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Estimation of water erosion rates in Espírito Santo state, Brazil[1]

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ABSTRACT - Water erosion is a natural geological process that is common in tropical regions. It is important to monitor it to contain its physical, environmental, and socio-economic impacts. In the Espírito Santo state, Brazil, much of the land is used for agriculture and studies related to water erosion are scarce. The spatial modeling of water erosion is useful for proposing mitigating measures because combining it with data from geographic information systems can identify the areas most prone to soil loss. The Revised Universal Soil Loss Equation - RUSLE, is a model that requires little input data and is easy to use, providing results useful of helping to mitigate water erosion and promote sustainable land use planning. This study estimates the water erosion rates in the Espírito Santo state by RUSLE and compares them with the soil loss tolerance (T) limits. The parameters used in the model are the land use and management, the soil attributes, the relief and the climate factors. Approximately 38.65% of the state's area shows soil loss above the T limit (7.79 - 14.14 Mg ha^{-1} year^{-1}). The areas with steeper slopes and low vegetation cover have most of the highest erosion rates. The mean annual soil loss of the entire state is 33.55 Mg ha^{-1} year^{-1}. RUSLE provided a diagnosis useful of directing erosion mitigation measures to the most susceptible areas, enabling sustainable planning to support the state's socio-economic development.

Key words: Modeling. RUSLE. Soil conservation.

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INTRODUCTION

Approximately 70% of the territory of Espírito Santo state, Brazil, is covered by pasture, temporary and permanent crops or planted forest (MAPBIOMAS PROJECT, 2019). Water erosion is a common problem in these areas, especially in regions with more pronounced slopes. In addition, the conversion of natural vegetation into agricultural systems and their exploitation beyond the soil recovery capacity have contributed to increased soil loss rates.

In Brazil, the cost of soil erosion related to the loss of nutrients such as P, K^+, Ca^+, and Mg^+ in annual crops is approximately US $ 1.3 billion annually (DECHEN *et al*., 2015). By reducing the availability of fertile soils, the sustainability of agricultural systems is compromised by the increased soil losses from erosion. The consequences of erosion can affect local and regional hydrological processes, change sediment flows, and even affect climate patterns (DOTTERWEICH, 2013).

Thus, the adoption of predictive technologies, such as water erosion modeling, can help in the adoption of sustainable agricultural practices. In some European countries, the modeling of water erosion over large areas contributes to the proposition and adoption of environmental and agricultural policies to reduce the negative impacts of erosion (ALEWELL *et al*., 2019). In Brazil, despite the many studies on the deleterious effects of water erosion (BATISTA *et al*., 2017; LENSE *et al*., 2021; MEDEIROS *et al*., 2016; STEINMETZ *et al*., 2018), their findings are still unknown and little used by farmers, authorities, or government agencies. This, despite the usefulness of water erosion estimates for the formulation of sustainable management planning policies and the implementation of soil conservation practices.

The Revised Universal Soil Loss Equation - RUSLE (RENARD *et al*., 1997) is a model used worldwide to estimate erosion rates (OLIVEIRA; SERAPHIM; BORJA, 2015; PANAGOS *et al*., 2015). A distinctive characteristic of RUSLE is the need for little input data, overcoming the lack of climatic and geographic information in some regions (BHANDARI; ARYAL; DARNSAWASDI, 2015). After estimating soil losses by RUSLE, especially over large areas, geographic information systems enable the spatialization of the results (GANASRI; RAMESH, 2016). The main limitation of the application of the RUSLE model is the fact that this model was developed for temperate edaphoclimatic conditions, different from the Brazilian tropical edaphoclimatic conditions (AMORIM *et al*., 2010). Despite these differences, this limitation has been overcome due to several works applying RUSLE in Brazilian soils, where the model parameters are constantly adapted to tropical climatic conditions (BATISTA *et al*., 2017; DECHEN *et al*., 2015; MANNIGEL *et al*., 2002; MARTINS *et al*., 2010; MELLO *et al*., 2013).

The results of soil loss rate estimates can be compared to soil loss tolerance (T) limits (WISCHMEIER; SMITH, 1978). The T-index suggests the rate of erosion that a soil can withstand without compromising its productive capacity. The values found for T are highly important for decision-making for the control of water erosion. Although in the short term it is possible to use T values as an index of soil sustainability, in the long term, the erosion rates should tend to zero for the productive capacity of arable land to be sustainable (MENDES JÚNIOR *et al*., 2018).

