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Erosivity index based on climatological norms from 1991 to 2020 for the state of Rio Grande do Sul

Índice de erosividade baseado nas normais climatológicas de 1991 a 2020 para o Estado do Rio Grande do Sul

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ABSTRACT

Water erosion is one of the main cause of soil degradation and the pollution of water resources. The aim of the present study is to update and evaluate the seasonal variation of the erosivity index and the Modified Fournier Index as a tool to predict rain erosivity for the state of Rio Grande do Sul. A series of monthly average rainfall data was used from 112 rainfall stations based on the Climatological Norms of the period between 1991 and 2020. Based on 16 regression equations, the values of the Modified Fournier Index (MFI) and the EI30 index were estimated, assessing their spatial and seasonal variation. Results show a strong seasonal variation with greater erosivity in the months of April, October and December. The EI30 varied between 3500 and 12500 MJ, ha^{-1} h^{-1} year^{-1}. A significant spatial variation could be observed, with an increase in values in the east-west direction.

Keywords: Soil loss; Direct planting method; Modeling; Conservation practices.

RESUMO

A erosão hídrica é uma das principais causas de degradação de solos e poluição dos recursos hídricos. Este trabalho teve como objetivo atualizar e avaliar a variação sazonal do índice de erosividade e do Índice de Fournier Modificado como ferramenta para prever a erosividade das chuvas para o estado de Rio Grande do Sul. Foram usadas as séries de dados de precipitação média mensal tendo como base as Normais Climatológicas do período de 1991 a 2020 de 112 estações pluviométricas. Com base em 16 equações de regressão formam estimados os valores dos Índices de Fournier Modificado (IFM) e do índice EI30, avaliando-se sua variação espacial e sazonal. Os resultados mostram uma forte variação sazonal, com maiores erosividades nos meses de abril, outubro e dezembro. O EI30 variou entre 3.500 a 12.500 MJ mm ha^{-1} h^{-1} ano^{-1}. Observou-se uma marcante variação espacial, com aumento dos valores no sentido leste a oeste.

Palavras-chave: Perdas de solo; Sistema plantio direto; Modelagem; Práticas conservacionistas.

INTRODUCTION

Soil erosion is described as one of the greatest environmental problems in Europe and other parts of the world (Lukic et al., 2018; Oguz, 2019). Of the different types of erosion, water erosion is the most predominant form of soil degradation since, besides reducing productivity, it accelerates silting in rivers and dam reservoirs, as well as the degradation of water quality due to pesticide and fertilizer runoffs that are carried with sediments (Bosco et al., 2015). Freires et al. (2023) posit that in tropical climate locations such as Brazil, with high rainfall indices, rainfall erosion is the main cause of soil degradation. To understand how current systems are affected and interfere with water erosion, as well as for the planning of soil management practices and more sustainable farming techniques, estimates on soil loss, considering climate conditions, types of soil and soil management and use practices, are essential. Hence, the use of the Universal Soil Loss Equation (USLE) and its derivatives (MUSLE, RUSLE) (Renard et al., 1997) as tools to understand the process and establishment of proactive actions to mitigate water erosion problems must be highlighted.

USLE considers six factors that influence the understanding of the erosive process. These are rain erosivity factor (R), soil erodibility factor (K), slope length factor (L), slope factor of the terrain being studied (S), soil use and management factor (C) and associated conservation practice factor (P). Rain erosivity is considered the leading factor in soil loss and represents a natural environmental limitation, hence, differently from the other factors, it cannot be altered by human action (Santos Neto & Chistofaro, 2019).

Rain erosivity represents a climatic factor and is considered the most sensitive to climate change (Nearing et al., 2005). In the last years, different climatic models have projected an increase in temperatures and rainfall, pointing to an increase in the frequency of extreme event occurrences in several locations around the world. In the southern region of Brazil this is no different (Zilli et al., 2020; Ávila et al., 2019; Marengo et al., 2020). These changes can affect rain erosivity, with an impact on farm production systems and future productivity. Thus, it is paramount that rain erosivity indices be updated in the medium and long term, along with the evaluation of their dynamics.

