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# EROSIVITY INDEX FOR BRASIL BASED ON CLIMATOLOGICAL NORMALS FROM 1991 TO 2020

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## ABSTRACT

This work aimed to update and spatialize the erosivity indices in Brazil based on the most recent climatological normals. The erosivity indices were calculated based on regression equations of 90 pluviographic stations available in the Brazilian territory. Average monthly precipitation data from 1991 to 2020 from 1918 rainfall stations were used. Data were interpolated by ordinary kriging in ArcGis 10.8 (ESRI, 2019) software. The average erosivity was determined for each municipality in the Brazilian territory. The estimated erosivity index varied from values below 1,400 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ in the Northeast region to values above 17,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ in some points in the extreme North of the Amazon Basin. A strong seasonal variation in erosivity was observed, with a predominance of erosivity in the very high classes in the months of December to March, while in the month of September a very low erosivity value predominates.

**KEYWORDS**: Erosion, soils, universal soil loss equation, soil conservation, climatology.

# ÍNDICE DE EROSIVIDADE PARA O BRASIL COM BASE NAS NORMAIS CLIMATOLÓGICAS DE 1991 A 2020

## RESUMO

Este trabalho teve como objetivo atualizar e espacializar os índices de erosividade no Brasil com base nas normais climatológicas mais recentes. Os índices de erosividade foram calculados com base em equações de regressão de 90 estações pluviográficas disponíveis no território brasileiro. Foram utilizados dados de precipitação média mensal de 1991 a 2020 de 1918 estações pluviométricas. Os dados foram interpolados por krigagem ordinária no software ArcGis 10.8 (ESRI, 2019). Foi determinada a erosividade média para cada município do território brasileiro. O índice de erosividade estimado variou de valores abaixo de 1.400 MJ mm $ha^{-1}$ $h^{-1}$ $ano^{-1}$ na região Nordeste até valores acima de 17.000 MJ mm $ha^{-1}$ $h^{-1}$ $ano^{-1}$ em alguns pontos do extremo Norte da Bacia Amazônica. Foi constatada forte variação sazonal na erosividade, com predomínio da erosividade nas classes muito altas nos meses de dezembro a março, enquanto que no mês de setembro predomina valor de erosividade muito baixo.

**Palavras chave**: Erosão, solos, equação universal de perda de solo, conservação do solo, climatologia.

## 1 INTRODUCTION

In Brazil, there are several works carried out with the objective of adjusting the equations for estimating erosivity based on rainfall data from the analysis of rainfall series data (Gonçalves et al., 2006; Oliveira, Wendland & Nearing, 2012; Mello & Silva, 2013; Back & Poleto, 2018). However, there are few studies in Brazil on the spatialization and generation of erosion maps, among which those by Silva (2004), Mello, Viola, Beskom and Norton (2013), Trindade, Oliveira, Anache and Wendland (2016), Hernani, Gonçalves, Ortolan and Souza (2020). Among the main works, the erosivity map of Brazil prepared by Silva (2004) stands out, in which the author used eight regression equations and rainfall data from 1600 stations with historical series of precipitation for at least 10 years. Also Mello et al. (2013) presented an erosivity map for Brazil where they considered 54 regression equations and applied 773 rainfall stations with at least 15 years of data, to estimate rainfall erosivity in Brazil. Trinidad et al. (2016) presented an erosion map for Brazil built based on 75 regression equations and 1521 rainfall stations with a series of more than 20 years. Embrapa (Empresa Brasileira de Pesquisa Agropecuária) presented a publication containing maps of susceptibility and vulnerability of Brazilian soils to water erosion (Hernani et al., 2020), based on the equations by Oliveira et al. (2012).

The spatial distribution of erosivity values depends on the regression equation used and the series of pluviometric data used. In the various studies carried out in Brazil, there was no standardization of the rainfall data period, which may have affected the spatialization of the data. Several regression equations not considered in previous works were also identified. In addition, in recent decades, the vulnerability of the climate has motivated a constant concern regarding the factors of global climate change, whether due to interference from natural and/or anthropogenic activities (Inmet 2022). Angulo-Martínez and Beguería (2009) point out that, in the context of climate change, the effect of changing rainfall characteristics on soil erosion has been increasingly evaluated in studies related to soil conservation. The behavior of rainfall regimes due to climate change can affect erosivity values, so there is a need for constant updating of rainfall erosivity index values, considering more recent data that can demonstrate a change in temporal and spatial patterns of erosivity. Thus, this work aimed to update and spatialize the erosivity indexes in Brazil based on climatological normals from 1991 to 2020.

