Modelling the spatial dependence of the rainfall erosivity index in the Brazilian semiarid region

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Abstract – The objective of this work was to model the spatial dependence and to map the rainfall erosivity index (EI_{30}) in the semiarid region of Brazil. Registers of monthly erosivity from 210 rainfall stations were used, with daily time series equal to or greater than 15 years. Based on the values of the EI_{30}, a spatial dependence model was made by adjusting the semivariogram. From the semivariogram models, erosivity isoline maps were generated with a kriging interpolator. According to the historical data series, the maximum monthly average value of the EI_{30} was observed in March, and the annual value ranged from 1,439 to 5,864 MJ mm ha^{-1} per year, classified as low and moderate, respectively. The highest EI_{30} values were obtained in the northern and southern extremes of the semiarid region. Average spatial dependence was observed for rainfall erosivity, in most months, especially with the spherical semivariogram model. The range of erosivity varied from 62 to 1,508 km for the monthly EI_{30} and was of approximately 1,046 km for the annual one. The applied model, with the validation of the semivariograms using the jackknife test, allows the spatialization of the EI_{30} for the semiarid region of Brazil.

Index terms: EI_{30}, geostatistics, Northeastern Brazil, semivariogram.

Modelagem da dependência espacial do índice de erosividade das chuvas no semiárido brasileiro

Resumo – O objetivo deste trabalho foi modelar a dependência espacial e mapear o índice de erosividade das chuvas (EI_{30}) na região semiárida do Brasil. Foram utilizados registros de erosividade mensal de 210 postos pluviométricos, com série temporal diária igual ou superior a 15 anos. Com base nos valores do EI_{30}, a modelagem da dependência espacial foi realizada pelo ajuste do semivariograma. A partir dos modelos de semivariograma, foram gerados mapas de isolinhas de erosividade com interpolador da krigagem. De acordo com a série histórica de dados, o valor máximo mensal médio do EI_{30} foi observado em março, e o valor anual variou de 1.439 a 5.864 MJ mm ha^{-1} por ano, classificado como baixo e moderado, respectivamente. Os maiores valores do EI_{30} foram obtidos nos extremos norte e sul da região semiárida. Foi observada dependência espacial média para erosividade da chuva, para a maioria dos meses, principalmente com o modelo de semivariograma esférico. O alcance da erosividade variou entre 62 e 1.508 km, para o EI_{30} mensal, e foi de, aproximadamente, 1.046 km para o anual. A modelagem aplicada, com a validação dos semivariogramas pelo teste de jackknife, permite a espacialização do EI_{30} para a região semiárida do Brasil.

Termos para indexação: EI_{30}, geoestatística, Nordeste, semivariograma.

Introduction

Brazil, due to its size, is affected by different climate types. According to official data from Ministério da Integração Nacional, the Brazilian semiarid is located in most of the Northeastern region of the country and covers an area of 969,589 km^2 (Brasil, 2005). The semiarid climate has very peculiar characteristics: low annual rainfall values, ranging from 445 to 1,218 mm,

concentrated in a few months of the year; average air temperatures between 23 and 27°C; low relative humidity values; and potential evapotranspiration of approximately 2,000 mm per year (Moscati & Gan, 2007; Hastenrath, 2012). However, the various atmospheric circulation systems in the region make climatology complex, resulting in great climatic variability, mainly in relation to rainfall, with precipitation events that vary in time and space.

The characterization of rainfall in a certain region is an important tool for soil management and conservation (Silva et al., 2010). This is because, in the erosive process, the factor erosivity reflects the capacity of rainfall to erode the soil in an area with no cover, which is directly related to the duration, intensity, and frequency of precipitation events (Montebeller et al., 2007; Peñalva Bazzano et al., 2010; Mello et al., 2012).

The factor rainfall erosivity is one of the main parameters entered into the universal soil loss equation (USLE) proposed by Wischmeier & Smith (1978) and can be expressed by indexes that are based on the physical characteristics of local rainfall. The erosivity index (EI_{30}) is the most commonly used for Brazilian conditions, since it is considered the most suitable for intertropical reality, and represents the result of the kinetic energy of a raindrop when it reaches the soil by its maximum intensity (Mello et al., 2015).