According to Lal (1990), rainfall erosivity is defined as the aggressiveness of rainfall as an erosive agent. The term rain aggressiveness was used as an indication of the degree of rainfall erosivity; however, it should not be confused with the erosivity index used in USLE. Many aggressivity and erosivity indices were developed to estimate soil erosion. Among the most adequate are those that connect soil erosion to the kinetic energy of rain, such as the EI30. To obtain trustworthy EI30 values, historical series of pluviographic data are needed, with at least 20 years of consistent and uninterrupted data (Renard et al., 1997; Majhi et al., 2021). A commonly used way to fill in the lack of data is to estimate erosivity with erosivity indices obtained from rainfall station monthly data, of which the Modified Fournier Index (MFI) should be highlighted. The MFI has been used as a rainfall intensity and supply factor in models since it corresponds adequately to the USLE erosivity factor (Yin et al., 2015; Essel et al., 2016; Yahaya et al., 2016; Lima et al., 2021). Correlations between the MFI and the USLE R factor (rain erosivity factor) were described in a number of studies (Renard & Freimund, 1994; Gabriels, 2001; Loureiro & Coutinho, 2001; Mello et al., 2013), and, as such, they are commonly used as an entry aggressivity factor in the development of regional models (Bosco et al., 2015; Oguz, 2019; Majhi et al., 2021).

To apply this methodology, an adjustment of equations related to the EI30 erosivity index with monthly rain data is needed. Oliveira et al. (2013) conducted a survey of these equations in which important studies carried out for different locations in Rio Grande do Sul stand out (Morais et al., 1988; Cassol et al., 2008; Roncato et al., 2004; Cogo et al., 2006; Peñalva Bazzano et al., 2007; Hickmann et al.; 2008; Santos, 2008, Martins et al. 2009).

There is a scarcity of studies characterizing the spatial and seasonal variation for erosivity for Rio Grande do Sul. Santos (2008) presented erosivity maps for RS based on 91 rainfall stations with rainfall data extending to 2005. There are also nationally known studies (Silva, 2004; Mello et al., 2013; Trindade et al., 2016; Hernani et al., 2020) that do not consider several regression equations and do not present a standardization for the size and period of rainfall series to analyze spatial variation in greater detail. Therefore, this study aims at updating and evaluating the seasonal variation of the MFI and the EI30 erosivity index as a tool to predict rain erosivity for the state of Rio Grande do Sul based on the Climatological Norms for rainfall from 1991 to 2020.

MATERIALS AND METHODS

Adjusted regression equations for the states of Rio Grande do Sul and Santa Catarina were considered (Table 1).

The equations to estimate the erosivity index were, respectively, the linear or potential model, according to Equations 1 and 2, given by:

$$EI_{30} = a.Rc + b \tag{1}$$

$$EI_{30} = a.Rc^{b} \tag{2}$$

In which:
EI30 = erosivity index (MJ mm $ha^{-1}h^{-1}$ $year^{-1}$);
a and b = adjusted coefficient for a specific rainfall station;
Rc = rain coefficient.

$$Rc = \frac{p^2}{P} \tag{3}$$

Where:
p = monthly average rainfall (mm);
P = annual average rainfall (mm);

The Modified Fournier Index is given by:

$$IFM = \sum_{i=1}^{12} Rc_i \tag{4}$$

Determining the area of influence of each station was based on Thiessen polygons (Figure 1). The climatological norms of 112 rainfall stations between 1991 and 2020 were used. 15 were from the Instituto Nacional de Meteorologia (2022) and 97 from the

Table 1. Regression equations used to estimate EI30.

N	Town	State	Model	a	b	Source
1	Bagé	RS	linear	37.96	174.58	Santos (2008)
2	Caxias do Sul	RS	linear	21.29	250.87	Santos (2008)
3	Hulha Negra	RS	potential	208.09	0.399	Martins et al. (2009)
4	Ijuí	RS	potential	109.65	0.76	Cassol et al. (2007)
5	Pelotas	RS	linear	31.2	167.5	Santos (2008)
6	Quaraí	RS	linear	82.72	-47.35	Peñalva-Bazzano et al. (2007)
7	Santa Rosa	RS	potential	118.52	0.803	Mazurana et al. (2009)
8	São Borja	RS	potential	55.564	1.105	Cassol et al. (2008)
9	Torres	RS	linear	58.81	-221	Santos (2008)
10	Uruguaiana	RS	linear	81.967	-96.735	Hickmann et al. (2008)
11	São M. Oeste	SC	potential	83.07	0.864	Back (2020)
12	Chapecó	SC	linear	44.31	109.6	Back (2020)
13	Ponte Serrada	SC	potential	68.59	0.8706	Back (2020)
14	Campos Novos	SC	linear	39.2	101.3	Back (2020)
15	Lages	SC	linear	35.4	49.1	Back (2020)
16	Urussanga	SC	linear	45.1	-127	Back (2020)

