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Soil and organic carbon losses by water erosion in coffee production areas in southern Minas Gerais, Brazil

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Abstract: Organic carbon performs essential functions in soils, which act as sources or sinks of atmospheric organic carbon. Agricultural management affects the carbon cycle in the soil, with effects on climate change. One of the crops most vulnerable to climate change is coffee. Brazil is the world's largest coffee producer, with a predominance of management under a conventional system, with sloping terrain and the absence of conservationist practices. The absence of conservationist practices increases in soil loss rates due to water management and carbon emissions, as well as a reduction in coffee production. This paper intended to estimate soil and organic carbon losses by RUSLE in coffee farms in southern Minas Gerais, south-eastern Brazil. Data were obtained from fieldwork, laboratory analysis, and cartographic products. The results indicated, exclusively for coffee crops, soil and carbon losses between 7 and 32 Mg ha^{-1} $year^{-1}$ and 87 and 460kg ha^{-1} $year^{-1}$, respectively. However, the highest soil losses occurred on sloping terrains with eucalyptus plantations located downhill, and the lowest losses occurred on flat land with native forests. Organic carbon losses were linked directly to soil losses, as a result from the land practices, slope and agricultural management adopted. These results can be used for the planning and priority definition of areas needing conservationist practices, such as green manuring, planting in contour and maintaining of vegetation between coffee rows, which are already used in some sites of the study area.

Key words: RUSLE, land use, soil organic matter, agricultural systems

1. Introduction

The problem with land degradation, water pollution and with decrease and lose of natural resources is one of the key environmental problems. Soil pollution by heavy metals due to agricultural and industrial practices is a serious environmental concern today (Yazdanpanah-Ravari et al., 2022). Over the course of the 20th century, population growth and the expansion of human activities led to an increase in per capita water consumption (Hosseini Beryekhani and Parsa, 2021). Water is essential to humanity, but it is associated with soil depletion through water erosion, which is one of the leading causes of soil degradation worldwide (Spalevic et al., 2020). It is a natural process intensified by human lifestyle (Khosravi et al., 2023). The main consequences of water erosion are losses of soil, nutrients, soil organic matter (SOM), and soil organic carbon (SOC) (Dechen et al., 2015). Approximately 75 Pg of soil is eroded annually from arable land worldwide at a projected economic value of US$ 400 billion (Borrelli et al., 2017). In Brazil, it is estimated that approximately 3 Pg is lost per year, with an estimated loss of US$ 15.7 billion, considering the replacement costs of fertilizers and limestone (Polidoro et al., 2021).

The carbon reserves in the Earth's biosphere have been significantly altered in recent centuries due to anthropogenic disturbances, such as the transformation of natural lands into agricultural systems, which regularly results in the loss of carbon from the soil. (Janes-Bassett et al., 2021). The global SOC stock is in the order of 1350 Pg, which is greater than that of the atmosphere and vegetation cover combined (Georgiou et al., 2022). Most of the SOC is in the first 2 m of the soil profile (Lal, 2004). The SOC content is conditioned by the parent material, climate, slope, structure, texture, amount of SOM, vegetation, and

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management (Muhammed et al., 2018; Koç et al., 2020). It is an indicator of the sustainability of the management adopted in agricultural areas. High SOC rates denote higher soil physical quality and better soil characteristics (Davis et al., 2018) and contribute to mitigating climate change and extreme weather phenomena (Jordahl et al., 2023). Water erosion causes the oxidation of SOC, which releases carbon dioxide (CO_2) into the atmosphere. Such emissions, even at small rates, are sufficient to elevate greenhouse gases (GHG) and adversely affect climate change (Friedlingstein et al., 2020). Worldwide, between 42 and 78 Pg of SOC have been lost in the last century due to badly management practices and erosion (Lal, 2004). In this scenario, land conversion from native forest to agricultural systems can emit 20% to 40% of the initial SOC stock over dozens of years of cultivation (Polyakov and Lal, 2008). Therefore, the incorporation of sustainable agricultural practices is crucial (Sedighi et al., 2022), and thus, the loss of soil organic matter (SOM) through intensive cultivation is the focus of studies that encompass climate change and food security (Jakab et al., 2023). In this scenario, coffee is one of the most important commodities produced in Brazil. Production began in the 18th century, and in the 20th century it became the world's largest coffee producer and exporter (Castro and Queiroz Neto, 2009). Minas Gerais state accounts for approximately 50% of national production. However, for historical and cultural reasons, cultivation characterized by extensive land use predominates, with inadequate conventional production systems, such as the absence of permanent preservation areas and mechanical, edaphological, and vegetative conservation practices, which result in soil degradation by increasing water erosion and GHG emissions (Aslam et al., 2021).

Water erosion impact studies can use digital simulation models. Such models allow for low-cost applications, quickness and good accuracy compared to traditional empirical models (Liu et al., 2021). The most commonly used model is the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which allows spatialization and estimation of soil losses and SOC. Its success worldwide stems from its low input requirements and applicability at regional scales (Halder, 2023). However, there is still a lack of studies on SOC losses caused by water erosion (Wang et al., 2022). In view of the above and considering the different land uses in coffee plantation areas in the south of Minas Gerais, soil and SOC losses were estimated by RUSLE.

2. Materials and methods

2.1 Study area

The research was carried out at the Conquista coffee producing units (Conquista Farm) in Alfenas Municipality (Figure 1a), Capoeirinha (Capoeirinha Farm) in Alfenas and Machado Municipalities (Figure 1b), and Rio Verde (Rio Verde and Pinheirinho Farms) in Conceição do Rio Verde and Cambuquira Municipalities (Figure 1c), owned by company Ipanema Coffees.

Alfenas and Machado are part of the Guaxupé Massif (Hasui, 2010). The slope of rounded and gentle hills is partially conditioned by the lithological type, with

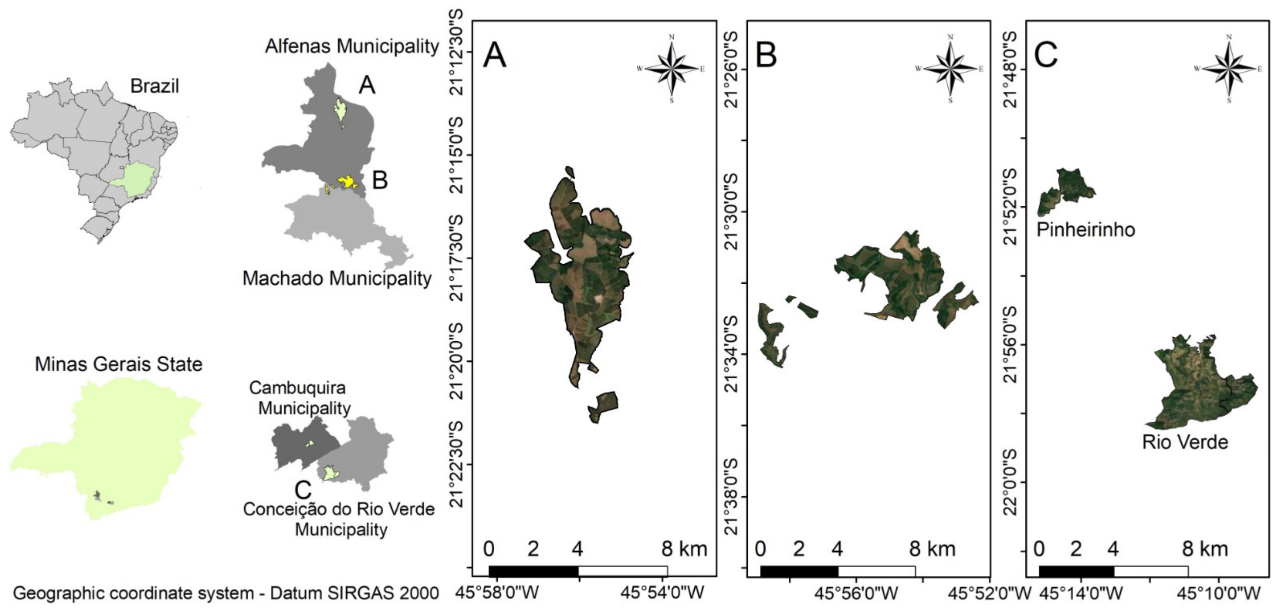

Figure 1. Location maps of Conquista (a), Capoeirinha (b), and Rio Verde and Pinheirinho (c) farms.

mountains supported by gneisses and quartzites; the lower altitude and flat areas consist of granulites, orthogneiss and paragneiss (CPRM, 2020). Clayey colluvial and eluvial soils predominate in large areas without rocky outcrops (CPRM, 2020). Native vegetation is formed by the Cerrado with transition zones to the Atlantic Forest (CPRM, 2020).