Determining EI_{30} values during the year allows identifying the months when the risks of soil and water losses are higher (Silva et al., 2010). In addition, understanding the pattern of the spatial distribution of erosivity is important for planning and managing water resources, as well as for establishing priority areas and times of the year for soil and water conservation and management.

Studies on the spatial dependence of rainfall erosivity were developed for some regions of Brazil (Mello et al., 2007, 2008; Silva et al., 2010). Mello et al. (2012), for example, modeled the spatial dependence of the monthly and annual EI_{30} for the entire state of Espírito Santo, and found a high degree of spatial dependence. Silva et al. (2010), in turn, adjusted geostatistical models using rainfall data for the southeastern region of the state of Minas Gerais, for fast-growing tree farming. The results

obtained in these studies are indicative that the EI_{30} values show a wide range and degree of spatial dependence.

However, in general, studies on rainfall erosivity in Northeastern Brazil are not very common (Oliveira et al., 2013), among which stands out the one carried out by Cantalice et al. (2009). The apparent lack of interest in the EI_{30} in this region might be related to the shortage of historical rainfall records older than 20 years, in short-time intervals (less than 10 min), which are needed to calculate the EI_{30}. Regarding spatial dependence, the number of studies in Northeastern Brazil is even more limited, especially in the semiarid region. Recently, some studies on rainfall erosivity were conducted, but for the entire country. Mello et al. (2013) adjusted multiple models to calculate rainfall erosivity for the whole country, according to geographic coordinates, whereas Mello et al. (2015) assessed the performance of different interpolation methods, including kriging, to spatialize EI_{30} values for the Brazilian territory.

The objective of this work was to model the spatial dependence and to map the EI_{30} in the semiarid region of Brazil.

Materials and Methods

The study was carried out using data from the semiarid region of Brazil (Figure 1 A), which has an area of 969,589 km^2, including parts of nine Brazilian states (Brasil, 2005): Alagoas, Bahia, Ceará, Minas Gerais, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, and Sergipe. The approximate population is of 22 million inhabitants, which represents 11.8% of the country's population, according to Instituto Brasileiro de Geografia e Estatística (IBGE, 2010). The terrain of the region is varied, with altitudes ranging from 0 to 2,000 m, mainly in the central region (Figure 1 B). The average annual rainfall ranges between 290 and 1,300 mm per year (Figure 1 C).

Series of 210 rainfall stations of Agência Nacional de Águas (ANA, 2015), with daily records for rainfall equal to or greater than 15 years (Figure 1 D), were used; however, the monitoring periods did not necessarily take place at the same time. The station (code 640003) with the greatest number of years monitored had data from 96 years, from 10/1/1910 to 12/1/2006, whereas