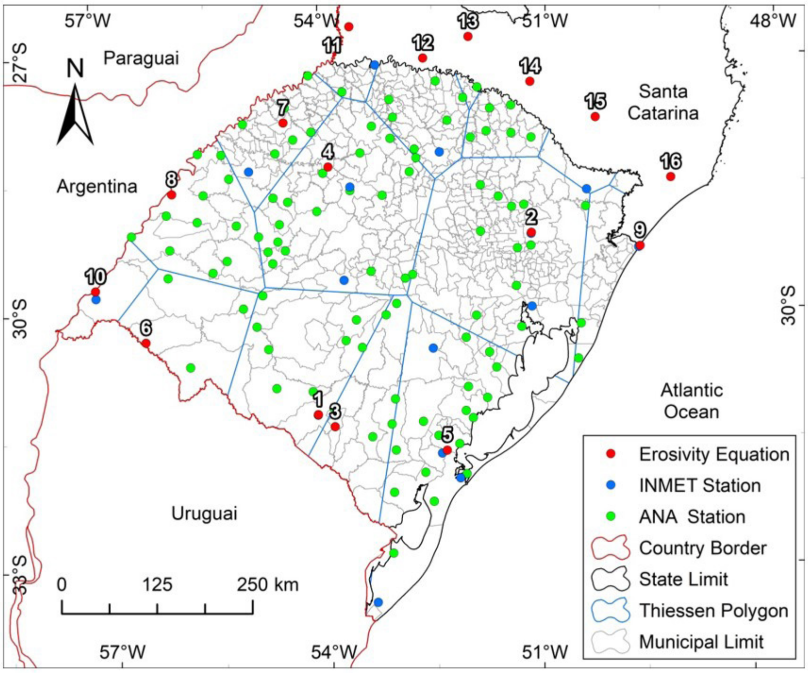

Figure 1. Location of rainfall stations and Thiessen polygons with an influence area in pluviographic stations.

Agência Nacional de Águas e Saneamento Básico (2023). The criteria adopted for selecting stations was that, there be less than 5% in errors for the months analyzed. In Figure 1, the distribution of stations in the state of Rio Grande do Sul can be seen.

With the compilation of data from each of the stations in the different locations, the data was interpreted to obtain the annual rainfall volume for each region, thus allowing for the development and elaboration of the EI30 and MFI factors.

RESULTS AND DISCUSSION

The value of annual average rainfalls varies from 1,350 to over 1,950 mm (Figure 2). In a normal situation, the spatial rainfall variation is lower in the southern coast and higher in the state´s Planto and Alto Uruguay regions. The spatial distribution in rainfall is caused by the interaction between terrains and the action of air masses (Reboita et al., 2010) due to variations in altitude, climatic characteristics that predominate in the state (Figure 3), and phenomena such as El Niño and La Niña. According to CONAB data (Companhia Nacional de Abastecimento, 2023), the state has recorded a frequency of 21 droughts in 43 harvests. In other words, though data indicates annual rainfall volumes that are adequate for the main crops, distribution throughout the year and between years is abnormal, diverging from the needs of the main crops in the state.

Figure 3 shows the Köppen climatic classification for the state of Rio Grande do Sul which has a subtropical climate with

