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Estimates of Annual Soil Loss Rates in the State of São Paulo, Brazil

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ABSTRACT: Soil is a natural resource that has been affected by human pressures beyond its renewal capacity. For this reason, large agricultural areas that were productive have been abandoned due to soil degradation, mainly caused by the erosion process. The objective of this study was to apply the Universal Soil Loss Equation to generate more recent estimates of soil loss rates for the state of São Paulo using a database with information from medium resolution (30 m). The results showed that many areas of the state have high (critical) levels of soil degradation due to the predominance of consolidated human activities, especially in growing sugarcane and pasture use. The average estimated rate of soil loss is 30 Mg ha^{-1} yr^{-1} and 59 % of the area of the state (except for water bodies and urban areas) had estimated rates above 12 Mg ha^{-1} yr^{-1}, considered as the average tolerance limit in the literature. The average rates of soil loss in areas with annual agricultural crops, semi-perennial agricultural crops (sugarcane), and permanent agricultural crops were 118, 78, and 38 Mg ha^{-1} yr^{-1} respectively. The state of São Paulo requires attention to conservation of soil resources, since most soils led to estimates beyond the tolerance limit.

Keywords: erosion, USLE, soil conservation, GIS, geoprocessing.

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INTRODUCTION

Recent scientific discussions emphasize the need to set limits for exploitation of natural resources with a view to poverty eradication, food security, and economic growth (Rockström et al., 2009; Reid et al., 2010). Increased soil erosion arising from conversion of natural lands into agricultural systems and intensive soil exploitation beyond soil capability for recovery, driven by the growing demand for food, energy, and fiber, intensified by projections of population growth for the coming decades, have been severe consequences of anthropogenic pressures on soil resources (Lal, 2007a,b).

As a result of this intense exploitation of the soil resource, about 12 million ha of arable land is abandoned annually in the world (Pimentel et al., 1995). In the state of São Paulo, 80 % of cultivated land has been affected by erosion beyond the limits of natural soil recovery (São Paulo, 2000). Worldwide about 1 billion hectares has already been affected, 70 % of which is severely compromised (Lal, 2003).

The problems caused by erosion have implications on different scales, ranging from interference in local/regional hydrological processes, sediment flow, and even changes in climate patterns (Dotterweich, 2013), in addition to socioeconomic losses (Telles, 2010). Loss of nutrients and organic matter frequently lead to decline in soil quality and yield losses *in locu* to sedimentation, silting of lakes and rivers, loss of biodiversity, reduced food supply, and increasing food prices on the local, regional, and global level (Lal, 1998). Erosion processes occur significantly faster in Brazil than in temperate climate regions, which has been attributed by Stocking (2003) to rainfall high intensity and the occurrence of erosion-prone soils.

Estimation of soil erosion rates is an important initial step in diagnosing the intensity of erosive processes and in relating erosion to economic, environmental, and social problems (D'Agostini, 1999). In this context, erosion models provide predictions of soil loss rates that are valuable tools for developing public policies, such as priority setting for areas of applying investments, control of urban sprawl, and recommendation of conservation practices for agricultural areas, among others. These models involve biophysical and anthropic parameters (Kinnell, 2010; Vente et al., 2013). In recent years, ease in establishing models, owing to development of Geographic Information Systems (GIS) and advances in data acquisition by Remote Sensing, has paved the way for dissemination of analytical methods and applications on regional scales (Renschler and Harbor, 2002). Meanwhile, Soil Science, recognized since the late nineteenth century as an independent science with specific subject matter (soil) and methodologies, has been increasingly required in issues involving Earth System Science (Janzen, 2004; Bockheim and Gennadiyev, 2010; Janzen et al., 2011).

Therefore, current studies on erosion and soil conservation indicate an imminent demand for interdisciplinary applications on larger scales and kindle discussions in the systemic context of global sustainability beyond the original scope (Hartemink, 2008; Hartemink and McBratney, 2008; Camargo et al., 2010; Bouma, 2014; Díaz-Fierros, 2015; Bellacasa, 2015).

As a consequence, soil conservation studies have become possible on the regional scale by the implementation of soil loss estimation models in the computer environment (Lu et al., 2004; Lino, 2010; Pulido-Gómez, 2012; Rocha, 2013). For the state of São Paulo, available studies focusing on estimation of soil loss are outdated due to an intense process of converting lands from natural to anthropogenic uses, which has been going on over the past decades. Relevant erosion studies for the state were carried out by Marques et al. (1961) and Kertzman et al. (1995), despite the limitations of platforms and digital data, as well as by Bertoni and Lombardi Neto (2012) and other researchers of the Agronomic Institute of Campinas (Instituto Agronômico de Campinas - IAC), a pioneer institution in investigation of erosion and related themes in this region over the past several decades.

Another important aspect in the study of erosion refers to the concept of "soil loss tolerance" or "T-value", a criterion to interpret soil loss rates, defined by Wischmeier and Smith (1978) as "the maximum annual soil erosion rate that still allows a high level of crop productivity". For the state of São Paulo, Lombardi Neto and Bertoni (1975) established standards of soil loss tolerance considering the *solum* depth and other physical soil properties from 375 soil profiles. The estimated T-values ranged from 4.5 to 13.4 Mg ha^{-1} yr^{-1}, for soils with textural B horizon (argillic horizon), and from 9.6 to 15 Mg ha^{-1} yr^{-1} for soils with a Latosolic B horizon (Oxisol horizon). For the state of Santa Catarina, Bertol and Almeida (2000) estimated tolerance limits from 14.5 to 1.88 Mg ha^{-1} yr^{-1} for *Terra Bruna Estruturada* (Alfisols and/or Ultisols) and for *Solos Litólicos* (Entisols), respectively. In general, soil loss tolerance corresponds to a mean tolerable loss of up to 12.5 Mg ha^{-1} yr^{-1} for deep, well-drained, and permeable soils, whereas mean losses from 2 to 4 Mg ha^{-1} yr^{-1} are tolerable for soils with unfavorable, shallower subsoil (Bertoni and Lombardi Neto, 2012).

Considering that studies related to soil loss for the state of São Paulo are outdated and, according to the literature cited, there is an imminent need to estimate soil loss rates to establish limits of soil exploration, which is a non-renewable resource with regard to energy and food security (Rockström et al., 2009), erosion in the state of São Paulo should be diagnosed as a contribution to discussion addressing conservation. Thus, the objective of this study was to estimate soil loss rates for the state of São Paulo by the Universal Soil Loss Equation (Wischmeier and Smith 1965, 1978) on a regional scale, using GIS and medium resolution spatial data (30 m).