the stations (codes 1036063 and 124102) with the smallest monitoring interval had data from 15 years, from 10/1/1991 to 12/1/2006. Of the 210 stations, 42 neighbored the study area and were used to improve the interpolation process. The errors found in the daily records were corrected by the inverse distance
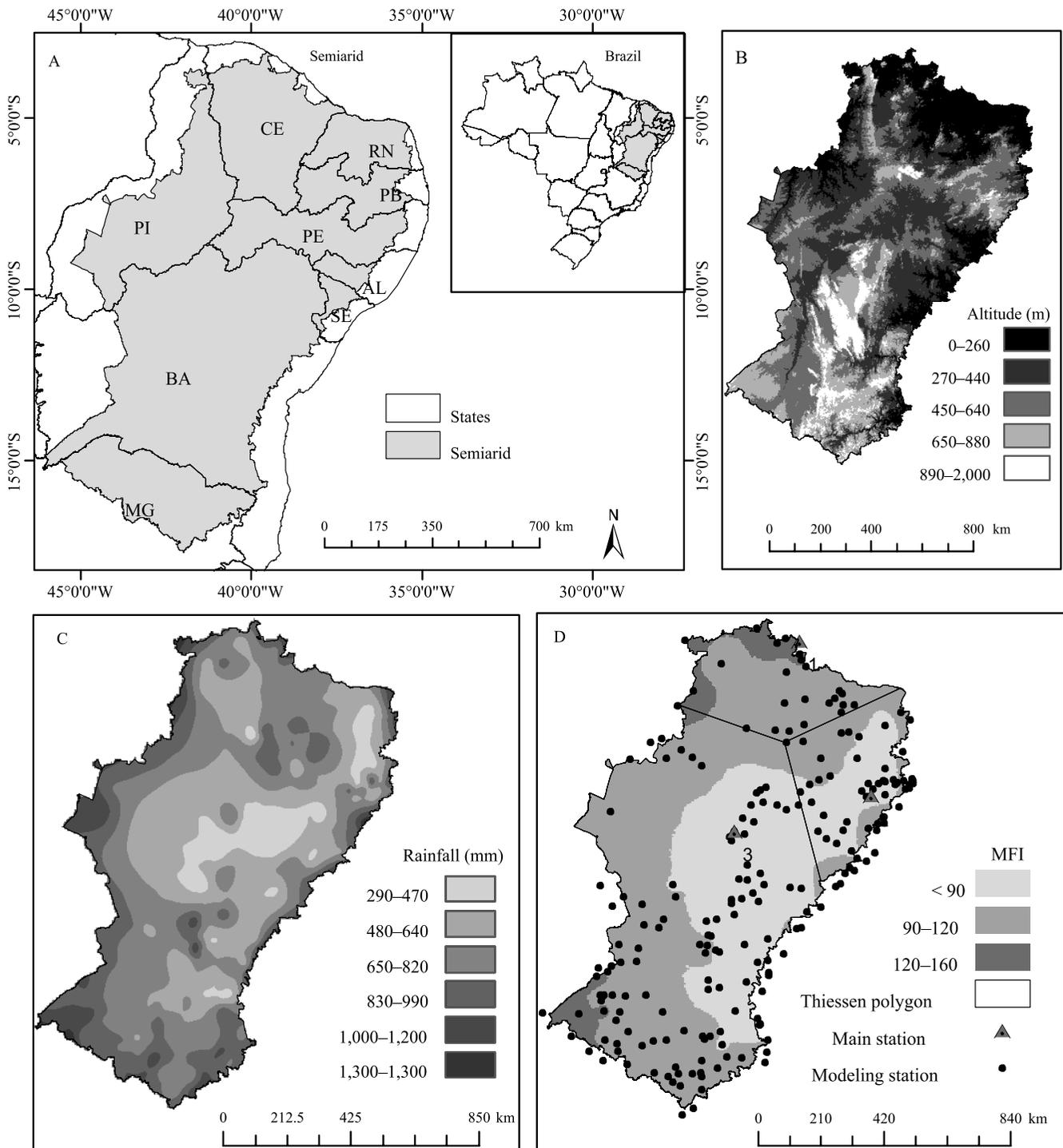

Figure 1. Location map of the Brazilian semiarid region (A), altitude map (B), rainfall map (C), and annual map of the modified Fournier index (MFI) (D). Daily series equal to or greater than 15 years of data.

weighting method (Di Luzio et al., 2008), based on the three closest stations.

Three main equations were used to calculate the monthly EI$_{30}$, according to the modified Fournier index (MFI). The first equation was obtained by Silva (2004), and the second and third ones by Cantalice et al. (2009), as follows:

$$EI_{30i} = 73.989\left(p_i^2/Pa\right)^{0.7387};$$

$$EI_{30i} = 61.81\left(p_i^2/Pa\right)^{0.58};$$

$$EI_{30i} = 95.48\left(p_i^2/Pa\right)^{0.56};$$

in which EI$_{30i}$ is the erosivity index of the average monthly rainfall (MJ mm ha^{-1} per month); p$_i$ is the historical rainfall (mm) for month i, based on the daily series equal to or greater than 15 years; and Pa is the historical annual rainfall (mm). The annual erosivity value (EI$_{30}$) was calculated by adding the monthly values from each rainfall station.

These equations were used to estimate the monthly erosivity of the 210 rainfall stations used for modelling, by considering the similarity of each station with the area of the Thiessen polygon for each main station (Figure 1 D).

The MFI reflects the potential of rainfall to erode the soil of a certain region and was estimated for each of the 210 stations by the equation:

$$MFI = \sum_{i=1}^{12}\left(\frac{p_i^2}{Pa}\right)$$

Afterwards, a map of the MFI was created by using the inverse distance weighted interpolation method for the entire semiarid region (Figure 1 D). Consequently, it was possible to identify the spatial distribution of this index throughout the area, as well as the location of the main stations, according to this distribution.

