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ESTIMATES OF SOIL LOSSES DUE TO WATER EROSION IN THE AMAZON BIOME

SUMMARY

Located in the Brazilian Amazon biome, the Chico Mendes Extractive Reserve, Acre state, is an important area for the conservation of biodiversity and ecosystem services in the region. Despite its importance, it faces challenges such as illegal deforestation, mining, and forest fires, which increase water erosion processes and generate environmental and socioeconomic negative impacts. The need to understand these impacts motivate this research, with the objective of evaluating the influence of forest fires on water erosion and quantify soil losses at this site. For this purpose, we employed the Revised Universal Soil Loss Equation (RUSLE), utilizing parameters obtained from scientific literature and remote sensing data, such as the Normalized Difference Vegetation Index (NDVI), enabling a temporal analysis of vegetation cover. Our results indicate low variations in average soil loss rates, ranging from 3.00 to 3.74 Mg ha^{-1} yr^{-1} from 2019 to 2021. In 2021, an increase in soil loss rates was observed due to a higher incidence of forest fires, especially in pasture areas. It is concluded that the preservation and adequate management of vegetation cover are essential for the protection of natural resources. The need to adopt and develop conservation and sustainable management strategies through public policy should contribute to the mitigation of environmental impacts. Furthermore, the results obtained can highlight the importance of environmental conservation.

Keywords: Soil Degradation, Forest Fires, Land Use and Land Cover, MapBiomas Project, Remote Sensing.

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INTRODUCTION

The global climate crisis is evident through the increase in temperatures and extreme weather events (Aghakouchak *et al.*, 2020). The Amazon biome spans 419,694,300 hectares, covering 40% of Brazil's territory, and plays a fundamental role in climate and rainfall regulation. However, it has been continually impacted due to illegal activities such as deforestation, mining, and forest fires, which contribute to widespread environmental and soil degradation (Gatti *et al.*, 2021) and the climate changes (Silva *et al.*, 2019).

The creation of protected areas by law within the Amazon biome is essential to its protection, covering 27.56% of the biome (IBGE, 2023) and contributing to the resilience of local ecosystems (Campos-Silva *et al.*, 2021). These protected areas safeguard biodiversity, maintain ecosystem functions, and serve as carbon sinks against climate change (Paiva *et al.*, 2020; Franco *et al.*, 2021). Despite Brazil's robust environmental laws, their effectiveness in practice is often compromised by challenges in implementation, supervision, and enforcement (Raftopoulos and Morley, 2020), proving insufficient to contain the environmental impacts of illegal human actions.

In Brazil, the Chico Mendes Reserve is a protected area categorized as Conservation Unit of Sustainable Use (Brasil, 2000; Brasil, 2006), which aims to keep the balance between environmental conservation and the well-being of local communities (Roberts *et al.*, 2020). However, also the Reserve is subject to environmental degradation resulting from deforestation, advance of urban areas, changes in land use and land cover (LULC), forest fires and water erosion (Mascarenhas *et al.*, 2018; Marengo *et al.*, 2022), emphasizing the need for urgency of protection (Silva *et al.*, 2019).

Monitoring and addressing the phenomena rely on the assistance of environmental technologies that help in the mitigation measures of environmental degradation, such as geotechnologies tools, that provide a comprehensive spatiotemporal view of the patterns of change in landscape (Avtar *et al.*, 2020). In Brazil, owing to its vast territorial expanse, these tools become pivotal for environmental diagnostics and prognostics (D'Andrimont *et al.*, 2021; Lense *et al.*, 2021; INPE, 2023).

In this way, the use of Geographic Information Systems (GIS) makes it possible to estimate soil loss rates caused by water erosion. Thus, the Revised Universal Soil Loss Equation - RUSLE (Renard *et al.*, 1997) is widely used to estimate these rates in large areas and river basins. Several studies have evaluated the effectiveness of erosion prediction models in Brazilian soils, including research conducted by Nachtigall *et al.* (2020), Lense *et al.* (2021), and Macedo *et al.* (2021).

Considering that forest fires alter vegetation cover, we chose to emphasize factor C, which considers the impact of soil management, vegetation cover and residual biomass in estimating soil loss due to water erosion (Bertol *et al.*, 2019). The C factor can be obtained from experimental plots (Wischmeier and Smith, 1978) or vegetation index, such as the Normalized Difference Vegetation Index -

NDVI (Durigon *et al.*, 2014). From this perspective, the preservation and sustainable management of vegetation cover are pivotal for the conservation of natural resources, particularly concerning soil and water. Given the aforementioned context, our objectives were to quantify forest fires in the Reserve from 2019 to 2021 and evaluate their influence on the C factor and soil losses due to water erosion.