## 2 BIBLIOGRAFIC REVIEW

Water erosion is one of the major environmental problems, responsible for the degradation of agricultural land and reduced productivity in several countries, with environmental, economic and social impacts (Sadeghi, Zabihi, Vafakhah and Hazbavi, 2017; Wang , Zheng and Guan, 2016). According to the report presented by the Food and Agriculture Organization of the United Nations (FAO 2017), 33% of the world's soils are degraded by several factors, including accelerated erosion processes. In recent decades, issues associated with the concept of sustainability have assumed greater relevance (Santos et al., 2022; Pontes and Figueiredo, 2023).

Brazil has approximately 81 million hectares of agricultural area and 179 million of pasture areas, occupying 10% and 21% of the national territory, respectively, many of which without conservationist practices, where erosion processes occur with losses of soil and inputs. Manzatto et al. (2002) highlighted that 65% of the Brazilian territory is suitable for annual or perennial cultivation. However, Bai, Dent, Olsson and Shaepman (2008) pointed out that around 22% of the territory is occupied by land with varying levels of degradation. Anache, Wendland, Oliveira, Flanagan and Nearing (2017) highlight that for Brazil, erosion caused by rainwater is the most significant form of soil degradation, with estimates of the volume of soil lost ranging from 0.1 to 136.0 t $ha^{-1}$, depending on use and the coverage.

Soil loss estimation models and the spatialization of information are important tools for environmental planning and studies of alternative practices for soil management and conservation (Couto Júnior et al., 2019; Nachtigall et al., 2020). Empirical models include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised version, RUSLE (Renard, Foster, Weesies, Mccool and Yoder, 1997), which are used worldwide to estimate soil loss (Panagos et al., 2015; Oliveira, Guedes, Santos and Silva, 2023). Chaves (2010) points out that the USLE is widely used all over the world, including the tropics, and its reasonable accuracy in estimating annual soil loss, as well as its simplicity of application and availability of data, allows for a practically universal application.

The USLE is composed of the main factors that influence erosion, which are rainfall erosivity (R factor), soil erodibility (K factor), slope length (L factor), soil slope (S factor), use and management (C factor) and conservationist practices (P factor).

Rainfall erosivity represents an interaction between kinetic energy and runoff movement, and the erosivity index represents the relationship between climate parameters and soil (Zhao et al., 2017; Li and Ye, 2018, Panagos, Borrelli and Poesen, 2019; Panagos et al., 2021).

When compared to the other USLE factors, it is the factor that greatly influences soil losses (Sadeghi et al., 2011; Shamshad, Azhari, Isa, Wan and Parida, 2008). Unlike other factors, such as relief and soil characteristics, erosivity cannot be altered by human action, representing a natural environmental limitation to land use and management.

The erosivity index (EI30) depends on the physical characteristics of the rains, such as: intensity, duration, distribution and size of the drops (Wischmeier and Smith, 1978). The erosivity index is the most used in Brazilian conditions, as it is considered the most adequate to the intertropical reality, and represents the product of kinetic energy (Ec) and the maximum intensity of rain in 30 minutes (I30) (Wischmeier and Smith, 1978; Hoyos, Waylen and Jaramillo, 2005).

Determining the R factor requires a historical series of rainfall data, with minimum periods of 20 years being recommended (Wischmeier and Smith, 1978; Renard et al., 1997). Several authors comment on the difficulty of obtaining these data, both in Brazil and in other countries (Back and Poleto, 2018; Baecheler and Bravo, 2019). An alternative used in the absence of such data is to estimate the erosivity index from monthly rainfall averages, called the pluviometric method (Waltrick, Machado, Dieckon and Oliveira, 2015). For this method, it is essential to fit the regression equations between the erosivity indices and the rainfall values. The regressions of the EI30 erosivity indices with the rainfall coefficients (Rc), also known as the Modified Fournier Index (MFI) (Renard and Freimund, 1994) stand out. Due to the good availability of rainfall data and ease of application, this method is widely used and considered to have satisfactory accuracy in estimating the R factor (Angulo-Martínez and Beguería, 2009; Nearing, Yin, Borrelli and Polyakov, 2017).