MATERIALS AND METHODS

Study area

The study addressed the entire area of the state of São Paulo, between the parallels 19° 50' S and 24° 30' S and the meridians 44° W and 53° 30' W, covering an area of 248,209.4 km^2 (Figure 1).

The state of São Paulo is part of the Southeastern region of Brazil and includes several soil types due to the occurrence of a great diversity of climate, parent materials, relief, and vegetation (Lepsch, 2010). The climate in the south of the state is humid temperate with hot summers (Cfa), based on the Köppen (1936) classification system; in the central and northwest parts, it is humid temperate with dry winters and hot summers (Cwa); and in the

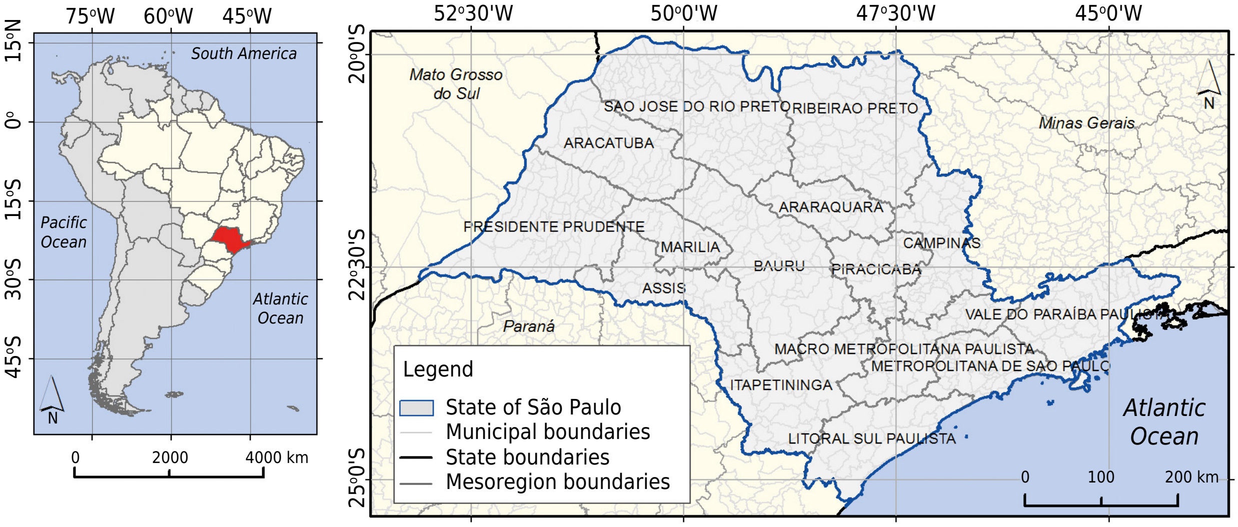

Figure 1. Localization of study area, state of São Paulo (Brazil).

north it is classified as humid temperate with dry winters and temperate summers (Cwb). Total average annual rainfall ranges from 1,000 to 1,400 mm and is concentrated in the summer.

Latossolos (Oxisols) and *Argissolos* (Ultisols and Alfisols) are prevalent and are distributed across the highlands and peripheral depression. In the mountainous region, the less developed *Cambissolos* (Inceptisols) and *Neossolos Litólicos* (Entisols) are predominant. Along rivers, there are *Gleissolos* (Aquents, Aqualfs, Aquepts), *Organossolos* (Histosols), and *Neossolos Flúvicos* (Entsols/Fluvents) (Oliveira et al., 1999).

Cartographic material, basic data, and software

The digital data used in this study were stored and processed by ArcGIS 10.1 software (ESRI, 2014) to constitute the database, proceed with analysis, and present results and included: 1) vector soil map (Oliveira et al., 1999) at a 1:500,000 scale (Figure 2a) for the state of São Paulo; 2) land use cover map of 2005 in raster format at 1:100,000 (São Paulo, 2013) (Figure 1b), and 3) digital Elevation Model of the TOPODATA project (Valeriano, 2008), with a spatial resolution of 30 m (Figure 2c).

METHODS

Erosion model

The annual soil loss rates were estimated by the Universal Soil Loss Equation (USLE), an empirical erosion model “designed to predict longtime average soil loss rates in runoff from specific field areas in specified cropping and management systems” (Wischmeier

