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# Rainfall erosivity in Brazil: A review

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ABSTRACT

In this paper, we review the erosivity studies conducted in Brazil to verify the quality and representativeness of the results generated and to provide a greater understanding of the rainfall erosivity (R factor) in Brazil. We searched the ISI Web of Science, Scopus, SciELO, and Google Scholar databases and in recent theses and dissertations to obtain the following information: latitude, longitude, city, states, length of record (years), altitude, precipitation, R factor, equations calculated and respective determination coefficient ($R^2$). We found 35 studies in Brazil that used pluviographic rainfall data to calculate the rainfall erosivity. These studies were concentrated in the cities of the south and southeast regions (~60% of all the cities studied in Brazil) with a few studies in other regions, mainly in the north. The annual rainfall erosivity in Brazil ranged from 1672 to 22,452 MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$. The lowest values were found in the northeast region, and the highest values were found in the north region. The rainfall erosivity tends to increase from east to west, particularly in the northern part of the country. In Brazil, there are 73 regression equations to calculate erosivity. These equations can be useful to map rainfall erosivity for the entire country. To this end, techniques already established in Brazil may be used for the interpolation of rainfall erosivity, such as geostatistics and artificial neural networks.

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**Contents**

## 1. Introduction

Soil loss prediction is important to assess the risks of soil erosion and to determine appropriate soil use and management (Oliveira et al., 2011a). Several mathematical models (empirical, conceptual and physical-based processes) have been developed to estimate soil erosion on different spatial and temporal scales (Ferro, 2010; Moehansyah et al., 2004). The erosion models vary from complex procedures that require a series of input parameters, such as Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), Kinematic Runoff and Erosion (KINEROS) (Woolhiser et al., 1990) and European Soil Erosion Model (EUROSEM) (Morgan et al., 1998) to more simplified methods, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) and Morgan-Morgan and Finney (MMF) (Morgan, 2001).

Models that require multiple input parameters may not be feasible for use in locations with no data or with difficult access, as in several regions of Brazil. Several authors consider the USLE to provide an excellent model for predicting soil loss because of its applicability (in terms of required input data) and the reliability of the obtained soil loss estimates (Ferro, 2010; Risse et al., 1993). The application of USLE on a river basin scale has been facilitated by the use of

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Geographic Information Systems (GIS). This combination is considered a useful tool for soil and water conservation planning (Oliveira et al., 2011a).

The USLE is the most widely used erosion model in the world, and it provides useful information for the adequate planning of soil and water conservation. This model is characterized by establishing an estimate of the average annual soil loss caused by rill and interril erosion (Kinnell, 2010; Oliveira et al., 2011a). The input data for the model are composed of natural factors (rainfall erosivity – R, erodibility – K, slope length – L, and slope – S) and anthropogenic factors (cover and management – C, and conservation practices – P). Among the factors that compose the USLE and RUSLE, the rainfall erosivity (R factor) is highly important because precipitation is the driving force of erosion and has a direct influence on aggregate breakdown and runoff. Erosivity is also an important parameter for soil erosion risk assessment under future land use and climate change (Meusburger et al., 2011; Nearing et al., 2005).

Several studies using natural and artificial rain have been conducted to understand the role of droplet size and the distribution of rainfall on the detachment of soil particles. However, the data are difficult to measure and are scarce, both spatially and temporally. Accordingly, studies related to rainfall, such as the maximum intensity over a period of time, the total energy of the rain or the rate of direct breakdown of the soil, have been conducted (Angulo-Martínez and Beguería, 2009). As an example of the erosivity index, we can cite the R factor of the USLE, which summarizes all the erosive events quantified by the $EI_{30}$ index throughout the year (Wischmeier and Smith, 1978), the KE>25 index for southern Africa (Hudson, 1971), the AIm index for Nigeria (Lal, 1976), and the modified Fournier index for Morocco (Arnoldus, 1977).

The $EI_{30}$ index has been the most widely used index (Hoyos et al., 2005) and provides a good correlation with soil loss in several studies in Brazil (Bertol et al., 2007, 2008; Lombardi Neto and Moldenhauer, 1992; Silva et al., 2009a). However, a series of more than 20 years of rain gauge is recommended to calculate this factor, but this length of time series is not found in many parts of the world (Capolongo et al., 2008; Hoyos et al., 2005; Lee and Heo, 2011). Simplified methods for predicting rainfall erosivity using readily available data have been presented and are used in many countries because the high-resolution rainfall data needed to directly compute the rainfall erosivity are not available for many locations; moreover, calculations of such data (when available) are intricate and time consuming (Lee and Heo, 2011). Models that relate the erosivity index with pluviometric data (e.g., monthly precipitation, annual total precipitation and modified Fournier index) were proposed to obtain the R factor. These daily pluviometric records are generally available for most locations with good spatial and temporal coverage, allowing the calculation of the erosivity index in regions that have no pluviographic rainfall data (Angulo-Martínez and Beguería, 2009; Renard and Freimund, 1994; Silva, 2004).

In Brazil, some regression equations are used widely to obtain the local values of erosivity from pluviometric data. However, the interpretation of the input data must be realistic and must match the local climate characteristics. In this paper, we review the erosivity studies conducted in Brazil to verify the quality and representativeness of the results generated and to provide a better understanding of the rainfall erosivity in Brazil. The R factor was used as the index to show the rainfall erosivity.

## 2. Materials and methods

Rainfall erosivity has been calculated for Brazilian regions using recording rain gauge data as the source of input. We review the ISI Web of Science, Scopus, SciELO, and Google Scholar databases and recent theses and dissertations that have not been published in journals. The following information was obtained from the published works: latitude, longitude, city, states, length of record (years), altitude, precipitation, R factor, equations calculated and respective determination coefficient ($R^2$).

We analyze the spatial distribution of the erosivity studies for the regions of Brazil to determine which areas have an abundance or lack of information. In addition, the erosivity information was compared with the calculated values of erosivity derived from regression equations.

## 3. Results and discussion

### 3.1. Calculation of the erosivity index ($EI_{30}$) in Brazil

The erosivity index ($EI_{30}$) is determined for isolated rainfalls and classified as either erosive or nonerosive. In Brazil, periods of rainfall are considered to be isolated and non-erosive when they are separated by periods of precipitation between 0 (no rain) and 1.0 mm for at least 6 h and are considered to be erosive when 6.0 mm of rain falls in 15 min or 10.0 mm of rain falls over a longer time period (Oliveira et al., 2011a; Wischmeier, 1959).