The EI$_{30i}$ and EI$_{30}$ values were evaluated by the average, maximum, and minimum values; the standard deviation; and the coefficient of variation (CV). Variability was classified according to the CV values (Pimentel-Gomes & Garcia, 2002), as: low, CV <10%; medium, 10%< CV <20%; high, 20%< CV <30%; and very high, CV >30%. The data normality hypothesis was evaluated by the Kolmogorov-Smirnov test.

Spatial dependence was analyzed by geostatistical techniques, using adjusted semivariograms. The semivariance function was calculated for all directions (isotropic semivariogram), in order to observe the spatial dependence of the data. Previously, the following theoretical models of semivariograms were adjusted: spherical, exponential, and Gaussian.

The choice of the best adjustment was made by validating the semivariograms after running the jackknife test (Vieira et al., 2010), which analyzes the consistency of the data calculated by the kriging interpolator, based on the adjusted (experimental) semivariograms. The estimate is considered adequate when the average (μ_{jk}) and the variance (σ_{jk}) of the reduced error are close to 0 and 1, respectively. The semivariogram was adjusted by the weighted least squares method, using the R 3.2.2 software (R Core Team, 2015) and the geoR package (Ribeiro Jr. & Diggle, 2001).

The degree of spatial dependence (DSD) was calculated based on the percent relationship between the nugget effect (C$_0$) and the sill, given by the sum of C$_0$ and the structured variation (C) [DSD = C/(C$_0$ + C)100]. The DSD was classified as: low, DSD <25%; medium, 25%≤ DSD ≤75%; and strong, DSD >75% (Robertson, 1998).

Results and Discussion

The highest EI$_{30i}$ values (1,676 MJ mm ha^{-1} per month) were observed in March, and the lowest ones from June to November (Table 1), with greatest variation in the period between December and May, when soil and water conservation and management practices in the region must be intensified. The greatest standard deviation in the data was obtained in December and the smallest one in September, which showed the greatest rate of generalized drought throughout the semiarid region; it should be noted that although this month had a low average erosivity index (57 MJ mm ha^{-1}), this value might be enough to cause soil loss, depending on other factors.

The erosivity index from June to October presented distribution close to normal, since the variables with skewed values between 0 and ±0.5 tend to show normal distribution. The normality of the data ensures optimal statistical properties, such as maximum likelihood (Diggle & Ribeiro Jr., 2007), although this is not a prerequisite for the

spatial dependence analysis. Moreover, the CVs for the EI_{30} for the semiarid region were high, which can be justified, given the fact that the region is strongly affected by different rainfall patterns (Moscati & Gan, 2007; Hastenrath, 2012; Rodriguez et al., 2015).

The annual minimum, maximum, and average values for the EI_{30} were 1,439, 5,865, and 2,988 MJ mm ha^{-1} per year, respectively, which can be classified as being of medium potential. These results were similar to those reported by Mello et al. (2013) in the Northeastern region of Brazil, when adjusting

several models to estimate rainfall erosivity for the whole country.

All months presented spatial dependence (Table 2). The spherical semivariogram model performed best for modelling spatial dependence between January and September. In October, due to the abrupt change in the EI_{30}, the exponential model showed better results. In November and December, the Gaussian model provided the best adjustments for the semivariograms. Although the application of the exponential model is more commonly accepted

Table 1. Descriptive statistics of the rainfall erosivity index in the semiarid region of Brazil, based on daily rainfall series equal to or greater than 15 years of data.

Month	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation	Asymmetry	Curthose
	---------------------------------(MJ mm ha^{-1})---------------------------------				(%)		
January	69	848	357	178	50	-0.001	-1.044
February	72	876	329	152	46	0.510	0.096
March	101	1,676	482	281	58	1.832	3.869
April	91	1,597	368	295	80	2.269	4.721
May	9	808	209	175	83	0.900	-0.030
June	1	646	159	169	106	1.064	-0.033
July	0	576	127	150	117	1.179	0.147
August	0	424	76	97	127	1.379	0.937
September	0	303	57	53	92	1.596	2.707
October	0	345	128	97	75	0.244	-1.342
November	0	810	309	265	85	0.296	-1.493
December	18	984	380	296	77	0.277	-1.361
Year	1,439	5,864	2,988	742	24	0.377	0.921

Table 2. Estimates of the semivariograms adjusted for the monthly and annual rainfall (MJ mm ha^{-1}) values for the semiarid region of Brazil, calculated from daily series equal to or greater than 15 years of data.

