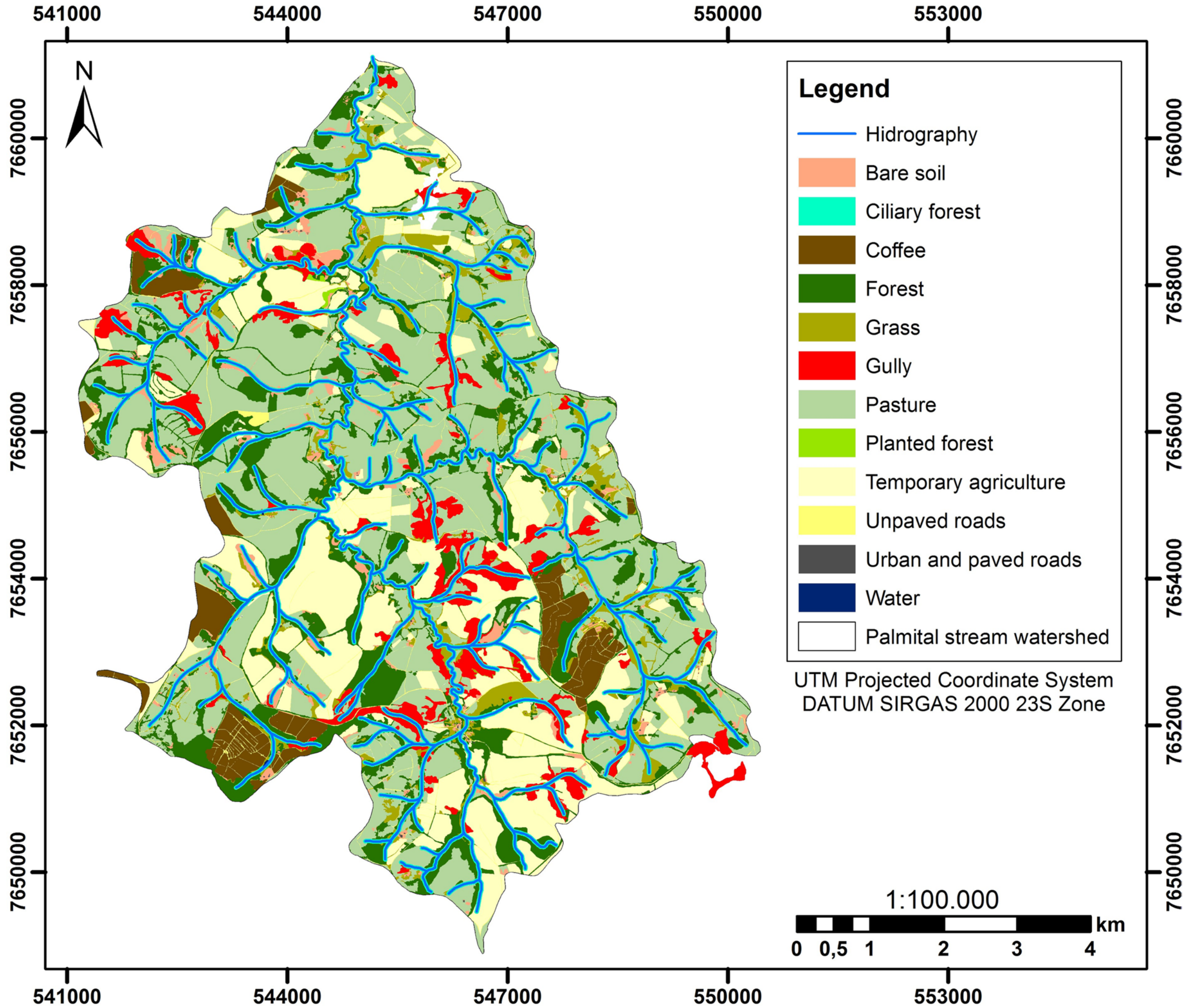

Fig. 9 Map of land use and land cover of the Palmital stream watershed from 2019 with preservation areas

forests in the present context would require reforestation and time to recover the area. Despite the legal obligation of 30 m from the water courses, it may not be possible to maintain a uniform zone, which can also change results for soil loss. Additionally, recovering degraded areas, such as gullies, demand more complex measures to avoid recurrences. Hereupon, results for the hypothetical scenario 3, considering a regular 30-m buffer area from rivers to simplify the model, are shown in Table 6.

The reforestation of areas along the water bodies protects from splash erosion and captures sediments from crop areas (Lense et al., 2022a, 2022b), acting as a sediments retention zone. Tree root networks also provide soil stability, due to larger and deeper roots (Gibson et al., 2022; Madern, 2012) that form macro-aggregates embracing part of the soil (Morgan, 2005). The lowest mean erosion per area was identified in forests (0.0046 t/ha year) and ciliary forests (0.0092 t/ha year). A comparison of this hypothesis with the present scenario revealed 14%, 57%, and 10% reductions for mean erosion per area, sediment exportation, and deposition, respectively. The sediment retention was increased by 9%.