Erosive rain is analyzed by identifying the segments with the same inclination that represent periods of rain with the same intensity. For each segment with uniform rainfall, the unitary kinetic energy is determined by Eq. (1) (Wischmeier and Smith, 1978).

$$e = 0.119 + 0.0873\ \log_{10}\ i \qquad (1)$$

where $e$ is the unitary kinetic energy (MJ $ha^{-1}$ $mm^{-1}$) and $i$ represents the segments of rainfall intensity (mm $h^{-1}$).

The rainfall kinetic energy can be directly calculated from drop size distribution and terminal velocity of the drops. This way, is important to study better these relationship at different regions (Cerdà, 1997). In Brazil, Wagner and Massambini (1988) developed the relationship between kinetic energy and rainfall intensity from 533 samples of the drop size distribution. The authors concluded that the equation generated (from observed data) to calculate kinetic energy don't have any significant difference of the equation from Wischmeier and Smith (1978). Thus, Eq. (1) still widely used in Brazil.

**Fig. 1.** Spatial distribution of studies on erosivity in Brazil.

**Table 1**
Studies on erosivity in Brazil.

| Latitude | Longitude | City | States | Years | Altitude | Precipitation | R factor | Equations | $R^2$ | Authors |
|---|---|---|---|---|---|---|---|---|---|---|
| 3° 0′ 0″S | 60° 0′ 0″W | Manaus | AM | – | – | 2219 | 14,129 | $EI_{30}=42.77+3.76\ (MFI)$ | – | Oliveira and Medina, 1990 |
| 3° 44′ 0″S | 38° 33′ 0″W | Fortaleza | CE | 20 | 20 | 1677 | 6774 | – | – | Dias and Silva, 2003 |
| 19° 35′ 0″S | 40° 0′ 0″W | Aracruz | ES | 7 | 40 | 1400 | 8536 | $EI_{30}=40.578+7.9075\ (P)$ | 0.61 | Martins et al., 2010 |
| 16° 41′ 0″S | 49° 23′ 0″W | Goiânia | GO | 5 | 750 | 1280 | 8353 | $EI_{30}=215.33+30.23\ (MFI)$ | 0.77 | Silva et al., 1997 |
| 21° 8′ 24″S | 45° 0′ 0″W | Lavras | MG | 15 | 919 | 1530 | 5403 | – | – | Evangelista et al., 2006 |
| 19° 25′ 0″S | 44° 15′ 0″W | Sete Lagoas | MG | 3 | 732 | 1340 | 5835 | $EI_{30}=25.3+43.35\ (MFI)-0.232\ (MFI)^2$ | – | Marques et al., 1997 |
| 19° 04′ 11″S | 42° 32′ 56″W | Açucena | MG | 3 | 493 | 1481 | 18,646 | $EI_{30}=158.35\ (MFI)^{0.85}$ | 0.88 | Silva et al., 2010b |
| 19° 38′ 23″S | 42° 51′ 13″W | Antônio Dias | MG | 3 | 420 | 1198 | 12,919 | $EI_{30}=-119.27+7.84\ (P)$ | 0.9 | Silva et al., 2010b |
| 19° 13′ 20″S | 42° 29′ 41″W | Belo Oriente | MG | 3 | 280 | 1223 | 8670 | $EI_{30}=215.4\ (MFI)^{0.65}$ | 0.89 | Silva et al., 2010b |
| 19° 47′ 55″S | 42° 08′ 51″W | Caratinga | MG | 3 | 660 | 1037 | 10,115 | $EI_{30}=321.63\ (MFI)^{0.48}$ | 0.86 | Silva et al., 2010b |
| 18° 33′ 25″S | 42° 32′ 35″W | Peçanha | MG | 3 | 890 | 1100 | 9013 | $EI_{30}=-141.07+9.63\ (P)$ | 0.9 | Silva et al., 2010b |
| 18° 40′ 23″S | 43° 04′ 52″W | Sabinópolis | MG | 3 | 760 | 1078 | 8670 | $EI_{30}=123.33\ (MFI)^{0.74}$ | 0.95 | Silva et al., 2010b |
| 19° 57′ 26″S | 43° 24′ 60″W | Santa Bárbara | MG | 3 | 810 | 1272 | 9145 | $EI_{30}=170.59\ (MFI)^{0.64}$ | 0.93 | Silva et al., 2010b |
| 18° 27′ 19″S | 43° 18′ 16″W | Sto. Ant. Itambé | MG | 3 | 720 | 1411 | 15,280 | $EI_{30}=179.33\ (MFI)^{0.77}$ | 0.9 | Silva et al., 2010b |
| 18° 51′ 87″S | 42° 58′ 29″W | Sto D. do Prata | MG | 3 | 621 | 1102 | 13,145 | $EI_{30}=114.42\ (MFI)^{0.81}$ | 0.86 | Silva et al., 2010b |
| 22° 6′ 54″S | 54° 33′ 39″W | Dourados | MS | 8 | 458 | 1378 | 9256 | $EI_{30}=73.464+56.562\ (MFI)$ | 0.80 | Oliveira et al., 2011b |