Month	Model	C_0	C	DSD (%)	A (km)	μ_{jk}	σ_{jk}
January	Spherical	11,750	42,597	21.62	1,508	-0.0004	0.9020
February	Spherical	14,312	12,165	54.05	914	0.0006	0.9404
March	Spherical	24,268	57,360	29.73	789	0.0002	0.9884
April	Spherical	7,856	72,194	9.81	831	-0.0001	1.0245
May	Spherical	4,738	24,484	16.22	762	0.0061	1.1357
June	Spherical	14,282	14,282	50.00	700	0.0021	0.9207
July	Spherical	10,213	12,128	45.71	439	0.0040	0.9942
August	Spherical	4,448	5,560	44.44	431	0.0042	0.9626
September	Spherical	823	2,044	28.70	308	0.0054	0.9669
October	Exponential	480	1,222	28.23	62	0.0023	1.4465
November	Gaussian	2,814	52,067	5.13	614	0.0006	1.3759
December	Gaussian	6,936	513,281	1.33	1,038	-0.0005	1.6684
Total	Spherical	154,158	617,702	19.97	1,046	0.0044	0.9961

C_0, nugget effect; C, variance dispersion; DSD, degree of spatial dependence; A, range; μ_{jk}, reduced mean error; and σ_{jk}, reduced error variance.

(Mello et al., 2007, 2008, 2012; Montebeller et al., 2007), the spherical (more frequently) and the Gaussian models showed the best results in the present study. While studying the modelling and continuity of the EI_{30} in eastern Minas Gerais, Silva et al. (2010) also found better results with Gaussian models.

The parameters obtained from the theoretical semivariograms (C_0, C, range, and DSD) showed different classes of variability during the year in the semiarid region (Table 2). Overall, C_0 increased linearly with average erosivity, which shows that the absolute error in the sampling was greater during the rainy months. According to Burgos et al. (2006), the C_0 is directly related to the sampling error, to short-range or to unexplained variability. The relationship with average erosivity may be an indicative of the need for a greater number of meteorological stations in order to reduce this error, especially during the rainy season. In 7 of the 12 months, erosivity presented a medium degree of spatial dependence and, in the rest of them, a low one.

The range is an important parameter of the semivariogram that has practical interpretations, since it shows the distance between two points that have spatial dependence. Samplings separated

by a distance lower than the range are spatially correlated, whereas those separated by a greater distance are independent (Wang et al., 2015). The range of erosivity varied from 62.18 km in October to 1,508 km in January (Table 2). The temporal variability of rainfall significantly ($p<0.01$) affected the range of erosivity, which was represented by a logarithmic regression (Figure 2). It is possible to observe two clusters, which corresponded to the rainy season, from November to April, and to the dry season, from May to October.

In the months with rainfall above 60 mm, the average erosivity was greater than 300 MJ mm ha^{-1} per month, and the range in this season was of at least 600 km. The low range during the dry season in the semiarid region indicates that the rainfall events in this season were isolated.

As observed in the semivariograms, it was possible to note the effect of the monthly seasonality of erosivity in the region (Figure 3). The erosivity values started to increase in October, starting in the state of Minas Gerais and in the south of Bahia. Over the months, these values increased significantly in the northern direction of the semiarid region. The highest values were observed in March and April, concentrated in the states of Ceará, Piauí, and Maranhão; and the lowest ones were recorded in September. In the fifth month of the year, rainfall erosivity started to decrease, following the same direction, from the south to the north of the semiarid region.