Table 3 Modeling results for the present scenario (2019) in the Palmital stream watershed

LULC	Area (ha)	Total mean erosion (t/year)	Mean erosion (t/ha year)	Sediment exportation (t/year)	Sediment retention (t/year)	Sediment deposition (t/year)
Urban area and paved roads	4.52	37.84	8.37	0.93	10,490.74	36.91
Unpaved roads	99.20	103.24	1.04	2.04	10,489.63	101.20
Gullies	383.70	5,117.03	13.34	532.98	9,958.69	4,584.06
Exposed soil	221.00	2,407.10	10.89	162.89	10,328.78	2,244.21
Grass	311.97	41.61	0.13	0.96	10,490.71	40.65
Coffee	267.84	245.84	0.92	7.49	10,484.18	238.35
Planted forest	3.46	0.50	0.14	0.0031	10,491.67	0.49
Temporary agriculture	1,195.45	3,116.27	2.61	142.21	10,349.46	2,974.06
Pasture	2,297.54	5,052.51	2.20	223.04	10,268.63	4,829.43
Forest	1,037.32	4.92	0.0047	0.06	10,491.61	4.87
Water	27.33	0	0	0	0	0
Total	**5,866.52**	**16,126.86**	**2.75**	**1,449.54**	**9,042.13**	**14,677.29**

Table 4 Modeling results for hypothetical scenario 1 in the Palmital stream watershed

LULC	Area (ha)	Total mean erosion (t/year)	Mean erosion (t/ha year)	Sediment exportation (t/year)	Sediment retention (t/year)	Sediment deposition (t/year)
Urban area and paved roads	4.52	37.84	8.37	0.93	10,490.74	36.91
Unpaved roads	99.20	103.24	1.04	2.04	10,489.63	101.20
Gullies	383.70	5,117.03	13.34	532.98	9,958.69	4,584.06
Exposed soil	221.00	2,407.10	10.89	162.89	10,328.78	2,244.21
Grass	311.97	41.61	0.13	0.96	10,490.71	40.65
Coffee	267.84	122.92	0.46	3.75	10,487.93	119.17
Planted forest	3.46	0.50	0.14	0.0031	10,491.67	0.49
Temporary agriculture	1,195.45	1,558.13	1.30	71.10	10,420.57	1,487.03
Pasture*	2,297.54	3,663.07	1.59	177.94	10,313.73	3,485.10
Forest	1,037.32	4.92	0.0047	0.06	10,491.61	4.87
Water	27.33	0.00	0.00	0.00	0.00	0.00
Total	**5,866.52**	**13,056.37**	**2.23**	**1,300.59**	**9,191.08**	**11,755.76**

*Pasture area replaced for temporary agriculture

Mean erosion for the four scenarios

Estimated average rates of soil loss depend on variables related to RUSLE. The state of São Paulo showed a 30-t/ha year average (Medeiros et al., 2016), and some watersheds in its territory showed 13 t/ha year (Cantareira System) (Lense et al., 2023) and 8.9 t/ha year (Tietê river watershed) (Lense et al., 2022a, 2022b) averages. The results of the Palmital stream watershed, displayed in Figs. 10 and 11, were below those values for soil loss; however, a higher concentration of erosive features, especially gullies, was observed in a smaller area. Additionally, average rates from the most erosive LULC of the Palmital stream watershed can be classified as moderate — between 10 and 20 t/ha year (Lense et al., 2023).

All hypothetical scenarios showed reductions in mean erosion, sediment exportation, and deposition and an increase in sediment retention. The reforestation of pasture areas hypothesis provided the lowest values for mean erosion per area and sediment deposition, due to lower soil erosion and silting. The

Table 5 Modeling results for hypothetical scenario 2 in the Palmital stream watershed

LULC	Area (ha)	Total mean erosion (t/year)	Mean erosion (t/ha year)	Sediment exportation (t/year)	Sediment retention (t/year)	Sediment deposition (t/year)
Urban area and paved roads	4.52	37.84	8.37	0.93	10,490.74	36.91
Unpaved roads	99.20	103.24	1.04	2.04	10,489.63	101.20
Gullies	383.70	5,117.03	13.34	532.98	9,958.69	4,584.06
Exposed soil	221.00	2,407.10	10.89	162.89	10,328.78	2,244.21
Grass	311.97	41.61	0.13	0.96	10,490.71	40.65
Coffee	267.84	245.84	0.92	7.49	10,484.18	238.35
Planted forest	3.46	0.50	0.14	0.0031	10,491.67	0.49
Temporary agriculture	1,195.45	3,116.27	2.61	142.21	10,349.46	2,974.06
Pasture*	2297.54	202.10	0.09	3.73	10,487.94	198.37
Forest	1037.32	4.92	0.0047	0.06	10,491.61	4.87
Water	27.33	0.00	0.00	0.00	0.00	0.00
Total	**5,866.52**	**11,276.45**	**1.92**	**1,046.69**	**9,444.98**	**10,229.77**