|  |  |  |  |  |  |  |  | $EI_{30}=80.305\ (MFI)^{0.8966}$ | 0.88 |  |
| 18° 18′ 10″S | 54° 26′ 43″W | Coxim | MS | 4 | 238 | 1371 | 10,439 | $EI_{30}=247.35+41.036\ (MFI)$ | 0.90 | Oliveira et al., 2011b |
|  |  |  |  |  |  |  |  | $EI_{30}=138.33\ (MFI)^{0.7431}$ | 0.91 |  |
| 20° 15′ 57″S | 54° 18′ 54″W | Campo Grande | MS | 3 | 592 | 1419 | 9872 | $EI_{30}=171.40+42.173\ (MFI)$ | 0.78 | Oliveira et al, 2011b |
|  |  |  |  |  |  |  |  | $EI_{30}=139.44\ (MFI)^{0.6784}$ | 0.91 |  |
| 15° 37′ 18″S | 56° 06′ 30″W | Cuiabá | MT | 18 | 151 | 1387 | 8810 | $EI_{30}=109.412\ (MFI)^{0.744}$ | 0.91 | Almeida et al., 2011a |
| 16° 27′ 0″S | 54° 34′ 12″W | Rondonopolis | MT | 6 | 284 | 1274 | 6641 | $EI_{30}=133.2004291\ (MFI)^{0.5372499}$ | 0.90 | Almeida et al., 2011b |
| 16° 03′ 0″S | 57° 40′ 48″W | Caceres | MT | 7 | 118 | 1191 | 5056 | $EI_{30}=172.6326451\ (MFI)^{0.5245258}$ | 0.94 | Almeida et al., 2011b |
| 15° 39′ 0″S | 57° 29′ 00″W | Caceres | MT | 9 | 135 | 1369 | 8493 | $EI_{30}=56.115\ (MFI)^{0.9504}$ | 0.87 | Morais et al., 1991 |
| 16° 02′ 0″S | 57° 16′ 00″W | Caceres | MT | 7 | 155 | 1316 | 7830 | $EI_{30}=36.849\ (MFI)^{1.0852}$ | 0.84 | Morais et al., 1991 |
| 13° 33′ 0″S | 52° 15′ 36″W | Canarana | MT | – | 406 | 1796 | 12,516 | $EI_{30}=317.397829\ (MFI)^{0.484654}$ | 0.86 | Almeida et al., 2011c |
| 12° 17′ 24″S | 55° 17′ 24″W | Vera | MT | – | 379 | 2259 | 15,965 | $EI_{30}=399.538719\ (MFI)^{0.458718}$ | 0.84 | Almeida et al., 2011c |
| 15° 50′ 24″S | 54° 23′ 24″W | Poxoréo | MT | – | 370 | 1688 | 8652 | $EI_{30}=272.865645\ (MFI)^{0.419164}$ | 0.66 | Almeida et al., 2011c |
| 13° 26′ 24″S | 56° 42′ 36″W | São J. Rio Claro | MT | – | 360 | 1881 | 7107 | $EI_{30}=147.262400\ (MFI)^{0.533025}$ | 0.83 | Almeida et al., 2011c |
| 8° 13′ 42″S | 49° 21′ 58″W | Conc. Araguaia | PA | 8 | 203 | 1729 | 11,487 | $EI_{30}=321.5+36.2\ (MFI)$ | 0.89 | Oliveira, 1996 |
| 5° 24′ 35″S | 49° 06′ 48″W | Marabá | PA | – | 98 | 1969 | 13,915 | – | – | Oliveira et al., 1992 |
| 1° 04′ 48″S | 46° 47′ 21″W | Bragança | PA | – | 21 | 2318 | 12,351 | – | – | Oliveira et al., 1992 |
| 2° 15′ 30″S | 49° 31′ 06″W | Cametá | PA | – | 11 | 2255 | 14,756 | – | – | Oliveira et al., 1989 |
| 3° 47′ 04″S | 49° 42′ 18″W | Tucuruí | PA | – | 203 | 2207 | 14,487 | – | – | Oliveira et al., 1989 |
| 3° 01′ 41″S | 47° 21′ 10″W | Paragominas | PA | – | 140 | 1954 | 13,251 | – | – | Oliveira et al., 1989 |
| 1° 26′ 37″S | 48° 28′ 30″W | Belem | PA | – | 15 | 3144 | 22,452 | – | – | Oliveira et al., 1995 |
| 7° 58′ 48″S | 35° 8′ 60″W | Olinda | PE | 10 | 61 | 1852 | 6325 | $EI_{30}=57.25+30.8\ (MFI)$ | 0.88 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=69.24(MFI)^{0.75}$ | 0.87 |  |
| 8° 24′ 4″S | 35° 25′ 54″W | Catende | PE | 5 | 160 | 699 | 3601 | $EI_{30}=57.32\ (MFI)^{0.618}$ | 0.75 | Cantalice et al., 2009 |
| 8° 0′ 1″S | 35° 10′ 42″W | Gloria do Goitá | PE | 10 | 153 | 956 | 3212 | $EI_{30}=97.79+15\ (MFI)$ | 0.72 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=50.75\ (MFI)^{0.724}$ | 0.78 |  |
| 8° 17′ 17″S | 35° 58′ 56″W | Caruaru | PE | 9 | 540 | 501 | 1909 | $EI_{30}=61.81\ (MFI)^{0.58}$ | 0.67 | Cantalice et al., 2009 |
| 8° 11′ 33″S | 36° 4′ 53″W | São Caetano | PE | 11 | 650 | 500 | 1672 | $EI_{30}=61.81\ (MFI)^{0.58}$ | 0.67 | Cantalice et al., 2009 |
| 8° 20′ 38″S | 36° 25′ 26″W | Belo Jardim | PE | 7 | 610 | 628 | 2862 | $EI_{30}=61.81(MFI)^{0.58}$ | 0.67 | Cantalice et al., 2009 |