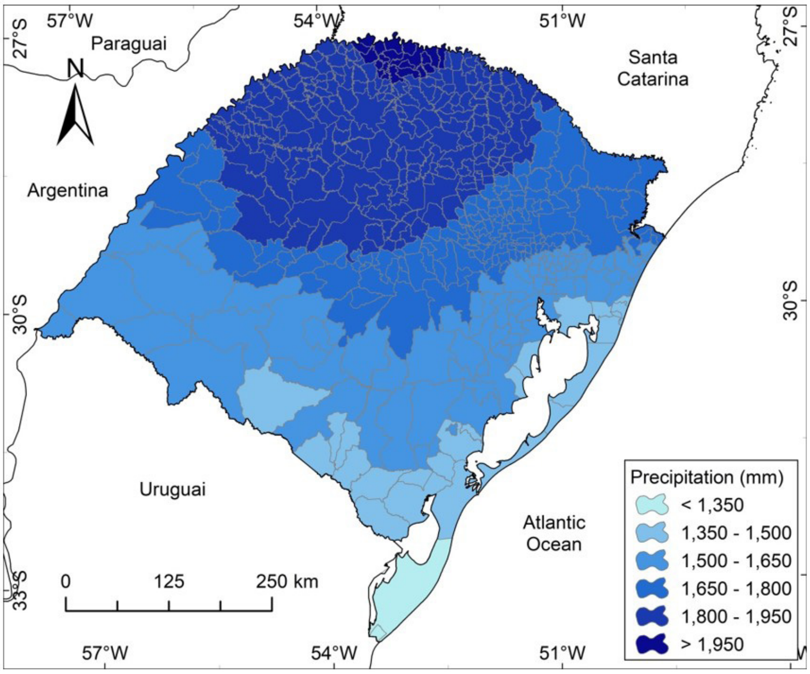

Figure 2. Spatial distribution of annual average rainfall in the state of Rio Grande do Sul for the 1991-2020 period.

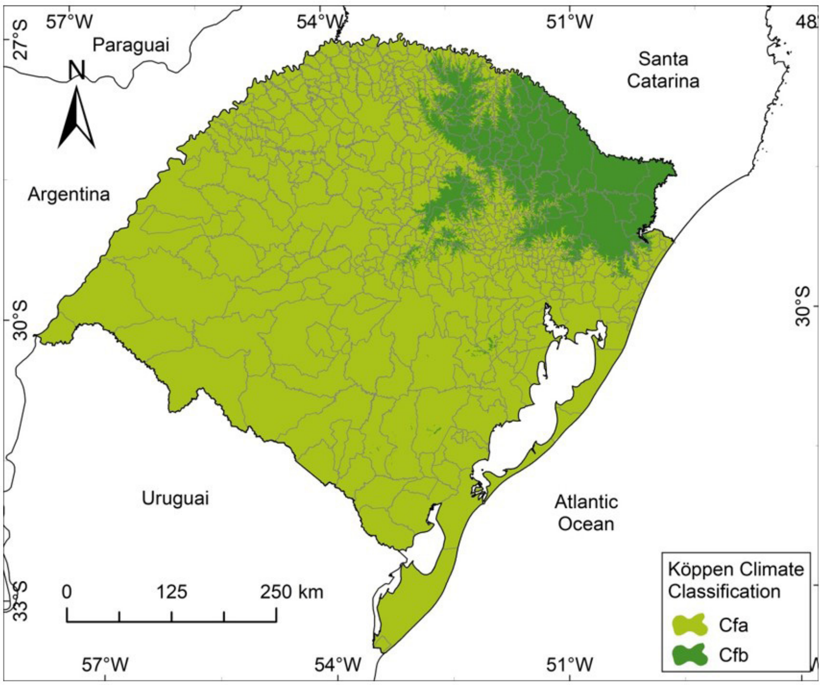

Figure 3. Classification and Köppen climatic distribution in the state of Rio Grande do Sul.

no defined dry season (Cf), and warm (a) or mild (b) summers defined mainly by altitude. Although it does not have a defined dry season, the state has experienced summers and dry spells with a higher frequency than what can be seen in other states that concentrate a significant grain productivity. On the other hand, extreme events, with a high rainfall volume concentrated in low intervals, have historically led to significant soil loss. These situations have been the focus of public policies to mitigate the issue of erosion, such as the Projeto Integrado de Uso e Conservação do Solo (Integrated Project for Soil Use and Conservation - PIUCS) developed in 1970; the Saraquá project with the aim of developing soil conservation practices on the basaltic slopes of the Alto Uruguay region in 1980; and the METAS project, created to enable the direct planting system in Rio Grande do Sul.

The Modified Fournier Index (MFI) presented Moderate values (90 <MFI < 120) on the state's coast, while High (120 <MFI

