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SOIL COVER IS STRATEGIC TO REMEDY EROSION IN SANDY SOILS

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KEYWORDS

rainfall erosivity, soil conservation, geostatistics.

ABSTRACT

Sandy-textured soils are naturally more vulnerable to the erosion process and their exploitation, although possible, is often performed inappropriately, favoring its degradation. In this context, this study aimed to classify the rainfall erosivity in a region of sandy soils to identify critical situations of soil and water loss and also correlate it with rainfall data to assess whether there is temporal dependence of this variable using geostatistical techniques. The potential for alternative and sustainable production systems to be used in regions with sandy soils was also analyzed. Historical data of precipitation in the study region were analyzed to determine the average monthly and annual erosivity indices, which were classified and its temporal dependence was assessed by applying geostatistics. NDVI data from satellite images were used to investigate the soil cover pattern in different production systems. Geostatistics was adequate for the analysis of rainfall erosivity, which showed moderate to strong temporal dependence. It was classified between strong and very strong and was highly dependent on precipitation, with events of higher erosion potential between October and March in the studied region. The vicious circle of degradation of sandy soils, such as those of the Bolsão region of Mato Grosso do Sul, Brazil, can be modified by adopting alternative and sustainable production systems that value the maximization of soil cover.

INTRODUCTION

Water erosion, caused by rain, is the main form of soil degradation in Brazil, directly interfering with its conservation. This degradation can lead to problems such as loss of water, soil, nutrients, and organic matter, favoring the reduction of agricultural productivity and the pollution of water bodies (Pimentel, 2006). It threatens food production and environmental resources (Oliveira et al., 2015), generating an estimated global cost of US$ 10.6 trillion year^{-1}, equivalent to 17% of the global GDP (Stewart, 2015). In Brazil, these costs vary from US$ 18.15 to 107.76 ha^{-1} year^{-1}, depending on the soil cover level (Dechen et al., 2015).

The best-known model for estimating soil loss from water erosion and guiding soil conservation planning is the Universal Soil Loss Equation (USLE) and its revised version (RUSLE). According to its developers, Wischmeier & Smith (1978), rainfall erosivity in this equation represents the potential of rain to cause erosion in an unprotected area and is expressed by the R factor. This factor is numerically equal to the EI_{30} index, which expresses, in a given rain event, the product of the kinetic energy of the rain (E) by its maximum intensity in a period of 30 minutes (I_{30}).

The hourly distribution of rainfall intensity is required to be known to quantify EI_{30}, but these data are scarce in Brazil (Trindade et al., 2016) and many parts of the world (Yu et al., 2001). Therefore, alternative ways to estimate erosivity through more accessible data, such as monthly and annual precipitation values, are essential. The rainfall coefficient (Rc), proposed by Fournier (1956) and modified by Lombardi Neto (1977), is a widely used index. This index has become an important tool to help decision-making about soil and water conservation practices (Lee & Heo, 2011; Oliveira et al., 2013).

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The monthly assessment of the rainfall erosivity index is important for the planning of farmers' activities on a small time scale, while the estimation of annual soil and water losses is essential to assess the impacts of crops for correct management and adoption of conservation practices (Cardoso et al., 2022).

In this sense, studies that deal with precipitation and its erosive potential are of paramount importance in the planning of agricultural areas and the use of geoprocessing techniques can contribute to establishing integrated soil and water conservation plans, enabling sustainable solutions that reconcile environmental and economic interests.

Geostatistics is an interpolator that describes promising and accurate results on erosion in agricultural areas (Pérez-Rodriguez et al., 2007). It considers the distance between observations and the spatial and/or temporal dependence between them. It allows obtaining estimates in non-sampled locations and, in addition, time series allow studying changes that may occur with a given variable, becoming an important tool to anticipate future trends through past behavior.

According to Donagemma et al. (2016), sandy soils are genuinely quite susceptible to erosion and degradation. Several sandy areas in Brazil, especially those explored with livestock, present accentuated degradation processes. However, according to these authors, this reality has been changing little by little, as improvements in production systems and agricultural practices are incorporated.

A relevant factor for sustainability is how the farming practice is conducted on these sandy soils, given that it is crucial to define how soil use and occupation contribute to its degradation since the soil cover is a fundamental factor for its conservation, as predicted in the cover factor (C) of the soil loss equation.

Therefore, this study aimed to classify the rainfall erosivity in a region of sandy soils to identify critical situations of soil and water loss and also correlate it with rainfall data to assess whether there is temporal dependence of this variable using geostatistical techniques. In addition, considering the recurrence of degradation scenarios in regions with sandy soils, this study also aimed to evaluate the effects of preserving or restoring native forest, as well as the soil use and occupation with sustainable alternatives, such as planted forests of eucalyptus, on the reduction of the erosion and remediation of the degradation process.

METHODOLOGY

Study region

According to the State Secretariat for the Environment, Economic Development, Production, and Family Agriculture of Mato Grosso do Sul (SEMAGRO/MS), the state of Mato Grosso do Sul (Brazil) is divided into nine economic planning regions. The Bolsão region is one of them, located in the northeast of the state and made up of ten municipalities (Figure 1).

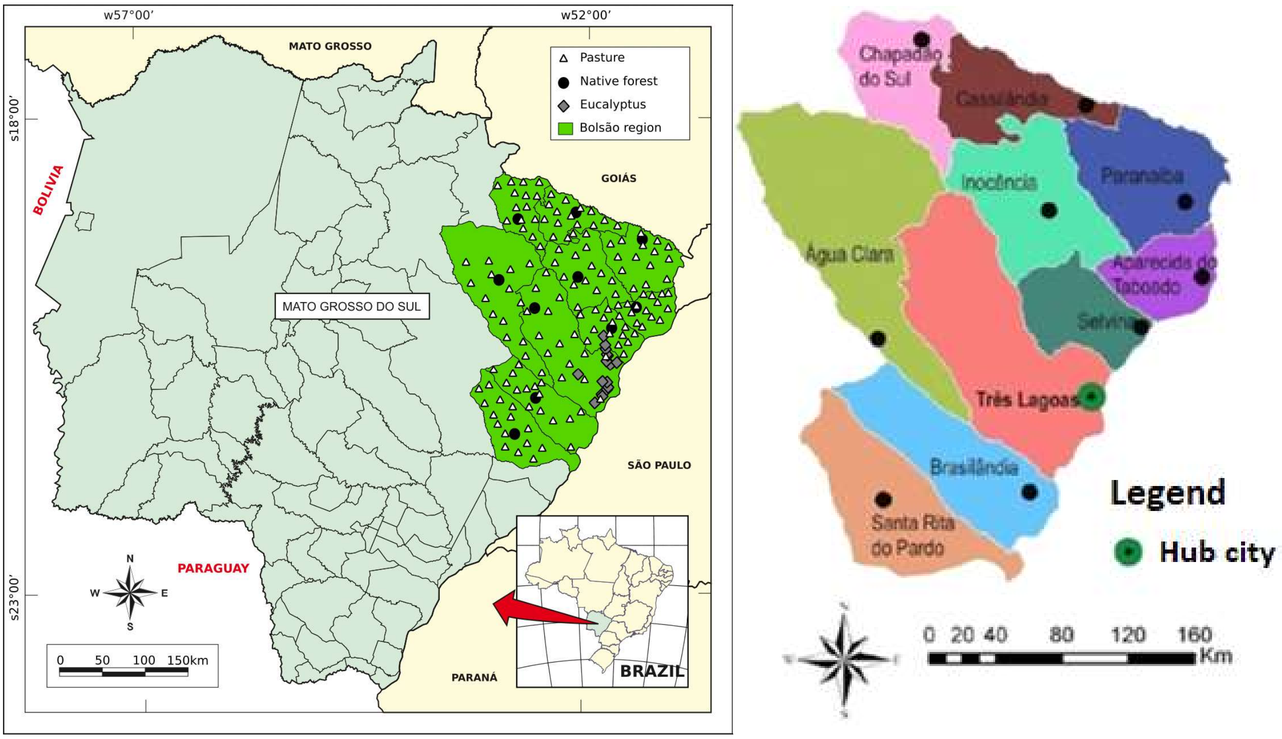


FIGURE 1. Bolsão region of Mato Grosso do Sul, Brazil (SEMAGRO/MS, 2011), its municipalities, and the collection points of satellite images for analysis of the NDVI index.