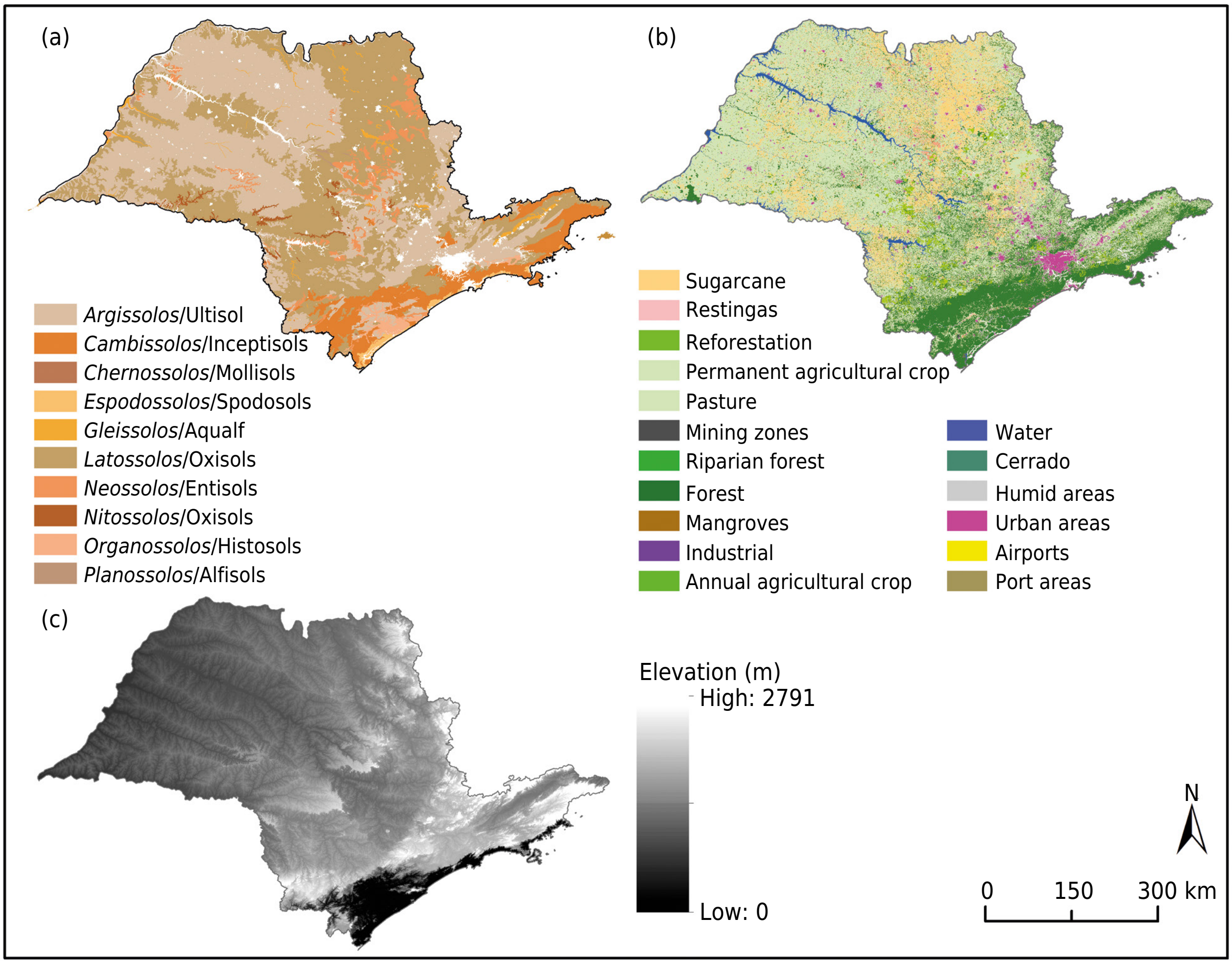

Figure 2. Data used: (a) Pedological map; (b) Land use map of 2005; and (c) Map of Digital Elevation Model (m).

and Smith, 1965; 1978). The model is easy to implement and requires relatively simple entry data; according to Chaves (2010), it has been more effective in predicting erosion on hillsides than other robust methods. Although this model was originally designed to estimate erosion in homogeneous plots (Bertoni and Lombardi Neto, 2012), it has been successfully applied to estimate soil loss rates from complex topographies on regional scales (Martín-Fernández and Martínez-Núñez, 2011; Tetzlaff et al., 2013; Galdino et al., 2015).

As described by equation 1, the USLE model consists of the product of six major factors, which predicts soil loss per unit area in Mg ha^{-1} yr^{-1}.

$$A = R \times K \times L \times S \times C \times P \qquad \text{Eq. 1}$$

where A: computed soil loss per unit area or soil loss rate (Mg ha^{-1} yr^{-1}), R: rainfall and runoff factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K: soil erodibility factor (Mg h MJ^{-1} mm^{-1}), L: slope-length factor (adimensional), S: slope-steepness factor (adimensional), C: cover and management factor (adimensional), and P: support practice factor (adimensional).

Rainfall erosion index (Factor R)

The rainfall erosion index (R) expresses the ability of rainfall to induce erosion in an area without protection from vegetation. The factor R is directly proportional to the product of two rainfall characteristics: total kinetic energy (Ec) and maximum rainfall intensity in 30 min (I30) (Bertoni and Lombardi Neto, 2012). In our study, however, we employed the annual erosion indexes determined by Medeiros (2016) (Figure 3), using the regionalized calculation method proposed by Mello et al. (2013).

Soil erodibility factor (K-Factor)

The soil erodibility factor (K-factor) is a quantitative value experimentally determined by the rate of soil loss per erosion index unit (Wischmeier and Smith, 1978). Denardin (1990) and Mannigel et al. (2002) describe the diversity of soil erodibility in São Paulo based on their classes and subclasses. Data compiled by Silva and Alvares (2005) were used in this study.

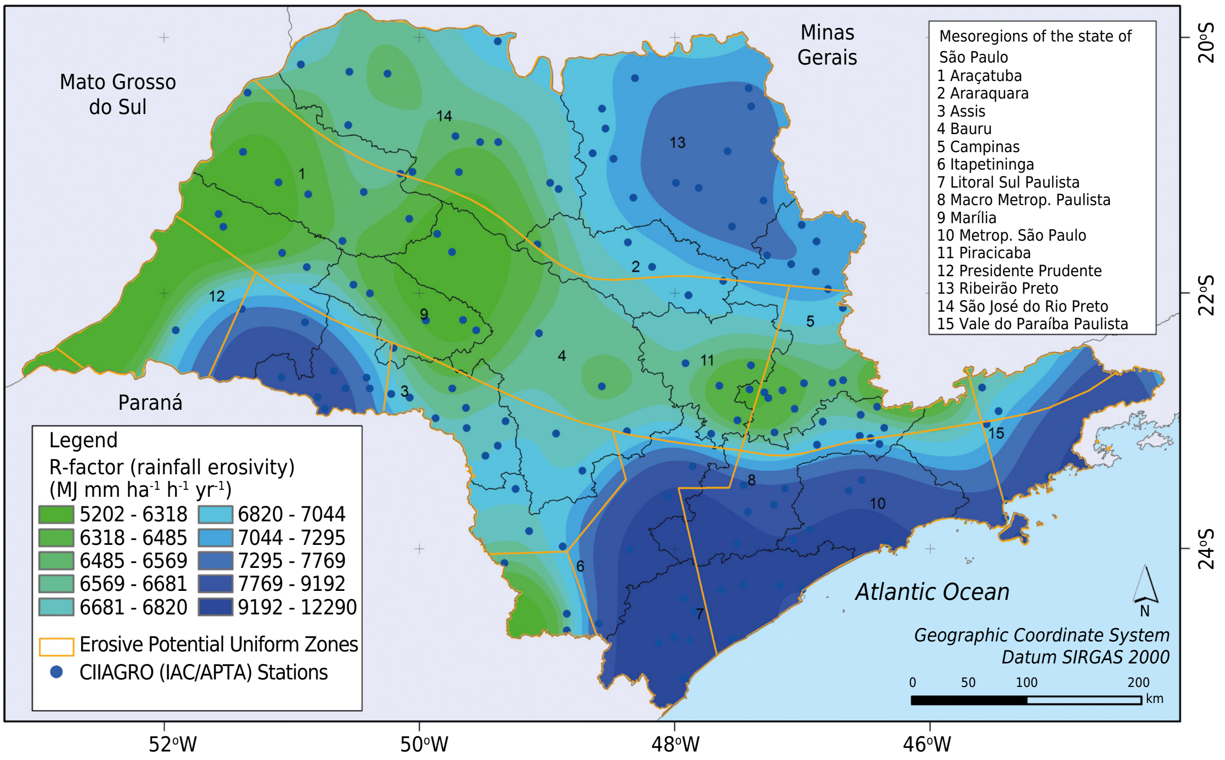

Figure 3. Rainfall erosivity map obtained by Medeiros (2016).