< 160) and partially Very High (MFI > 160) is predominant in the northeastern region and part of the Alto Uruguay region of the state (Figure 4). The values found are consistent with studies conducted in Brazil, such as those by Back et al. (2019) and Galatto et al. (2023). Back et al. (2019) evaluated the MFI for the rainfall series at 181 stations in the south of Brazil, with data from 1976 to 2015. They found MFI values that varied from 140 to 350, with an average value of 19.7. The MFI has been used as an erosivity indicator in several countries such as Germany (Sauerborn et al., 1999), Argentina (Busnelli et al., 2006), Spain (Angulo-Martínez & Beguería, 2009), Jordan (Eltaif et al., 2010), Cape Verde (Sanchez-Moreno et al., 2014), Greece (Efthimiou, 2018), Holland (Lukic et al., 2018), and Turkey (Oguz, 2019). It is also used to evaluate tendencies in erosivity temporal series (Mohtar et al., 2015). MFI values observed in Rio Grande do Sul, as well as in other regions in Brazil (Back et al., 2019; Galatto et al., 2023), are higher than values cited in other countries. Lukic et al. (2019) found MFI values that varied from 62 to 75 for the Serbian region, with a rainfall between 510 and 680mm. Lukic et al. (2019) mention MFI values that vary between 77.93 and 97.27 for Holland. Bouderbala et al. (2019) found MFI values for a river basin in Algeria that varies from 39.15 to 73.38, where annual rainfall varies from 203 to 480 mm. Di Lena et al. (2013) identified MFI values between 70 and 151.7 for the region of Abruzzo (Italy), while Patriche et al. (2023) identified MFI values that vary from 23 to 131 for Romania. Deyanira & Donald (2005) observed an adequate correlation between the MFI and the erosivity factor for several regions in Venezuela. Fernandez et al. (2018) state that the MFI is a strong indicator of rain aggressivity and has been applied to represent the spatial distribution of erosivity. The European project CORINE (Coordination of Information on the Environment) adopted the MFI index to determine an index of climate erosivity that is useful to evaluate the current potential risk of erosion (European Commission, 1995). Cardoso et al. (2022) evaluated several methods to estimate erosivity based on rain data for the state of São Paulo, including the MFI index. They concluded that this index is shown to be able to consistently replace the standard method. Coman et al. (2019) determined USLE parameters, emphasizing the rain erosivity factor by using the MFI.

The EI30 erosivity index varied between 3500 and 12500 MJ mm ha^{-1} h^{-1} $year^{-1}$. A significant spatial variation was observed, with an increase in values in the east-west direction (Figure 5). Similar results were observed by Santos (2008) who presented values that varied from 3000 MJ mm ha^{-1} h^{-1} $year^{-1}$ on the southern coast to 10000 MJ mm ha^{-1} h^{-1} $year^{-1}$ in the northwestern region of the state of RS, also pointing out that, in El Niño years, these values can reach 13000 MJ mm ha^{-1} h^{-1} $year^{-1}$. The author notes that in the state's central-southern coast and east of the Depressão Central region annual erosivity rates were classified as low.

As for erosivity classifications (Figure 6), we can observe a predominance (50.1%) of Average (5,000 < EI30 < 7,500 MJ mm ha^{-1} h^{-1} $year^{-1}$), followed by High (7,500 < EI30 <10,000 MJ mm ha^{-1} h^{-1} $year^{-1}$), and 31.6% of Very High (EI30 > 10,000 MJ mm ha^{-1} h^{-1} $year^{-1}$), with 16.2% and 2% of the area with an erosivity classified as Low (2,500 < EI30 < 5,000 MJ mm ha^{-1} h^{-1} $year^{-1}$).

The data obtained is similar to Santos (2008) who observed that isoerodents grow from the coastline in direction to the state's hinterland, in a southeast-northeast direction. The author also underlines that 83.8% of the towns studied are submitted to erosivity indices that vary from 4,910 to 9,820 MJ mm ha^{-1} h^{-1} $year^{-1}$. Oliveira et al. (2013) presented the erosivity map for Brazil in which erosivity ranging from 6,000 to 8,000 MJ mm ha^{-1} h^{-1} $year^{-1}$ in the east, and 8,000 to 10,000 MJ mm ha^{-1} h^{-1} $year^{-1}$ in the west occurred for the southern region. Trindade et al. (2016) presented an erosivity map for Brazil in which erosivity was classified as Very High and Average-High for Rio Grande do Sul, with a similar spatial distribution to what