For places without rainfall data, it is possible to obtain an estimate of the erosivity index from the interpolation of maps or with the use of geoprocessing tools, obtain punctual estimates through the spatialization of the data. The spatialization of erosivity is also important for the identification and comparison of areas with greater erosion potential, due to climatic factors. The association of erosion maps with relief maps and soil type allows identifying regions with greater risks of erosion, landslides or landslipping (Mello and Silva, 2013).

## 3 METHODOLOGY

To determine the monthly and annual values of the EI30 Erosivity Index, the rainfall method was used (Waltrick et al., 2015) based on the regression equations as a function of the Modified Fournier Index (MFI). In the study, linear or potential equations were considered, adopting the one with the highest coefficient of determination ($R^2$), from 90 rainfall stations in which the erosivity index is calculated by Equations (1 and 2):

$$EI_{30} = a.MFI + b \quad (1)$$

$$EI_{30} = a.MFI \quad (2)$$

where: EI30 is the erosivity index (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$); a and b are the adjusted coefficients for a given rainfall station; MFI the Fournier index calculated by Equation (3).

$$MFI = \frac{p^2}{P} \quad (3)$$

where: p is the average monthly precipitation (mm); P is the average annual precipitation (mm).

The 73 equations by Trindade et al. (2016) were used, being complemented with recent research including the equations presented by Back and Poletto (2018), Santos (2008), Martins, Cassol, Eltz and Bueno (2009), Pereira (1983), Matos et al. (2017), Barbosa, Blanco and Melo (2015).

With the coordinates (latitude and longitude) of the rainfall stations and using the Geographic Information System (GIS), it was possible to spatialize each of the equations, determining their respective areas of influence using the Thiessen polygon method (Figure 1).

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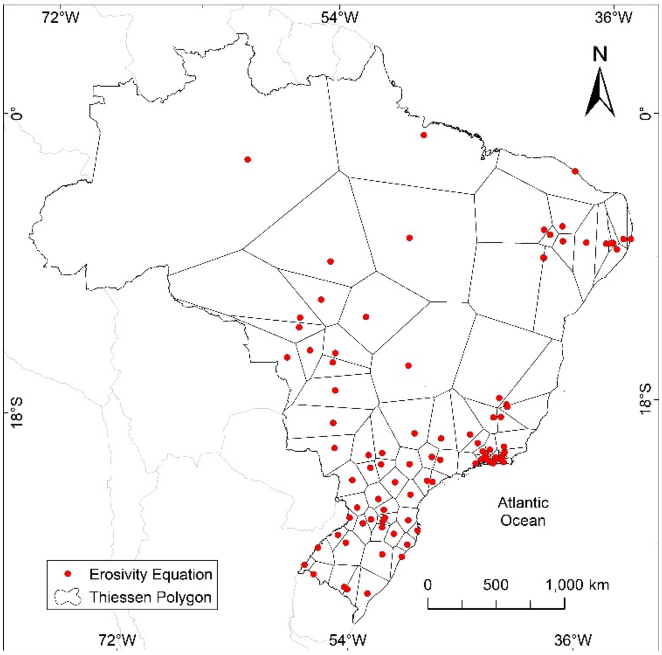


**Figure 1. Thiessen polygons with the influence areas of the equations used in the study.**

Regarding rainfall stations, 1918 rainfall stations were used with monthly data from 1991 to 2020, corresponding to the most recent Climatological Normal (Inmet 2022). The stations used belong to federal and state public bodies, and the criterion adopted was to use only stations that failed less than 5% of the evaluated months. Of these stations, 221 belong to the National Institute of Meteorology (Inmet 2022) and 1406 to the National Water and Basic Sanitation Agency (ANA 2023). Of the state agencies, 284 rainfall stations from the Department of Water and Electricity of the State of São Paulo (DAEE 2023) and seven from the Rural Development Institute of Paraná IDR-Paraná were used. The distribution of stations in the Brazilian territory can be seen in Figure 2.