Topographic factor (LS-Factor)

Slope-length and slope-steepness effects (L-Factor and S-Factor)

The topographic properties required in the USLE, slope-length (L) and slope-steepness (S), were calculated from the Digital Elevation Model of the state of São Paulo provided by the TOPODATA project (Valeriano, 2008).

For application of the model to the conditions of complex topography on a regional scale, the L-factor was calculated employing the method of Desmet and Govers (1996), Equation 2, whose algorithm uses the concept of accumulated area and flow directions (Moore et al., 1991). This transposition in scale was also possible due to considerable development of GIS technology in recent decades, which has enabled the implementation of methods and handling of data on digital platforms for large areas, as well as advances in data acquisition, particularly topographical data, by Remote Sensing.

$$L_{i,j} = \frac{(A_{i,j-i,n} + D^2)^{m+1} - (A_{i,j-i,n})^{m+1}}{(D^{m+2}) \times (x_{i,j}^{m}) \times (22,13)^m} \qquad \text{Eq. 2}$$

where is the slope-length factor of a grid cell (i,j), is the area of contribution of a grid cell (i,j), D is the width/height of the cells forming a regular grid (m) (in this case 30 m), is the flow direction value calculated according to the aspect [$x = \text{sen}(\beta) + \cos(\beta)$, where β is aspect – see Moore et al. (1991) about topographic attibutes], and m is the coefficient determined according to steepness (θ): 0.5 if $\theta \geq 5$ %; 0.4 if $3 \% \leq \theta \leq 5$ %; 0.3 if $1 \% \leq \theta \leq 3$ %, and 0.2 if $\theta > 1$ %.

The S-Factor was calculated from equations 3 and 4 as proposed by McCool et al. (1987), considering a steepness threshold (α) of 9 %. The slope map used was obtained from manipulation the topographic data from the TOPODATA database in ArcGIS software.

$$S = 10.8 \times \text{sen}(\alpha) + 0.03; \text{ if } \alpha < 9 \% \qquad \text{Eq. 3}$$

$$S = 16.8 \times \text{sen}(\alpha) - 0.5; \text{ if } \alpha \geq 9 \% \qquad \text{Eq. 4}$$

where S is the slope-steepness factor (adimensional), and is the slope or steepness angle (degrees).

Cover and management factor (C-factor)

The cover and management factor (C-factor) is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). The different aspects of a given crop system, e.g., soil tillage, management effectiveness, rainfall, soil fertility, and the crop development stage, are obtained from experimental results. In our study, however, average values of the C-factor extracted from the literature (Table 1) were associated with the mapped categories of land use cover (Figure 2c).

Support practice factor (P-Factor)

The support practice factor (P-factor) is calculated by the "ratio of soil loss with a specific support practice to the corresponding loss with up-and-down-slope culture" (Wischmeier and Smith, 1978; Bertoni and Lombardi Neto, 2012). In the case of the state of São Paulo, it can generally be assumed that agricultural management is largely mechanical in all stages of agricultural production, but the conservation practices for each production plot cannot be determined. Therefore, as suggested by Bertoni and Lombardi Neto (2012), we used the methodology proposed by Oliveira et al. (2007), which defines the slope (α) as the key property for soil conservation practices and states the following p values according to the slope angle (α): p=0.6, for $0 \leq \alpha \leq 5\%$; $p = 0.69947 - 0.08991\,\alpha + 0.01184\,\alpha^2 – 0.00035\,\alpha^3$, for $5 \% < \alpha \leq 20 \%$; and p=1, for $\alpha > 20$ %.

Table 1. C-factor for each land use cover class of the state of São Paulo in 2005

Land use cover	Factor C	Reference
Annual agricultural crop	0.4238	Lino (2010)
Sugarcane	0.3066	Weill (1999)
Permanent agricultural crop	0.1318	Lino (2010)
Pasture	0.0610	Galdino (2012)
Reforestation	0.0030	Bertoni and Lombardi Neto (2012), Resende and Almeida (1985)
Forest	0.0001	Bertoni and Lombardi Neto (2012)
Riparian forest	0.0001	Bertoni and Lombardi Neto (2012)
Humid areas	0.0001	Adapted from De Maria (1995)
Mangroves	0.0010	De Maria (1995)
Restingas	0.0007	Rio de Janeiro (2009)
Cerrado	0.1500	Pulido-Gómez (2012)

To simplify discussions, these six factors were analyzed according to the mesoeconomic division of the state of São Paulo, as proposed by IBGE (2002). Multiplying these factors, the soil loss rates (Mg ha^{-1} yr^{-1}) for the state of São Paulo is estimated. The application of USLE on a regional scale, favored by digital data management in GIS, results in generalizations, as mentioned particularly for the factors C and P. In addition, it is known that the USLE does not take the sediment deposition on the slopes into account (Zhang et al., 1995), but only estimates the interrill erosion and soil loss from small grooves, a weakness limiting approaches focused on nutrient planning and transport, for example. Another interesting aspect is that the results are related to potential soil loss rates based on mean erosivity values (R) calculated for a wide range of data and do not apply to a particular rainfall event (Merrit et al., 2003), but they still satisfactorily indicate the need for erosion control in the most critical areas.

RESULTS AND DISCUSSION

Erosion modeling

Spatial variability of soil erodibility (K-factor) in the state of São Paulo is high, with numerous areas susceptible to erosion (Figure 4). This is a result of the presence of Argisols, whose mean soil erodibility value reaches 0.0425 Mg h^{-1} MJ^{-1} mm^{-1} on 43 % of the territory. These soils have an eluvial A horizon that is coarse textured and generally sandy (Lepsch, 2010), which is conducive to water erosion because of its fragil structure and weak aggregation. Furthermore, during longer rainfall events, the water flow could reach the illuvial B horizon (argillic), which is less permeable, resulting in the loss of large quantities of soil.

The Oxisols (*Latossolos*), with their high state of weathering, are normally erosion resistant, due to physical conditions unfavorable to soil loss and through being mostly located on smooth landscapes. The erodibility value of this class is low (0.0162 Mg yr^{-1} MJ^{-1} mm^{-1}). These soils occur in 43 % of the state of São Paulo and are predominant in areas where slopes allow agricultural mechanization.