Cambuquira and Conceição do Rio Verde are located on the outskirts of the Mantiqueira mountain range, next to the Rio Verde Depression, and between the Lambari, Baependi and Rio Verde Rivers (Brasil, 1983). The area is characterized by elevations with irregular relief, hills with gentle slopes and shallow valleys with broad bottoms with river plains and alluvial terraces. The region is part of the Atlantic Forest biome (Silva et al., 2021).

According to Köppen (1936), the areas are classified as humid subtropical climate (Cwb). Alfenas and Machado have an average annual temperature of 21.2 °C and average annual rainfall of 1500 to 1750 mm. On the other hand, Conceição do Rio Verde and Cambuquira have a mean annual temperature of 20.1 °C and 19.9 °C and mean annual rainfall of 1660 to 1900 mm and 1690 to 1920 mm, respectively (Alvares et al., 2013).

The Conquista farm has an area of 2045 ha, of which 82.26% is coffee cultivation, 14.54% is native forest, 1% is eucalyptus, 0.91% is pasture, 0.88% is facility area and 0.41% is water bodies. The Ferralsol (Red Latosol) type and the gentle-wavy slope predominate, with altitudes ranging from 760 to 890 m. The Capoeirinha farm has an area of 1772 ha, of which 68.07% is coffee cultivation, 23.08% is native forest, 5.26% is eucalyptus, 1.8% is water bodies, 0.93% is pasture and 0.86% is facility area. Ferralsol (Red and Red-yellow Latosol) and undulating slope predominate, with altitudes ranging from 781 to 971 m. The Rio Verde and Pinheirinho farms have a total area of 1666 ha, of which 45.28% is native forest, 44.90% is coffee cultivation, 8.29% is pasture, 0.60% is facility area, 0.49% is eucalyptus and 0.44% is water bodies. Acrisol (Red Argisol) and Ferralsol (Red-yellow Latosol) predominate, the slope is gentle-wavy, and the altitudes range from 839 to 1341 m.

Mechanized harvesting is 100% at the Conquista, 98% at the Capoeirinha and 69% at the Rio Verde. Manual harvesting, in turn, occurs in approximately 12% of the coffee area, especially in the steeper slopes of the Rio Verde and Pinheirinho farms. In the Conquista, spacing varied from 3.5 to 4.0 m between planting lines and from 0.5 to 1.0 m between plants; in the Capoeirinha from 2 to 4.8 m and 0.5 to 1.5 m; and in the Rio Verde from 2 to 4 m and from 0.5 to 2 m, respectively.

2.2 Methodological procedures

All maps were made in ArcGIS 10.8 software (ESRI, 2020). The land use map was based on field observations, Landsat-8 TM (Thematic Mapper) satellite images, orbit 219/75, TM6, TM5, and TM4, obtained on USGS digital platform[1] from 2023 and the MapBiomas collection 7 from 2021[2]. The data were compared and validated in fieldwork, confirming the absence of significant changes in land use. The classes of native forest, coffee, eucalyptus, water bodies, pastures, and facilities were identical (Figures 2a–2d).

The soil class map was produced according to McBratney et al. (2003), based on the Minas Gerais Soil Map, at a scale of 1:650,000 (UFV et al., 2010). Next, we mapped the indiscriminate floodplain soils (IFS) with delimitation adjacent to the water bodies (Figures 3a–3d). The soil classification was based on Santos et al. (2018) and was correlated with the World Reference Base for Soil Resources[3] (WRB). The slope was processed using a digital elevation model (DEM) with 30 m spatial resolution from the ALOS PALSAR mission (Figures 4a–4d), obtained from the L band with images from February 2011 (absolute orbit n° 27875) and extracted from the NASA digital platform[4].

The slope was classified, according to EMBRAPA (1979), as flat (0–3%), gently undulating (>3–8%), undulating (>8–20%), strongly undulating (>20–45%), mountainous (>45–75%), and rugged (>75%) (Figures 5a–5d).

2.3 Revised Universal Soil Loss Equation (RUSLE)

The RUSLE was used to estimate and spatialize annual soil losses. The RUSLE considers the factors of rainfall erosivity, soil erodibility, slope length and steepness, land use and management, and conservation practices (Equation 1).

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the average annual soil loss rate in $\mathrm{Mg\ ha^{-1}\ year^{-1}}$; R is the rainfall erosivity factor in $\mathrm{MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}}$; K is the soil erodibility factor in $\mathrm{MJ^{-1}\ mm^{-1}}$; LS is the topographic factor expressing slope length and steepness (dimensionless); C is the factor for land use and management (dimensionless); and P is the factor for conservation practices (dimensionless) (Wischmeier and Smith, 1978).

[1]USGS United States Geological Survey (2023). EarthExplorer [online]. Website www.earthexplorer.usgs.gov [accessed 11 March 2023].

[2]Projeto MapBiomas (2021). Map Biomas Project - Collection 7 Annual Series Maps of Land Use and Land Cover in Brazil [online]. Website https://brasil.mapbiomas.org/download [accessed 17 May 2023].

[3]USS International Union of Soil Sciences (2015). World Reference Base for Soil Resources (WRB) Sistema Universal Recognized by the International Union of Soil Science (IUSS) and FAO [online]. Website. http://www.fao.org/3/a-i3794e.pdf. [accessed 16 January 2023].

[4]ALOS PALSAR (2015). Radiometric_Terrain_Corrected_low_res; Includes Material © JAXA/METI 2007 [online]. Website. https://doi.org/10.5067/JBYK3J6HFSVF [accessed 17 March 2023].