| 7° 34′ 12″S | 40° 30′ 02″W | Araripina | PE | 9 | 630 | 719 | 2860 | $EI_{30}=73.34+23.18\ (MFI)$ | 0.94 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=95.48\ (MFI)^{0.56}$ | 0.82 |  |
| 8° 17′ 1″S | 39° 14′ 7″W | Cabrobó | PE | 9 | 336 | 446 | 2518 | $EI_{30}=73.34+23.18\ (MFI)$ | 0.94 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=95.48\ (MFI)^{0.56}$ | 0.82 |  |
| 7° 52′ 57″S | 40° 04′ 49″W | Ouricuri | PE | 11 | 450 | 580 | 2538 | $EI_{30}=73.34+23.18\ (MFI)$ | 0.94 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=95.48(MFI)0.56$ | 0.82 |  |
| 9° 23′ 33″S | 40° 30′ 16″W | Petrolina | PE | 8 | 370 | 438 | 3480 | $EI_{30}=73.34+23.18\ (MFI)$ | 0.94 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=95.48\ (MFI)^{0.56}$ | 0.82 |  |
| 8° 19′ 16″S | 37° 43′ 26″W | Poço da Cruz | PE | 8 | 470 | 498 | 3159 | $EI_{30}=73.34+23.18\ (MFI)$ | 0.94 | Cantalice et al., 2009 |
|  |  |  |  |  |  |  |  | $EI_{30}=95.48\ (MFI)^{0.56}$ | 0.82 |  |
| 24° 15′ 18″S | 53° 20′ 35″W | Oeste Paraná | PR | – | – | – | – | $EI_{30}=182.86+56.21\ (MFI)$ | – | Rufino et al., 1993 |
| 26° 4′ 21″S | 53° 1′ 31″W | Sudoeste Paraná | PR | – | – | – | – | $EI_{30}=144.86+55.20\ (MFI)$ | – | Rufino et al., 1993 |
| 22° 28′ 57″S | 51° 11′ 29″W | Norte Paraná | PR | – | – | – | – | $EI_{30}=216.31+41.30\ (MFI)$ | – | Rufino et al., 1993 |
| 23° 13′ 25″S | 51° 16′ 13″W | Noroeste Paraná | PR | – | – | – | – | $EI_{30}=164.12+39.44\ (MFI)$ | – | Rufino et al., 1993 |
| 23° 26′ 43″S | 52° 1′ 54″W | Centro Paraná | PR | – | – | – | – | $EI_{30}=191.79+48.40\ (MFI)$ | – | Rufino et al., 1993 |
| 25° 30′ 55″S | 51° 27′ 51″W | Centro S. Paraná | PR | – | – | – | – | $EI_{30}=107.52+46.89\ (MFI)$ | – | Rufino et al., 1993 |
| 24° 24′ 19″S | 50° 15′ 45″W | Centro L. Paraná | PR | – | – | – | – | $EI_{30}=93.29+41.20\ (MFI)$ | – | Rufino et al., 1993 |
| 25° 13′ 30″S | 49° 8′ 32″W | Leste Paraná | PR | – | – | – | – | $EI_{30}=33.26+40.71\ (MFI)$ | – | Rufino et al., 1993 |
| 22° 10′ 12″S | 42° 19′ 17″W | Nova Friburgo | RJ | 5 | 857 | 1063 | 5431 | $EI_{30}=-67.99+33.86\ (MFI)$ | 0.85 | Carvalho et al., 2005 |
| 22° 27′ 30″S | 43° 24′ 39″W | Seropédica | RJ | 7 | 33 | 1118 | 5472 | $EI_{30}=64.87+38.14\ (MFI)$ | 0.82 | Carvalho et al., 2005 |
| 22° 04′ 04″S | 43° 33′ 30″W | Rio das Flores | RJ | 5 | 400 | 1028 | 4118 | $EI_{30}=112.54+20.70\ (MFI)$ | 0.82 | Gonçalves et al., 2006 |
| 22° 13′ 39″S | 44° 03′ 41″W | Valença | RJ | 7 | 567 | 1550 | 6971 | $EI_{30}=194.08+27.74\ (MFI)$ | 0.82 | Gonçalves et al., 2006 |
| 23° 1′ 48″S | 44° 31′ 12″W | Angra dos Reis | RJ | 6 | 6 | 2034 | 10,140 | $EI_{30}=73.21+44.61\ (MFI)$ | 0.84 | Gonçalves et al., 2006 |
| 21° 50′ 24″S | 44° 34′ 48″W | Carmo | RJ | 15 | 146 | 1013 | 5653 | $EI_{30}=223.87+21.00\ (MFI)$ | 0.72 | Gonçalves et al., 2006 |
| 22° 28′ 48″S | 43° 50′ 24″W | Barra do Piraí | RJ | 14 | 371 | 1486 | 4985 | $EI_{30}=50.36+24.53\ (MFI)$ | 0.96 | Gonçalves et al., 2006 |
| 22° 41′ 60″S | 43° 52′ 48″W | Pirai | RJ | 15 | 462 | 1451 | 6696 | $EI_{30}=112.54+20.70\ (MFI)$ | 0.82 | Gonçalves et al., 2006 |
| 22° 45′ 0″S | 44° 7′ 12″W | Rio Claro | RJ | 15 | 479 | 1466 | 9031 | $EI_{30}=118.71+38.48\ (MFI)$ | 0.98 | Gonçalves et al., 2006 |
| 22° 42′ 36″S | 42° 42′ 0″W | Rio Bonito | RJ | 16 | 40 | 1387 | 5289 | $EI_{30}=38.48+35.13\ (MFI)$ | 0.81 | Gonçalves et al., 2006 |
| 22° 34′ 48″S | 42° 56′ 24″W | Magé | RJ | 19 | 10 | 1859 | 10,235 | $EI_{30}=64.59+47.68\ (MFI)$ | 0.89 | Gonçalves et al., 2006 |