When considering the annual values for the EI_{30}, a variation between 1,757 and 4,870 MJ mm ha^{-1} per year was observed, which allowed classifying the semiarid region as having a weak erosive potential. However, this does not mean that water and soil conservation and management practices and techniques do not have to be applied in areas with low erosive potential (Figure 4 A and B). While analyzing the annual spatial variability of rainfall erosivity in the state of Rio de Janeiro, Montebeller et al. (2007) found values between 2,000 and 6,000 MJ mm ha^{-1} per year for the northern region of the state. In the northern region of the state of Espírito Santo, Mello et al. (2007) also obtained low annual erosivity values associated with lower rainfall.
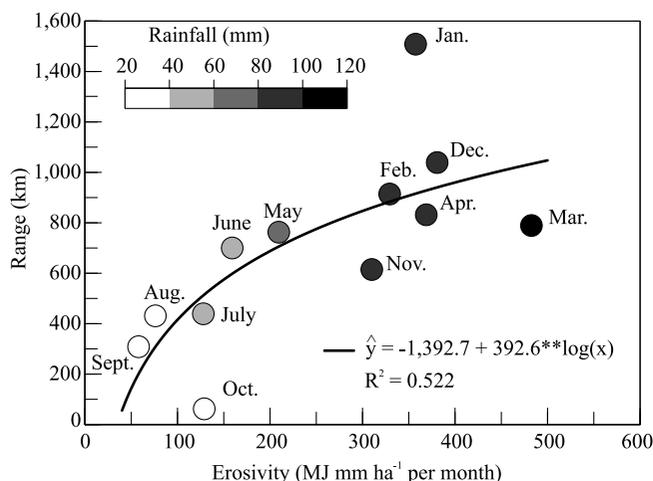