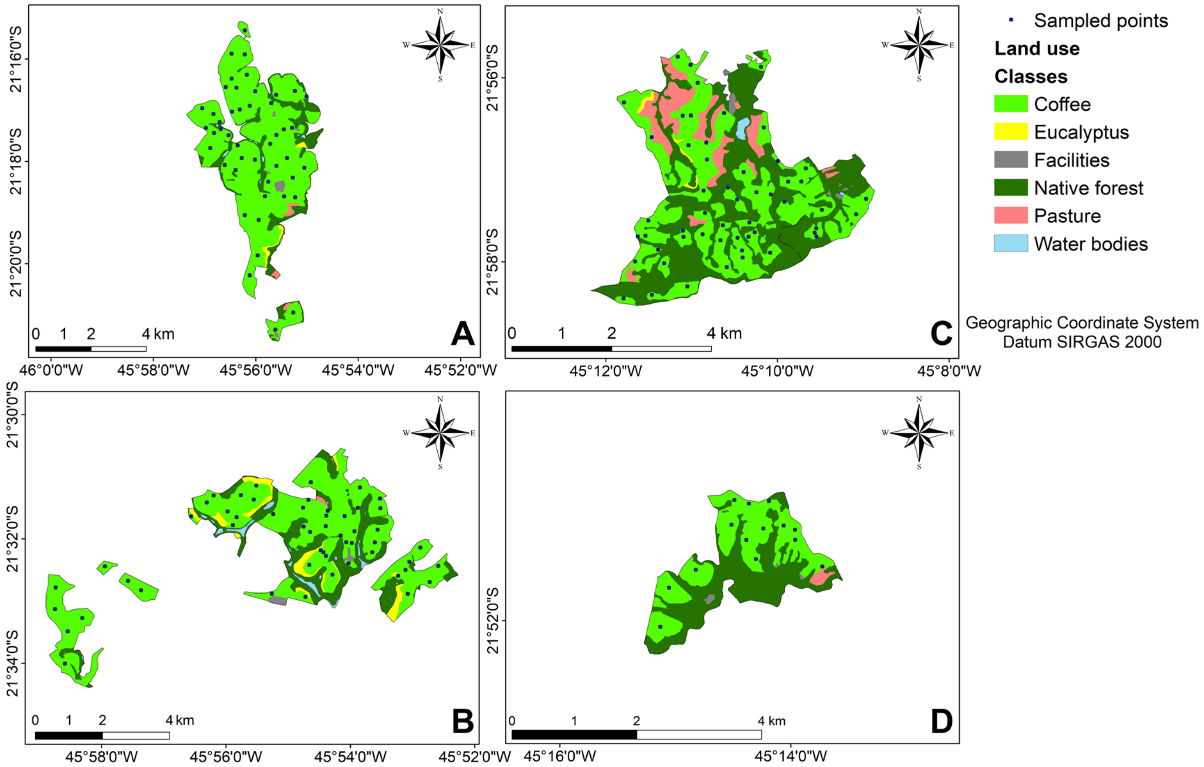

Figure 2. Mapping of land use; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

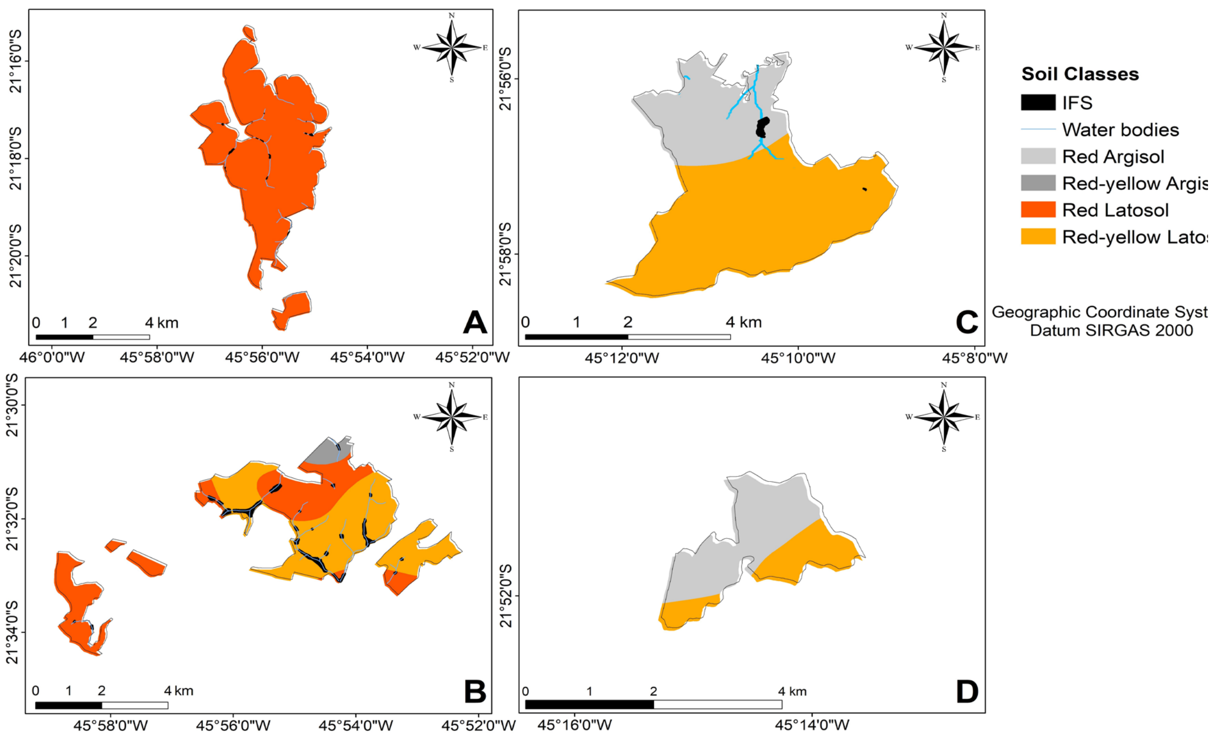

Figure 3. Mapping of soil classes; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

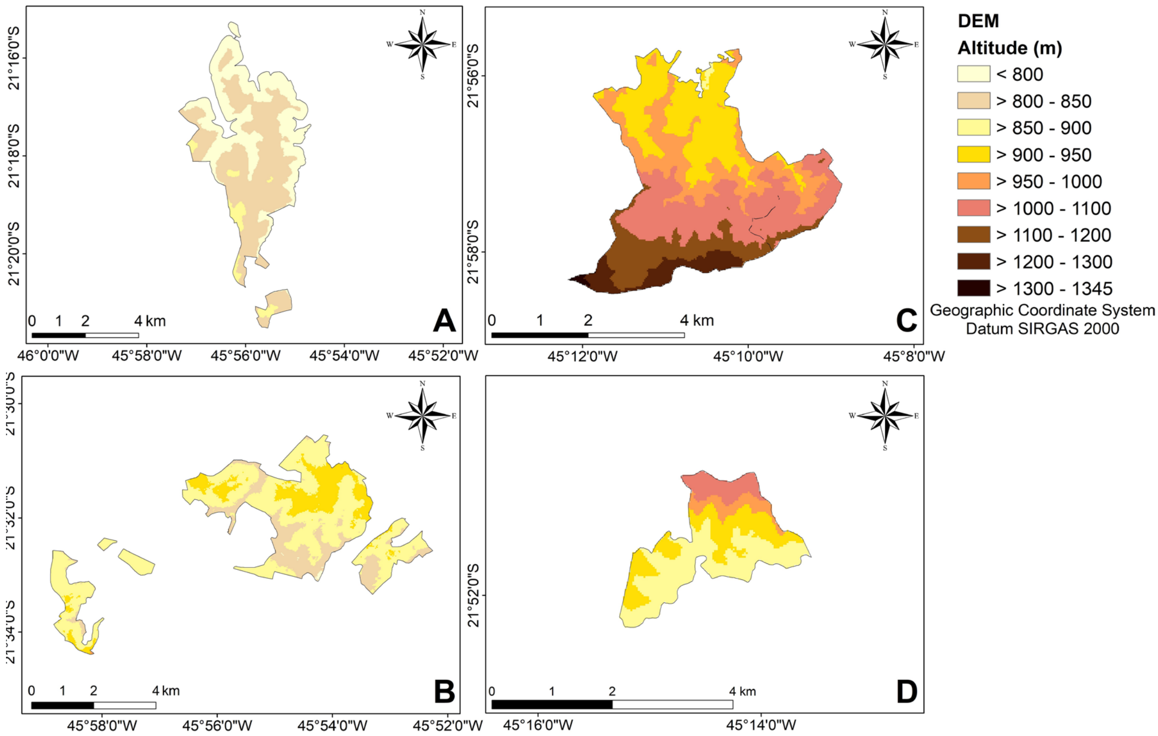

Figure 4. Mapping of digital elevation model; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