*(continued on next page)*

**Table 1** (*continued*)

| Latitude | Longitude | City | States | Years | Altitude | Precipitation | R factor | Equations | $R^2$ | Authors |
|---|---|---|---|---|---|---|---|---|---|---|
| 22° 28′ 48″S | 42° 39′ 36″W | Conc. Macabu | RJ | 15 | 40 | 1915 | 7961 | $EI_{30} = 39.86 + 37.90\ (MFI)$ | 0.91 | Gonçalves et al., 2006 |
| 22° 28′ 48″S | 43° 0′ 0″W | Magé | RJ | 16 | 640 | 3006 | 15,806 | $EI_{30} = 146.28 + 46.37\ (MFI)$ | 0.70 | Gonçalves et al., 2006 |
| 22° 51′ 0″S | 42° 32′ 60″W | Saquarema | RJ | 15 | 10 | 1252 | 5448 | $EI_{30} = -13.36 + 50.02\ (MFI)$ | 0.65 | Gonçalves et al., 2006 |
| 22° 55′ 12″S | 43° 25′ 12″W | Rio de Janeiro | RJ | 17 | 40 | 1280 | 4439 | $EI_{30} = 3.89 + 37.76\ (MFI)$ | 0.79 | Gonçalves et al., 2006 |
| 22° 57′ 36″S | 43° 16′ 48″W | Rio de Janeiro | RJ | 16 | 460 | 2170 | 9331 | $EI_{30} = -76.27 + 53.31\ (MFI)$ | 0.40 | Gonçalves et al., 2006 |
| 22° 42′ 38″S | 43° 52′ 41″W | Piraí | RJ | 18 | 462 | – | 6772 | – | – | Machado et al., 2008 |
| 30° 23′ 0″S | 56° 26′ 0″W | Quaraí | RS | 38 | 100 | 1513 | 9292 | $EI_{30} = -47.35 + 82.72\ (MFI)$ | 0.84 | Bazzano et al., 2007 |
| 32° 01′ 0″S | 52° 09′ 0″W | Rio Grande | RS | 23 | 15 | 1162 | 5135 | Non-significant correlation | – | Bazzano et al., 2010 |
| 28° 39′ 0″S | 56° 0′ 0″W | São Borja | RS | 48 | 99 | 1540 | 9751 | $EI_{30} = 99.646 + 63.874\ (MFI)$<br>$EI_{30} = 55.564\ (MFI)^{1.1054}$ | 0.77<br>0.84 | Cassol et al., 2008 |
| 30° 32′ 0″S | 52° 31′ 0″W | Enc. do Sul | RS | 31 | 420 | 1279 | 5534 | Non-significant correlation | – | Eltz et al., 2011 |
| 29° 45′ 0″S | 57° 05′ 0″W | Uruguaiana | RS | 29 | 74 | 1171 | 8875 | $EI_{30} = -96735 + 81.967\ (MFI)$ | 0.94 | Hickmann et al., 2008 |
| 28° 33′ 0″S | 53° 54′ 0″W | Ijuí | RS | 31 | 448 | 1667 | 8825 | $EI_{30} = 330.86 + 34.54\ (MFI)$<br>$EI_{30} = 109.65\ (MFI)^{0.76}$ | 0.40<br>0.53 | Cassol et al., 2007 |
| 27° 51′ 0″S | 54° 29′ 0″W | Santa Rosa | RS | 29 | 273 | 1832 | 11,217 | $EI_{30} = 354.71 + 44.927\ (MFI)$<br>$EI_{30} = 118.52\ (MFI)^{0.8034}$ | 0.41<br>0.50 | Mazurana et al., 2009 |
| 27° 24′ 0″S | 51° 12′ 0″W | Campos Novos | SC | 10 | 947 | 1754 | 6329 | $EI_{30} = 238.585 + 22.626\ (MFI)$<br>$EI_{30} = 59.265\ (MFI)^{1.087}$ | 0.50<br>0.86 | Bertol, 1994 |
| 27° 49′ 0″S | 50° 20′ 0″W | Lages | SC | 10 | 953 | 1549 | 5790 | – | – | Bertol et al., 2002 |
| 22° 37′ 0″S | 52° 10′ 0″W | Teod. Sampaio | SP | 19 | 255 | 1282 | 7172 | $EI_{30} = 106.8183 + 46.9562\ (MFI)$ | 0.93 | Colodro et al., 2002 |
| 22° 31′ 12″S | 47° 2′ 40″W | Campinas | SP | 22 | 670 | 1280 | 6738 | $EI_{30} = 68.730\ (MFI)^{0.841}$ | 0.98 | Lombardi Neto and Moldenhauer, 1992 |
| 23° 13′ 0″S | 49° 14′ 0″W | Piraju | SP | 23 | 571 | 1482 | 7074 | $EI_{30} = 72.5488\ (MFI)^{0.8488}$ | 0.93 | Roque et al., 2001 |
| 24° 17′ 0″S | 47° 57′ 0″W | Sete Barras | SP | 9 | 30 | 1434 | 12,664 | $EI_{30} = 316.20 + 55.40\ (MFI)$ | 0.98 | Silva et al., 2009b |
| 24° 24′ 0″S | 47° 45′ 0″W | Juquiá | SP | 7 | 60 | 824 | 6145 | $EI_{30} = 207.21 + 40.65\ (MFI)$ | 0.90 | Silva et al., 2009b |
| 21° 16′ 58″S | 47° 0′ 36″W | Mococa | SP | – | – | – | – | $EI_{30} = 111.173\ (MFI)^{0.691}$ | 0.98 | Carvalho et al., 1991 |

Years = length of record, altitude (m), P = average annual precipitation (mm), R = R factor (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$), and (–) not available.
States by region: north (Amazonas, AM and Pará, PA); northeast (Ceará, CE and Pernambuco, PE); central-west (Mato Grosso do Sul, MS; Mato Grosso, MT and Goiás, GO); southeast (Espírito Santo,ES; Minas Gerais, MG; Rio de Janeiro, RJ and São Paulo, SP) and south (Paraná, PR; Rio Grande do Sul, RS and Santa Catarina, SC).

The value obtained in Eq. (1) is multiplied by the amount of rain in the respective uniform segment to express the kinetic energy of the segment in MJ $ha^{-1}$. The total kinetic energy of rain (Ect) is obtained by adding the kinetic energy of all the uniform segments of rain. The $EI_{30}$ is defined as the product of the maximum rain intensity during a 30-minute period ($I_{30}$) and the Ect.

$$EI_{30} = Ect\ \ I_{30} \tag{2}$$

where $EI_{30}$ is the rainfall erosivity index (MJ mm $ha^{-1}$ $h^{-1}$), Ect is the total kinetic energy of the rain (MJ $ha^{-1}$), and $I_{30}$ is the maximum rain intensity during a 30-minute period (mm $h^{-1}$).

The RUSLE R factor is obtained from the average annual values of the $EI_{30}$ erosion index:

$$R = \frac{1}{n}\sum_{j=1}^{n}\sum_{k=1}^{m_j}(EI_{30})_k \tag{3}$$

where $R$ is the average of the annual rainfall erosivity (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$), $n$ is the number of years of records, $m_j$ is the number of erosive events in a given year $j$, and $EI_{30}$ is the rainfall erosivity index of a single event $k$.

After calculating the values of $EI_{30,}$ a regression analysis is performed, usually using the Fournier index modified by Lombardi Neto (1977) or mean annual precipitation (P) (Eq. (4)) as independent variables. In Brazil, several researchers showed that the modified Fournier index (MFI) have achieved best results in the calculating of the R Factor (Carvalho et al., 2005; Cassol et al., 2008; Lombardi Neto and Moldenhauer, 1992; Oliveira et al., 2011b). These resulting regression equations generally are used to calculate the erosivity from pluviometric data in regions that have no pluviographic rainfall data.

$$MFI = p_i^2 P^{-1} \tag{4}$$

where MFI is the modified Fournier index, $p$ is the mean monthly precipitation at month $i$ (mm), and $P$ is the mean annual precipitation (mm).

### 3.2. Mapping rainfall erosivity

The erosivity map can be obtained by interpolation methods using sampled values to estimate the erosivity values in places where no rainfall data are available (Montebeller et al., 2007). Until the late 1980s, interpolation techniques such as inverse distance, Thiessen polygons, or isohyetal method were the most popular techniques for the interpolation of rainfall data (Goovaerts, 1999). Silva (2004) used point erosivity values (calculated from regression equations) and the inverse distance method to obtain an erosivity map of Brazil. This study provided a good overall understanding of the occurrence of larger and smaller values of erosivity throughout the country.

Since the 1990s, a geostatistical interpolation method based on the regionalized variables theory has been widely used (Goovaerts, 1999) because it allows estimation at nonsampled points without bias and with minimum variance (Montebeller et al., 2007). Several studies were performed using the Kriging interpolation method to obtain erosivity maps. We can cite the works of Shamshad et al. (2008) in Peninsular Malaysia, Angulo-Martínez et al. (2009) in northeastern Spain, Zhang et al. (2010) in northeastern China, Meusburger et al. (2011) in Switzerland, and Bonilla and Vidal (2011) in central Chile. In Brazil, erosivity maps were created by Vieira and Lombardi Neto (1995) in São Paulo State, Mello et al. (2007) in Minas Gerais State, Montebeller et al. (2007) in Rio de Janeiro State, and Oliveira et al. (2011b) in Mato Grosso do Sul State.