MATERIAL AND METHODS

Study area. The Chico Mendes Extractive Reserve covers 970,570 hectares and is situated in the south-eastern part of Acre, accounting for 3.14% of the Legal Amazon (Figure 1). Its establishment occurred through Decree No. 99,144, dated March 12, 1990 (Brasil, 1990).

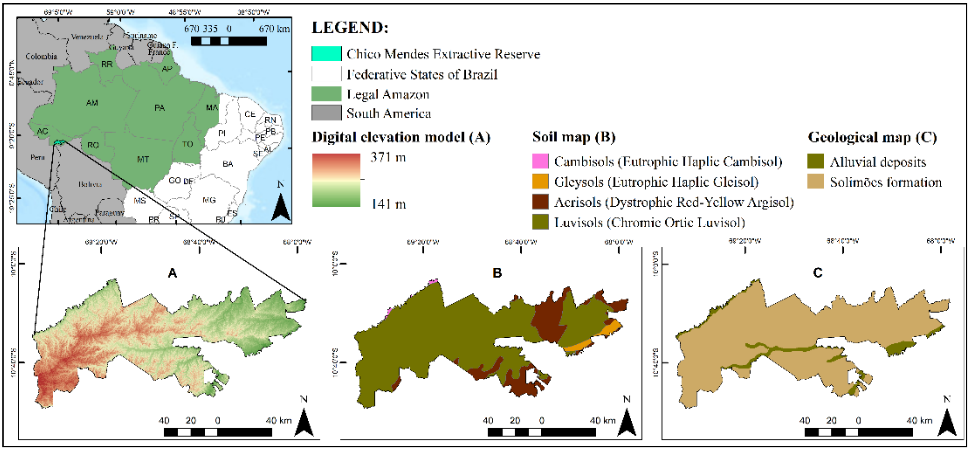

Figure 1. Location map of the Chico Mendes Extractive Reserve (A) Copernicus mission's Digital Elevation Model (DEM) with a 30 m resolution (ESA, 2023); (B) Soil map at a 1:5,000,000 scale (Santos *et al.*, 2018); (C) Geological map at a 1:1,000,000 scale (CPRM, 2021).

The main economic activity of the population in the Chico Mendes Extractive Reserve is nut and rubber extraction (Silva *et al.*, 2019). The Reserve is predominantly covered by dense forest formations with large trees, spanning 851,324 hectares, which accounts for 91.4% of its territory (Brasil, 2006).

The climate, according to the Köppen classification (Köppen, 1936), is the Am type (tropical monsoon climate), characterized by high temperatures and a well-defined rainy season. The average annual temperature is 27°C, and the precipitation is 2,000 mm (Alvares *et al.*, 2013).

The area is composed of sedimentary rocks represented by sandstones, siltstones, mudstones, and conglomerates. The coarser textures tend to have lower erodibility, as figure 1C (CPRM, 2006; Salgado *et al.*, 2019).

The geomorphology is characterized by low relief diversity, with altitudes varying from 141 to 371 m (Figure 1A) (Cavalcante, 2005; Salgado *et al.*, 2019).

The hydrography covers the rivers Acre, Iaco and Xapuri, flowing from west to east (ANA, 2023).

According to Santos *et al.* (2018) and correlated to the IUSS (2015), the Reserve soils are Chromic Ortic Luvisoils (Luvisols) (81.5%); Dystrophic Red Yellow Argisoils (Acrisols) (16.1%); Haplic Eutrophic Gleysoils (Gleysols) (2.1%) and Haplic Eutrophic Cambisoils (Cambisols) (0.3%) (Figure 1B). There is a predominance of Luvisols. These soils offer high fertility and good water retention.

Methodological procedures. The study involved four steps, as in Figure 2.