This study estimates the rates of soil loss due to water erosion in the Espírito Santo state using the RUSLE and compares them to the T.

MATERIAL AND METHODS

Study site

The study was conducted in the Espírito Santo state, located in the Southeast region of Brazil, between latitudes 17° 53′ and 21° 17′ S and longitudes 39° 39′ and 41° 52′ W, Datum SIRGAS 2000 (Figure 1). The state has 46,184.1 km².

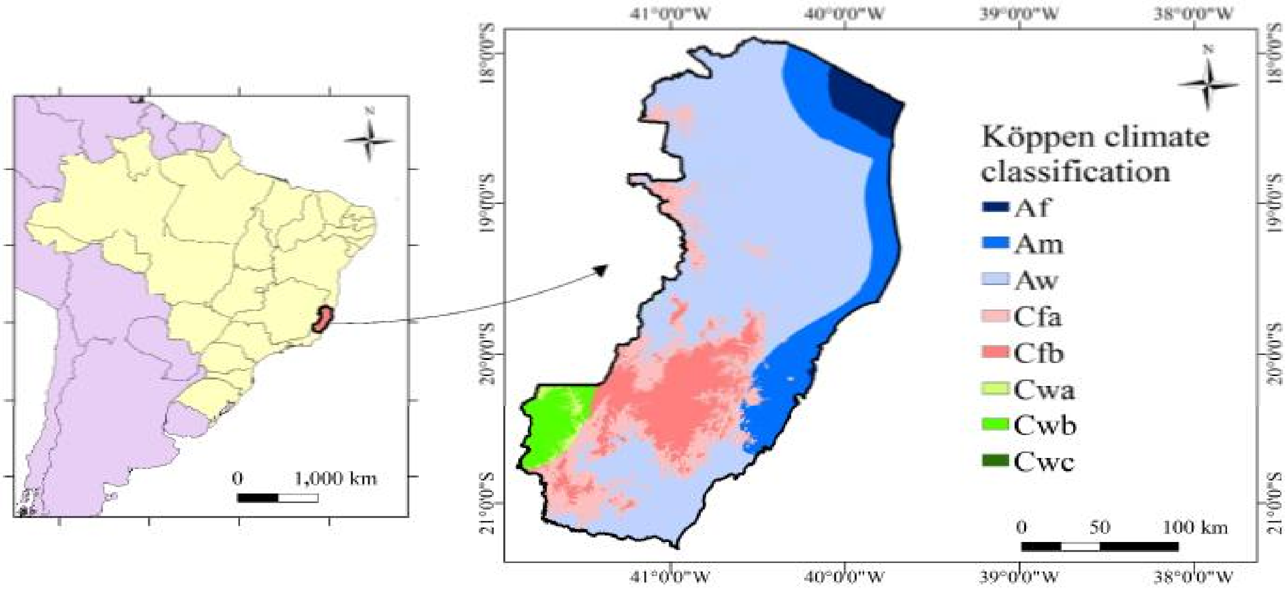
Because it is located in a coastal region of Southeast Brazil, the general climatic characteristic of the Espírito Santo state is a warm and rainy tropical regime, with no defined cold season. According to Alvares *et al*. (2013), who applied the Köppen system to classify this state, most of the state has an Aw (tropical savanna) climate (Figure 1). The mean temperatures in the state vary between 22 and 24 °C, and the annual rainfall volume is greater than 1,400 mm, which is especially concentrated in the summer (ALVARES *et al*., 2013).

The land use map (Figure 2), which was extracted from the digital platform of the Mapbiomas Project (2019), indicates that the main land-use classes in the Espírito Santo state are pasture (39.12%), followed by native forest (24.60%), temporary crops (18.65%), and permanent crops (8.30%). In addition, areas of planted forest (5.64%), urban infrastructure (1.38%), water bodies (1.03%), rocky outcrops (0.70%), other natural formations (0.18%), non-vegetated areas (0.17%), mangrove areas (0.14%), and beaches and dunes (0.09%). The planted forest use class consists mainly of eucalyptus plantations.

Latosols are the main soil class of Espírito Santo (49.71%), followed by Argisols (25.50%) and Cambisols (12.00%). The other soil classes are Neosols (4.13%), Gleysols (2.70%), Nitosols (2.30%), Charmosos (0.93%), Spodosols (0.85%) and Indiscriminate Mangrove Soils (0.15%). There are also rocky outcrops (0.70%). Figure 3 shows the soil map of the Espírito Santo state, scale 1:250,000 (CUNHA *et al*., 2016).