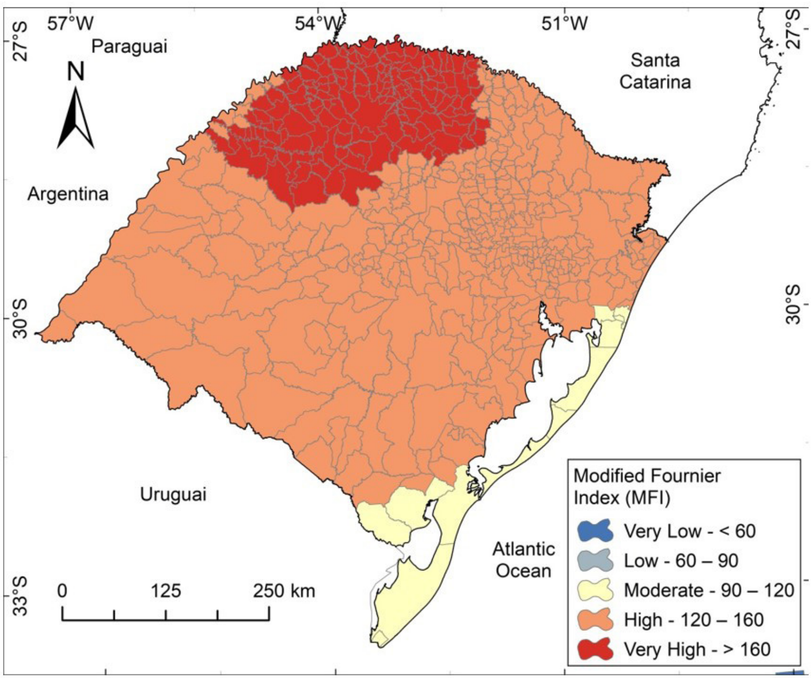

Figure 4. Modified Fournier Index for the state of Rio Grande do Sul.

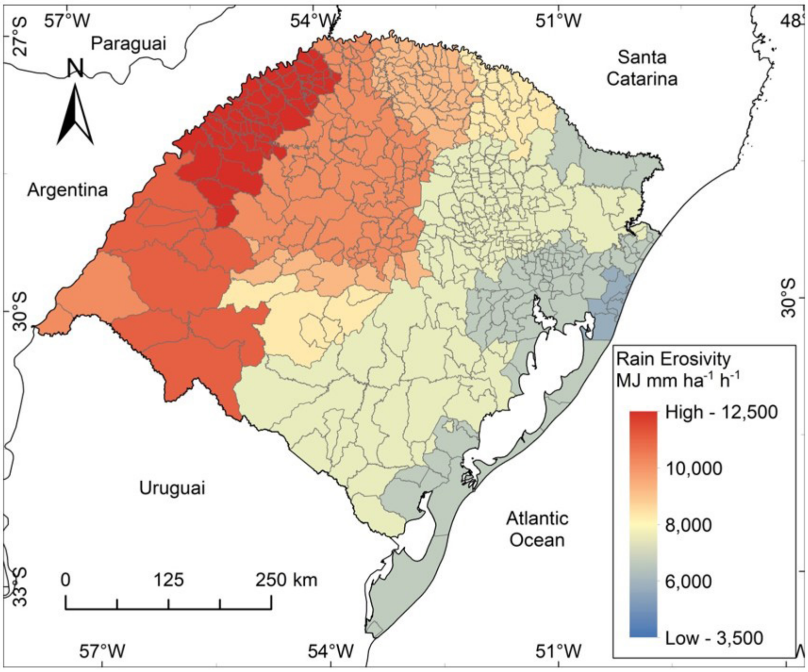

Figure 5. Annual EI30 erosivity index for towns in the state of Rio Grande do Sul.

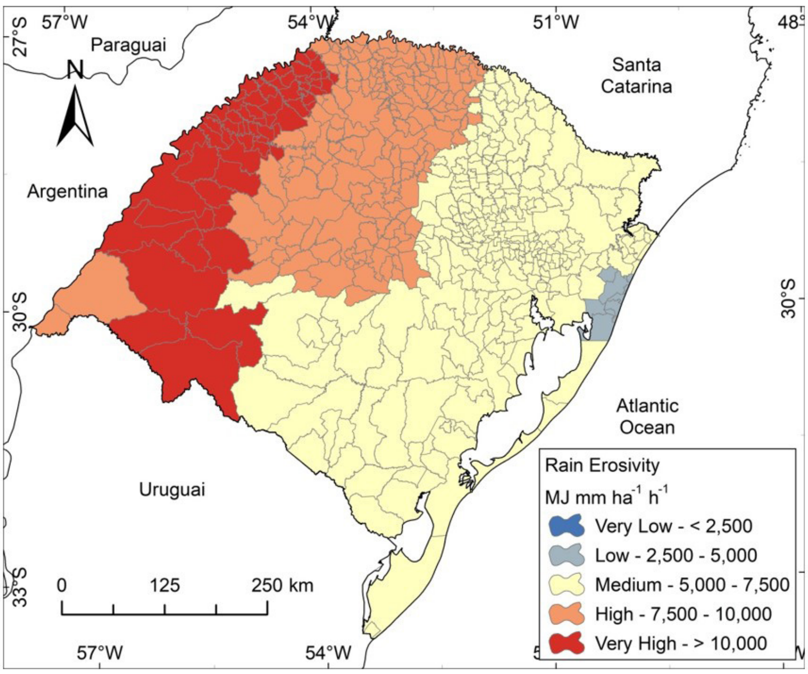

Figure 6. Annual EI30 erosivity classifications for towns in the state of Rio Grande do Sul.