Erodibility indices above 0.0508 Mg yr^{-1} MJ^{-1} mm^{-1} in the state of São Paulo are observed in soils of the southern region where Inceptisols (*Cambissolos*), Podzols (*Espodossolos*), and Histosols (*Organossolos*) occur. Poorly developed Inceptisols, with a cambic B horizon, occur on approximately 4 % of the surface area of the state. In the case of Podzols

(*Espodossolos*), which account for less than 1 % of the area of the state, the sandy texture in most of the profile and the presence of a spodic horizon, a drainage barrier horizon of low fertility, explain their medium value of soil erodibility (0.0592 Mg yr^{-1} MJ^{-1} mm^{-1}). Finally, the Histosols (*Organossolos*), characterized by a composition of at least 80 g kg^{-1} of organic matter, also occur in less than 1 % of the area of the state, and their soil erodibility could exceed 0.0310 Mg yr^{-1} MJ^{-1} mm^{-1}.

The L-factor ranges from 0 (zero) to 3,141 (Figure 5); the lowest values occur in interfluves (hilltops) and the highest towards the bottom of the valley, exactly where the distances from the interfluve zone and the flow convergence are significant and steep slopes (same behavior as in the cumulative area), with conditions similar to those found by Silva (2003) and Michette (2015). The detail of figure 5 shows that the higher the L factor, the greater the runoff speed and concentration, leading to the conclusion that these areas are prone to the occurrence of laminar erosion.

This study used data with a spatial resolution of 30 m. According to Wu et al. (2005), soil loss rates are extremely sensitive to the effect of factor L, so that the more refined the topographical data are, the higher the reliability of the estimates will be.

The slope-steepness factor (S-factor) ranges from 0.03 to 9.89 (Figure 6). The lowest values indicate regions with plain and gently rolling topography and account for 60 % of the study area, according to the slope-steepness category map (Figure 7). The highest values were found for hilly, mountainous, strongly rolling, and rugged areas, and account for 40 % of the total area. The highest S-factor values are predominant in the southern and southeastern regions, which correspond to the geomorphological areas of the Serra do Mar, some areas of the mesoregions of Marília, Araraquara, and Piracicaba, and in the east on the border with the state of Minas Gerais. In the soil exploration context, slope-steepness is a topographical property that predicts land use, particularly agricultural and livestock use, and land occupations, because management techniques, soil acidity, and fertility correction can be used to minimize chemical limitations related to the concentrations of calcium, iron, magnesium, potassium, and other nutrients. Thus, in the

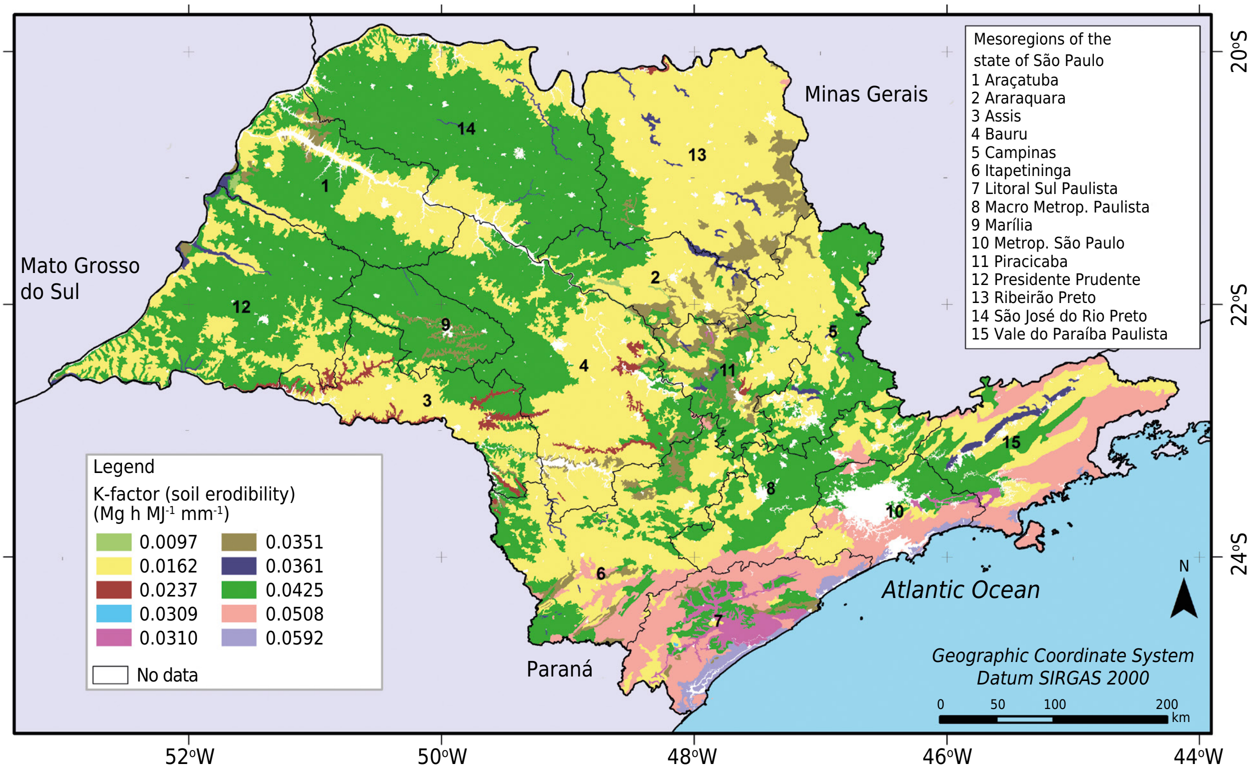

Figure 4. K-factor map of the state of São Paulo.

flat and gently rolling areas appropriate for agricultural activities, the use of agricultural machinery or other management practices tends to be intensive, confirming the high soil loss rates in these locations.