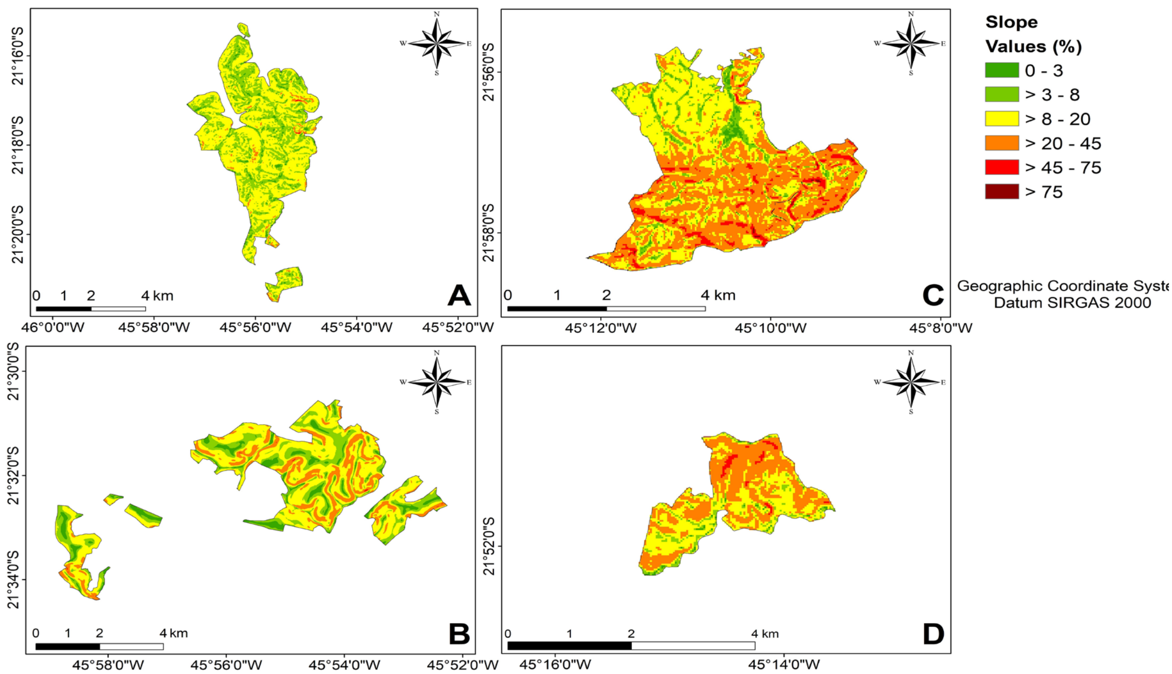

Figure 5. Mapping of slope; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

The R factor was acquired from Souza et al. (2022), the K factor for Latosols from Lense et al. (2020a) and the K factor for Argisols from Marques et al. (1997). The researchers disregarded K for the IFS because it is a sediment deposition area.

The LS factor was estimated from the DEM, according to the equation proposed by Moore and Burch (1986), using the Raster Calculator tool (Equation 2):

$$LS = \left\{\frac{(FA \times ResDEM)}{22.13}\right\}^{0.4} \times \left\{\frac{(\sin S)}{0.0896}\right\}^{1.3}, \quad (2)$$

$$SDR = 0.472 \times A^{-0.125}$$

where LS is a topographic factor (dimensionless); FA is the flow accumulation, which represents the upstream contributing area accumulated for a cell; sin S is the sine of the slope area (degrees); and ResDEM is the spatial resolution of the DEM (meters).

The values of C and P were adapted from the specialized literature (Table 1). The values range from 0 to 1 and indicate higher erosive potential as they approach 1.

The RUSLE factors were changed to raster files and multiplied in the Raster Calculator tab, which resulted in the spatial distribution of soil losses.

The RUSLE results were validated by integrating this model with the sediment delivery rate (SDR), which represents the ratio between total erosion and sediment that reaches water bodies (Ebrahimzadeh et al., 2018); the SDR was monitored at hydro-sedimentological stations of the Minas Gerais Institute for Water Resources Management (IGAM), located in Alfenas and Cambuquira, according to Batista et al. (2017). The SDR was estimated using Equation 3 of Vanoni (1975):

$$SDR = 0.472 \times A^{-0.125} \quad (3)$$

where SDR is the sediment delivery rate (%) and A is the watershed area (km^2).

2.4 Soil organic carbon (SOC) losses

Unlike soil losses, which were calculated for all land uses, the SOC loss rates were calculated based on the SOM contents exclusively under coffee crops. The soil was sampled at a depth of 0 to 20 cm by Ipanema Coffees and analyzed by Cooperativa Cooxupé, which calculated SOM contents, according to EMBRAPA (2017), in January 2023 (Supplementary document). We performed spatial distribution by kriging interpolation using the Geostatistical Wizard tool (Chen et al., 2019).

SOC concentrations were calculated according to the USDA and NRCS (1996) by multiplying the SOM by Van Bemmelen's constant of 0.58 (Van Bemmelen, 1890). We then calculated the SOC losses by water erosion (Starr et al., 2000) by multiplying the SOM values by the soil losses in the Raster Calculator tool.

3. Results and discussion

3.1 Revised Universal Soil Loss Equation (RUSLE)

Table 2 presents the RUSLE results.

The R factor varied between 7070 and 7390 $MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$ (Table 2) and was thus classified as strong erosivity (Mello et al., 2013). The K factor was classified as medium, with values ranged from 0.015 to 0.030 $Mg\ h\ MJ^{-1}\ mm^{-1}$, due to the predominance of Latosols, which have a low natural susceptibility to water erosion as a result of their textural and permeability characteristics (Bertol and Almeida, 2000; Mannigel et al., 2002). As the areas have high erosivity rates, proper land use planning and priority adoption of conservation practices are required (Zanchin et al., 2021, Lense et al., 2022).

The highest mean LS factor was observed at Pinheirinho farm (Table 2). The highest LS values are associated with the highest slopes, more susceptible to water erosion. The Capoerinha and Rio Verde farms too have steep slopes, which indicate the need for water erosion mitigation.

Due to high R values, land use and management (factor C) and conservation practices (factor P) play key roles in controlling soil losses in places most vulnerable to water erosion; this is because lower C values result in higher plant density and lower water erosion rates (Renard et al., 1997). Alternative soil management strategies can also reduce soil and SOC losses. Examples are the addition of sewage sludge in maize cultivation (Moreira et al., 2020), and farmyard manure and green manure in sesame cultivation (Jalilian et al., 2022), which contribute

Table 1. C and P factor values.

Land use	C factor	Source C factor	P factor*
Water bodies	-	-	-
Facilities	-	-	-
Coffee	0.086	Prochnow et al. (2005)	0.350
Eucalyptus	0.121	Silva et al. (2016)	0.560
Native forest	0.015	Silva et al. (2016)	0.200
Pasture	0.061	Galdino et al. (2015)	0.350

* Senanayake et al. (2022).

Table 2. Mean values of rainfall erosivity (R), soil erodibility (K), topographic (LS), land use and management (C), and conservation practices (P) factors; total and average soil loss rates, sediment delivery rate (SDR), estimated and observed sediment by areas.

RUSLE factors and SDR	Conquista	Capoeirinha	Rio Verde	Pinheirinho
R($MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$)	7070	7099	7200	7390
K($Mg\ h\ MJ^{-1}\ mm^{-1}$)	0.020	0.020	0.022	0.024
LS (dimensionless)	1.80	3.60	4.00	5.30
C (dimensionless)	0.074	0.068	0.051	0.049
P (dimensionless)	0.032	0.031	0.280	0.270
Total soil losses ($Mg\ year^{-1}$)	12,945	20,807	19,662	5736
Average soil losses ($Mg\ ha^{-1}\ year^{-1}$)	6.20	11.40	13.4	17.2
SDR (%)	32.1%	32.6%	32.5%	40.6%
Estimated SDR ($Mg\ ha^{-1}\ year^{-1}$)	2.0	3.7	4.3	6.9
Observed SDR ($Mg\ ha^{-1}\ year^{-1}$)	2.7	3.04	1.16	1.22

to improving the physicochemical properties of soils and agricultural production.

The lowest C values were obtained on the Pinheirinho farm (Table 2), which is composed almost entirely of native forest and coffee. On the Rio Verde and Pinheirinho farms, the smaller spacing between planting lines provides a higher density of plants per hectare, which generates higher levels of SOM, increases the water infiltration rate and reduces runoff. Manual harvesting was higher on these two farms, which reduces soil compaction by agricultural machinery. Regarding the P factor, in all productive areas, the planting of coffee was associated with conservation practices such as level planting, the construction of drainage terraces and the presence of infiltration basins.