This region is sparsely populated (almost 300,000 inhabitants), but it covers a large territory (58,000 km^2). There is a predominance of light, sandy-textured soils, with 27.2% of the territory comprising areas of Quartzipsamments, totaling 1.5 million hectares. Other soil types present in the region are medium-textured Oxisols and sandy/medium-textured Ultisols. In any case, the regional soils are, as a rule, of low natural fertility and highly vulnerable to the erosion process, with most of the areas occupied by livestock, which in most cases present some level of degradation.

Rainfall data and erosivity determination

Historical series of rainfall data were analyzed for each municipality in the Bolsão region, namely: Água Clara, Aparecida do Taboado, Brasilândia, Cassilândia, Chapadão do Sul, Inocência, Paranaíba, Santa Rita do Pardo, and Três Lagoas; We could not get data for Selvíria. The data were obtained from rainfall stations of the Geological Survey of Brazil or the National Institute of Meteorology, available on the HidroWeb platform (https://www.snirh.gov.br/hidroweb/apresentacao) and described by Flumignan et al. (2015).

The data were daily and were submitted to quality analysis before use. Data with no quality were submitted for correction or discarded. Therefore, a consecutive and common data interval could not be selected for all rainfall stations. Historical series were used with different periods between municipalities, ranging from 10 to 31 years. These data allowed the calculation of precipitation on the monthly and annual scales for each station.

The erosivity indices were determined using [eq. (1)], which is a potential regression model with a coefficient of determination (R^2) of 0.912. This equation was adjusted for the municipality of Campo Grande, located between 190 and 460 km from the analyzed municipalities. Oliveira et al. (2012) concluded that the equation is valid for estimating values in neighboring locations within a maximum radius of 580 km.

$$EI_{30} = 139.44(Rc)^{0.6784} \quad (1)$$

in which:

EI_{30} is the erosivity index of the month (MJ mm h^{-1} ha^{-1} month^{-1}), and

Rc is the rainfall coefficient (mm).

Equation (1) associates EI_{30} and the rainfall coefficient (Rc), which is represented in [eq. (2)], according to Renard & Freimund (1994).

$$Rc = p^2 P^{-1} \quad (2)$$

Where:

Rc is the rainfall coefficient (mm);

p is the monthly precipitation (mm), and

P is annual precipitation (average of the historical series) (mm).

The characteristic values of each month for the R factor were obtained from the average of the calculated monthly values of EI_{30}. Similarly, the R factor on the annual scale was obtained by accumulating the monthly values. The R factor was then classified according to the classes described in Table 1.

TABLE 1. Criteria for classifying rainfall erosivity (R) on a monthly and annual scale, as provided by Carvalho (2008).

MONTHLY erosivity classes	**R (MJ mm h^{-1} ha^{-1} month^{-1})**
Very weak	$R \le 250$
Weak	$250 < R \le 500$
Moderate	$500 < R \le 750$
Strong	$750 < R \le 1,000$
Very strong	$R > 1,000$
ANNUAL erosivity classes	**R (MJ mm h^{-1} ha^{-1} year^{-1})**
Weak	$R \le 2,452$
Moderate	$2,452 < R \le 4,905$
Moderate to strong	$4,905 < R \le 7,357$
Strong	$7,357 < R \le 9,810$
Very strong	$R > 9,810$

Precipitation and erosivity values were analyzed using descriptive statistics: minimum, maximum, mean, and coefficient of variation.

Geostatistical analysis

Geostatistical analysis was used to assess the temporal dependence of the rainfall erosivity variable by adjusting Matheron's classic semivariogram, using the GS+ 5.0 computer program, based on the assumptions of stationarity of the intrinsic hypothesis, estimated by [eq. (3)].

$$\gamma(t)=\frac{1}{2N(t)} \sum_{i=1}^{N(t)}[Z(x_i)-Z(x_i+t)]^2 \quad (3)$$

in which:

$\gamma(t)$ is the semivariance for a vector t (months);

$Z(x_i)$ and $Z(x_i+t)$ are the pairs of rainfall erosivity observations separated by the vector t (months), and

N(t) is the number of pairs of measured values $Z(x_i)$ and $Z(x_i+t)$, separated by a vector t.

The following coefficients were estimated from the adjustment of the data to a spherical mathematical model of the semivariogram: nugget effect (C_0) – semivariance value when t = 0; range (A_0) – time in which the semivariance remains constant after increasing with an increase in t, considering the time limit of the temporal dependence; and sill (C_0+C) – value at which the semivariance stabilizes and is approximately equal to the variance of the data.

The temporal dependence index (TDI) was classified by [eq. (4)] and the intervals proposed by Zimback (2001), which considers that TDI<25% represents a weak temporal dependence, 25%≤TDI<75% represents a moderate temporal dependence, and TDI≥75% represents a strong temporal dependence.

$$\text{TDI} = \frac{\text{C}}{\text{C}_0+\text{C}} * 100 \qquad (4)$$

The estimated erosivity values at non-sampled times were obtained by punctual kriging, using the parameters of the adjusted semivariograms. Cross-validation was applied using the least squares method by adjusting a linear regression equation. In this method, a sampled value is taken, and an estimated value is obtained by kriging, using the values of neighboring points. This procedure is performed for all sampled points in such a way that, for each true value, there will be an estimated value (Kravchenko, 2003). Sixteen neighbors were used in the interpolation process. A good estimate of the data is considered to be obtained when the regression coefficient, given by the angular coefficient of the line, is equal to or close to 1.

Soil cover analysis

Soil cover was assessed based on the Normalized Difference Vegetation Index (NDVI), obtained by remote sensing through the SATVeg system (https://www.satveg.cnptia.embrapa.br/).

The data originated from MODIS sensor images, aboard the Terra and Aqua satellites, and each analyzed pixel consisted of a grid of 250 × 250 m (6.25 ha). The historical series available and used was from February 2000 to May 2021, with the satellite passing every 16 days. A pre-filtering was applied to the time series to remove data considered marginal or invalid and data classified with the presence of clouds. In addition, the Savitzky–Golay filter, with a moving window size equal to 3, was applied for smoothing purposes.

Fifteen pixels (sites) were analyzed in pasture areas in each of the ten municipalities in the region, totaling 150 sampled pastures (Figure 1). In addition, 10 sites of preserved native forest were also analyzed, one in each municipality (10 samples in total). Finally, 16 samples from production areas with planted eucalyptus forests, located in the production hub of Três Lagoas and Selvíria, were analyzed.