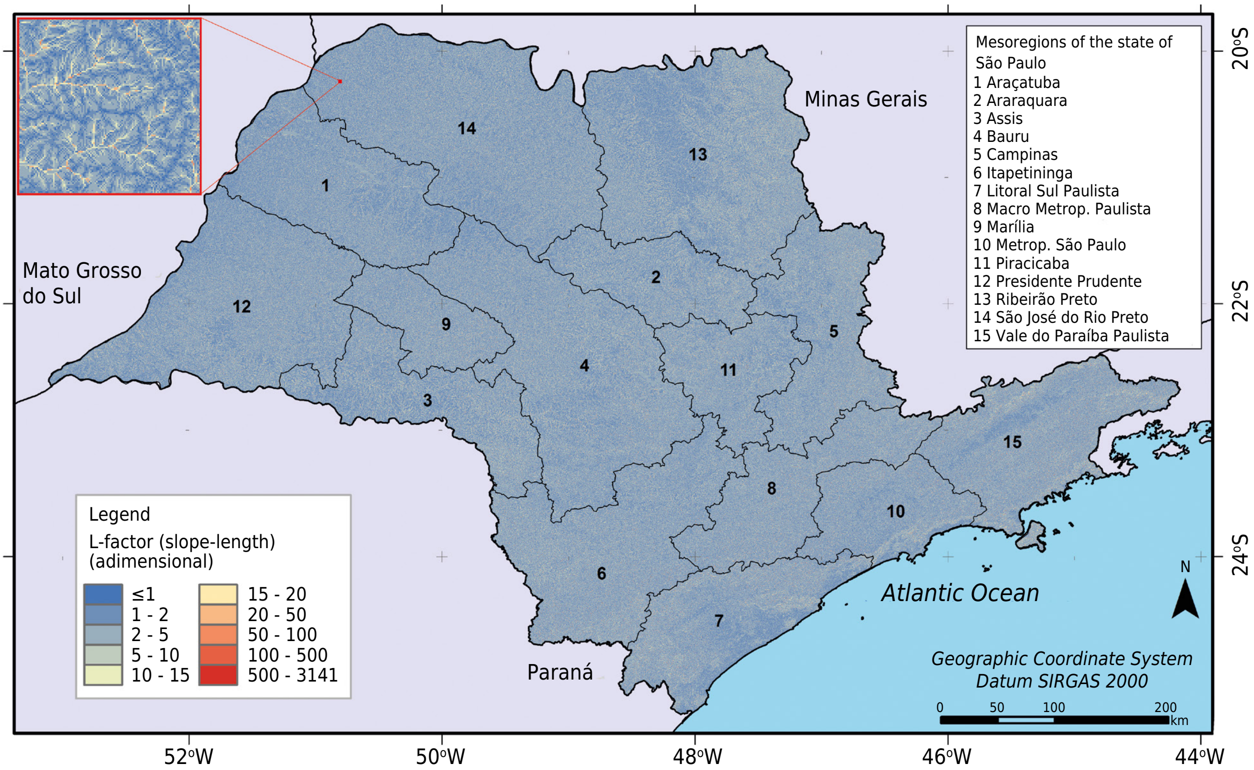

Figure 5. L-factor map of the state of São Paulo.

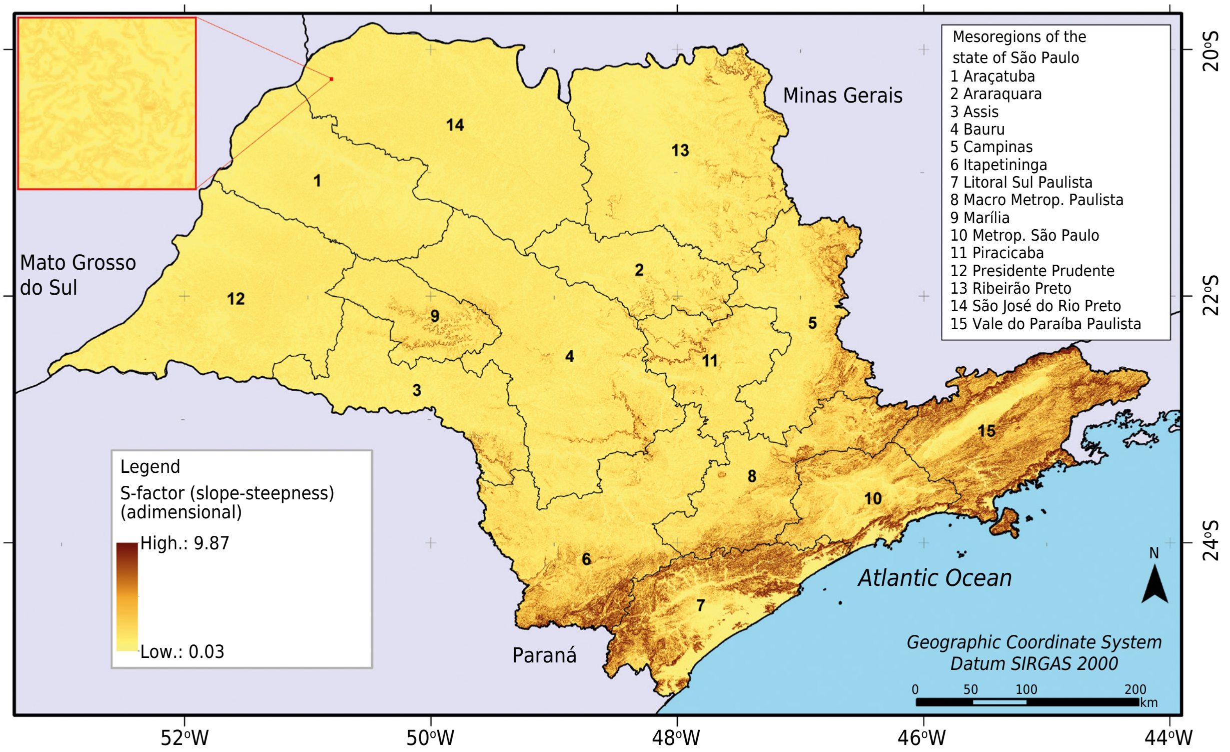

Figure 6. S-factor map of the state of São Paulo.