The annual total soil losses were approximately 60 thousand tons on all four farms. The highest average soil losses were observed on the Pinheirinho, Rio Verde and Capoeirinha farms due to the higher slopes (Table 2). The results were close to those of Lense et al. (2020b), with an average soil loss of 19.0 $Mg\ ha^{-1}\ year^{-1}$. In Conquista, was estimated an mean soil loss of 6.2 $Mg\ ha^{-1}\ year^{-1}$ due to the lower slope (Figures 6a–6d).

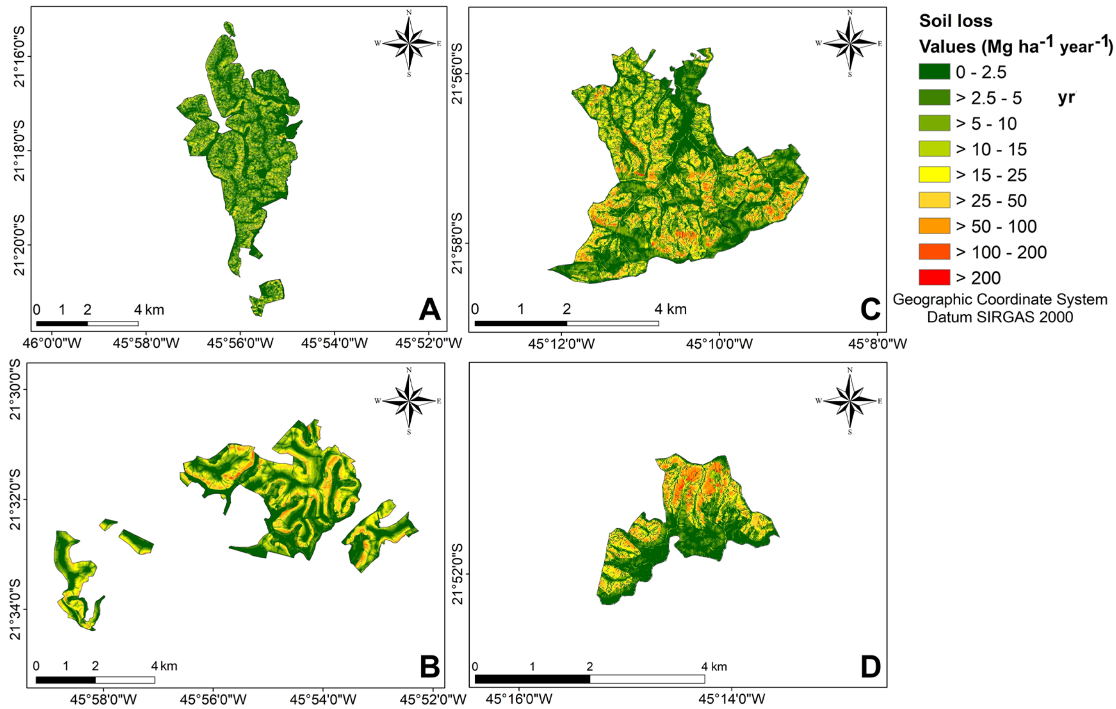

Figure 6. Spatialization of soil losses from Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

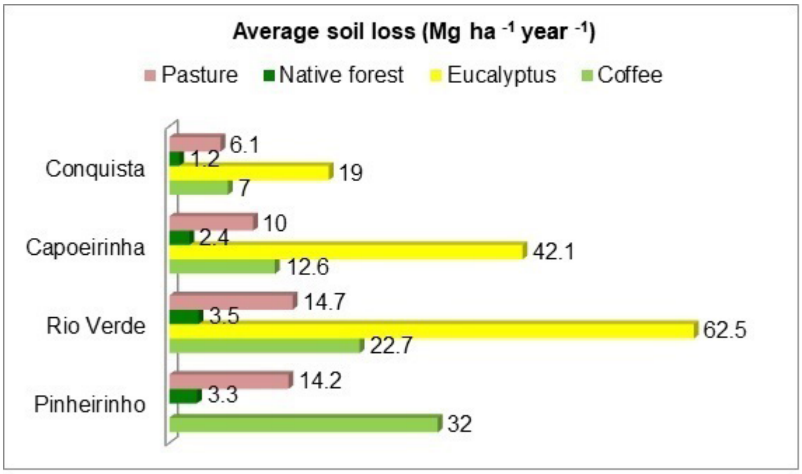

Figure 7. Average soil loss($Mg\ ha^{-1}\ year^{-1}$) according to land use classes.

The SDR ranged from 32.1% to 40.6%, with an average of 34.45%. The areas with a higher SDR also had higher LS and C values (Table 1), which highlights the greater gravitational potential that favors the acceleration of runoff and hydrosedimentological flow and the intensification of water erosion in these areas.

The comparison of the estimated and observed SDRs (Table 2) showed that on the Conquista and Capoeirinha farms, the results were close, with errors of 26% and 22%, respectively. However, on the Rio Verde and Pinheirinho farms, the variation was high (Table 2), which could be explained by the greater slope, since the RUSLE tends to overestimate soil erosion on high-slope terrain (Nearing, 1998; Bircher et al., 2022). Nevertheless, the lowest errors were associated with the highest soil loss estimates (Amorim et al., 2010). However, Bircher et al. (2022) consider that overestimated results are better than underestimated ones, especially when assessing environmental risks. Notably, all modelling is prone to inaccuracies. However, the application of a model must be understood with all the interrelationships of a given process, such as water erosion (Alewell et al., 2019). Estimating soil losses on farms is an important tool to evaluate the dimensions of the erosion process and to identify priority areas for the adoption of conservation practices (Amorim et al., 2010).

Figure 7 illustrates the average soil loss rates according to land use.

The highest average soil loss rates occurred in eucalyptus areas, with values between 19 and 62.50 $Mg\ ha^{-1}\ year^{-1}$. Such areas create shades by the canopy of the plants, which, associated with litter, make it difficult to plant other species, reduce soil aggregation and structuring and can even harm agricultural production in the surrounding areas (Latini et al., 2020; Desta et al., 2023). Eucalyptus is planted downhill on farms, with a spacing of up to 2 m between plants in steep areas. In addition, the eucalyptus cycle, which is approximately 6 years, as a source of energy biomass that can be used for drying coffee, tends to leave the soil exposed for long periods at the beginning of planting compared to coffee, though there are plants up to 45 years old in the area.

Soil losses in coffee ranged from 7 to 32 $Mg\ ha^{-1}\ year^{-1}$. The values were similar to those of Cerretelli et al. (2023), who estimated losses of 20.8 $Mg\ ha^{-1}\ year^{-1}$ in Costa Rica and 7 $Mg\ ha^{-1}\ year^{-1}$ in Guatemala in agroforestry systems. Therefore, the similarities between the results obtained in Central America and the study area reveal the effectiveness of the different management strategies adopted. In the case of farms, these practices ensure better protection of the soil against rainfall and favor the stability of soil aggregates due to (i) vegetation in coffee growing; (ii) planting on contour lines; (iii) infiltration basins; (iv) the use of manual harvesting in steep areas; (v) incorporation of plant residues into the soil; and (vi) organic fertilization (Didoné et al., 2019; Alele et al., 2023).

The lowest average soil loss was found in the native forest (Figure 6) due to (i) vegetation hindering the release of soil particles by runoff (Alele et al., 2023); (ii) vegetation protects the supply of environmental and ecosystem services; (iii) increased soil moisture; and (iv) increased pollination, increasing productivity gains (Roubik, 2002; Latini et al., 2020).

3.2 Soil organic matter (SOM) content

Contrary to expectations, the SOM content ranged from 1.5% to 4.4%. The lowest values were obtained in the flat and lower altitude areas of Conquista, and the highest were obtained in greater altitudes in Rio Verde (Figures 8a–8d).