Monthly average values and coefficient of variation were calculated from the NDVI historical series data for each type of land use and occupation and then analyzed against the previously calculated R values.

RESULTS AND DISCUSSION

Analysis of rainfall and its erosion potential

The average annual precipitation in the studied region (1,446 mm) comes from a variation of 1,250 mm in the municipality of Aparecida do Taboado to 1,665 mm in Chapadão do Sul (Table 2). Higher places, such as Cassilândia, Chapadão do Sul, and Inocência, generally have higher incidences of wind and precipitation. According to Carvalho et al. (2012), altitude can even be used to determine the spatial distribution of precipitation, as these variables demonstrate highly significant correlations. In the present study, these municipalities are among those with the highest annual rainfall and the highest altitudes.

TABLE 2. Statistics of precipitation (mm) in the Bolsão region of Mato Grosso do Sul (Brazil) and altitude at the urban area of the municipalities.

Municipality	History (years)	Monthly minimum	Monthly maximum	Monthly average	Annual average	CV* (%)	Altitude (m)
Água Clara	17	0	546	129	1,550	7.71	327
Aparecida do Taboado	20	0	555	104	1,250	7.80	392
Brasilândia	13	0	510	109	1,310	7.55	350
Cassilândia	15	0	553	138	1,655	7.41	462
Chapadão do Sul	20	0	511	139	1,665	7.05	817
Inocência	19	0	558	126	1,509	7.49	510
Paranaíba	31	0	595	117	1,406	8.00	385
Santa Rita do Pardo	23	0	433	113	1,356	6.40	358
Três Lagoas	10	0	405	109	1,312	6.57	326
Average for the Bolsão region	19	0	518	120	1,446	7.33	436

*CV is the coefficient of variation associated with the annual average.
Note: The municipality of Selvíria was not computed due to the unavailability of data.

The annual rainfall erosivity determined in the Bolsão region of Mato Grosso do Sul was 9,450 MJ mm h^{-1} ha^{-1} $year^{-1}$ (Table 3), a value very similar to the entire state average of 9,318 MJ mm h^{-1} ha^{-1} $year^{-1}$ found by Oliveira et al. (2012). Água Clara, Cassilândia, and Chapadão do Sul are the municipalities where rainfall has the highest erosion potential, with erosivity values higher than 10,000 MJ mm h^{-1} ha^{-1} $year^{-1}$. The municipalities of Aparecida do Taboado, Brasilândia, Santa Rita do Pardo, and Três Lagoas presented the lowest erosion potential due to rainfall, with annual values lower than 9,000 MJ mm h^{-1} ha^{-1} $year^{-1}$. The observed variation in rainfall erosivity in the region is within the limit established in Brazil by Oliveira et al. (2013), predicted between 1,672 and 22,452 MJ mm h^{-1} ha^{-1} $year^{-1}$.

TABLE 3. Monthly (MJ mm h^{-1} ha^{-1} month^{-1}) and annual (MJ mm h^{-1} ha^{-1} year^{-1}) rainfall erosivity values (R factor) in the Bolsão region of Mato Grosso do Sul (Brazil).

Municipality	Monthly R			Annual R	CV* (%)
	Minimum	Maximum	Average		
Água Clara	0	4,941	839	10,074	9.57
Aparecida do Taboado	0	5,852	724	8,693	10.08
Brasilândia	0	5,052	741	8,895	9.59
Cassilândia	0	4,814	864	10,370	9.45
Chapadão do Sul	0	4,308	863	10,350	8.61
Inocência	0	5,177	818	9,811	9.31
Paranaíba	0	5,934	792	9,501	10.13
Santa Rita do Pardo	0	3,944	728	8,735	8.23
Três Lagoas	0	3,685	719	8,624	8.17
Average for the Bolsão region	0	4,856	788	9,450	9.24

*CV is the coefficient of variation associated with the annual R factor.
Note: The municipality of Selvíria was not computed due to the unavailability of data.

In general, the coefficients of variation (CV) for both precipitation (Table 2) and erosivity (Table 3) were low, with values ranging from 6.4 and 10.13%, indicating little data variability relative to the mean, according to criteria established by Pimentel-Gomes & Garcia (2002). The highest variability for erosivity was observed in Paranaíba (10.13%) and the lowest in Três Lagoas (8.17%), that is, the highest (31 years) and lowest (10 years) historical series of rainfall data in the region, respectively. This index (CV) provides a relative measure of experimental precision, applied in the analysis of data dispersion, thus evidencing the reliability of the analyses using the database.

Figure 2 shows the monthly averages of precipitation and rainfall erosivity. January is the rainiest month, with the highest erosivity in the region, as observed by Machado et al. (2014), followed by December, February, and March, in that order. The data trend is for lower R values in the period from April to September (includes the entire winter) and higher values from October to March (includes the entire summer). Importantly, the monthly erosivity in the rainy season (between October and March) exceeds the limit of soil loss considered critical by Silva et al. (1997), which is 500 MJ mm h^{-1} ha^{-1} month^{-1}. Oliveira et al. (2012) highlighted that erosivity in the state of Mato Grosso do Sul is associated with concentrations of rainfall at certain times of the year due to the climate characteristics of the region. It is precisely the regional climate patterns that justify a careful and differentiated look at each case, as can be seen when identifying that the rainfall erosivity obtained in this study for the Bolsão region of Mato Grosso do Sul was higher than that observed in Santa Catarina in the regions of São Joaquim and Lages (Back, 2018).