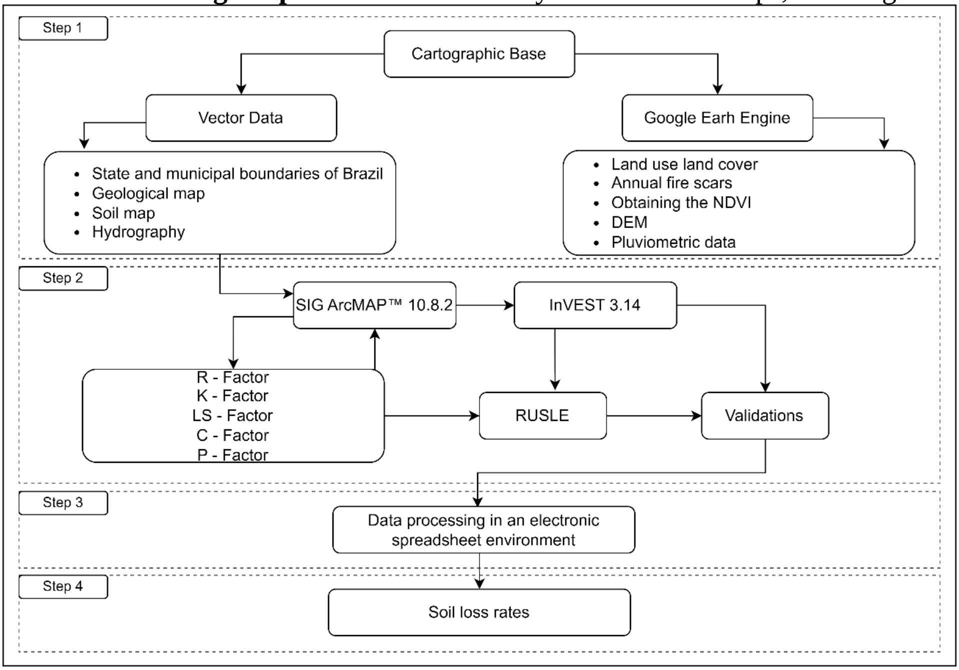

Figure 2. Flowchart of the research development

In step 1, we acquired the cartographic base in shapefile format, which includes the territorial limits used in this study (Ibge, 2022), the geological map of Brazil at scale 1:1,000,000 (Cprm, 2021), the soil map of Brazil at scale 1:5,000,000 (Santos *et al.*, 2018), hydrographic data (Ana, 2023) and the Digital Elevation Model (DEM) of the Copernicus mission with 30 m resolution (Esa, 2023). We process the files using ArcMap™ 10.8.2 (Esri, 2021).

We included data on fire scars and precipitation from 2019 to 2021. Data on fires and LULC were obtained from the MapBiomas Fire Project database - Collection 2 (Projeto Mapbiomas, 2022) and Collection 8 of the Annual Series of LULC Maps of the Brazil (Projeto Mapbiomas, 2023) in raster files. We processed the files in Google Earth Engine toolkit (Gorelick *et al.*, 2017) and converted to shapefiles in ArcGIS 10.8.2 (Esri, 2021).

We obtained precipitation data from the Climate Hazards Group InfraRed Precipitation (CHIRPS 2.0) satellite (Funk *et al.*, 2015), given the lack of operational hydrometeorological stations (ANA, 2023).

In step 2, we obtained the RUSLE factors (Renard *et al.*, 1997), described in Equation 1 (Table 1).

The R factor was obtained from the global rain erosivity map with a spatial resolution of 1 km, derived from 3,625 rain gauge stations (Panagos *et al.*, 2017; 2023). After downloading, the raster file was resized to a resolution of 30 m using the resample tool (ESRI, 2021).

The K factor was adapted from Mannigel *et al.* (2002), Cabral *et al.* (2005), and Farinasso *et al.* (2006). We inserted the K values into the attribute table (ESRI, 2021) and generated the soil map following McBratney *et al.* (2003), based on Santos *et al.* (2018).

The LS was obtained in the Digital Elevation Model (DEM) in the GIS System for Automated Geoscientific Analyzes (SAGA) (Pilesjö and Hasan, 2014), according to the method of Desmet and Govers (1996).

For factor C, we used the NDVI, according to Equation 2 (Rouse *et al.*, 1974) of Table 1, following Durigon *et al.* (2014) (factor Cr) and Macedo *et al.* (2021) (factor Cr2) (Table 1).

The method of Macedo *et al.* (2021) is an adaptation of Durigon *et al.* (2014) which considers effects of seasonality and precipitation in vegetation cover. To this end, the variables Pptx (accumulated precipitation in the 3 months prior to the first scene of the quarter to calculate the NDVI) and Lv (average accumulated precipitation in the 3 months following the first scene) are used. Thus, when Lv is less than or equal to Pptx, there is less presence of dry vegetation with low reflectance. In this case it is necessary to obtain the Cr2 factor (Equation 4). Therefore, if Lv is greater than Pptx, drier vegetation is expected due to seasonality. In this case, the CPC factor (Equation 5) is used to increase the NDVI values based on precipitation, allowing the reclassification of dry vegetation targets considered as bared soil.

The calculation of the NDVI C factor was based on Sentinel 2, Multispectral Instrument (MSI), Level-2A, orbit/point 002/067, 002/068 and 003/067, with a resolution of 10 m, including geometric data and atmospheric corrections, cloud and shadow mask (ESA, 2015). We obtained quarterly average NDVI values, processed in a script in Google Earth Engine (GEE). Thus, 1,374 scenes were processed in total, averaging 458 per year, to 2019, 2020 and 2021, providing comprehensive intra-annual spectral information. Seasonality influences NDVI values, with higher values during rainy months and lower values during dry months. This seasonality is consistent with the relationship between NDVI and soil water availability (Pettorelli *et al.*, 2005; Teixeira *et al.*, 2023).

We obtained P values from the literature, being 0.01 for forest formation and 0.5 for pastures and other temporary crops (Bertoni and Lombardi Neto, 2014).