Research presents conflicting information regarding the change in SOM content with altitude. Some indicate an increase in SOM at lower altitudes (Jeyakumar et al.,

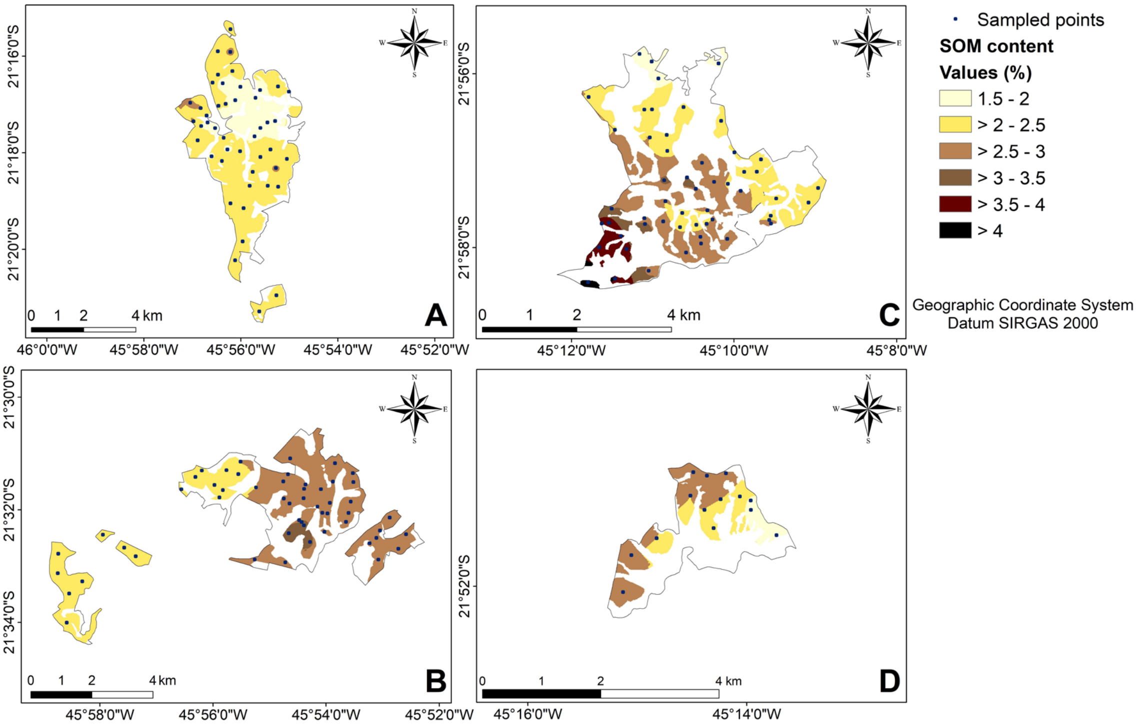

Figure 8. Spatial distribution of SOM content on Conquista (a), Capoeirinha (b), Rio Verde (c) and Pinheirinho (d) farms.

2020), while others indicate a decrease (He et al., 2023). This variation can be explained by climatic zones (Li et al., 2022; Yin et al., 2022). In tropical zones, SOM contents increase with altitude; in temperate regions, they decrease (Sundqvist et al., 2013). According to Yin et al. (2022), in tropical regions, high altitudes have lower temperatures, which slow decomposition and increase SOM levels and in temperate regions with higher altitudes, there is less plant biomass and consequently lower SOM.

There are higher levels of SOM due to manual harvesting in the higher altitudes and slopes of the Rio Verde and Capoeirinha farms, which incorporates a large amount of plant residues into the soil. In these areas, there is also a denser distribution of coffee plants, with smaller spacing, which provides a greater amount of SOM (Liu et al., 2021). In this scenario, the main indicator affecting the SOM content was agricultural management, as highlighted by Angeletti et al. (2021).

On the Conquista farm, although the climate is warmer and has lower rainfall, there is greater runoff due to the presence of streets and the wider spacing between plants. The crops are more spaced and less densely planted; therefore, there is a greater incidence of solar radiation on the soil, which reduces moisture and the incorporation of C. In addition, mechanized harvesting and sweeping management, which removes coffee that falls on the ground, removes plant residues and prevents their incorporation in the environment. Pinheirinho, with lower temperatures and higher precipitation, has lower SOM contents due to its lower altitude, similar to the Jinghe River Basin on the Chinese Loess Plateau (Zhao et al., 2021).

3.3 Soil organic carbon (SOC) losses

As expected, higher rates of SOC loss were associated with higher soil losses (Li et al., 2016; Imamoglu and Dengiz, 2017) (Figures 9a–9d).

The areas with the highest susceptibility to SOM loss and C emission from the soil occurred in Rio Verde and Pinheirinho farms while Conquista and Capoeirinha had the lowest susceptibility. These deleterious impacts showed similar patterns to water erosion, resulting from topography and erosivity. However, the management practices adopted also affect the intensity of water erosion.

In this context, eucalyptus areas were subject to more intense deleterious effects than coffee areas. Despite the variable soil loss rates, it is worth noting that there is no safe level of soil loss (Mendes Júnior et al., 2018), as the sustainability of agricultural systems demands the reduction of erosion rates to values close to zero (FAO and ITPS, 2015).

The spatialization of soil and SOC losses were similar to the results of Lense et al. (2019; 2020c) and Lense et al. (2022), who used the Erosion Potential Method (EPM)

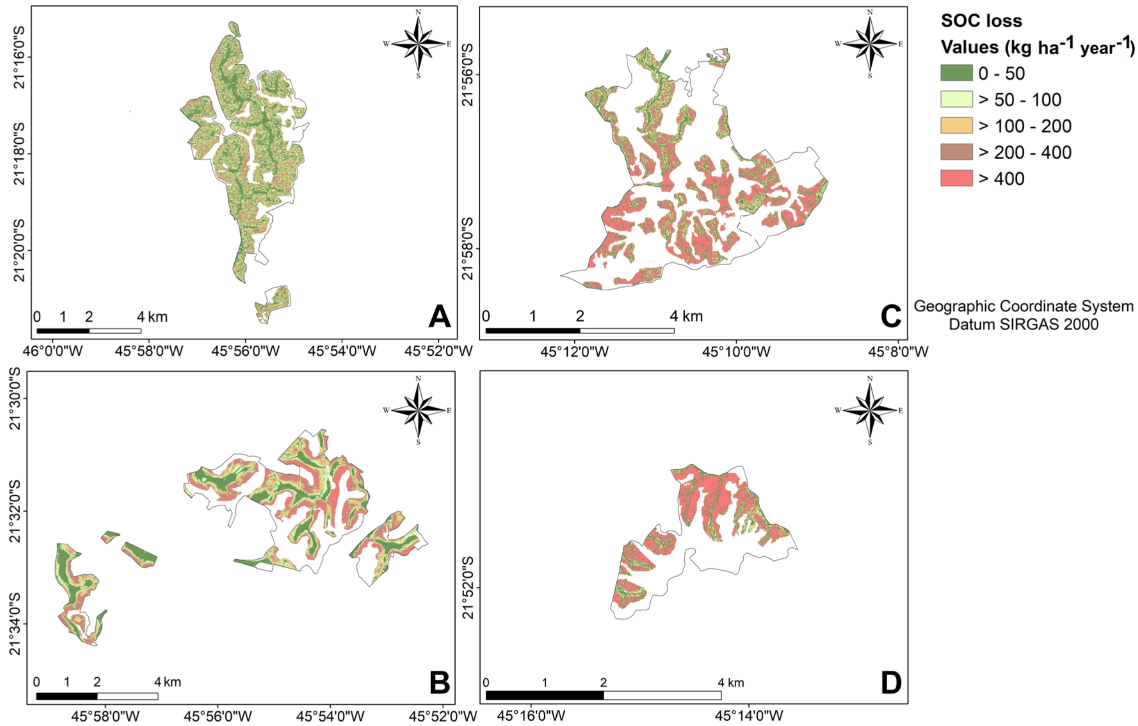

Figure 9. Spatial distribution of SOC losses in Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

(Gavrilovic, 1962), even when considering that EPM tends to underestimate such losses, unlike the RUSLE (Dragičević et al., 2016; Chalise et al., 2019; Lense et al., 2020a).