In addition to the use of the geostatistical method for erosivity mapping, the application of machine learning techniques (ML) also is successfully used as a tool to obtain values of erosivity in places where no rainfall data are available. One of the main techniques of ML is Artificial Neural Networks (ANN), which have been used satisfactorily for this purpose (Licznar, 2005). In Brazil, ANN was used to

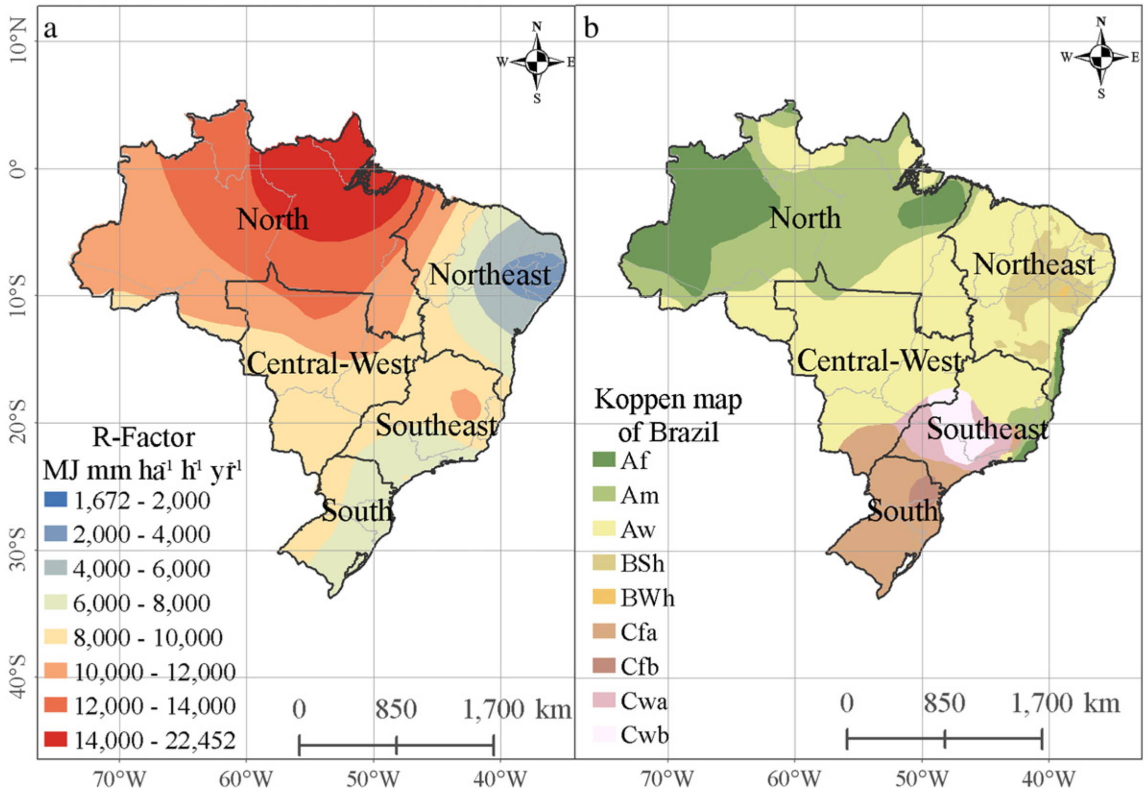

**Fig. 2.** a. R factor map of Brazil (an approximation). b. Koppen climate classification of Brazil. Where Af, equatorial, fully humid; Am, equatorial, monsoonal; Aw, equatorial, winter dry; BSh, hot arid steppe; BWh, hot arid desert; Cfa, humid, warm temperate, hot summer; Cfb, humid, warm temperate, warm summer; Cwa, winter dry, warm temperate, hot summer; Cwb, winter dry, warm temperate, warm summer.

estimate the rainfall erosivity in the States of São Paulo (Moreira et al., 2006), Minas Gerais (Moreira et al., 2008), and Mato Grosso do Sul (Alves Sobrinho et al., 2011), and Silva et al. (2010a) worked in the Vale do Ribeira, in southern São Paulo State. Like the rainfall erosivity mapping by geostatistical techniques, studies using ANN are concentrated in the southeastern region of Brazil. Thus, we find it necessary to perform further studies in other regions of Brazil because this kind of regional approach helps in effective land-use planning.

### 3.3. Spatial distribution of erosivity studies in Brazil

We found 35 studies that used pluviographic rainfall data to calculate the rainfall erosivity. These studies focused on 80 cities in 14 of the 26 Brazilian states, i.e. with no studies on erosivity in the other half of the states. Most studies concentrated on the cities of the south and southeast regions (~60% of all the cities studied in Brazil), with only a few studies in other regions, mainly in the north and central-west (Fig. 1 and Table 1). This concentration occurs because the south and southeast regions are the most economically prosperous and have a higher population density.

The rainfall erosivity values observed in Brazil ranges from 1672 to 22,452 MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$. The average erosivity (±sd) observed is 8403±4090 MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$. Lower values are found in the northeastern region, in the state of Pernambuco (PE), and the highest values are found in the north region (States of Para — PA and Amazonas — AM) and southeast region (States of Minas Gerais — MG, Rio de Janeiro — RJ, and Sao Paulo — SP) (Table 1 and Fig. 2a). Fig. 2a was derived using the data presented in Table 1 and kriging interpolation method. However, this map is

**Table 2**
Range of rainfall erosivity values for several locations of the world.

| Locate | Erosivity (MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$) | Source |
|---|---|---|
| *Tropical sites* | | |
| Honduras | 2980–7297 | Mikhailova et al. (1997) |
| Peninsular Malaysia | 9000–14,000 | Shamshad et al. (2008) |
| Colombian Andes | 10,409–15,975 | Hoyos et al. (2005) |
| El Salvador Republic | 7196–17,856 | Silva et al. (2011) |
| Southeastern Nigeria | 12,814–18,611 | Obi and Salako (1995) |
| Brazil | 1672–22,452 | Present paper |
| Australia's tropics | 1080–33,500 | Yu (1998) |
| *Temperate sites* | | |
| Slovenia | 1318–2995 | Mikos et al. (2006) |
| Mediterranean region | 100–3203 | Diodato and Bellocchi (2010) |
| Northeastern Spain | 40–4500 | Angulo-Martínez et al. (2009) |
| Switzerland | 124–5611 | Meusburger et al. (2011) |
| Korea | 2109–6876 | Lee and Heo (2011) |
| Central Chile | 50–7400 | Bonilla and Vidal (2011) |
| United States | 85–11,900 | Renard and Freimund (1994) |