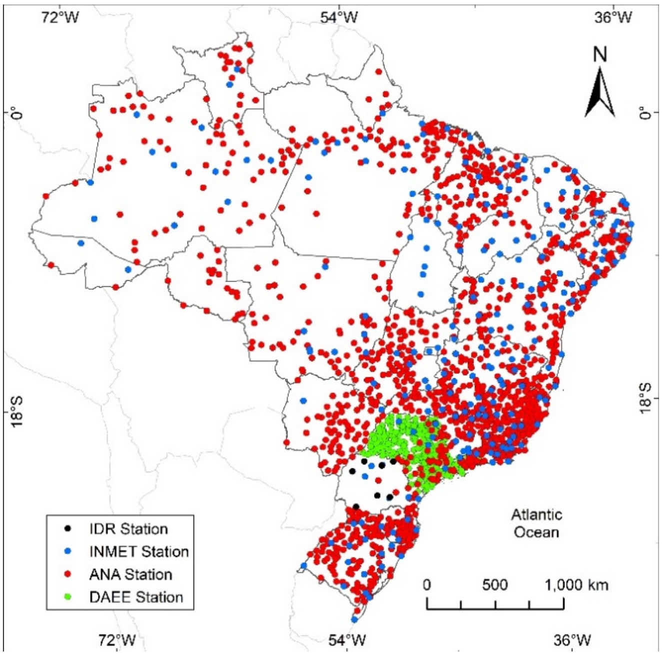


**Figure 2. Spatial distribution of rainfall stations used in the study.**

For the spatialization and interpolation of the erosivity data, the Ordinary Kriging method was used with a pixel resolution of 1 km². The intersection of monthly and annual precipitation data by municipality and the Thiessen polygons of the erosivity equations allowed the calculation of monthly and annual erosivity by municipality.

For the analysis, other calculations were generated that made it possible to also interpret the quarterly erosivity, Modified Fournier Index (MFI), in addition to representing the other data used in the study through figures. The EI30 values were classified according to the ranges presented in Table 1. The monthly erosivity values and the respective percentages for each quarter of the year were also determined, in order to characterize the seasonal variation.

**Table 1. Average annual and monthly rainfall erosivity classes.**

| Erosivity classes | EI30 (MJ mm $ha^{-1}h^{-1}$) | |
|---|---|---|
| | Annual | Montlyl |
| Very low | EI30 < 2,500 | EI30 < 250 |
| Low | 2,500 < EI30 < 5,000 | 250 < EI30 < 500 |
| Averagea | 5,000 < EI30 < 7,000 | 500 < EI30 < 700 |
| High | 7,000 < EI30 < 10,000 | 700 < EI30 < 1,000 |
| Very High | EI30 < 10,000 | EI30 < 1,000 |

## 4 RESULTS

Annual precipitation shows high spatial variation (Figure 3), with values below 500 mm in the Northeast region, where the BSh (semi-arid) climate occurs (Alvares, Stape, Sentelhas, Gonçalves and Sparovek, 2013), to values above 2,500 mm per year in the North region, where the Af climate (Tropical Rainforest) predominates. In the Amazon basin the average precipitation is above 2,000 mm with Af and Am climate (tropical climate with dry winter).