In Capoeirinha, the mean soil loss for coffee plantation was 12.60 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$, higher than the previously reported values of 1.58 and 2.12 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$ (Mendes Júnior et al., 2018; Lense et al., 2019). These authors classified access roads and streets as exposed soil. Regarding the average SOC losses, the values were similar to the agricultural areas in Italy, Spain, and Romania, with values between 50 and 450 kg (Lugato et al., 2016).

The average SOC loss is shown in Figure 10.

The adoption of sustainable management practices can mitigate soil, nutrient, and SOC losses through water erosion. The study areas have already adopted measures to improve soil aggregation and SOC fixation by reducing runoff. The vegetation cover in coffee streets improves soil structure, increases water retention capacity, and reduces the requirement for fertilizers and pesticides, all of which benefit the environment. This set of actions, combined with technologies in the field, increases productivity and reduces costs due to water erosion (Ayer et al., 2015); furthermore, this approach can help maintain and open new C credit markets (Caramori et al., 2020; Guimarães et al., 2021).

SOC sequestration reduces GHG emissions. According to Hergoualc'h et al. (2012), a full sun coffee growing system stores an average carbon amount of 10.38$\mathrm{Mg\,C\,ha^{-1}}$, while the system afforested with *Inga densiflora*, a fruit tree species widely grown in Central America, stores an average of 12.55 $\mathrm{Mg\,C\,ha^{-1}}$. In addition to positive climatic effects, such management reduces temperatures, which delays fruit ripening and generates larger grains of better quality (Muschler, 2001). In addition, the forests surrounding coffee plantations favor the presence of birds and insects, which contribute to pollination and plague control (Chain-Guadarrama et al., 2019). This type of management is an alternative method for the study area and is intended to reduce susceptibility to water erosion and increase carbon sequestration.

4. Conclusion

1. Average soil losses in coffee production ranged from 6.2 to 17.2 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$, with higher rates on the steeper slopes. The values indicate that conservation management is mainly responsible for reducing soil losses and mitigating the impacts associated with water erosion.

2. SOC levels in coffee growing varied because of agricultural management, with higher values associated with higher altitudes in fields with denser coffee plants and manual harvesting.

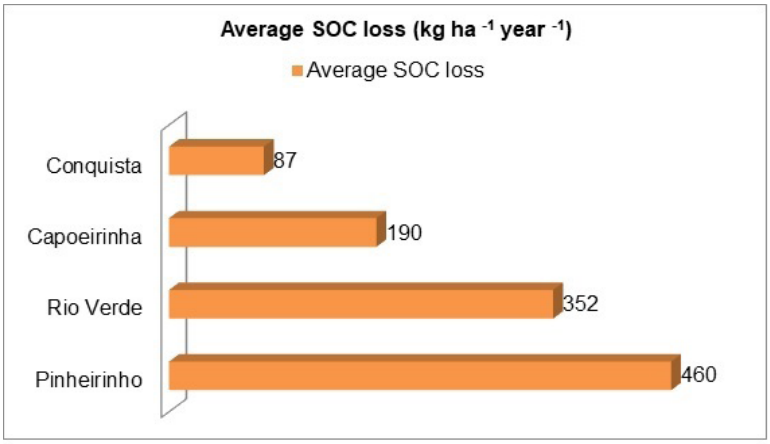

Figure 10. Average SOC loss (kg ha^{-1} $year^{-1}$) in coffee growing areas.

3. SOC losses ranged from 1 to 6600kg ha^{-1} $year^{-1}$, with high rates on the highest slopes. The methodological procedures were successful in spatializing the areas with the highest SOC losses. The use of conservation management favors SOC stocks and reduces the impacts of coffee growing on climate change.

4. The use of environmental modelling and remote sensing technologies is a fast and efficient tool to monitor the water erosion processes, soil, nutrient, and SOC losses under spatiotemporal variations.

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Supplementary document

FID (for ArcGIS)	Sequence number	Latitude	Longitude	Gleb coffee identification	Soil organic matter (%)	Soil organic carbon (%)
0	1	-45,93690109	-21,25740051	A1	2,90	1,68
109	2	-45,24700165	-21,85930061	A10	2,70	1,57
23	3	-45,93989944	-21,30279922	A12	3,10	1,80
27	4	-45,93270111	-21,33069992	A15	2,90	1,68
25	5	-45,93030167	-21,31139946	A16	2,80	1,62
29	6	-45,9292984	-21,30660057	A17	2,40	1,39
36	7	-45,92660141	-21,30150032	A18	2,30	1,33
2	8	-45,93690109	-21,26519966	A2	2,90	1,68
31	9	-45,92409897	-21,31139946	A20	2,60	1,51
32	10	-45,92050171	-21,31170082	A21	2,60	1,51
138	11	-45,18500137	-21,94020081	A22	2,40	1,39
133	12	-45.193677	-21.941174	A24	2,60	1,51
164	13	-45,16460037	-21,95219994	A25	3,50	2,03
6	14	-45,9396019	-21,27599907	A28	2,70	1,57
34	15	-45,91749954	-21,30209923	A29	2,50	1,45
3	16	-45,93619919	-21,27179909	A3	2,80	1,62
114	17	-45,23730087	-21,85339928	A31	3,10	1,80
117	18	-45,2344017	-21,85289955	A32	3,40	1,97
159	19	-45,17070007	-21,95409966	A33	2,90	1,68
130	20	-45,19169998	-21,95919991	A35	2,50	1,45
40	21	-45,92419815	-21,28949928	A36	1,90	1,10
77	22	-45,90650177	-21,52709961	A37	4,00	2,32
78	23	-45,90660095	-21,5298996	A38	3,20	1,86
79	24	-45,91080093	-21,53149986	A39	2,70	1,57
7	25	-45,93349838	-21,2772007	A4	2,60	1,51
43	26	-45,17440033	-21,96240044	A40	2,60	1,51
151	27	-45,92060089	-21,27709961	A40	2,90	1,68
167	28	-45,16529846	-21,95590019	A41	3,00	1,74
51	29	-45,97230148	-21,55290031	A41	2,30	1,33
41	30	-45,97829819	-21,55540085	A42	1,80	1,04
49	31	-45,92160034	-21,28910065	A42	2,70	1,57
9	32	-45,93849945	-21,28310013	A46	2,80	1,62
45	33	-45,18489838	-21,96220016	A48	2,20	1,28
100	34	-45,88119888	-21,53569984	A48	3,00	1,74
129	35	-45,91680145	-21,27890015	A48	3,10	1,80
19	36	-45,17449951	-21,95549965	A49	2,40	1,39
156	37	-45,93920135	-21,2947998	A49	2,70	1,57
1	38	-45,94129944	-21,26490021	A5	3,10	1,80
153	39	-45,17100143	-21,96139908	A50	3,30	1,91
105	40	-45,17620087	-21,95330048	A51	1,90	1,10
157	41	-45,87639999	-21,54059982	A51	2,70	1,57
97	42	-45,89339828	-21,53429985	A53	2,10	1,22
62	43	-45,95529938	-21,54780006	A55	2,60	1,51
61	44	-45,95819855	-21,54450035	A56	2,50	1,45
73	45	-45,91260147	-21,52490044	A57	2,80	1,62
46	46	-45,97999954	-21,54759979	A58	2,20	1,28
66	47	-45,1731987	-21,95050049	A61	2,00	1,16
158	48	-45,93289948	-21,52599907	A61	3,70	2,15
70	49	-45,16650009	-21,94849968	A62	2,00	1,16
163	50	-45,9292984	-21,52160072	A62	3,50	2,03
143	51	-45,18030167	-21,94820023	A7	2,70	1,57
136	52	-45,18349838	-21,93099976	A74	2,80	1,62
21	53	-45,25090027	-21,86190033	A9	2,50	1,45
108	54	-45,93790054	-21,2989006	A9	2,80	1,62
33	55	-45.922198	-21.315642	AR1	2,90	1,68
30	56	-45.7925975	-21.313495	AR2	2,90	1,68
142	57	-45,18389893	-21,94560051	B1	3,00	1,74
104	58	-45,2397995	-21,85499954	B11	2,90	1,68
115	59	-45,87870026	-21,54490089	B11	3,10	1,80
110	60	-45,24150085	-21,8491993	B12	3,30	1,91
92	61	-45,89799881	-21,52499962	B19	3,30	1,91
85	62	-45,90480042	-21,54290009	B20	2,20	1,28
81	63	-45,90790176	-21,53639984	B21	2,30	1,33
71	64	-45,92520142	-21,51910019	B22	2,00	1,16
123	65	-45,19430161	-21,96660042	B23	3,00	1,74
91	66	-45,9015007	-21,5272007	B27	4,40	2,55
93	67	-45,8973999	-21,51959991	B28	3,20	1,86
96	68	-45,8927002	-21,53089905	B29	2,50	1,45
82	69	-45,1833992	-21,94020081	B3	3,10	1,80
139	70	-45,90719986	-21,53689957	B3	2,90	1,68
99	71	-45,8852005	-21,54170036	B30	2,60	1,51
124	72	-45,1841011	-21,97120094	B34	3,10	1,80
131	73	-45,18500137	-21,96109962	B36	2,60	1,51
152	74	-45,17219925	-21,96220016	B42	2,40	1,39
150	75	-45,17720032	-21,96010017	B5	2,50	1,45
144	76	-45,18099976	-21,9538002	B64	2,70	1,57
122	77	-45,19100189	-21,97270012	B65	3,40	1,97
84	78	-45,16799927	-21,96509933	B66	2,20	1,28
154	79	-45,9109993	-21,54030037	B66	3,50	2,03
145	80	-45,18069839	-21,95779991	B67	3,80	2,20
126	81	-45,18980026	-21,96450043	B68	4,20	2,44
125	82	-45,18870163	-21,96699905	B69	3,10	1,80
149	83	-45,17770004	-21,96279907	B70	3,50	2,03
128	84	-45,19369888	-21,96209908	B71	2,30	1,33
121	85	-45,19649887	-21,97330093	B73	4,40	2,55
60	86	-45,96590042	-21,54000092	B75	2,50	1,45
69	87	-45,92589951	-21,52280045	B77	2,40	1,39
72	88	-45,92070007	-21,52669907	B78	2,20	1,28
146	89	-45,18119812	-21,96170044	C14	2,50	1,45
160	90	-45,16790009	-21,9545002	C16	2,20	1,28
147	91	-45,17340088	-21,96590042	C26	3,00	1,74
148	92	-45,17649841	-21,96769905	C27	3,00	1,74
113	93	-45,23649979	-21,84939957	C28	3,70	2,15
112	94	-45,23939896	-21,84980011	C29	4,00	2,32
111	95	-45,2419014	-21,85280037	C30	4,20	2,44
89	96	-45,90259933	-21,53240013	C31	3,80	2,20
35	97	-45,92129898	-21,30529976	C33	2,30	1,33
127	98	-45,19219971	-21,96199989	C38	2,90	1,68
155	99	-45,17350006	-21,9647007	C39	3,80	2,20
141	100	-45,18040085	-21,94510078	C46	2,40	1,39
119	101	-45,23270035	-21,85359955	C52	2,90	1,68
140	102	-45,17699814	-21,93969917	C56	2,30	1,33
98	103	-45,89410019	-21,53689957	C6	2,30	1,33