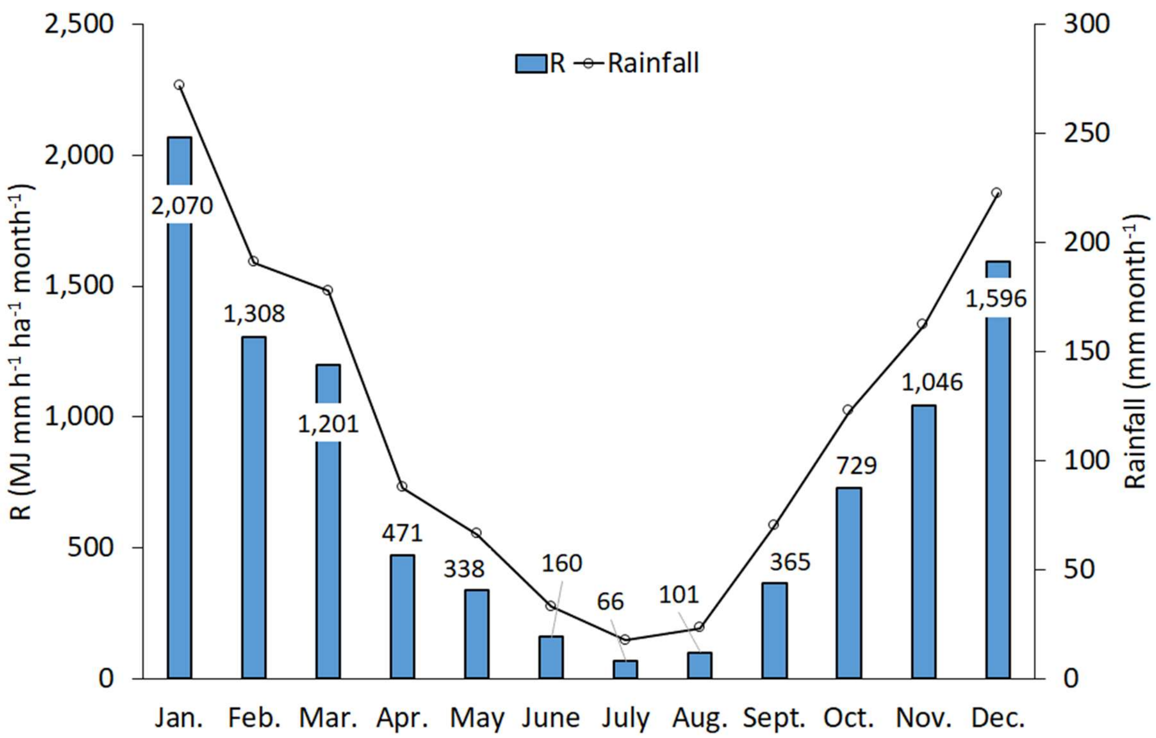


FIGURE 2. Monthly distribution of rainfall erosivity (R) and rainfall in the Bolsão region of Mato Grosso do Sul, Brazil (average of the historical series of all municipalities).

Rainfall patterns and their erosion potential in a scenario of global climate change may change over time (Zilli et al., 2020, Regoto et al., 2021). These changes can take the form of isolated high-intensity rainfall events, which can become more or less intense and/or frequent, or in the form of changes in rainfall patterns, implying that specific months may become more or less rainy. These changes may have negative consequences for water erosion in sandy soils in Brazil. The expectation is that the erosion power of rains will increase from 15.7 to 25% in Europe if the climate changes projected by 2050 are confirmed, a fact that would result in an increase in soil loss due to water erosion from 13 to 22.5% (Panagos et al., 2021).

Classification of rainfall erosivity

Rainfall erosivity was classified separately for each municipality (Figure 3), according to the criteria shown in Table 1, considering the annual temporal scale. The municipalities in the northwest region were classified as having very strong erosivity, the highest level, while the others presented strong erosivity. Only Selvíria was not classified due to a lack of data for the municipality. However, given its geographic insertion in the region and the climate homogeneity, this municipality is also presumed to have a strong or very strong classification. In general, the map shown in Figure 3 shows the high erosion potential of rainfall in the region, a fact that raises the need for systematic adoption of soil and water conservation practices to minimize water erosion.

FIGURE 3. Classification of rainfall erosivity by the annual R factor for the Bolsão region of Mato Grosso do Sul, Brazil.

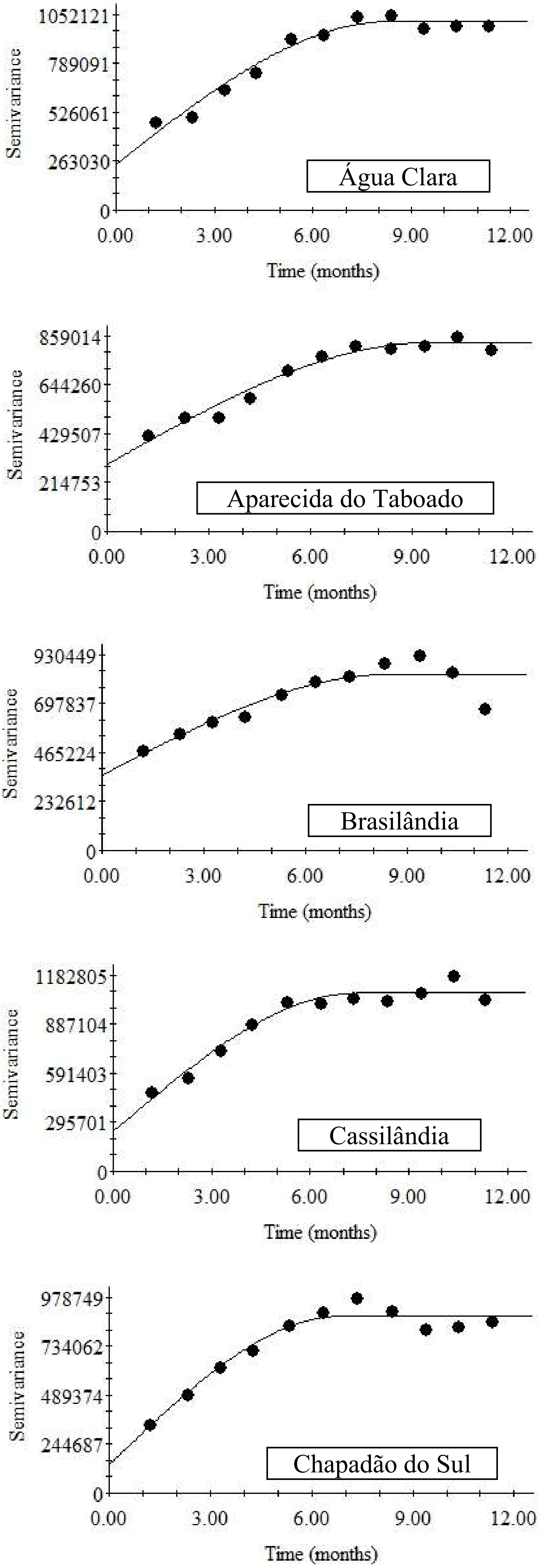
The rainfall erosivity in the Bolsão region of Mato Grosso do Sul is classified at the highest level, that is, very strong, from November to March when the monthly erosivity data of Figure 2 are analyzed considering the classification criteria presented in Table 1. Moreover, the rains that occur in October, classified as having a moderate erosion potential, stand out. The other months have milder and scarcer rainfall, being classified in lower erosivity levels (weak and very weak).

Table 3 shows the extreme months that have already occurred in each municipality, which are highly relevant for the occurrence of extreme erosion processes. The maximum R ever occurring in the region ranged from 3,685 MJ mm h^{-1} ha^{-1} $month^{-1}$ in Três Lagoas to 5,934 MJ mm h^{-1} ha^{-1} $month^{-1}$ in Paranaíba. These values represent, respectively, 3.7 and 5.9 times more than the limit for the classification of rainfall with very strong erosion potential.

These results should be considered in conservation planning, given the presence of sandy soils in the studied region and their natural vulnerability to the erosion process. In addition, according to SEMAGRO/MS (2011), the region shows from flat relief to locations where the average slope reaches 11°, and the more inclined the terrain, the higher the risk of the erosion process to happen.

Geostatistical analysis for temporal dependence

The geostatistical analysis showed that the erosivity indices had temporal dependence (Figure 4). The theoretical spherical model was adjusted to the semivariogram, corroborating the model with the best performance found by Saito et al. (2009) and Oliveira et al. (2012).