was found in this study. Hernani et al. (2020) presented a map with an erosivity classification that had small differences in classification limits and a similar spatial variation. However, there was a higher predominance of the Severe low Classification (7,357 – 9,810 MJ mm ha^{-1} h^{-1} $year^{-1}$) and lower values in the Average (4,905 – 7,357 MJ mm ha^{-1} h^{-1} $year^{-1}$), occurring only in the state's northern coast. The difference between these studies may be due in part to the series of pluviometric data and the regression models used.

The EI30 presents a significant seasonal variation (Figure 7). In the months of April, December and especially October, there are larger areas with Very High erosivity (EI30 > 1,000 MJ mm ha^{-1} h^{-1} $month^{-1}$). This can also be seen in some towns in the months of January, February, March and November. On the other hand, in August, no High or Very High erosivity can be found, with a predominance of Low (250 to 500 MJ mm ha^{-1} h^{-1} $month^{-1}$). In general, the lowest level of erosivity can be seen from July to

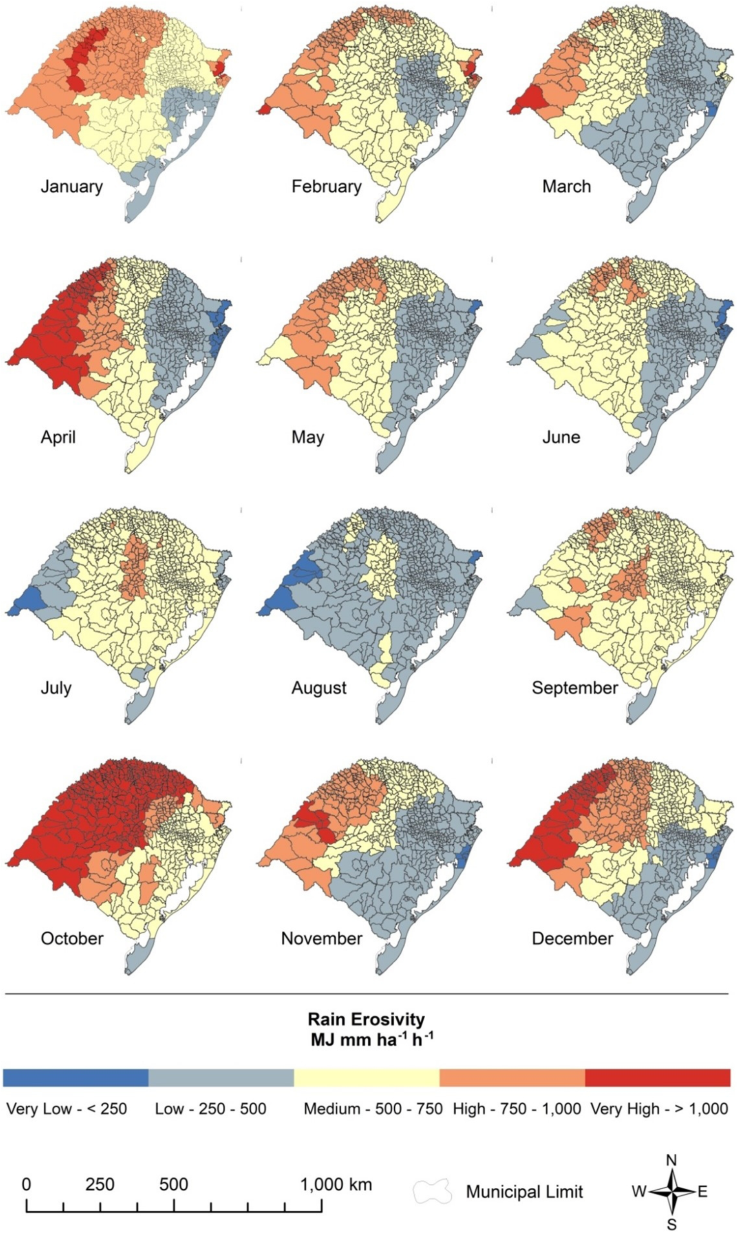

Figure 7. Monthly EI30 erosivity index for towns in the state of Rio Grande do Sul.