Table 1. Equations for calculating soil loss rates and obtaining C factors.

	Equations	Variables	Reference
(1)	$A = R \times K \times LS \times C \times P$	A is the average annual soil loss estimate (Mg ha^{-1} yr^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); K is the soil erodibility factor (Mg ha^{-1} MJ^{-1} mm^{-1}); LS is the topographic factor (dimensionless); C is the soil cover management factor (dimensionless); P is the soil conservation practice factor (dimensionless).	Renard *et al.* (1997)
(2)	$NDVI = \frac{NIR - R}{NIR + R}$	NDVI: Normalized Difference Vegetation Index (dimensionless); NIR: Near-Infrared surface reflectance (dimensionless); R: Red surface reflectance (dimensionless).	Rouse Jr. *et al.* (1974)
(3)	$Cr = \frac{(-NDVI + 1)}{2}$	-	Durigon *et al.* (2014)
(4)	$Cr2 = \frac{(-NDVI + z)}{2z}$	z is the variable representing the maximum NDVI pixel value.	Macedo *et al.* (2021)
(5)	$CPC = Cr2\left(\frac{Pptx}{Lv}\right)^{H}$	H is the percentage of the pixel area with low NDVI due to seasonality (Equation 7).	
(6)	$H = \frac{(NDVIPC - NDVI)}{100}$	NDVIPC is the precipitation correction (Equation 8).	
(7)	$NDVIPC = NDVI\frac{Lv}{PPtx}$	Lv is the leveling variable, equal to the average accumulated precipitation over x days in the studied historical series (mm). Pptx is the accumulated precipitation in the x period prior to the date of the image used in the NDVI calculation (mm).	

The modelling of soil losses by RUSLE does not differentiate between the fraction deposited on the ground and that which reaches water bodies. To overcome this and validate soil loss rates, we integrated the model with the Sediment Delivery Ratio tool (Sharp *et al.*, 2018) in the software InVEST 3.14, which uses the same input data for RUSLE calculations, according Vigiak *et al.* (2012), Cavalli *et al.* (2013) and López-Vicente *et al.* (2013), Borselli *et al.* (2008). Additionally, the variation of the sediment delivery rate was calculated according to the two C factors used.

RESULTS AND DISCUSSION

LULC changes. The main LULC changes occurred in the pasture, which increased by 14.35% in 2020 compared to 2019. In 2020, forest formation lost 1% of its area, equivalent to 9,200 ha. The temporary crops showed an increase of 22.27% in 2021 compared to 2020. The quantification of LULC data from 2019 to 2021 is presented in Table 2 and Figure 3.

Table 2. LULC classes in ha and percentages (Projeto Mapbiomas, 2023).

Classes	2019		2020		2021	
	Hectares	%	Hectares	%	Hectares	%
Forest formation	854,128	91.97	844,920	90.98	851,324	91.46
Pasture	64,007	6.90	73,195	7.88	68,652	7.38
Temporary crops	2	0.00	2	0.00	2	0.00
Rivers and wetlands	10,525	1.13	10,543	1.14	10,822	1.16

From 2019 to 2021, the LULC differences remained practically unchanged throughout the analyzed period.

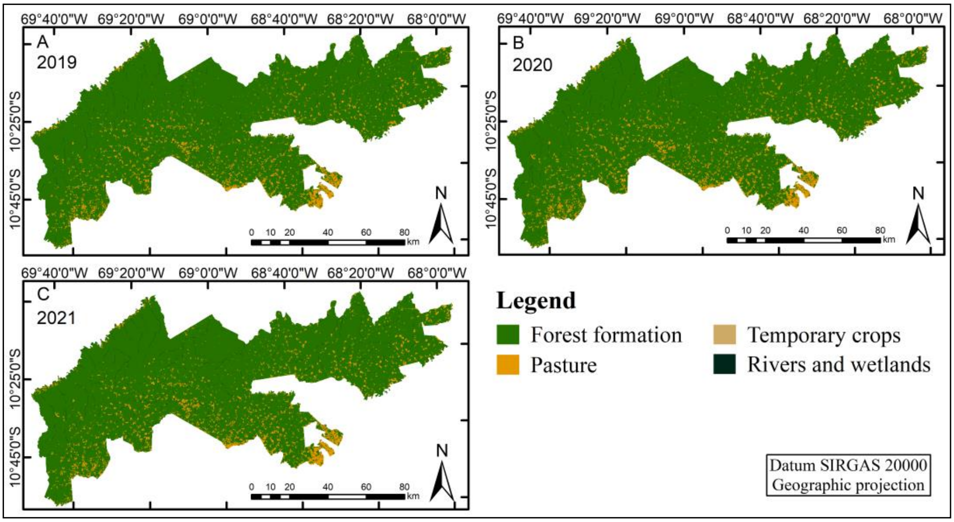

Figure 3. LULC map of the Chico Mendes Extractive Reserve (A) 2019; (B) 2020; (C) 2021.