The average altitude of the state of Espírito Santo varies between 650 and 750 m, and its highest altitude, in Serra do Caparaó, is Pico da Bandeira, with 2,892 m (Figure 4A). The Shuttle Radar Topography Mission digital elevation model (DEM), with 30 m spatial resolution, was extracted from the Brasil em Relevo digital platform, of the Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA (MIRANDA, 2005). The slope map (Figure 4B) was generated from the DEM using the Slope tool in ArcMap 10.5 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2017). In Espírito Santo, reliefs with slopes between 8-20% and 20-45% predominate, representing 28% and 30% of the state, respectively.

Figure 1 - Location and climate map of the Espírito Santo state, Brazil, according to the Köppen climate classification



Source: Alvares *et al*. (2013). Legend: Af = equatorial climate, Am = tropical monsoon climate, Aw = tropical savanna climate, Cfa = humid subtropical climate, Cfb = temperate oceanic climate, Cwa = humid subtropical climate with dry winter, Cwb = subtropical highland climate and Cwc = cold subtropical highland climate

Figure 2 - Land use map of the Espírito Santo state, Brazil

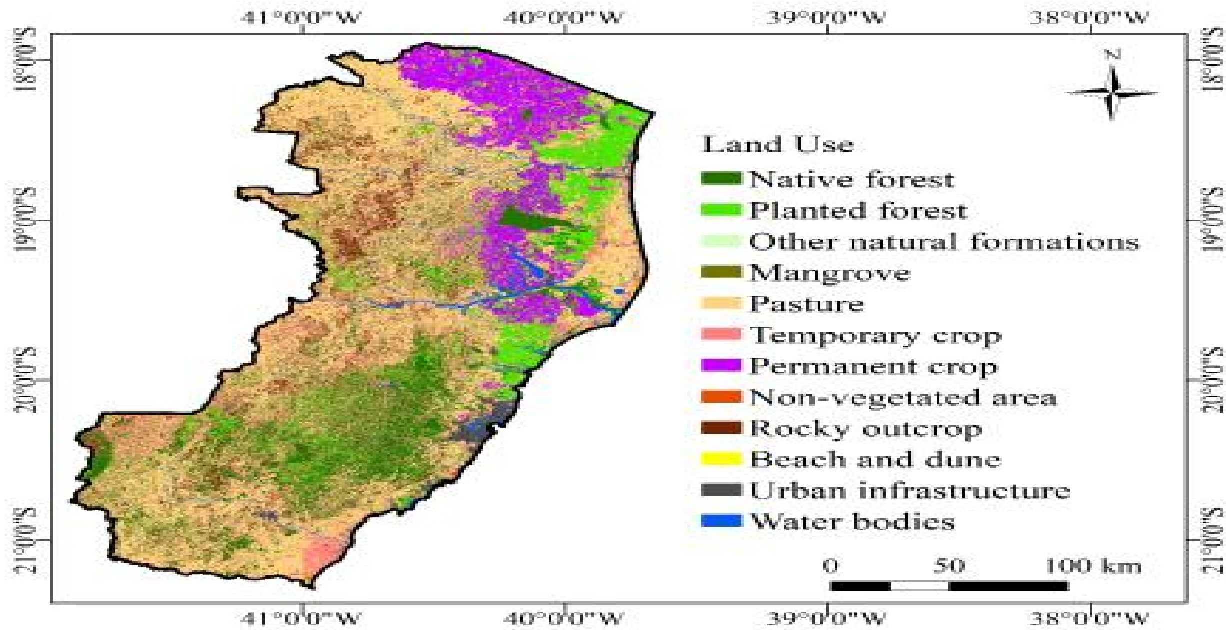
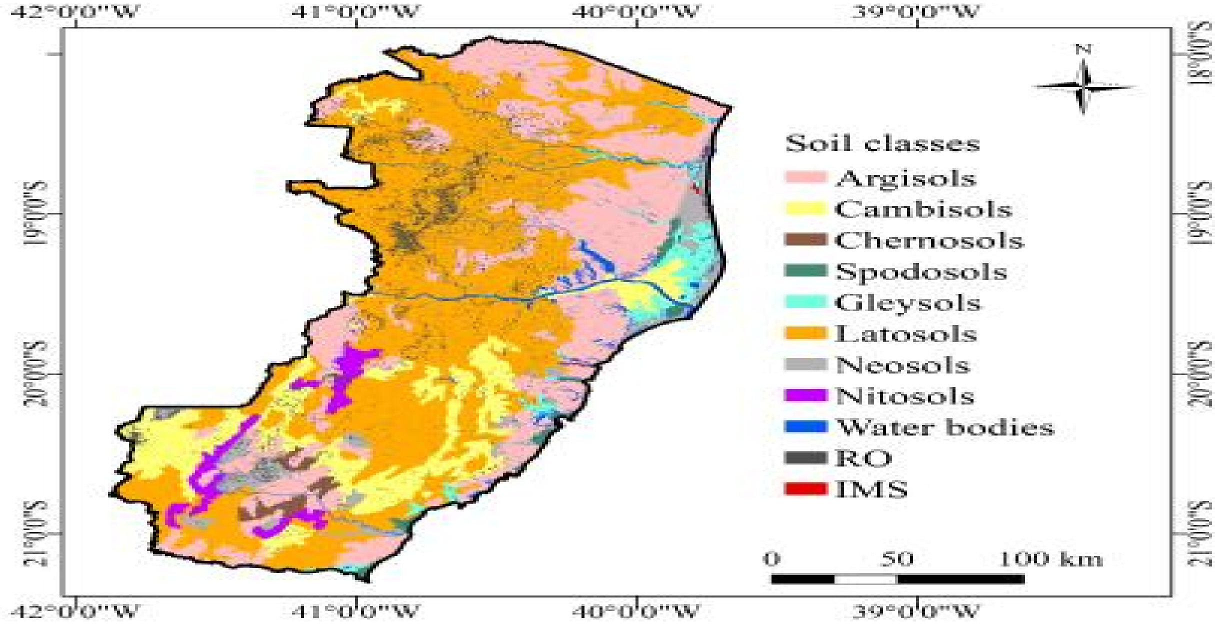
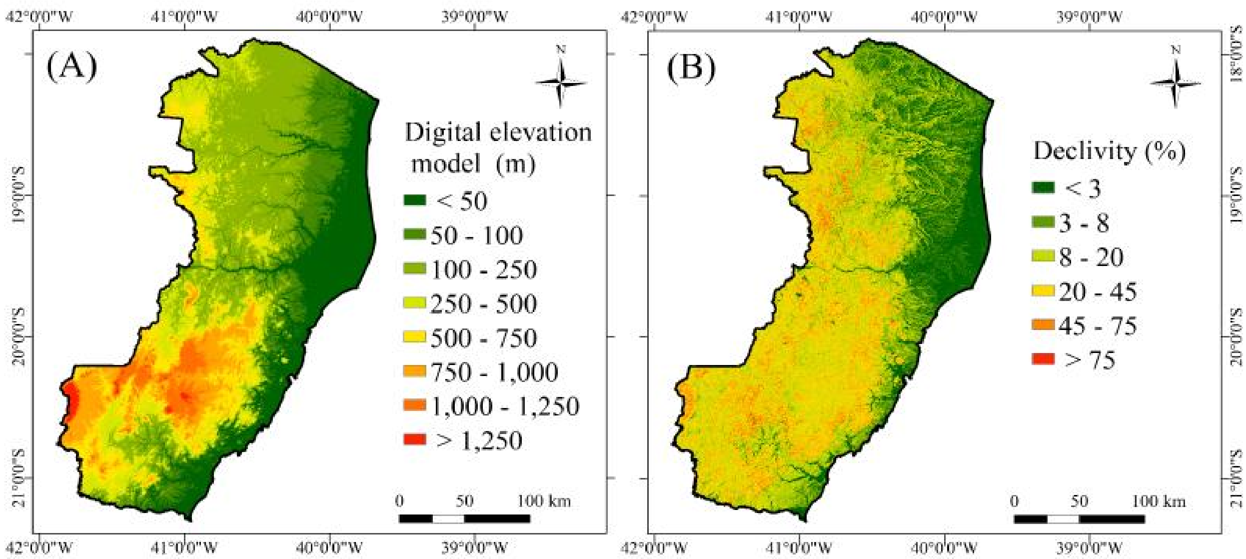


Figure 3 - Soil map of the Espírito Santo state, Brazil



Source: Cunha *et al.* (2016). Legend: RO = Rocky Outcrops, IMS = Indiscriminate Mangrove Soils

Figure 4 - Digital elevation model (A) and declivity map (B) of the Espírito Santo state, Brazil



Revised Universal Soil Loss Equation

The RUSLE model is represented by Equation 1.