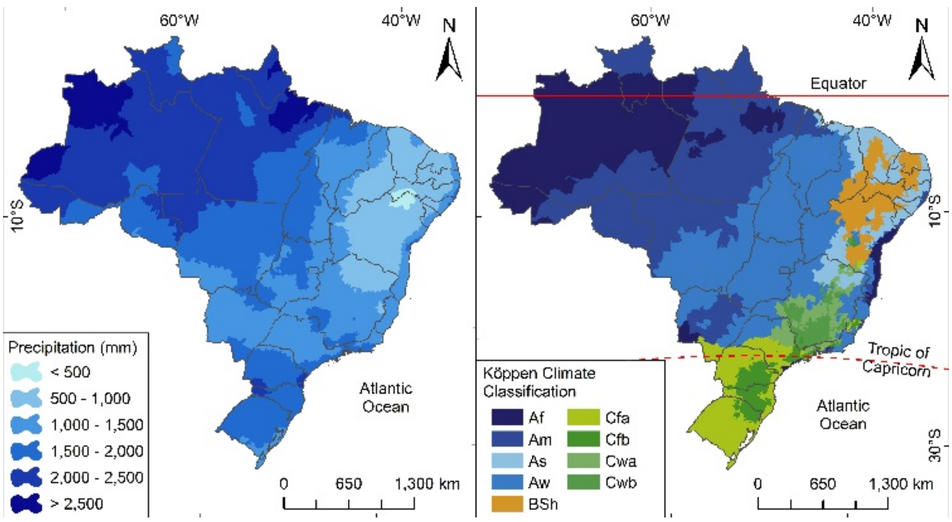


**Figure 3. Precipitation distribution and climate classification in Brazil.**

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In the Central-West region, the Aw climate (tropical monsoon climate) prevails, with precipitation between 1,000 and 2,000 mm. In the southern region of Brazil, the climate is Cf (humid temperate without a dry season) with precipitation between 1,000 and 2,000 mm in most parts, although in some areas precipitation can exceed 2,500 mm. The Southeast region has varied climates including Cf, Cw (humid temperate with dry winter), Aw (tropical with dry winter) and As (tropical with dry summer) with a predominance of precipitation in the range of 1,000 to 1,500 mm and some areas with precipitation above up to 2000 mm.

The MFI varied from values below 60 to values above 160 (Figure 4). In Brazil, it is observed that there is a predominance of areas with MFI above 160, classified as very high, including the entire Amazon Basin and most of the Central-West and South regions, also occurring in the Northeast region. Values classified as low and very low were found in the Northeast region, where the climate is semi-arid.

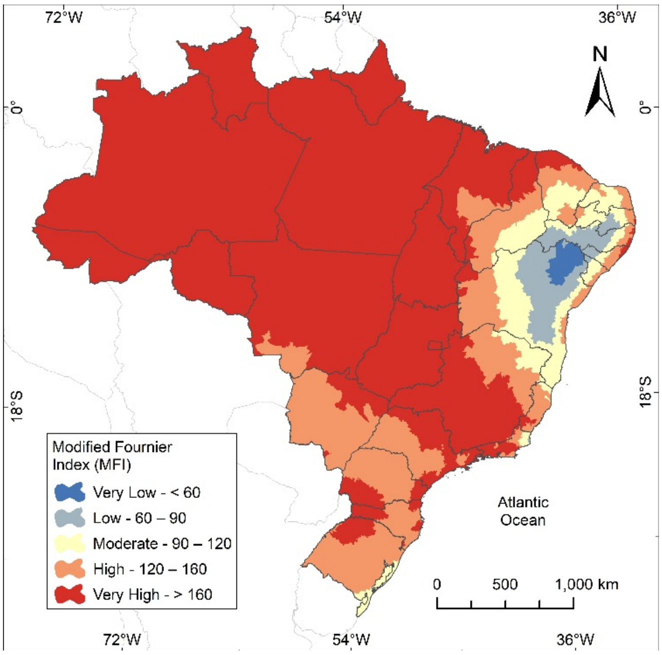


**Figure 4. Modified Fournier Index in Brazilian territory.**

Figure 5 presents the distribution of erosivity by state in Brazil. It is observed that the erosivity index varied from values below 1,400 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ in the Northeast region to values above 17,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ in some points of the extreme North, where the Amazon basin is located, the variation being directly related to the precipitation data and, consequently, to the MFI. The average erosivity for Brazil was 10,082 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$.