Forest fires. In the temporal series examined, there were larger fires in the Reserve, covering 16,769 hectares or 1.72%, 9,757 hectares or 1.00% and 16,986 hectares or 1.75%, to 2019, 2020 and 2021, respectively (Figure 4).

The intensity of fires is influenced by climatic variables, deforestation, and proximity to roads, since these areas close to roads are more susceptible to the phenomenon due to easy human access, agricultural activities and inadequate disposal of flammable materials (Ferreira and Féres, 2020; Melo and Rocha, 2023).

According to Zemp *et al.* (2017), Murad and Pearse (2018) and Leite-Filho (2021), there are a significant relationship between the extent of deforested areas and the incidence of fires. All this process results in the loss of vegetation cover, intensification of water erosion and compromise of water resources (Silva Junior *et al.*, 2018; Karamesouti *et al.*, 2023).

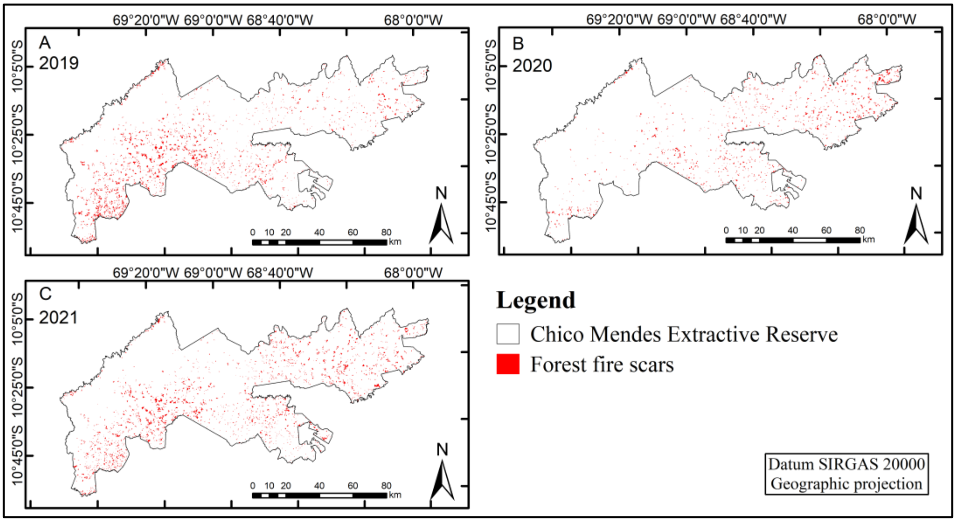

Figure 4. Forest fire scars in the Chico Mendes Extractive Reserve (A) 2019; (B) 2020; (C) 2021.

During a historical series, a class that had a higher incidence of forest fires was pasture, due to criminal management practices. In details, 2019, that had the largest burned area was pastures with 13,787 ha or 21.54%, followed by forest formation with 9,982 ha or 0.35%. While the temporary crops class did not show fire scars. By this way, in 2020 there was a reduction in burned areas, with pastures covering 8,164 ha or 11.15% and forest formation with 1,593 ha or 0.19%. Lastly, there was a significant increase in the area burned in 2021 for the forestry class, with 7,171 ha or 0.84%, and pastures, with 9,815 ha or 13.86%.

Erosivity, erodibility and topography. The R factor ranged from 7,923 to 9,739 MJ mm ha^{-1} h^{-1} yr^{-1}, with lower values in the eastern part. Erosivity ranged from medium to high (Mello *et al.*, 2013) (Figure 5A).

The reserve presents medium erodibility (Figure 5B). The highest values are observed in the Cambisols, which occupy only 0.3% of the area (Figure 5B). Luvisols and Acrisols cover, respectively, 81.5% and 16.1%, while Gleysols cover 2.1%. Luvisols and Cambisols are characterized by low depth and fragiles, making them more susceptible to erosion processes. The absence of a thicker, more resistant surface layer makes them vulnerable to the removal of particles by the impact of rainwater and runoff, leading to the loss of soil and nutrients. However, Gleysols, due to their high base saturation and the presence of highly active clay, have good natural fertility. Acrisols have their high water and nutrient retention capacity. Both are frequently used in agricultural crops. Nonetheless, their clayey texture and compacted structure can make them more susceptible to water erosion processes (IUSS, 2015).