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

Where: A is the mean annual soil loss, in Mg ha^{-1} year^{-1}; R is the rainfall erosivity factor, in MJ mm ha^{-1} h^{-1} year^{-1}; K is the soil erodibility factor, in Mg ha^{-1} MJ^{-1} mm^{-1}; LS is the topographic factor, dimensionless; C is the land use and management factor, dimensionless; and P is the conservation practices factor, dimensionless.

The R factor reflects the action of rain on soil water erosion. The R factor was determined based on the results of Saito *et al.* (2009), who calculated the mean annual erosivity for Espírito Santo from 88 rainfall stations distributed in the state. The K factor reflects the susceptibility of each soil to water erosion. This parameter varies according to the soil characteristics, and the higher it is, the more susceptible the soil is to erosion. For each of the main soil classes, a K value was assigned based on Silva and Alvares (2005) (Table 1).

The LS factor represents the effect of relief on soil loss rates. To calculate this parameter, the method of Moore and Burch (1986) was used, which is based on the DEM (Equation 2):

$$LS = \left(\frac{FA \ldots 30}{22.13}\right)^{0.4} \times \left(\frac{\sin \cdots (S)}{0.0896}\right)^{1.3} \quad (2)$$

Where LS is the topographic factor, dimensionless; FA is the flow accumulation expressed as the number of cells in the DEM grid; S is the slope of the relief in degrees; and 30 is the spatial resolution of the DEM in meters.

The LS parameter was calculated using the Raster Calculator tool in ArcMap 10.5 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2017).

Factor C represents the protection of the soil vegetation cover against the erosion process. This factor has higher values in areas with lower plant density and lower values in areas with good vegetation cover. In Espírito Santo, the C factor was obtained from values available in the scientific literature (Table 2). The P factor varies from close to 0 to 1, according to the presence or absence of soil conservation management practices. The parameter was determined according to the values reported by Bertoni and Lombardi Neto (2017) (Table 2).

All parameters of the RUSLE model were converted to raster data format and multiplied among themselves in the Raster Calculator tool in ArcMap 10.5 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2017), which generated the spatialization of the results.

The soil losses calculated for Espírito Santo state were compared with the T limits of each soil class, as shown in Table 3.

Table 1 - K factor values for the soils of the Espírito Santo state, Brazil

Soil class	K*	Soil class	K*
	Mg ha^{-1} MJ^{-1} mm^{-1}		Mg ha^{-1} MJ^{-1} mm^{-1}
Argisols	0.0425	Gleysols	0.0361
Cambisols	0.0508	Latosols	0.0162
Chernosols	0.0309	Neosols	0.0351
Spodosols	0.0592	Nitosols	0.0237

*Values from Silva and Alvares (2005)

Table 2 - Values of factors C and P for the land use classes of the Espírito Santo state, Brazil

Land use	C	P*	Authors
Native forest	0.020	0.2	Martins *et al*. (2010)
Planted forest	0.300	1.0	Martins *et al*. (2010)
Other natural formations	0.020	0.2	Martins *et al*. (2010)
Pasture	0.050	0.5	Silva *et al*. (2010)
Temporary crops	0.206	0.5	Silva *et al*. (2010)
Permanent crops	0.135	0.5	Silva *et al*. (2010)
Nonvegetated areas	1.000	1.0	Mendes Júnior *et al*. (2018)
Mangrove**	-		-
Rocky outcrop**	-		-
Beach and dune**	-		-
Urban infrastructure**	-		-
Water bodies**	-		-

*Values adapted from Bertoni and Lombardi Neto (2017). **Areas not considered in the soil loss calculation

Table 3 - Soil loss tolerance (T) limits for the soils of the Espírito Santo state, Brazil

Soil classes	T (Mg ha^{-1} $year^{-1}$)	Authors
Argisols	8.61	Nunes *et al*. (2012)
Cambisols	13.65	Nunes *et al*. (2012)
Chernosols	13.13	Muniz *et al*. (2015)
Spodosols	7.79	Mannigel *et al*. (2002)
Gleysols	14.14	Nunes *et al*. (2012)
Latosols	12.73	Nunes *et al*. (2012)
Neosols	10.48	Nunes *et al*. (2012)
Nitosols	11.10	Mannigel *et al*. (2002)

RESULTS AND DISCUSSION

The erosivity for Espírito Santo state varied between 4,843 and 7,783 MJ mm ha^{-1} h^{-1} $year^{-1}$ (Figure 5A), with a mean of 6,012 MJ mm ha^{-1} h^{-1} $year^{-1}$, which agrees with the values obtained by Mello *et al*. (2013). The classification by these authors ranks the erosivity of the state as "very strong" due to its high rainfall index, especially in the central and south mesoregions. The geographic location of the state is one factor that explains the high rainfall: it is coastal and more likely to receive rain from the ocean. In addition, the greater erosivity of some points is related to their higher altitude, indicating areas of more intense rainfall.