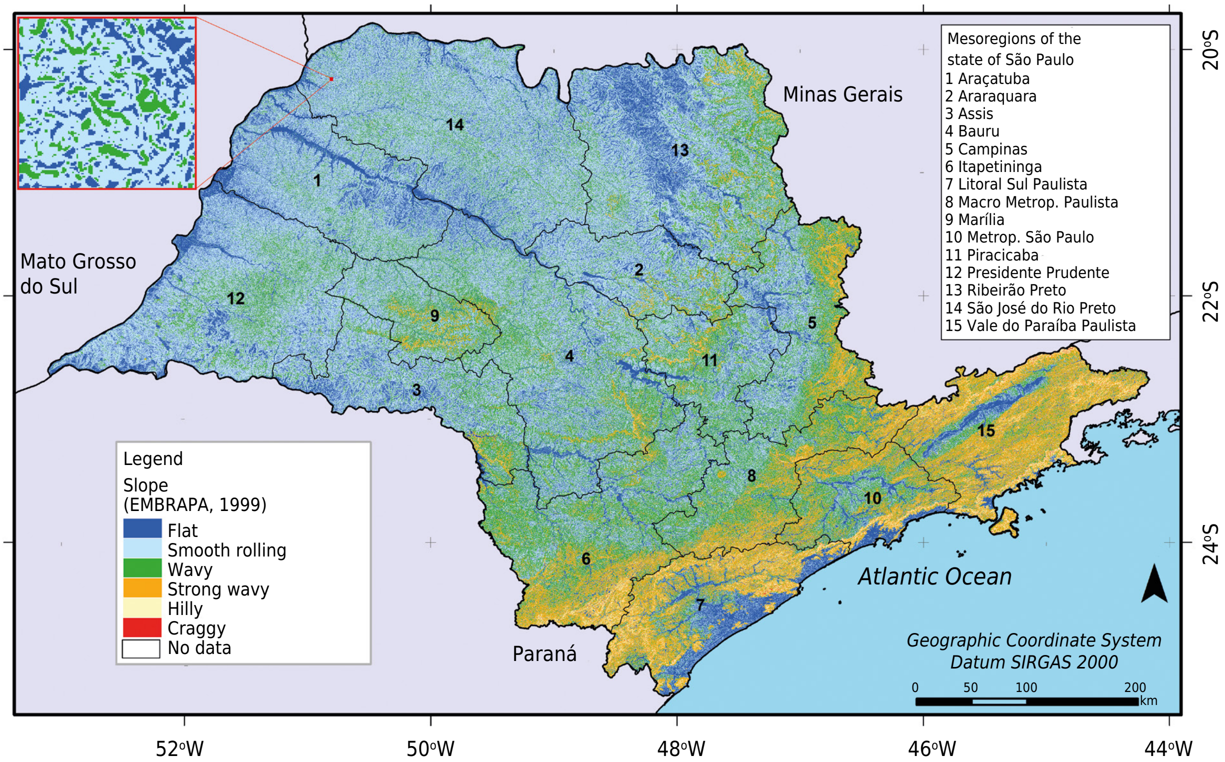

Figure 7. Slope map based on Embrapa classification.

The C-factor (Figure 8) ranges from 0 (zero) to 1. C-factor values closer to zero are indicative of very good protection by crop cover and management systems, and in contrast, values closer to one indicate very poor protection. Thus, predominantly in areas of crop production, higher C-factor values (>0.3) were attributed, according to surveys of the literature, highlighting vast areas in the mesoregions of Ribeirão Preto, Araraquara, Bauru, and Assis. According to the Agricultural Census of 2006 (IBGE, 2006), 76 % of crop/livestock farms employ conventional tillage (with plowing and disking), a practice that significantly contributes to the erosion process. This tillage practice is common throughout the study area, except in mountainous areas and the middle region of the south coast. Regarding the C-factor for pasture areas, we consider the degree of degradation of the pastures of the entire state of Sao Paulo as high, adopting the C-factor value of 0.0610, previously determined by Galdino (2012) from experimental data. Although the Agricultural Census of 2006 indicated that half of the state's pasture areas are natural and the other half correspond to planted pastures, and that of the total planted pasture area, only 4 % is degraded, one can not explicitly assign the location of each pasture type (natural, planted-degraded, or planted-in good condition) since the Census shows values for the municipality. For this reason, we consider that all pastures had at least some degree of degradation.

For the P-factor (Figure 9), the distribution patterns is similar to that of the slope values since the calculation method used in this study assumed that this was the critical topographical property to define the conservation practices. In the mesoregions along the state border with Minas Gerais and the mesoregions of Itapetininga, the southern coastal line of São Paulo, Metropolitan São Paulo, and Paraíba Valley of São Paulo, with rugged and strongly rolling relief, the P factor was close to 1. The minimum P value was calculated as 0.6 for the most effective conservation practices. For some widely used conservation practices, Marques et al. (1961) determined P-factor values (downslope cultivation = 1; contour planting = 0.5).

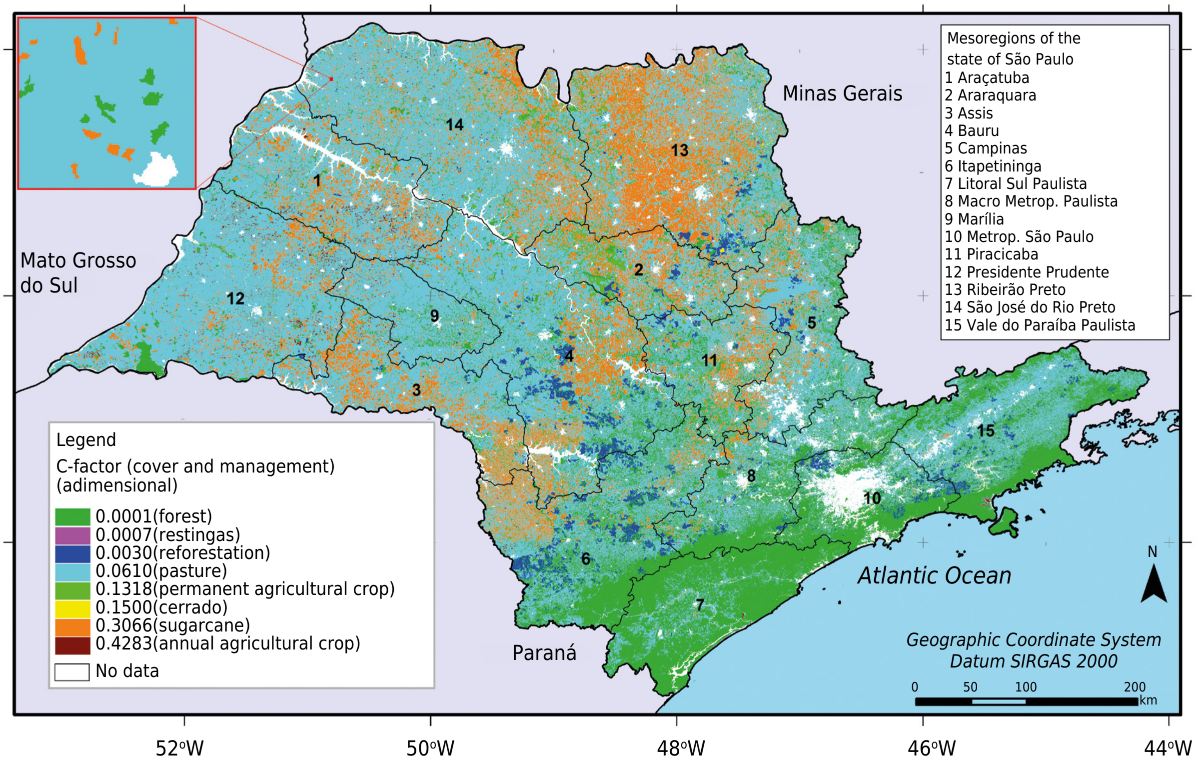

Figure 8. C-factor map of the state of São Paulo.