*Pasture area replaced for planted forest

Table 6 Modeling results for hypothetical scenario 3 in the Palmital stream watershed

LULC	Area (ha)	Total mean erosion (t/year)	Mean erosion (t/ha year)	Sediment exportation (t/year)	Sediment retention (t/year)	Sediment deposition (t/year)
Urban area and paved roads	4.27	44.61	10.45	1.11	10,477.60	43.50
Unpaved roads	95.22	93.40	0.98	1.71	10,477.00	91.68
Gullies	307.12	4,055.51	13.20	190.18	10,288.53	3,865.34
Exposed soil	163.82	1,828.61	11.16	67.32	10,411.39	1,761.29
Grass	222.09	25.33	0.11	0.39	10,478.32	24.94
Coffee	263.57	230.28	0.87	6.70	10,472.01	223.58
Planted forest	3.46	0.45	0.13	0.0027	10,478.71	0.45
Temporary agriculture	1,135.46	2,896.38	2.55	97.53	10,381.18	2,798.85
Pasture	2,146.52	4,637.88	2.16	150.92	10,327.79	4,486.96
Forest	823.74	3.80	0.0046	0.04	10,478.67	3.76
Water	27.33	0.00	0.00	0.00	0.00	0.00
Ciliary forest	745.66	6.85	0.0092	0.11	10,478.60	6.73
Total	**5,866.52**	**13,823.11**	**2.36**	**616.65**	**9,862.06**	**13,206.47**

preservation of ciliary forests hypothesis showed the lowest sediment exportation and the highest sediment retention, implying soil transport was better avoided. Those hypotheses considered increasing forested areas, therefore protecting more areas from erosive agents.

On the other hand, it is difficult to persuade agricultural producers to leave their productive areas for reforesting, threatening their profits, although portions of the properties have been lost for soil degradation. The quality of productive areas would be maintained if areas, which would be used for agriculture or pasture in a short-term, were protected and preserved. The long-term sustainability of agroecosystems is of higher importance (Lal, 2019).

Since 2016, producers that raised cattle have changed their land use for soybeans and corn crops, notably because of the high increase in grains prices. Since it is a trend, the replacement of pastures for temporary agriculture and application of conservation

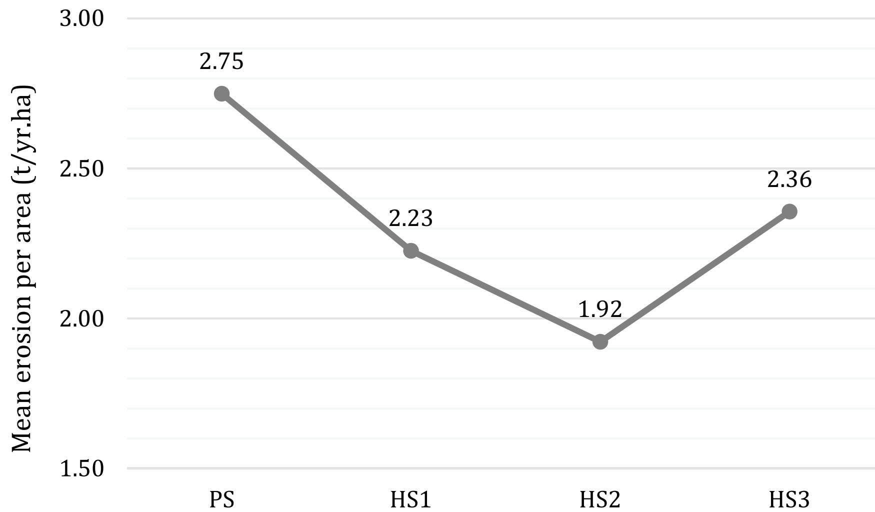

Fig. 10 Mean erosion per area for the present scenario and hypothetical scenarios 1, 2, and 3 from the Palmital stream watershed