Semivariance
1052121
789091
526061
263030
0
0.00
3.00
6.00
9.00
12.00
Time (months)
Água Clara
Semivariance
859014
644260
429507
214753
0
0.00
3.00
6.00
9.00
12.00
Time (months)
Aparecida do Taboado
Semivariance
930449
697837
465224
232612
0
0.00
3.00
6.00
9.00
12.00
Time (months)
Brasilândia
Semivariance
1182805
887104
591403
295701
0
0.00
3.00
6.00
9.00
12.00
Time (months)
Cassilândia
Semivariance
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734062
489374
244687
0
0.00
3.00
6.00
9.00
12.00
Time (months)
Chapadão do Sul

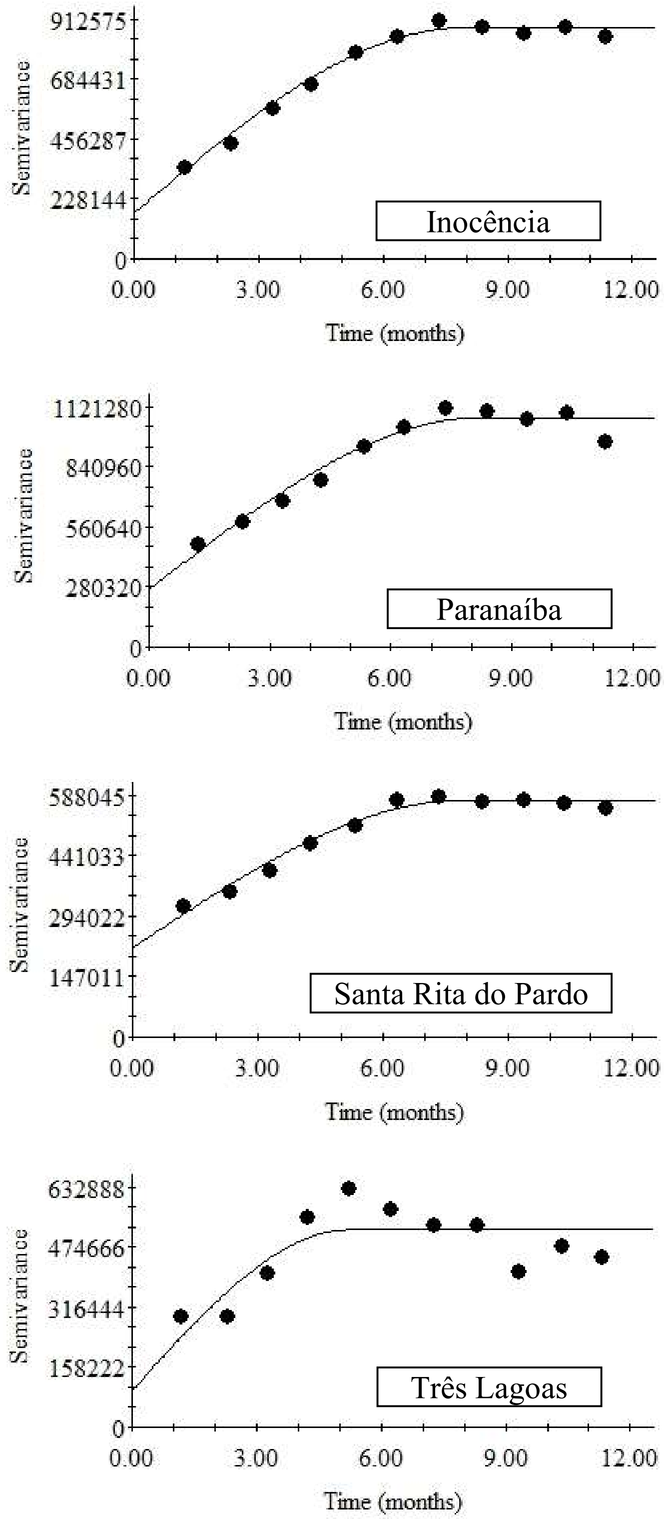


FIGURE 4. Semivariogram adjusted for monthly rainfall erosivity (R; MJ mm h^{-1} ha^{-1} $month^{-1}$) as a function of time (months) in municipalities of the Bolsão region of Mato Grosso do Sul (Brazil), except Selvíria.

The adjustment of the semivariograms to the data of the municipalities (Table 4) presented an average R^2 of 0.91. Seven out of the nine municipalities assessed presented an R^2 higher than or equal to 0.95, with the highest values found for Inocência and Santa Rita do Pardo (0.99 and 0.98, respectively). Exceptions were observed in Brasilândia (R^2 = 0.81) and Três Lagoas (R^2 = 0.63), probably because they have the shortest historical series (13 and 10 years, respectively). It indicates the difficulty in obtaining a model that best explains the phenomenon in these cases, requiring a higher number of pairs of values for its definition. The same behavior was observed by Montebeller et al. (2007).

TABLE 4. Parameters of the theoretical semivariograms adjusted to rainfall erosivity data in the Bolsão region of Mato Grosso do Sul, Brazil.

Municipality	Model	C_0	C_0+C	A_0	R^2
Água Clara	Spherical	248,000	1,013,000	8.36	0.96
Aparecida do Taboado	Spherical	294,000	828,800	9.57	0.96
Brasilândia	Spherical	357,000	836,200	8.59	0.81
Cassilândia	Spherical	240,000	1,073,000	7.43	0.95
Chapadão do Sul	Spherical	140,000	884,000	6.90	0.95
Inocência	Spherical	174,000	879,000	7.95	0.99
Paranaíba	Spherical	267,000	1,068,000	8.25	0.95
Santa Rita do Rio Pardo	Spherical	216,000	575,300	7.95	0.98
Três Lagoas	Spherical	95,000	519,600	5.24	0.63
Average for the Bolsão region	Spherical	225,667	852,989	7.80	0.91

Note: C_0 = nugget effect; C_0+C = sill; A_0 = range; R^2 = coefficient of determination of the adjusted model. The municipality of Selvíria was not computed due to the unavailability of data.

The lowest sill and nugget effect values were observed in Três Lagoas. According to Burgos et al. (2006), the nugget effect is directly related to sampling error, short-range variability, or unexplained variability, a fact that also justifies the smaller range obtained in this municipality. The range is important in determining the limit of temporal dependence and was higher in Aparecida do Taboado.

TDI in the study region was equal to or above 57% in all municipalities (Table 5) and was classified in the average of the region (73.2%) as moderate (25%≤TDI<75%), a value very close to the threshold for classification as strong (Zimback, 2001). Six municipalities showed strong dependence (TDI≥75%), and Chapadão do Sul had the highest TDI observed.

TABLE 5. Classification of the temporal dependence index (TDI) for the variable rainfall erosivity in the Bolsão region of Mato Grosso do Sul, Brazil.

Municipality	TDI (%)	Class
Água Clara	76	Strong
Aparecida do Taboado	65	Moderate
Brasilândia	57	Moderate
Cassilândia	78	Strong
Chapadão do Sul	84	Strong
Inocência	80	Strong
Paranaíba	75	Strong
Santa Rita do Pardo	62	Moderate
Três Lagoas	82	Strong
Average for the Bolsão region	73.2	Moderate

Note: The municipality of Selvíria was not computed due to the unavailability of data.

The cross-validation (Table 6) shows that the slope of the regression line between the measured and estimated values, the angular coefficient, approaches the ideal situation (b=1), except for the municipality of Três Lagoas, with a standard error close to zero, considering the used neighboring of 16 neighbors (Vieira et al., 2010).