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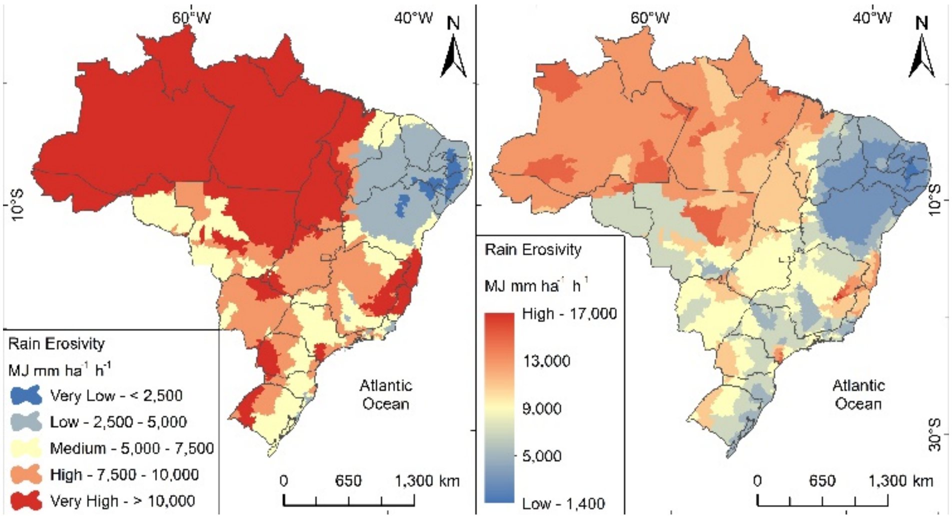


**Figure 5. Spatial distribution of erosivity by Brazilian state.**

It is observed that the class of erosivity Very high (EI30 > 10,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$) predominates, occurring in 56.1% of the territory, followed, respectively, by High (7,500 < EI30 <10,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$) in 19.8%, Medium (5,000 < EI30 < 7,500 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$) in 12.6%, Low (2,500 < EI30 <5,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$) in 10.3%. The Very low class (EI30 < 2500 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$) occurs only in 1.2% of the Brazilian territory.

Figure 6 represents the variation in erosivity over the months of the year, where it can be seen that there is a marked seasonality. From December to March, values of Very high erosivity predominate (EI30 > 1,000 MJ mm $ha^{-1}$ $h^{-1}$). On the other hand, from May to September, monthly erosivity values predominate in the Very low class (EI30 < 250 MJ mm $ha^{-1}$ $h^{-1}$), and in September there are no values in the Very high class, and in June to August, values above 1,000 MJ mm $ha^{-1}$ $h^{-1}$ only occur in small areas in the extreme north of Brazil. In October, there is a marked spatial variation in the Brazilian territory, with values above 1,000 MJ mm $ha^{-1}$ $h^{-1}$ in the western part of the South region and small areas in the central-west region and in the west of the Amazon Basin.

In Figure 7, the relative distribution of erosivity in the different quarters of the year can be seen. It should be noted that erosivity is concentrated in the first quarter of the year, when more than 40% of annual erosivity occurs in most of the Brazilian territory, reaching 80% in the semi-arid region. In the fourth quarter it is observed that 30 to 60% of the annual erosivity occurs in the Central-West and Southeast regions, while in the 3rd quarter less than 10% occurs in these regions.