171	104	-45,15909958	-21,96220016	C80	3,60	2,09
170	105	-45,15940094	-21,96150017	C81	3,00	1,74
169	106	-45,15909958	-21,96069908	C82	2,90	1,68
168	107	-45,15800095	-21,95730019	C83	2,90	1,68
5	108	-45,94120026	-21,2730999	I30	3,40	1,97
4	109	-45,90650177	-21,53790092	I32	2,90	1,68
83	110	-45,94309998	-21,2758007	I32	2,60	1,51
52	111	-45,97439957	-21,55470085	I33	2,10	1,22
88	112	-45,90110016	-21,53420067	I45	2,00	1,16
135	113	-45,18600082	-21,92959976	I58	2,40	1,39
137	114	-45,18209839	-21,93429947	I59	2,50	1,45
63	115	-45,16930008	-21,94239998	I63	2,40	1,39
162	116	-45,93849945	-21,52359962	I63	2,90	1,68
74	117	-45,91120148	-21,52280045	I64	2,30	1,33
80	118	-45,91249847	-21,53000069	I65	2,60	1,51
67	119	-45,93040085	-21,52750015	I67	2,60	1,51
68	120	-45,9314003	-21,52969933	I69	2,70	1,57
90	121	-45,89889908	-21,53129959	I79	2,30	1,33
106	122	-45,92100143	-21,54809952	I83	2,30	1,33
161	123	-45,17210007	-21,95960045	L13	2,20	1,28
95	124	-45,89199829	-21,52510071	L25	2,70	1,57
65	125	-45,93659973	-21,52169991	L26	2,00	1,16
16	126	-45,94689941	-21,29080009	L44	2,40	1,39
15	127	-45,94469833	-21,28949928	L45	1,80	1,04
59	128	-45,96870041	-21,56609917	M1	2,70	1,57
17	129	-45,91059875	-21,51810074	M10	2,60	1,51
75	130	-45,94820023	-21,29570007	M10	2,50	1,45
24	131	-45,89960098	-21,53440094	M13	2,50	1,45
87	132	-45,93690109	-21,31749916	M13	4,00	2,32
26	133	-45,93239975	-21,31909943	M14	2,30	1,33
103	134	-45,88460159	-21,54809952	M17	2,70	1,57
39	135	-45,92660141	-21,29140091	M19	2,00	1,16
13	136	-45,94960022	-21,28910065	M22	2,00	1,16
11	137	-45,94710159	-21,2845993	M23	2,30	1,33
12	138	-45,95080185	-21,28269958	M24	2,50	1,45
28	139	-45,93529892	-21,33720016	M25	2,30	1,33
134	140	-45,19100189	-21,94409943	M57	2,60	1,51
118	141	-45,23270035	-21,85499954	M8	2,50	1,45
165	142	-45,16109848	-21,94980049	M84	2,60	1,51
166	143	-45,16199875	-21,95219994	M85	2,10	1,22
102	144	-45,8871994	-21,54319954	P14	2,10	1,22
37	145	-45,92309952	-21,2989006	P34	2,30	1,33
101	146	-45,88410187	-21,53949928	P4	3,00	1,74
14	147	-45,94219971	-21,29150009	P41	2,60	1,51
18	148	-45,94509888	-21,28720093	P41	2,60	1,51
38	149	-45,92860031	-21,29430008	P43	2,90	1,68
8	150	-45,93529892	-21,28190041	P6	2,70	1,57
94	151	-45,89210129	-21,52249908	P68	2,40	1,39
22	152	-45,93360138	-21,29949951	P8	3,20	1,86
107	153	-45,91199875	-21,5489006	R24	2,70	1,57
42	154	-45,92829895	-21,28100014	R38	2,90	1,68
64	155	-45,94269943	-21,52729988	R74	2,50	1,45
20	156	-45,94340134	-21,30120087	S11	2,50	1,45
116	157	-45,23839951	-21,85779953	U20	3,20	1,86
132	158	-45,19639969	-21,93779945	U21	3,30	1,91
76	159	-45,90599823	-21,5258007	U23	3,00	1,74
10	160	-45,94100189	-21,28380013	U27	2,90	1,68
44	161	-45,92670059	-21,27829933	U47	2,10	1,22
86	162	-45,90050125	-21,53989983	U54	2,80	1,62
120	163	-45,22880173	-21,85890007	U55	2,60	1,51