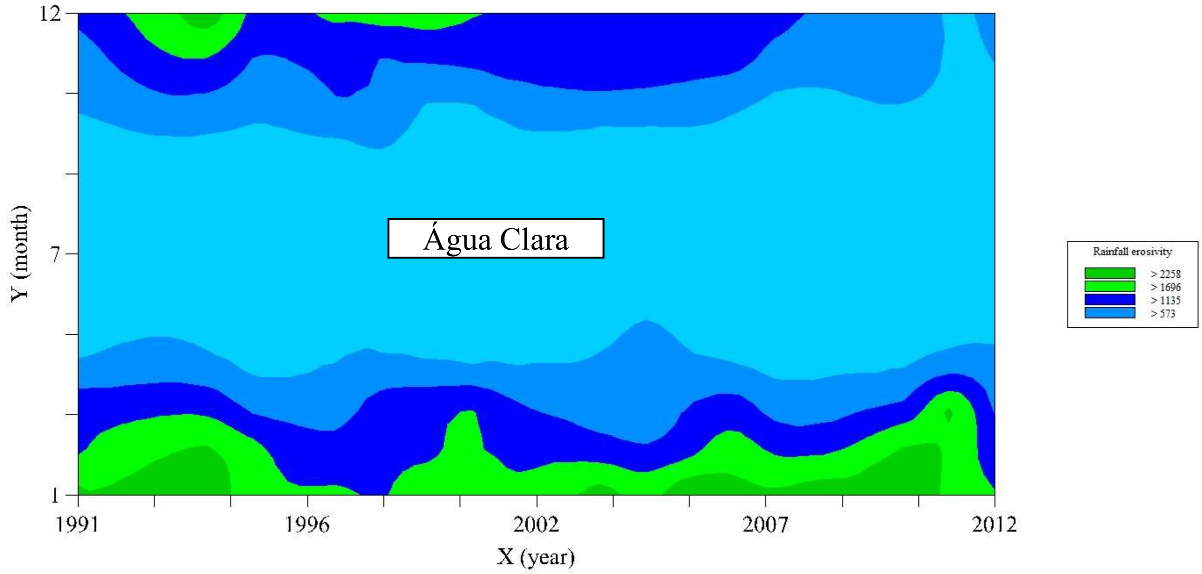
TABLE 6. Cross-validation of theoretical semivariogram models adjusted to rainfall erosivity data in the Bolsão region of Mato Grosso do Sul, Brazil.

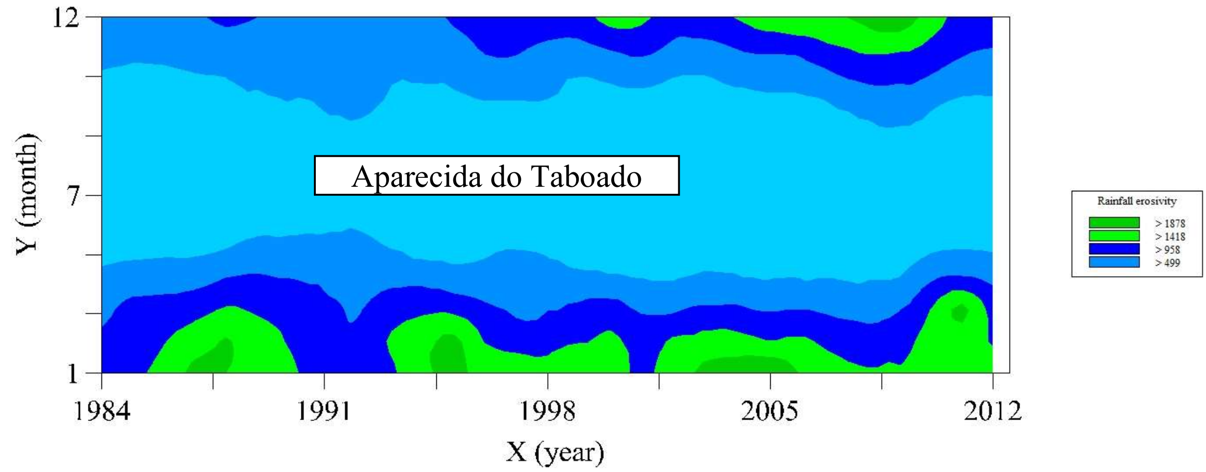
Municipality	Intercept (a)	Angular coefficient (b)	Standard error	R^2
Água Clara	25.4	0.97	0.07	0.46
Aparecida do Taboado	33.0	0.96	0.09	0.32
Brasilândia	29.7	0.98	0.13	0.28
Cassilândia	88.8	0.91	0.09	0.38
Chapadão do Sul	64.8	0.93	0.06	0.50
Inocência	40.0	0.95	0.07	0.48
Paranaíba	10.0	0.99	0.06	0.45
Santa Rita do Rio Pardo	14.5	0.99	0.09	0.32
Três Lagoas	145.7	0.81	0.11	0.32

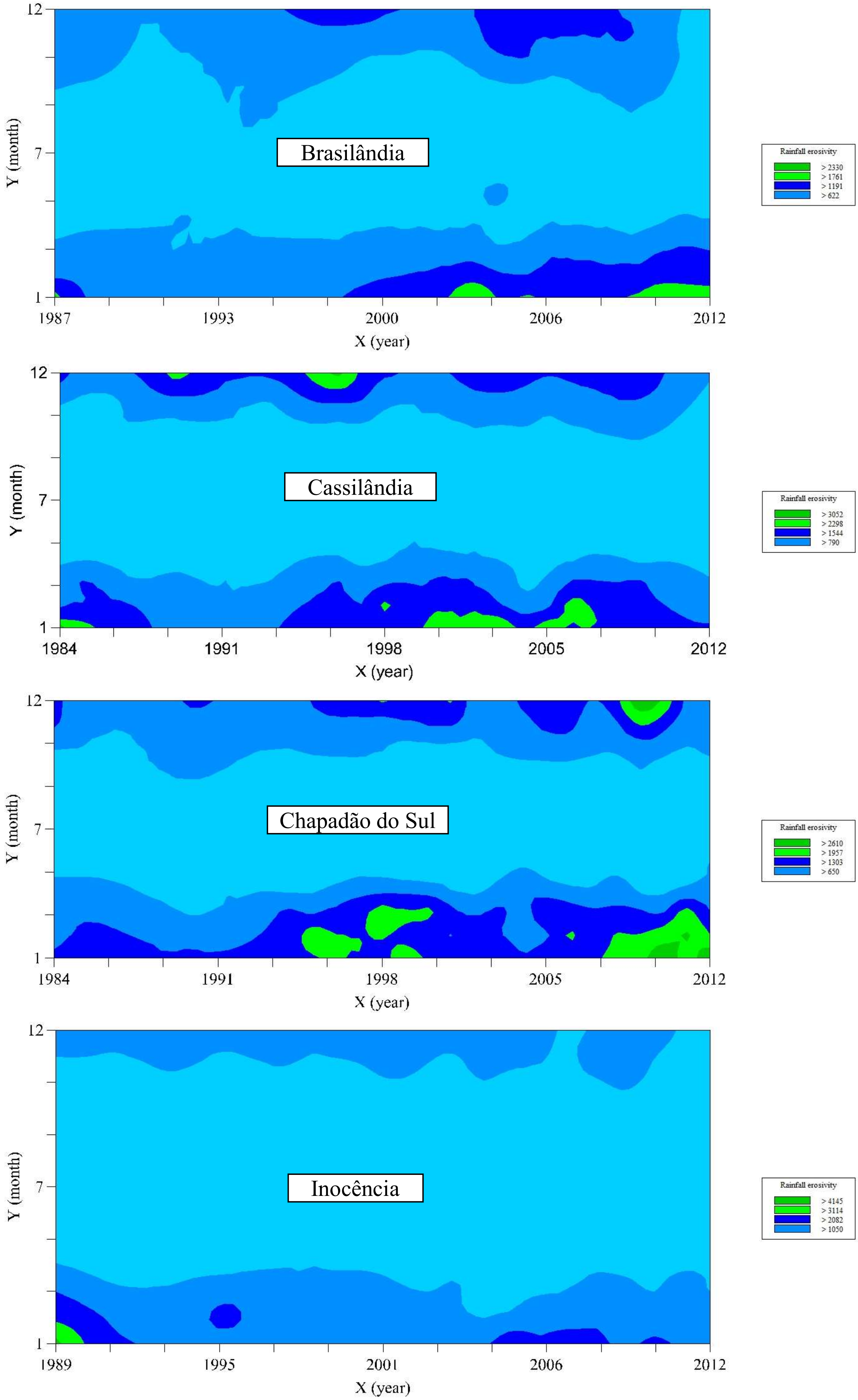
Note: R^2 = coefficient of determination. The municipality of Selvíria was not computed due to the unavailability of data.