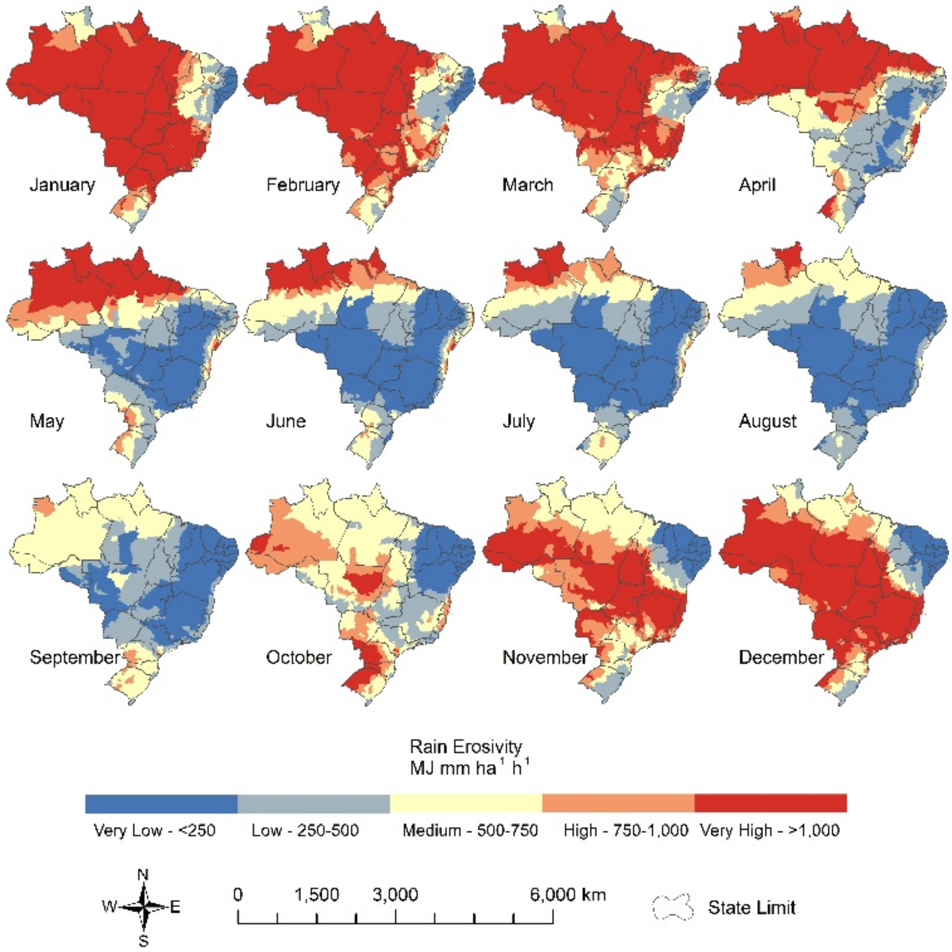


**Figure 6. Spatial distribution of monthly erosivity in Brazil.**

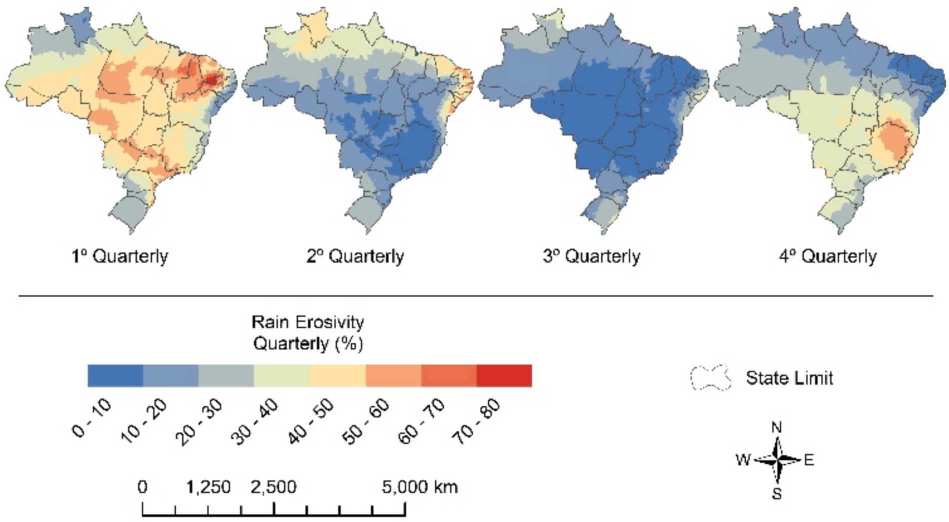


**Figure 7. Relative distribution of erosivity in Brazil in different quarters of the year.**

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## 5 DISCUSSIONS

The results of the precipitation distribution are in agreement with several similar studies in Brazil. For example, Reboita, Gan, Rocha and Ambrizzi (2010), in a study on the climate of South America, also found that one of the rainiest regions is in northwestern Brazil, which includes much of the Amazon basin, where average precipitation was greater than 2450 mm $year^{-1}$, being the highest value observed in the region of Amapá and Pará (2620 mm). Northeast Brazil is characterized by low levels of precipitation and high evaporation. In this region Silva, Pereira and Almeida (2012) found an average annual precipitation between 400 mm $year^{-1}$ (in the center of the semi-arid region) to 1800 mm on the east coast.

Mello et al. (2013) point out that the MMI map allows readers to assess the potential of rainfall to generate water erosion in Brazil. According to the information presented in Figure 4, it can be inferred that a large area from the Southeast to the Central-west of Brazil has a Very High potential for rainfall erosivity (MFI > 160).