For the LS factor, an average of 4.6 was obtained (Figure 5B). The map indicates that the regions with LS factors below 2 are concentrated mainly on the coast, where the gentlest slopes are found. On the other hand, in 24.85% of the state, the LS was greater than 10, indicating that these areas are highly vulnerable to water erosion. These sites lack incentives for stakeholders to establish soil conservation practices to reduce runoff energy due to topography (BATISTA *et al*., 2017; STEINMETZ *et al*., 2018).

The total soil loss in the Espírito Santo state was approximately 150 million tons per year, with an estimated mean of 33.55 Mg ha^{-1} $year^{-1}$. The spatialization of losses calculated by RUSLE is illustrated in Figure 6.

The highest soil losses were recorded in nonvegetated areas (137.05 Mg ha^{-1} $year^{-1}$), in annual crops (97.50 Mg ha^{-1} $year^{-1}$), and in planted forests (73.00 Mg ha^{-1} $year^{-1}$), while the lowest losses were estimated for native forests (2.65 Mg ha^{-1} $year^{-1}$) and other natural formations (1.58 Mg ha^{-1} $year^{-1}$). Permanent crops had lower soil loss values (18.20 Mg ha^{-1} $year^{-1}$) than temporary crops because permanent crop soil is not turned or exposed as often as temporary crop soil is. In pasture areas, soil losses were 22.64 Mg ha^{-1} $year^{-1}$.

The average soil losses estimated for the state of Espírito Santo (33.55 Mg ha^{-1} $year^{-1}$) were very close to those reported by Medeiros *et al*. (2016), for the state of São Paulo, with an average soil loss rate of 30 Mg ha^{-1} $year^{-1}$. However, higher than those of Lense *et al*. (2021) for the state of Rondônia, with an average soil loss of 22.5 Mg ha^{-1} $year^{-1}$, due to the greater areal coverage of the Amazon biome.

Espírito Santo has a percentage of 38.65% of its area with soil losses above the limits of T. These areas must be prioritized for the implementation of conservation practices to mitigate erosion. In addition, these sites with losses above the T limits are distributed throughout the state (Figure 7), demonstrating the need to define a comprehensive management plan to reduce water erosion.

As Espírito Santo has large areas covered by soils with high erosion susceptibility (Argisols and Cambisols, respectively, 25.50% and 12.00%), special attention should be given to the management of these soils, since when associated with uses with little or no vegetation cover, soil loss values higher than the T limits are reached (LENSE *et al*., 2021).

Latosols occupy about 50% of the state and, although they have greater resistance to water erosion, when associated with agricultural crops under inadequate management, they present significant losses and compromise soil sustainability. Mainly in areas with steeper slopes, indicating the importance of vegetation cover and management practices in reducing erosion rates (LENSE *et al*., 2020).

The regions with high erosivity and higher LS factor values show that the different soil classes are subject to high water erosion rates. Thus, management practices, changes in land use, and vegetation cover maintenance play important roles in reducing erosion rates, especially in the soil classes most vulnerable to water erosion (LENSE *et al*., 2020, 2021; MEDEIROS *et al*., 2016; STEINMETZ *et al*., 2018). These results reveal the need for planning, implementation, and dissemination of more effective soil management techniques and conservation practices for agricultural and pasture areas, and for reducing areas with exposed soil, in order to minimize the number of sites with erosion rates higher than the T limits.

Public policies should be formulated based on the results of the spatialization of soil losses to adjust land use according to agricultural suitability, especially in areas with high erosion rates (MEDEIROS *et al.*, 2016). Coordinated legislation should permeate the

Figure 5 - Spatial distribution of rainfall erosivity - R (A) and topographic factor - LS (B) for the Espírito Santo state, Brazil