The intercept values indicated that the parameters of the adjusted semivariograms resulted in an overestimation of small values and an underestimation of high values. This fact was more accentuated for the Três Lagoas data, which had the lowest range of temporal dependence. The R^2 of the cross-validation was relatively low for all municipalities, probably due to the high number of observations considered in the study, which also promotes a high number of data pairs that form the semivariogram. In general, extreme values (both low and high) have a higher error in the estimates. On the other hand, central values show higher adherence to the 1:1 line of the regression line.

Graphs were created with the parameters of adjusted semivariograms to illustrate the temporal distribution of the rainfall erosivity in the evaluated municipalities (Figure 5).






Brasilândia
Y (month)
12
7
1
1987
1993
2000
2006
2012
X (year)
Rainfall erosivity
> 2330
> 1761
> 1191
> 622
Cassilândia
Y (month)
12
7
1
1984
1991
1998
2005
2012
X (year)
Rainfall erosivity
> 3052
> 2298
> 1544
> 790
Chapadão do Sul
Y (month)
12
7
1
1984
1991
1998
2005
2012
X (year)
Rainfall erosivity
> 2610
> 1957
> 1303
> 650
Inocência
Y (month)
12
7
1
1989
1995
2001
2006
2012
X (year)
Rainfall erosivity
> 4145
> 3114
> 2082
> 1050

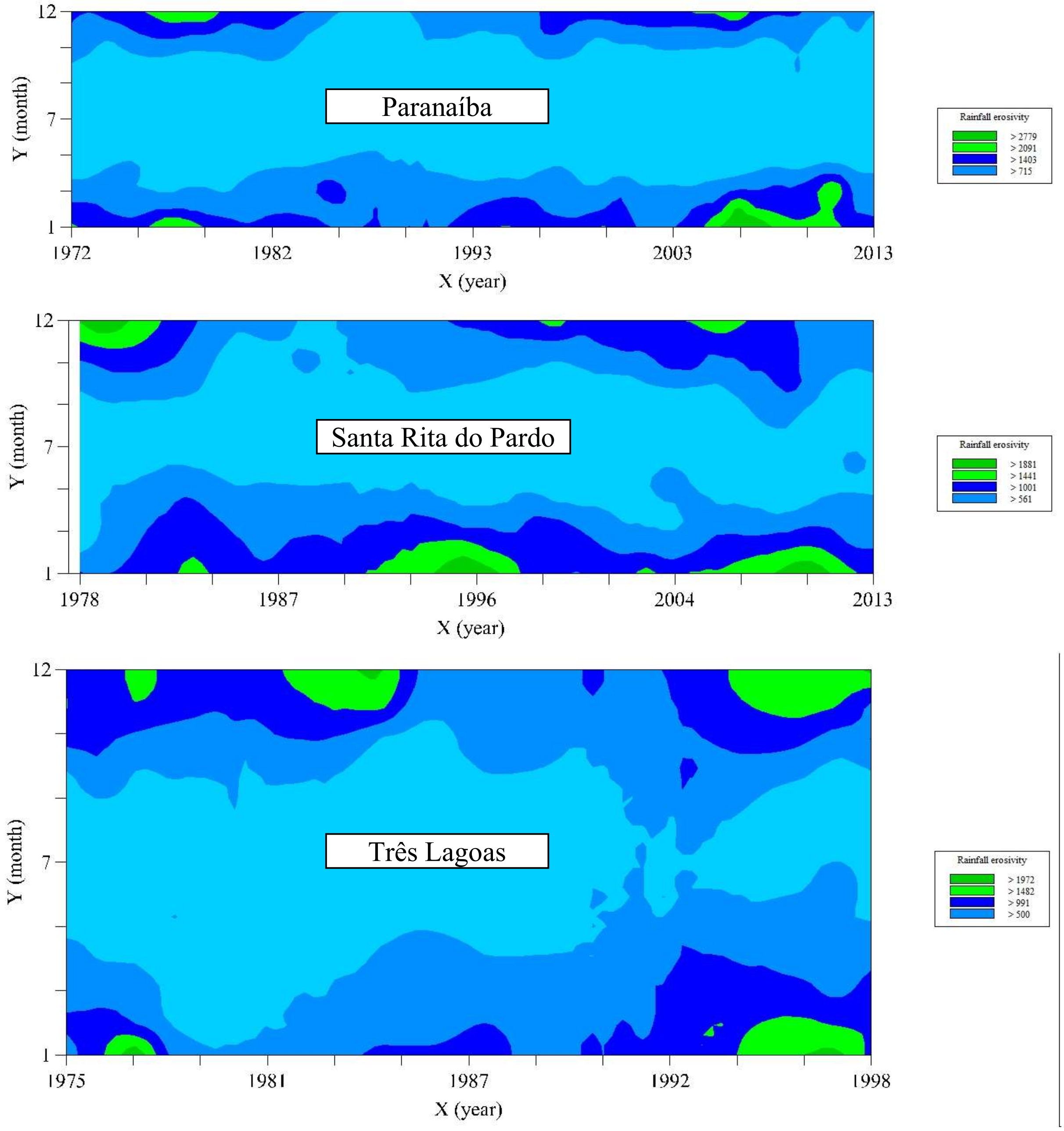


FIGURE 5. Temporal distribution of rainfall erosivity (R; MJ mm h^{-1} ha^{-1} $month^{-1}$) over months and years in the municipalities of the Bolsão region of Mato Grosso do Sul (Brazil), except for Selvíria.

Analysis of soil cover in different use and occupation models

The analysis of the components of the soil loss equation shows the need to properly plan soil use and occupation to face the erosion potential of rainfall in the study region. Therefore, planning must consider the components cover (C) and conservation practices (P) of the soil loss equation.

The data show that it is essential that the soil in the region is covered, especially from October to March, as the rains in this period have significant erosion potential. This proposition is in line with Waltrick et al. (2015), who emphasized that monthly erosivity information is important to identify critical situations in terms of soil and water losses. It directly influences the planning of conservationist practices based on maximum soil cover and agricultural management according to the planting time for each crop, preventing the soil from being uncovered during the most critical periods.

The Pearson correlation coefficient (r) obtained when evaluating the existing relationship between erosivity and precipitation makes it clear that the former is strongly and positively influenced by the latter (0.995 for the monthly scale and 0.97 for the annual scale). This demonstrates that a higher rainfall concentration favors the formation of events with higher erosion potential. Silva (2004) and Trindade et al. (2016) also found a high dependence between these parameters, unlike the results found by Oliveira et al. (2012) and Machado et al. (2014) in this same state, where high annual precipitation values do not necessarily produce high erosivity values.