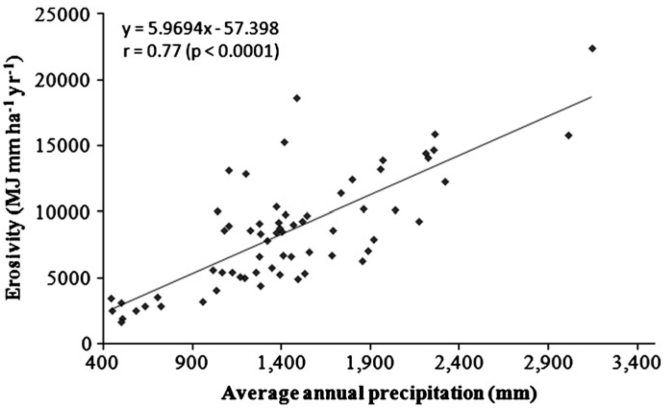

**Fig. 3.** Correlation between annual erosivity and annual precipitation.

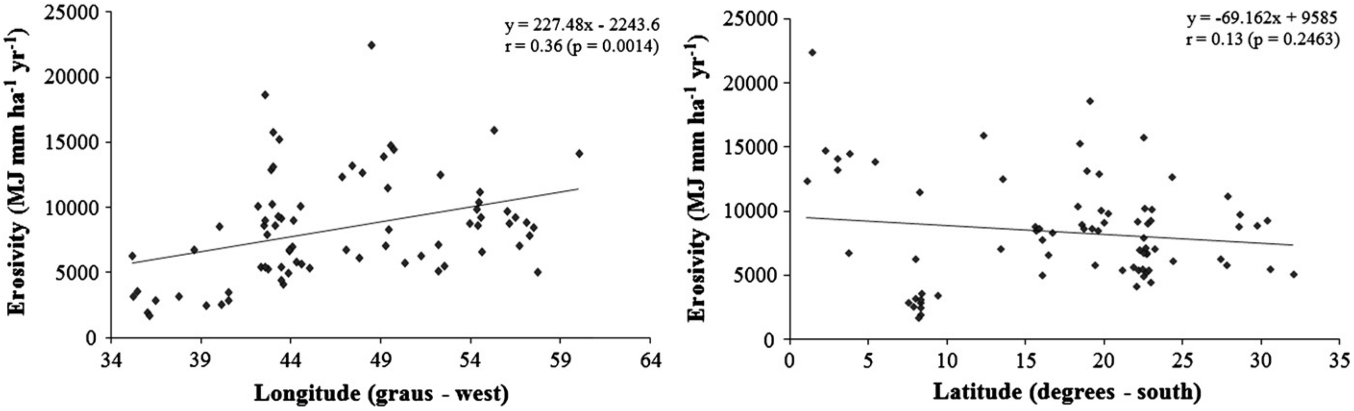

**Fig. 4.** Correlation of the longitude and latitude with the annual erosivity.

illustrative only because it is based on a sparse data set. To obtain a more accurate erosivity map, we recommend applying the equations presented in Table 1 in pluviometric data of other Brazilian places and after with several data points elaborating the map.

The influence of the climate in the annual rainfall erosivity can be observed in Fig. 2. The lower values are found in the northeast, in regions with climates hot arid steppe (BSh), and hot arid desert (BWh). In these regions, the average annual precipitation is below 800 mm. We found the highest annual erosivity values, such as those in the cities of Belem, PA and Tucurui, PA, with erosivity values of the 22,452 and 14,756 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$, respectively. This region has an equatorial, humid (Af) and equatorial monsoonal (Am) climates, with average annual precipitation of the 2300 mm and high intensity rainfall , thus resulting in high erosivity values.

The range of rainfall erosivity values of Brazil is similar to the range observed in other tropical regions, and they are higher than the observed in temperate climate regions (Table 2). These higher erosivity values observed in the tropics are caused by the high amount of precipitation, intensity and kinetic energy of rain. The main rainfall generating mechanism in most tropical regions is convection. As a result, the tropics receive more rain at higher intensities than the temperate regions, dominated by midlatitude cyclones (Hoyos et al., 2005).

The correlation between annual precipitation and erosivity ($r = 0.77$) was significant at the 0.05 level (Fig. 3). However, the pattern of rainfall erosivity in Brazil cannot be explained only by annual precipitation. Several researchers found that high values of annual precipitation does not necessarily produce higher values of erosivity (Bazzano et al., 2010; Mello et al., 2007; Oliveira et al., 2011b; Silva et al., 2010b). In Brazil, the greatest erosivity values are caused by intense rainfall occurring in certain times of the year.

We found that there was a significant correlation between longitude ($r = 0.36$) and annual erosivity at the 0.05 level (Fig. 4). Despite of the low value of the correlation coefficient, it is possible to verify the erosivity increase from east to west. It occurs mainly due to the low erosivity in the northeastern region and high in northwest region. We did not find significant correlation between latitude ($r = 0.13$) and annual erosivity at the 0.05 level.

According to classifications for the interpretation of the annual erosivity index of Brazil, we found that the erosivity rainfall values exceed 7357 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$ (strong erosivity) in 52.6% of the data (Table 3). From this results we found that in Brazil there are several areas of water erosion risk, mainly southeastern and central-west regions. In these regions the rapid expansion of sugar cane cultivation for production sugar and biofuel is occurring (Loarie et al., 2011). Thus, the knowledge of these areas with higher erosivity rainfall values is essential to assess the soil erosion risk and to support to soil and water conservation planning (Oliveira et al., 2011a).

In Brazil, 73 equations correlate the rainfall erosivity index ($EI_{30}$) with the mean annual precipitation (P) or the modified Fournier index (MFI) (Table 1 and Fig. 1). The equations presented in Table 1 can be used in areas that have no pluviographic rainfall data but that have similar climatic conditions. However, the equations cannot be extrapolated to a generalized form without underestimating or overestimating the erosivity values. Studies must be conducted on the local climate to determine which equation is best suited to the desired region.