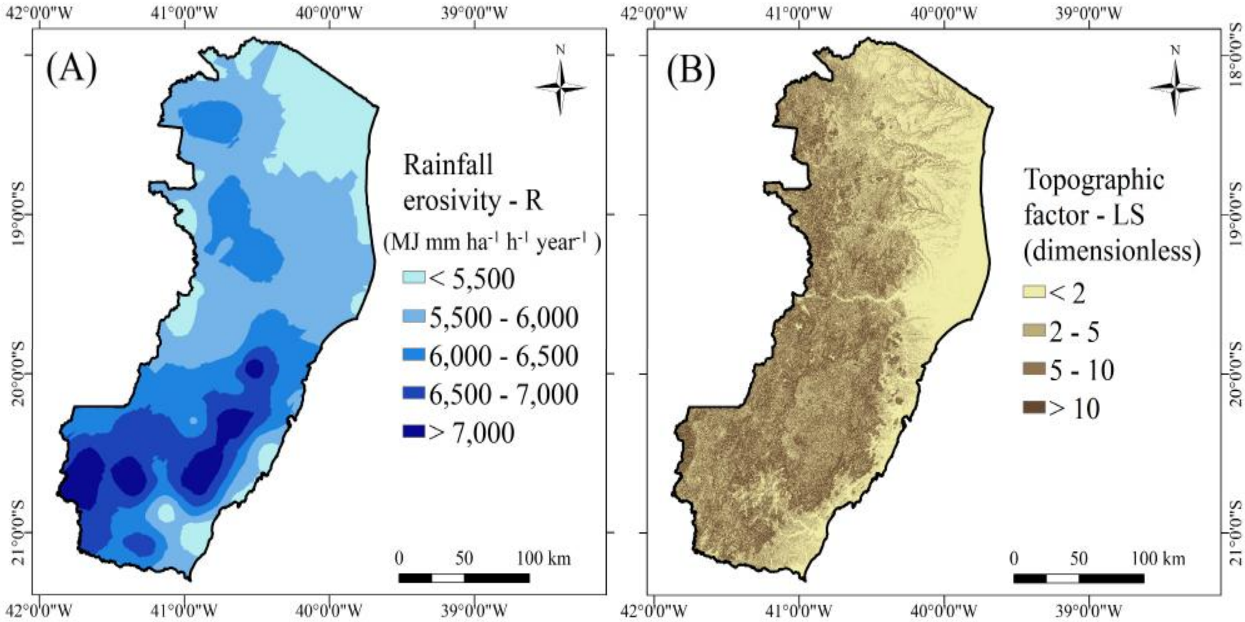
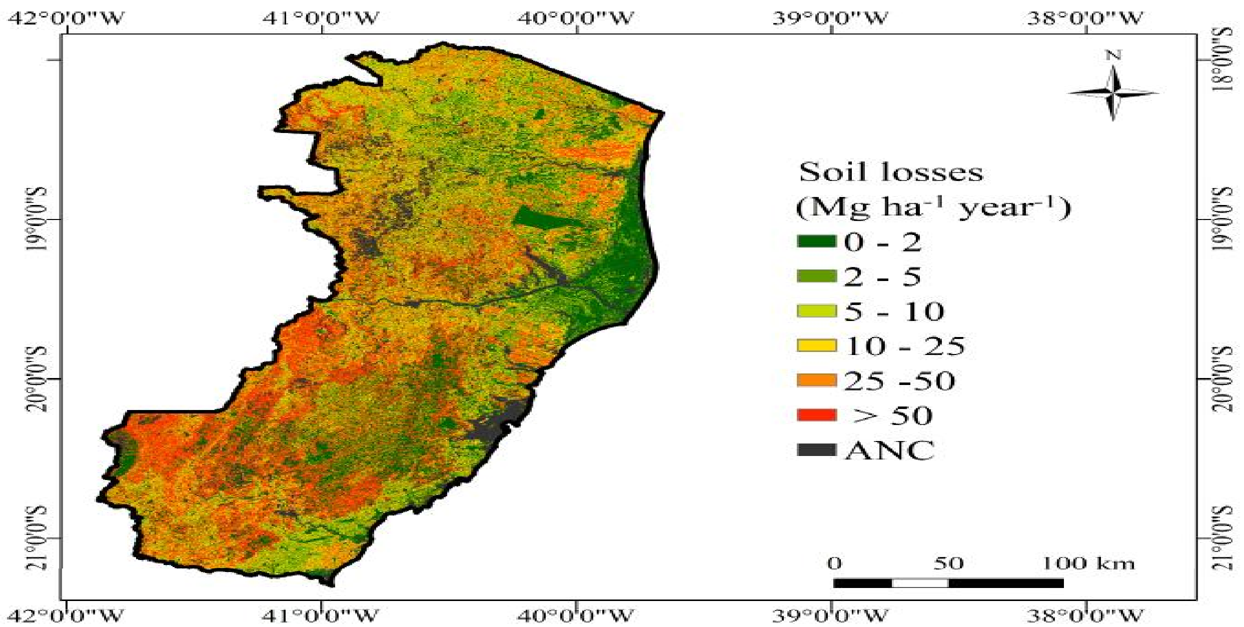
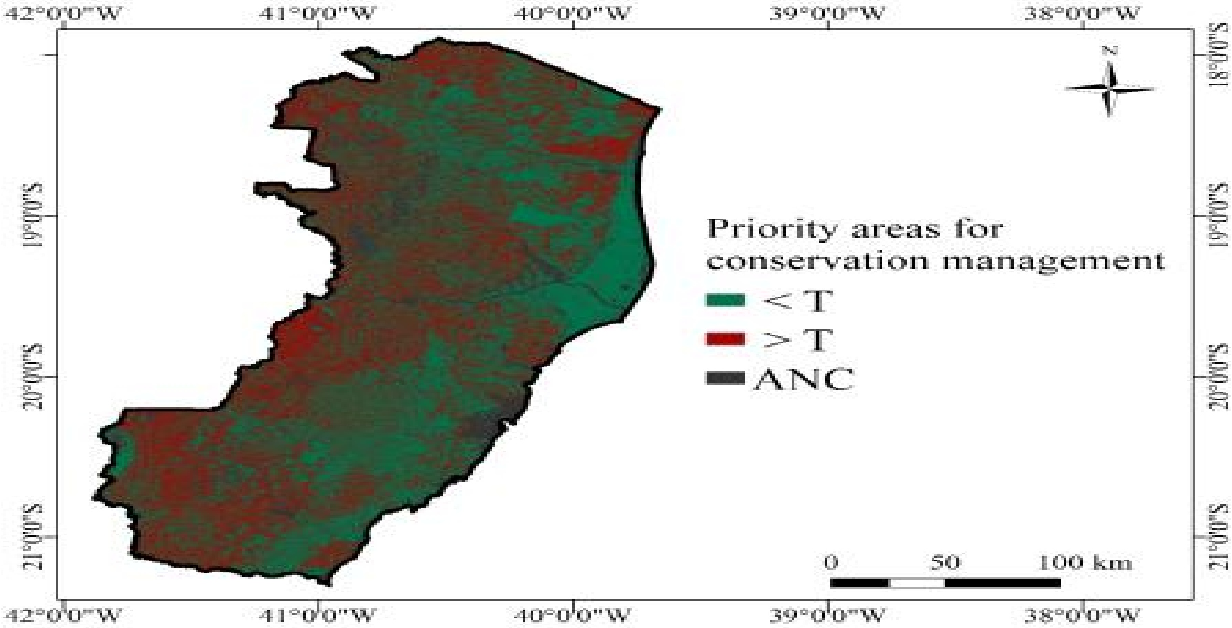