The predominant production system in the Bolsão region of Mato Grosso do Sul is extensive livestock, with a significant amount of areas under some degradation level. In these areas, plant biomass production is limited and, consequently, the soil is more often uncovered and vulnerable to the erosion process. It occurs even during the rainiest period, as shown by the NDVI data obtained in the 150 pastures sampled in the municipalities of the region (Figure 6 and Table 7). Similarly, Wang et al. (2020) and Senanayake et al. (2022) also observed that water erosion was greater the higher the levels of soil exposure, reflecting the significant negative impact of poorly conducted anthropic actions when exploiting the soil unsustainably, not prioritizing its coverage.

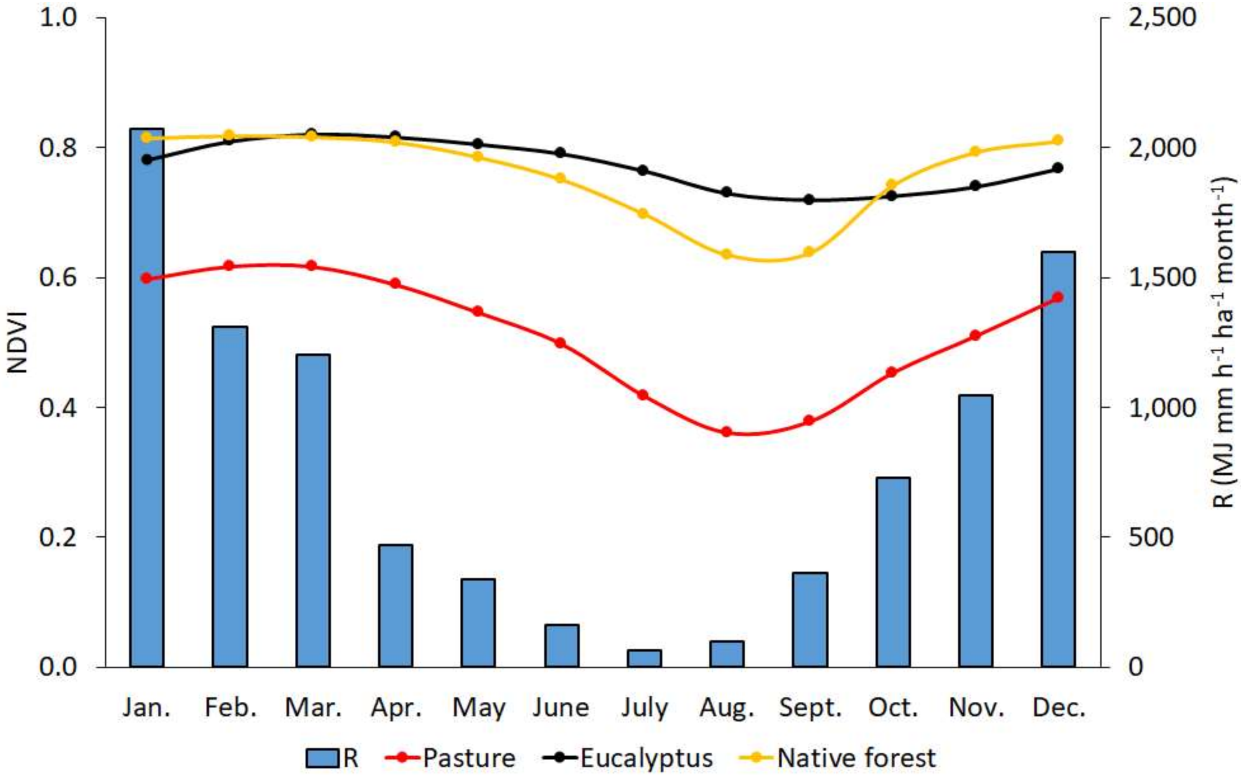


FIGURE 6. Monthly dynamics of rainfall erosivity (R) and NDVI in areas of pasture, planted eucalyptus forest, and native forest in the Bolsão region of Mato Grosso do Sul, Brazil.

TABLE 7. Average values of NDVI and its coefficient of variation (CV) in areas of pasture, planted eucalyptus forest, and native forest in the Bolsão region of Mato Grosso do Sul, Brazil.

Period	NDVI			CV (%)		
	Pasture	Eucalyptus	Native forest	Pasture	Eucalyptus	Native forest
January	0.6	0.78	0.81	18	21.3	7.1
February	0.62	0.81	0.82	16.3	19.5	6
March	0.62	0.82	0.82	16.5	19	6.4
April	0.59	0.82	0.81	17.9	19.1	8
May	0.55	0.80	0.78	18.8	20.6	7.7
June	0.5	0.79	0.75	20.2	21.1	7.9
July	0.42	0.76	0.7	21.6	21.7	10.4
August	0.36	0.73	0.63	19.1	22.3	11.9
September	0.38	0.72	0.64	25	21.3	14.1
October	0.45	0.73	0.74	23	22.8	10.2
November	0.51	0.74	0.79	20.1	22.4	7.8
December	0.57	0.77	0.81	19.3	22	7.5
Annual	0.51	0.77	0.76	-	-	-

In the case of pastures, in addition to the low biomass production, there is also the fact that the produced biomass is consumed by livestock, thus limiting the deposition of dead plant matter over the soil, which could also contribute to its protection. In contrast, areas of native vegetation and planted eucalyptus forests, naturally present a higher biomass production (see NDVI in Figure 6 and Table 7) and, consequently, a higher production of dead plant matter deposited over the soil (litter), resulting in a very valuable soil cover for its protection against the erosion process.

Other agricultural production systems have gradually become more and more common in the study region and bring with them a strong sustainability bias, which is important for regions with sandy soils. This is the case of integrated production systems (Salton et al., 2014; Zago et al., 2019; Zolin et al., 2021; Bansal et al., 2022), including the integrated crop-livestock (ICL), crop-livestock-forest (ICLF), and livestock-forest (ILF) systems. Among other benefits, such as the reconstruction of soil fertility, higher organic matter production, and diversification of plant species, all these systems value the maximization of soil cover by active vegetation and also the higher straw production, characteristics that are very favorable to soil conservation and remediation of the degradation process.

CONCLUSIONS

1. The municipalities in the Bolsão region of Mato Grosso do Sul (Brazil) have rainfall erosivity between strong and very strong, showing that planning regarding soil use and occupation, as well as the adoption of conservationist practices, must be considered to favor the sustainability of sandy soils in the region and contain their degradation.
2. Rainfall erosivity in the region varies throughout the year, with a rainy season with high erosion potential (October to March) and a drier season with low erosion potential (April to September). January and July show the highest and lowest erosivity indices (2,070 and 66 MJ mm h^{-1} ha^{-1} $month^{-1}$, respectively).
3. The spherical model of the geostatistical analysis presented a good adjustment to the observed values of rainfall erosivity, with temporal dependence from moderate to strong.
4. Traditional livestock farming, as practiced in the sandy-textured soils of the study region, consists of a vicious circle of soil degradation, which can be interrupted and remedied by adopting sustainable production alternatives, which value the maximization of soil cover, such as planted eucalyptus forests and integrated production systems (ICL, ICLF, and ILF), or even promoting the recomposition of native vegetation.

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