Silva (2004) proposed the division of Brazil into eight homogeneous regions according to rainfall. A single equation was designated for each region to allow the rainfall erosivity for each month to be estimated from the rainfall coefficient. In this proposal, the same equation was applied to several states. We compare the R factor values presented in Table 1 with the results calculated by Silva (2004). We conclude that despite providing a significant contribution

**Table 3**
Classifications for the interpretation of the annual erosivity index of Brazil.

| Erosivity[a] (MJ mm ha$^{-1}$ h$^{-1}$) | Erosivity class | Observed data (%) |
|---|---|---|
| $R \leq 2452$ | Low erosivity | 2.6 |
| $2452 < R \leq 4905$ | Medium erosivity | 13.2 |
| $4905 < R \leq 7357$ | Medium-strong erosivity | 31.6 |
| $7357 < R \leq 9810$ | Strong erosivity | 23.7 |
| $R > 9810$ | Very strong erosivity | 28.9 |

[a] Source: Carvalho (2008), modified to S.I. metric units according to Foster et al. (1981).

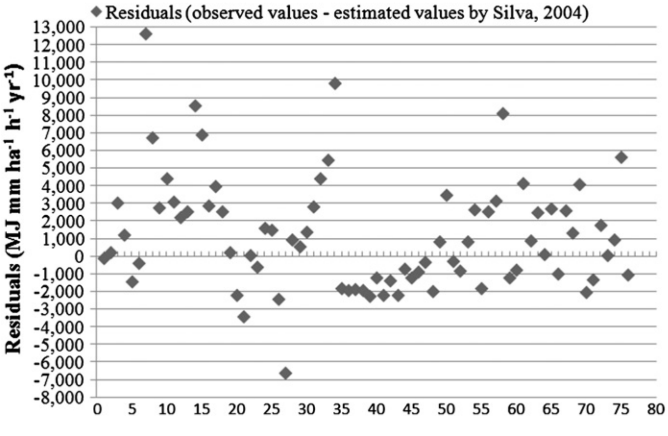

**Fig. 5.** Residual values of erosivity (observed values — estimated values by Silva, 2004).

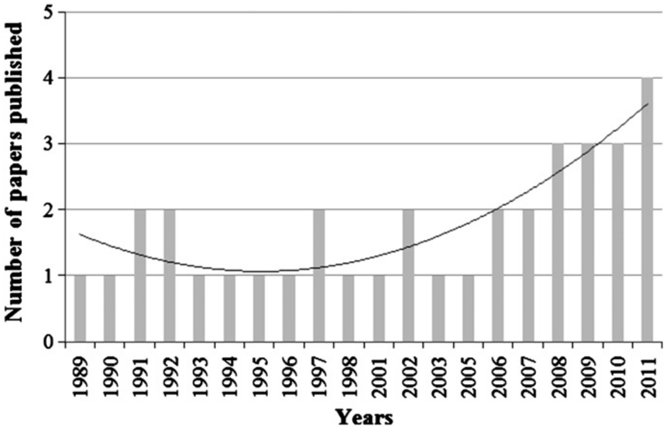

**Fig. 6.** Number of papers published per year.

to the understanding of rainfall erosivity in Brazil, the generalization of these equations produces many errors (Fig. 5). Therefore, the choice of equation to be used in different locations should be performed with caution and should be based on local climate studies.

Before Silva (2004), there were few studies on rainfall erosivity and few equations adjusted for the regions of Brazil. Since 2005, the number of publications on rainfall erosivity has increased significantly (Fig. 6). From the information presented in this present paper, new studies can be developed to map rainfall erosivity for the entire country. The equations that we found (Table 1) can be used with pluviometric data available for all Brazil by Agência Nacional de Águas (ANA) on website (http://hidroweb.ana.gov.br/). Furthermore, we recommend the inclusion of the rainfall return periods and the climate change in future studies.

In addition, the computational advances and the consolidation of the use of methodologies such as artificial neural networks and geostatistics techniques to obtain the rainfall erosivity can help to develop a more precise study for Brazil. These studies are fundamental for achieving effective environmental planning and may assist in analyzing vulnerability, risk forecasting and allocating financial resources for farmers in risk areas (Oliveira et al., 2011a; Rodrigues et al., 2011).

We found that 85% of the analyzed studies were developed using a historical series of less than 20 years, so only 15% of these studies used the minimum series required for RUSLE calculation (Renard et al., 1997) (Fig. 7).

In Brazil, in general, hydrological and meteorological information is scarce or difficult to access (Montebeller et al., 2007; Oliveira et al., 2011b). This is a constant problem in the development of research models in this country. We recommend maintaining the existing stations and establishing new stations because this is the only way to obtain more realistic results. In addition, the development of new regional and global models and new scientific discoveries are needed to obtain basic data for the calibration and validation of the results.

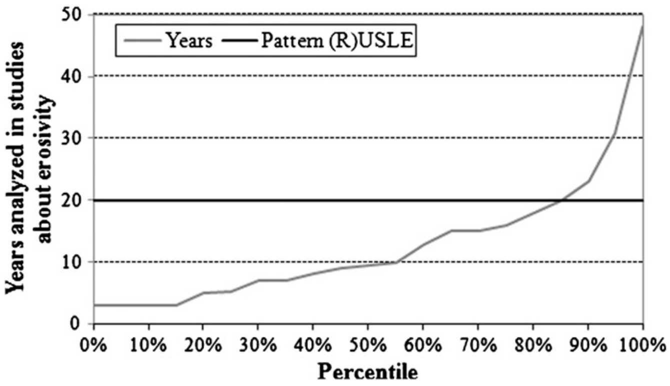

**Fig. 7.** Years of data analyzed in studies on erosivity.

## 4. Conclusions

The annual rainfall erosivity in Brazil, based on our review, ranges from 1672 to 22,452 MJ mm $ha^{-1}$ $h^{-1}$ $yr^{-1}$. The lowest values are found in the northeastern region, and the highest values are found in the north region and the southeastern region. The rainfall erosivity tends to increase from east to west. particularly in the northern part of the country.

We conclude that there are few studies on erosivity in Brazil and that these studies are concentrated in the south and southeast regions. In addition, the number of years of data used in most of those studies was less than the recommended standard for the application of RUSLE (20 years of data).

The regression equations of rainfall erosivity cannot be extrapolated to a generalized form without underestimating or overestimating the erosivity values. Studies must be conducted on the local climate to determine which equation is best suited to the desired region.

In Brazil, there are 73 regression equations to calculate erosivity. These equations can be useful to map rainfall erosivity for the entire country. To this end, techniques already established in Brazil may be used for the interpolation of rainfall erosivity, such as geostatistics and artificial neural networks.

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