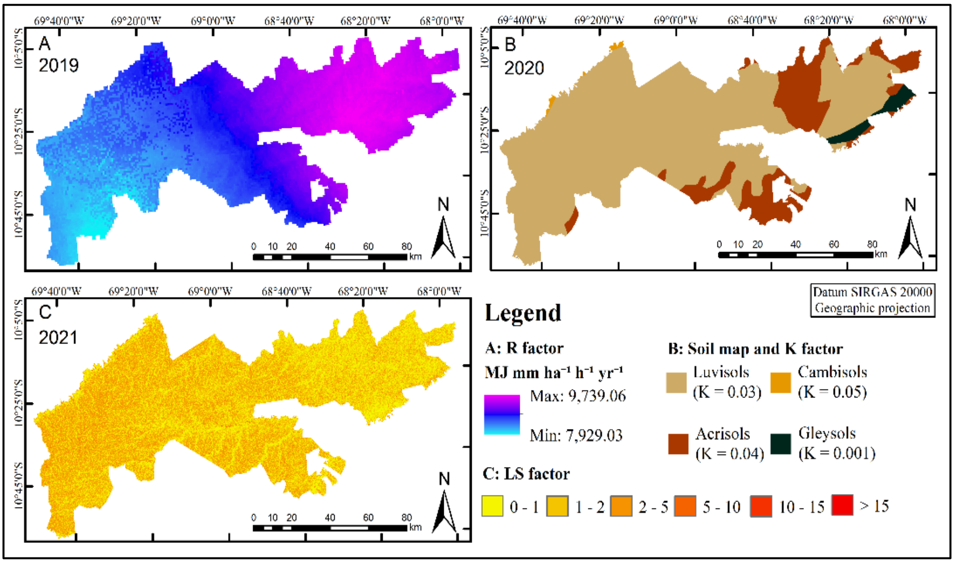

Figure 5. RUSLE factors: (A) R; (B) K; (C) LS from the Reserve.

Regarding to the LS factor, the intervals reveals that 99.4% of the area presents values below 5 and 0.03% presents values above 10 (Figure 5C). These values indicate, respectively, low to moderate vulnerability to water erosion (Beskow *et al.*, 2009) (Table 3).

Table 3. LS factor intervals for the Chico Mendes Extractive Reserve

Intervals	**%**
0-1	39.31
1-2	29.61
2-5	30.48
5-10	0.57
10-15	0.01
>15	0.02

The highest rainfall rates begin in September and end in May. 2019 presented the highest precipitation, surpassed only by the month of February 2021 (Figure 6).

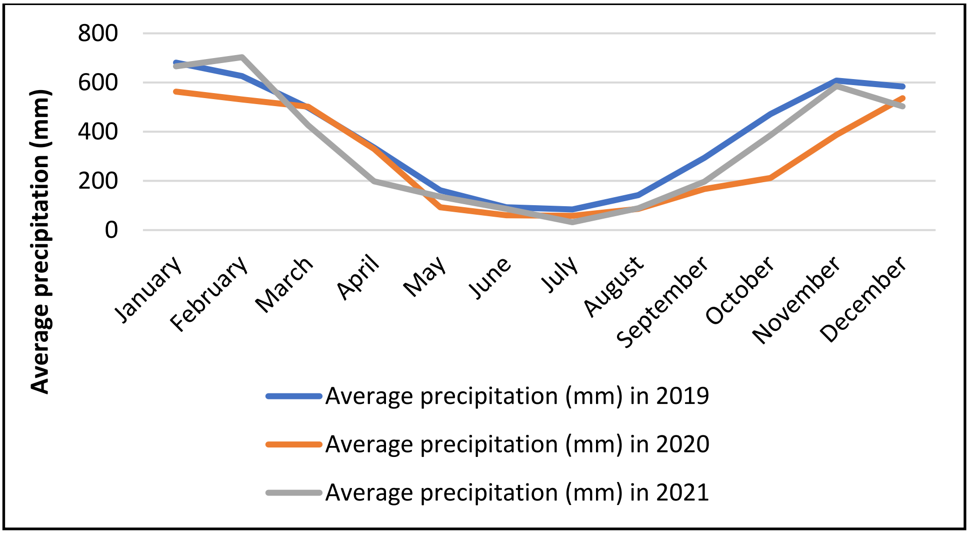

Figure 6. Chico Mendes Extractive Reserve quarterly average precipitation

C factor. The NDVI-derived C factors stand out for their ability to capture phenological and seasonal variations in vegetation cover, encompassing events such as droughts and forest fires. This effectiveness is attributed to the intrinsic ability of NDVI to identify changes in vegetation density within the same category (Rouse, 1974; Almagro *et al.*, 2019) (Table 4).

Table 4. Values of the soil cover management factor (Factors C_r and C_{r2})

Classes	2019		2020		2021	
	C_r	C_{r2}	C_r	C_{r2}	C_r	C_{r2}
Forest formation	0.157	0.128	0.139	0.100	0.148	0.113
Pasture	0.206	0.182	0.195	0.163	0.212	0.183
Temporary crops	0.210	0.187	0.215	0.184	0.235	0.208

The average values of the C_r and C_{r2} factors were slightly higher in 2019 and 2021, indicating that forest fires were also the cause of the elevation of these NDVI values. The largest fire scars are those with warmer colors on the maps, showing a growing trend of clandestine forest fires within the reserve's boundaries (Figures 7E and 7H).