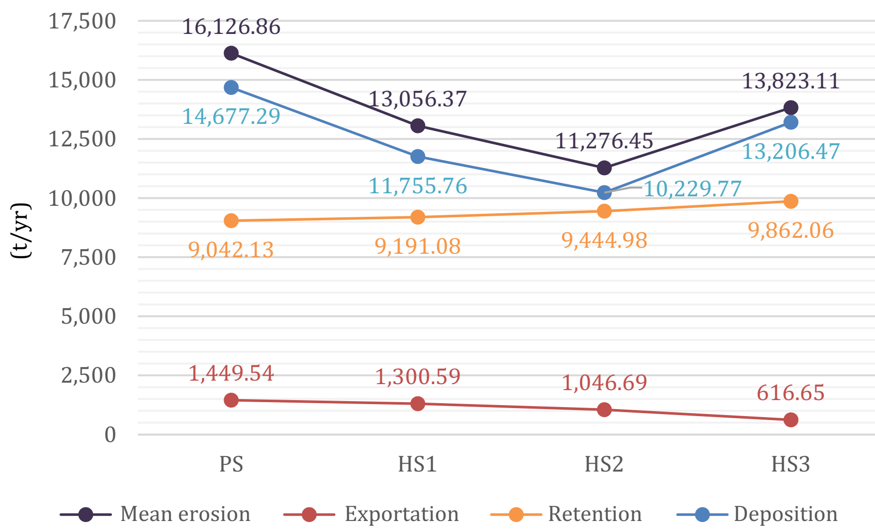

Fig. 11 Total mean erosion, sediment exportation, retention, and deposition for the present scenario and hypothetical scenarios 1, 2, and 3 from the Palmital stream watershed

practices instead of total reforestation of pasture areas would be a smoother transition. Ideally, the hypotheses should be mixed towards better results on soil loss prevention.

Soil is associated with many ecosystem services such as provisioning (food, water, and fiber), regulation (climate, water, and waste), supporting (soil formation and nutrients cycles), and cultural. Therefore, soil degradation must be avoided, and its equilibrium must be maintained considering resiliency. Studies of geologic-geotechnical conditions, erosion agents, land use and land cover, and erosive features surveys are essential for a better understanding of the area and supply of tools and knowledge to decision makers.

Conclusions

Values of mean erosion, sediment exportation, retention, and deposition from the Palmital stream watershed were obtained by SDR-InVEST model, to observe effects of LULC to soil loss and analyze consequences of alterations in LULC through three hypothetical scenarios. The present scenario, based on 2019 satellite images, showed 2.75 t/ha year total mean erosion. A replacement of pasture areas for temporary agriculture along with the implementation of conservation practices in temporary agriculture and coffee crops in hypothetical scenario 1 reduced 19% of mean erosion, 10% of sediment exportation, and 20% of sediment deposition. The sediment retention showed a 2% increase. Hypothetical scenario 2 consisted in reforesting pasture areas and a comparison of its results with those of the present scenario revealed reductions of 30% in mean erosion, 28% in sediment exportation, and 30% sediment deposition. The increase in sediment retention was 4%. The preservation of ciliary forests, hypothetical scenario 3, also showed reductions in mean erosion, sediment exportation, and sediment deposition of 14%, 57%, and 10%, respectively, with the highest increment of sediment retention, i.e., 9%, mostly because vegetation included areas previously classified as gullies and bare soil.

Then, all three simulated scenarios effectively reduced mean erosion, sediment exportation, and deposition in the watershed, indicating changes in land use and land cover to less soil degrading classes, application of conservation techniques, and preservation of ciliary forests are appropriate measures to protect erodible materials and lower the erosive potential of water, thus reducing soil erosion.

InVEST model application was effective to quantify soil loss, determine LULC contribution to erosion processes, and perform simulations for hypothetical scenarios. Therefore, it is a suitable alternative to assess erosion consequences, plan changes on LULC in vulnerable or degraded areas, assist recovering projects, and provide solutions for erosion driven problems, especially reduction of soil and water quality, as well as loss of land productivity and fertility, which impacts food security, economy, and social aspects related to rural activities.

Author contribution Ádria Kanome Mori Soares; Valéria Guimarães Silvestre Rodrigues; Rogério Resende Martins Ferreira: Conceptualization and Methodology. Ádria Kanome Mori Soares; Valéria Guimarães Silvestre Rodrigues; Rogério Resende Martins Ferreira; Silvio Crestana: Formal analysis and Investigation. Ádria Kanome Mori Soares: Writing—Original Draft. Ádria Kanome Mori Soares; Valéria Guimarães Silvestre Rodrigues: Writing – Review & Editing. Ádria Kanome Mori Soares; Valéria Guimarães Silvestre Rodrigues; Silvio Crestana: Resources and Supervision.

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Data availability The datasets created during and/or analyzed during the present study will be made available by the corresponding author upon reasonable request.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors. All authors read and approve this submission.

Consent to participate Not applicable as the study did not include human subjects.

Competing interests The authors declare no competing interests.

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