The MFI is widely used in soil erosion studies (Essel, Glover and Yeboah, 2016; Yahaya, Ahmad, Mohtar and Suri, 2023; Lima, Oliveira and Moura-Fé, 2021) and also in the determination and assessment of risk and erosion potential (Jericek and Mikoš, 2007). Baecheler and Bravo (2019) and Cardoso, Avanzi and Ferreira (2022), use the term rainfall aggressiveness, characterized by the MFI index, as an indicator of erosivity. The knowledge of the aggressiveness of the rains allows the zoning of the areas, according to the erosive potential and planning the adequate use of the soil, according to the risk of erosion. Baecheler and Bravo (2019) highlight that the aggressiveness of rainfall causes environmental impacts related to various natural hazards (for example, landslides and floods), so it is important to know its spatial and temporal variability, in order to adopt prevention and mitigation measures.

In southeastern Venezuela (on the border with northern Brazil), Rodriguez et al. (2011) found the same behavior of the MFI, as observed in the present work. However, if the two maps were compared, we could verify that the origin of this high potential for rainfall erosivity is partially explained by the concentration of precipitation, as in the Southeast and Central-west regions of Brazil.

Panagos et al. (2017) presented an erosivity analysis for the entire surface of the planet, based on an interpolation of data from existing studies around the world. In this analysis, the authors verified that South America has the highest R-Factor value among the planet's continents.

The distribution of erosivity presents similarities with studies by Oliveira et al. (2012) and Trindade et al. (2016). Oliveira et al. (2012) found that the lowest values occur in the northeast region, and the highest in the north region. The erosivity of the rains tends to increase from east to west, mainly in the northern region of the country.

The EI30 values obtained in this study can be used as an erosivity factor in estimating soil losses using the USLE model and its derivatives. The average erosivity verified for Brazil was 10,082 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$, a higher value than that found by Oliveira et al. (2012), who obtained values ranging from 1,672 to 22,452 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$, with a mean value of 8403 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$. Also, Trindade et al. (2016) found an R factor for Brazil, obtained by interpolation, between 1,782 and 16,583 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$. The differences obtained in these studies are mainly due to the greater uniformity and representativeness of the rainfall series, and also to the greater number of equations used, results that partially corroborate with previous works. Thus, with the use of a denser network of rainfall stations, with a standardized period of 30 years of data and an expansion of the regression equations, it is believed that these updated results represent an important contribution of this work.

Trinidad et al. (2016) point out that the distribution of rainfall throughout the year is the main factor that influences the values of rainfall coefficients. This influence was also observed by Mello et al. (2013) and Panagos et al. (2015). In this regard, knowledge of the seasonal distribution of erosivity is important for planning agricultural activities and conservation practices, which depend on the type of climate and soil in the region and on the characteristics of crops. The space-time analysis of the erosion potential and the intensities of extreme rainfall events, according to Méndez et al. (2020) are important for the design of preventive, mitigating and control measures for their impacts on the physical and socioeconomic environment, as well as for adapting agricultural uses and practices. In the study of the erosive potential of rainfall, the development of equations and indices that evaluate such rainfall characteristics have been very useful all over the world to quantify and qualify their impact on soil loss.

## 6 CONCLUSIONS

Based on the monthly averages for the period from 1991 to 2020 of 1,918 rainfall stations distributed in the Brazilian territory and on the estimates of the EI30 erosivity index through 90 regression equations, the following conclusions can be obtained:

- Annual precipitation presents high spatial variation with values below 500 mm in the Northeast region, where the semi-arid climate occurs, to values above 2,500 mm per year in the North region, where the Tropical Rainforest climate predominates.
- In Brazil, areas with MFI above 160, classified as very high, predominate.
- The EI30 erosivity index ranges from values below 1,400 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ (in the Northeast region) to values above 17,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ in some points in the extreme North of the Amazon Basin.
- In 56% of the Brazilian territory, erosivity was classified as very high (EI30 > 10,000 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$), with the rest classified as high (19%), low (12%) and very low (1.2%).
- There was a strong seasonal variation in erosivity, with a predominance of the very high class from December to March and very low in September.
- Erosivity is concentrated in the first quarter of the year, where, in most of the Brazilian territory, more than 40% of annual erosivity occurs, reaching 80% in the semi-arid region. In the fourth quarter, it is observed that 30 to 60% of the annual erosivity occurs in the Central-west and Southeast regions, while in the third quarter less than 10% of the annual erosivity occurs.

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