Figure 6 - Spatial distribution of soil losses of the Espírito Santo state, Brazil



Legend: ANC = areas not considered in the soil loss calculation (mangrove, rocky outcrop, beach and dune, urban infrastructure, and water bodies)

Figure 7 - Priority areas for conservation management of the Espírito Santo state, Brazil



Legend: T = Soil loss tolerance; ANC = areas not considered in the soil loss calculation (mangrove, rocky outcrop, beach and dune, urban infrastructure, and water bodies)

different hierarchical levels of public administration, from municipal to state, and should extend to partnerships with the federal government to popularize conservation practices and establish public policies that drive the sustainable use of soils based on their vulnerability to erosion (ALEWELL *et al*., 2019; LENSE *et al*., 2021).

With the provision of information on sustainable land use techniques, the interaction of the people with these data favors a scenario in which economic and social development coexist with respect of the environment, and such practices will tend to become permanent over time through the cultural habits of successive generations. It is important to apply the knowledge acquired through geographic and soil sciences as a development tool in a society in which these practices were previously uncommon.

CONCLUSIONS

1. The Espírito Santo state has high erosivity indices, steep reliefs, and soils with high vulnerability to erosion processes. Thus, plant cover and soil management practices will play an essential role in reducing soil losses in the region;
2. RUSLE estimates a mean soil loss of 33.55 Mg ha^{-1} year^{-1}, and in 38.65% of the Espírito Santo state, the erosion rates are above the soil loss tolerance limits. These areas should be prioritized in the adoption of mitigation measures to reduce water erosion;
3. The results of this study may contribute to the development of different soil management and conservation planning scenarios and may help in developing public policies that encourage conservation and sustainable land use in the Espírito Santo state.

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