The C indices obtained with NDVI identify the classes most impacted by seasonal effects or forest fires, given the variability of values. These approaches allow for more precise analyses, where lower NDVI values are directly proportional to higher C values (Durigon *et al.*, 2014; Macedo *et al.*, 2021).

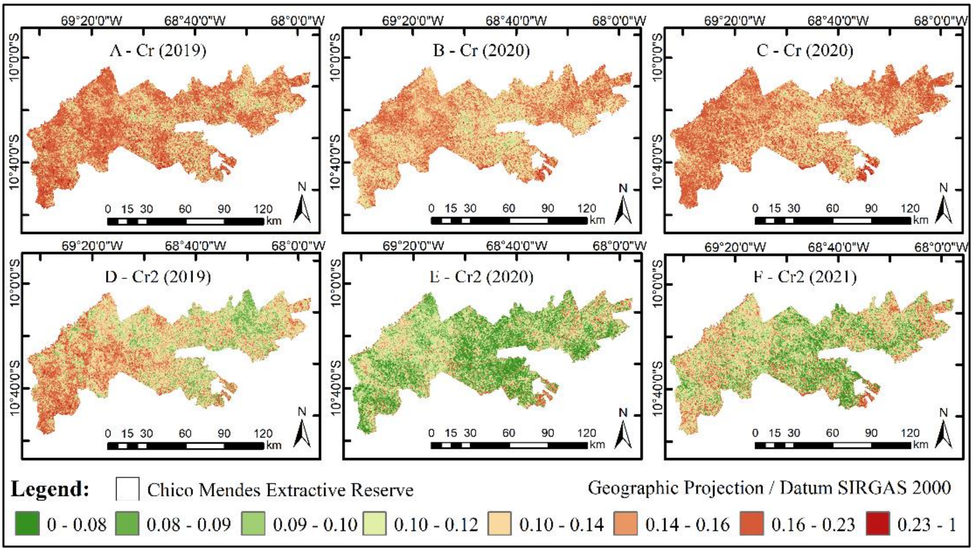

Figure 7. Maps of the Cr (A) 2019; (B) 2020; (C) 2021 and Cr2 (D) 2019; (E) 2020; (F) 2021 factors for the Chico Mendes Extractive Reserve.

Assessment of the influence of fires on C factor on soil loss rates. The estimated soil loss rates in Reserve ranged from 3.50 to 3.74 Mg ha^{-1} yr^{-1} using the C_r index and from 3.00 to 3.16 Mg ha^{-1} yr^{-1} with C_{r2} (Table 5), with slightly higher rates in 2021, likely due to a higher occurrence of forest fires. Among the LULC classes, pastures showed the highest average soil loss rates based on the used C factors (Table 5).

Table 5. Soil loss estimates in Chico Mendes Extractive Reserve from 2019 to 2021 using different obtained C factors.

LULC classes	**2019**		**2020**		**2021**	
	C_r	**C_{r2}**	**C_r**	**C_{r2}**	**C_r**	**C_{r2}**
	Mg ha^{-1} yr^{-1}					
Forest formation	0.84	0.72	0.79	0.57	0.82	0.63
Pasture	38.92	33.80	37.33	31.06	39.99	34.59
Temporary crops	26.16	22.27	27.69	23.77	23.98	21.01
Average loss	3.50	3.02	3.70	3.00	3.74	3.16

The percentages of mean soil loss rates per LULC class showed non-significant variations considering the two methods of obtaining the C factor. For pasture, using the C_r factor, there was a 4.08% decrease from 2019 to 2020 and an increase of 7.12% from 2020 to 2021. With the C_{r2} factor, there was a decrease of 8.10% from 2019 to 2020 and an increase of 11.36% from 2020 to 2021. These fluctuations likely reflect variations in deforestation rates and the occurrence of forest fires (Kumar *et al.*, 2022). The variations in soil loss rates, considering the

C_r and C_{r2} indices, demonstrated the same effectiveness in identifying areas most affected by water erosion.

We obtained the lowest soil loss rates with the C_{r2} factor, as it considers precipitation in the equation, thereby weighting spectral influences caused by seasonality (Macedo *et al.*, 2021). Thus, the C_{r2} factor better reflects the reduction in forest fires and, consequently, the increased soil protection provided by vegetation cover (Gwapedza *et al.*, 2021; Castro *et al.*, 2022).

Estimates of soil loss rate and sediment delivery rate. Our study indicated that areas with more fragile soils, steep terrain, low vegetation cover, and without conservation practices exhibit higher soil loss rates, as also observed by Liu *et al.* (2020) and Lense *et al.* (2021). The spatial distribution of areas most susceptible to water erosion is illustrated in Figure 7, following the intervals defined by Avanzi *et al.* (2013).