September (Figure 7). Santos (2008) presents an analysis of monthly erosivity related to the occurrence of El Niño. The author calls attention to January as being the second month with the highest number of towns located within the High and Very High erosivity range. The author sees the month of April as concerning in terms of soil management and conservation, observing that there is a higher concentration of the erosivity index in the Serra Sudeste, Campanha, São Borja, Missioneira and Alto Uruguay regions, with values surpassing 1,300 MJ mm ha^{-1} h^{-1} month^{-1}. He also points out August as being the month with the lowest erosivity rates among the twelve months.

The abrupt increase in erosivity in October was also observed by Santos (2008), a concern due to the fact that it coincides with the period of crop preparation. He posits the need to adopt efficient soil management techniques to minimize the effects of water erosion.

Due to its importance in understanding potential soil loss, which can be inferred by high EI30 values, whether they be associated or not with soil loss equations, Nachtigall et al. (2020) point out that the detailed mapping of the erosion process and the characterization of the extension and magnitude of annual and seasonal soil erosion rates regionally have become vital tools to define conservation practices. The authors observed that in the southern region of Rio Grande do Sul seasonal variation has caused the greatest soil losses with the highest erosion rates occurring from spring to summer.

Figure 8 represents the relative erosivity contribution in RS per trimester. We would like to call attention to the third and fourth trimester (October to December) which when added are over 50% of the annual erosivity in the state's western region. However, erosivity occurs in a relatively well-distributed manner

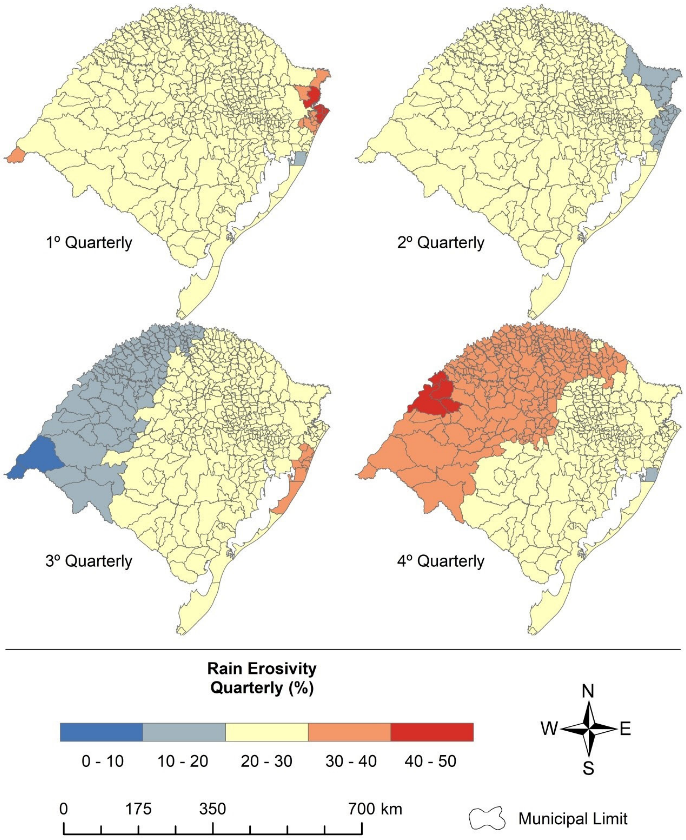

Figure 8. Trimestral EI30 erosivity index for towns in the state of Rio Grande do Sul.

throughout the year, with a predominance ranging from 20 to 30% in each trimester. This underlines the need of continuous action on the part of rural producers in maintaining soil cover with vegetation or straw to reduce the potential losses in soil and nutrients which leads not only to a reduction in productivity, but also to environmental issues. These characteristics are caused by a subtropical climate, with well-distributed rainfall throughout the year. It is important to state that, although in average, some months (April, October and December) have been known to present higher levels of erosivity, erosive rains occur throughout the year.

CONCLUSION

Based on the data studied, our conclusion is that the use of the Modified Fournier Index is comparable to the rain erosivity index (EI30), hence contributing to the understanding of potential rain erosivity in the state of Rio Grande do Sul. The use of this index enables modeling and predicting potential soil losses for locations in the state where there is an absence of continuous records of rainfall through time.

In general, the months of April, October and December have shown to be periods of greater erosivity in the state, regardless of the model used to determine erosivity. This is important since during these months, the soil presents low vegetation cover due to the seasonal transition of plant growth and establishment. Hence, the data reinforces the need for continued efforts in research and outreach programs to develop straw production strategies with producers to reduce the risks of soil loss.

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