Figure 2. Correlation between monthly mean erosivity and range of spatial dependence for the semiarid region of Brazil. Daily series equal to or greater than 15 years of data.
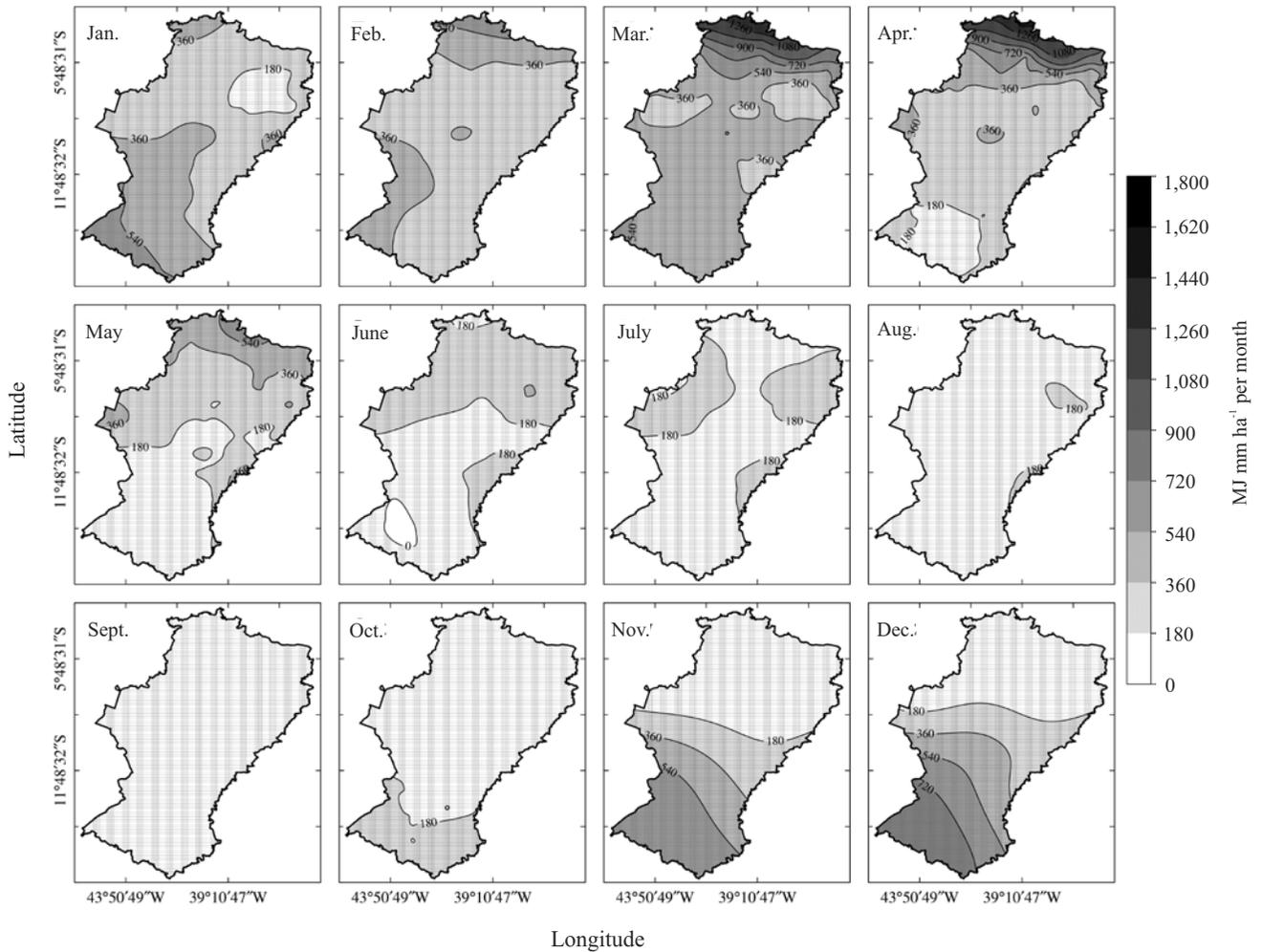
Figure 3. Spatial distribution of monthly mean erosivity in the semiarid region of Brazil. Daily series equal to or greater than 15 years of data.
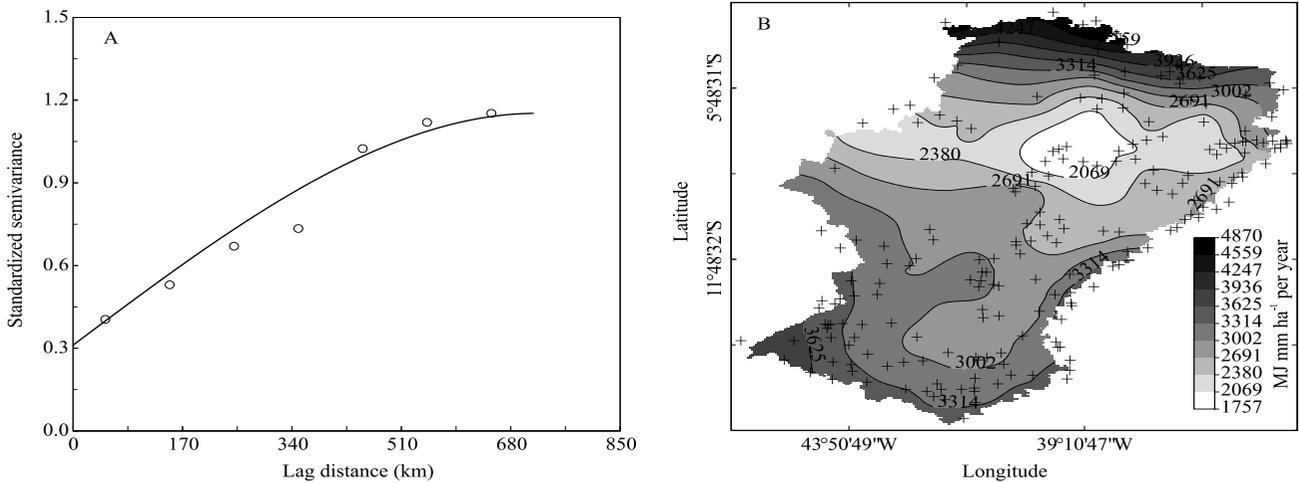

Figure 4. Annual semivariogram adjusted for erosivity values (A) and annual erosivity map for the semiarid region of Brazil (B). Daily series equal to or greater than 15 years of data.

Conclusions

1. The rainfall erosivity index in the semiarid region of Brazil shows a medium degree of spatial dependence from February to March and from June to October, and a low degree in the other months.

2. The spherical model is the most appropriate to represent the spatial distribution of erosivity and is better adjusted to the dry season, whereas the Gaussian model better represents the rainy season.

3. The applied models allow estimating the annual and monthly erosivity values, and the spatialization of the semiarid region of Brazil.

Acknowledgments

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