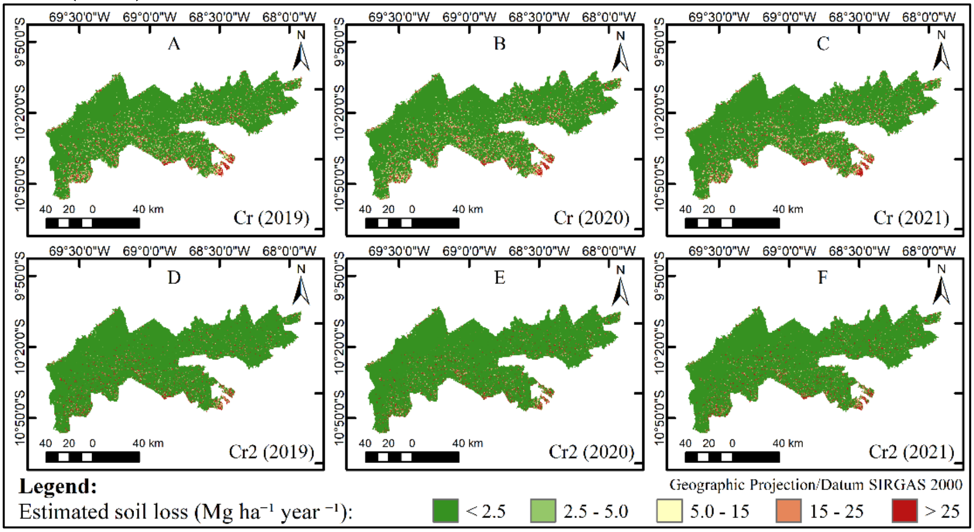

Figure 7. Soil loss estimates for C_r (A) 2019; (B) 2020; (C) 2021 and Cr2 (D) 2019; (E) 2020; (F) 2021 in Chico Mendes Extractive Reserve.

The southern margin is characterized as an area prone to the expansion of agricultural, resulting in illegal deforestation and forest fires as management practices. These activities increase environmental vulnerability (Azevedo, 2021). Therefore, this area exhibits the highest soil loss rates and lacks mitigating measures against soil degradation.

The validation of soil loss rates based on sediment delivery ratio using InVEST, for both C factors used, is presented in Table 6 (Sharp *et al.*, 2018). It is important to emphasize the effectiveness of this approach, supported by recent studies assessing erosive processes and sediment delivery rates (Hamel *et al.*, 2015; Bouguerra and Jebari, 2017; Matomela *et al.*, 2022). We estimate that, on average, only 0.10% and 0.06% of eroded sediments reach river channels, with the C_r and C_{r2} factors, respectively.

Forest fires are unsustainable and common management practices, especially during the dry season (Mascarenhas *et al.*, 2018). In early years, forest fires may initially increase soil nutrient levels, but they decline shortly after (Agbeshie *et al.*, 2022).

Table 6. Sediment delivery rate estimated by InVEST and error between C factors in Chico Mendes Extractive Reserve.

Year	Estimation of soil loss rates (Mg ha^{-1} yr^{-1})		Estimation of sediment delivery rate (Mg ha^{-1} yr^{-1})		C_r factor error (%)	C_{r2} factor error (%)
	C_r	C_{r2}	C_r	C_{r2}		
2019	3.50	3.02	0.025	0.020	0.09	0.06
2020	3.70	3.00	0.026	0.019	0.10	0.06
2021	3.74	3.16	0.027	0.021	0.10	0.07

Soil degradation resulting from forest fires intensifies hydrological erosion processes, leads to reduced water infiltration, increases soil loss rates, consequently affecting ecosystem services (Depountis *et al.*, 2020; Riquetti *et al.*, 2022), and contributes to greenhouse gas emissions (Friedlingstein *et al.*, 2020). Therefore, to promote sustainability and achieve the legal objectives of the Chico Mendes Extractive Reserve conservation unit (Brasil, 1990; 2000), it is essential to adopt sustainable soil and management practices, in addition to greater supervision, to effectively combat deforestation and illegal activities in the area.

CONCLUSION

As estimated average soil loss rates in Chico Mendes Extractive Reserve from 2019 to 2021 ranged from 3.00 to 3.74 Mg ha^{-1} yr^{-1}, with pasture areas experiencing the highest soil losses.

According to the validation, on average, only 0.10% and 0.06% of eroded sediments reach river channels with the Cr and Cr2 factors, respectively.

The estimation of sediment delivery rates by InVEST validated the soil loss rates estimated by RUSLE, with an average percentage error of 22.66% over the period.

Areas affected by forest fires exhibit the highest soil loss rates, characterized by vegetation indices based on NDVI. Therefore, the preservation and proper management of vegetation cover are essential for protecting natural resources and their services.

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