The estimated soil loss rates for the state of São Paulo ranges from 0 (zero) to 216,000 Mg ha^{-1} yr^{-1}, and the average soil loss rate was estimated as 30 Mg ha^{-1} yr^{-1} (Figure 10). In fact, since the model does not estimate sediment deposition on the slopes, those rates represent potential soil loss rates, which indicate the intensity of the erosion process in the different regions of the State.

Interpretation of these values considered the soil loss tolerance values (T-values) determined by Lombardi Neto and Bertoni (1975), who took into account the *solum* depth and the physical properties of 75 soil profiles of the state of São Paulo. The estimated T-values ranged from 4.5 to 13.4 Mg ha^{-1} yr^{-1} and from 9.6 to 15 Mg ha^{-1} yr^{-1} for soils with an argillic horizon (B *textural*) and oxic horizon (B *latossólico*), respectively. In general terms, however, according to Bertoni and Lombardi Neto (2012), an average T-value of 12 Mg ha^{-1} yr^{-1} could be adopted for deep, permeable, and well-drained soil. For shallow soils or for soils with very unfavorable subsoils, average T-values range from 2 to 4 Mg ha^{-1} yr^{-1}.

Thus, the results in figure 10 were classified in two categories according to the criterion of tolerance to soil loss: tolerable rates of soil loss, ranging from 0 to 12 Mg ha^{-1} yr^{-1}, and intolerable rates for those above 12 Mg ha^{-1} yr^{-1} (Bertoni and Lombardi Neto, 2012) (Figure 11). The results show marked ongoing erosion in 44 % of the soils of the state of São Paulo, where soil loss rates exceed the upper threshold of soil loss tolerance (12 Mg ha^{-1} yr^{-1}). The erosion rates throughout the state were also high, except in the mountainous region, due to protection from vegetation (rainforest).

Among areas with soil loss rates higher than 12 Mg ha^{-1} yr^{-1}, 30 % is dedicated to planting of sugarcane and other 67 % to pasture, corresponding to 29,000 and 65,000 km^2, respectively. Table 2 shows the proportion of the area by mesoregion where soil loss rates are superior to 12 Mg ha^{-1} yr^{-1} (not tolerable) and also shows that in 12 out of 15 regions analyzed, the predominant and secondary uses of these areas are pasture or sugarcane. The areas whose estimated erosion rates stand out through great intensity of soil loss processes are located mainly in the north and northeast of the state, corresponding to the mesoregions of Ribeirão Preto, São José do Rio Preto, Assis, Itapetininga, and Piracicaba, and in the central and southwest regions, such as the mesoregion of Assis and Itapetininga. These regions are historically dedicated to agricultural activities.

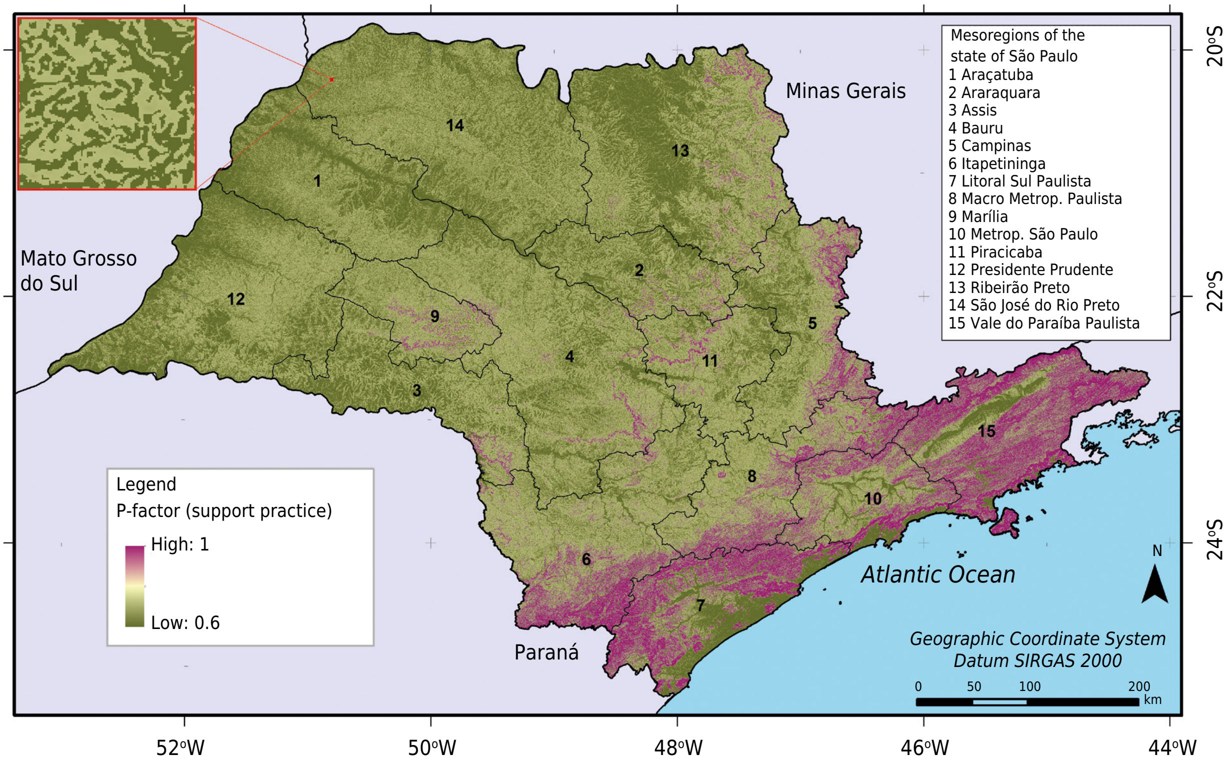

Figure 9. P-factor map of the state of São Paulo.

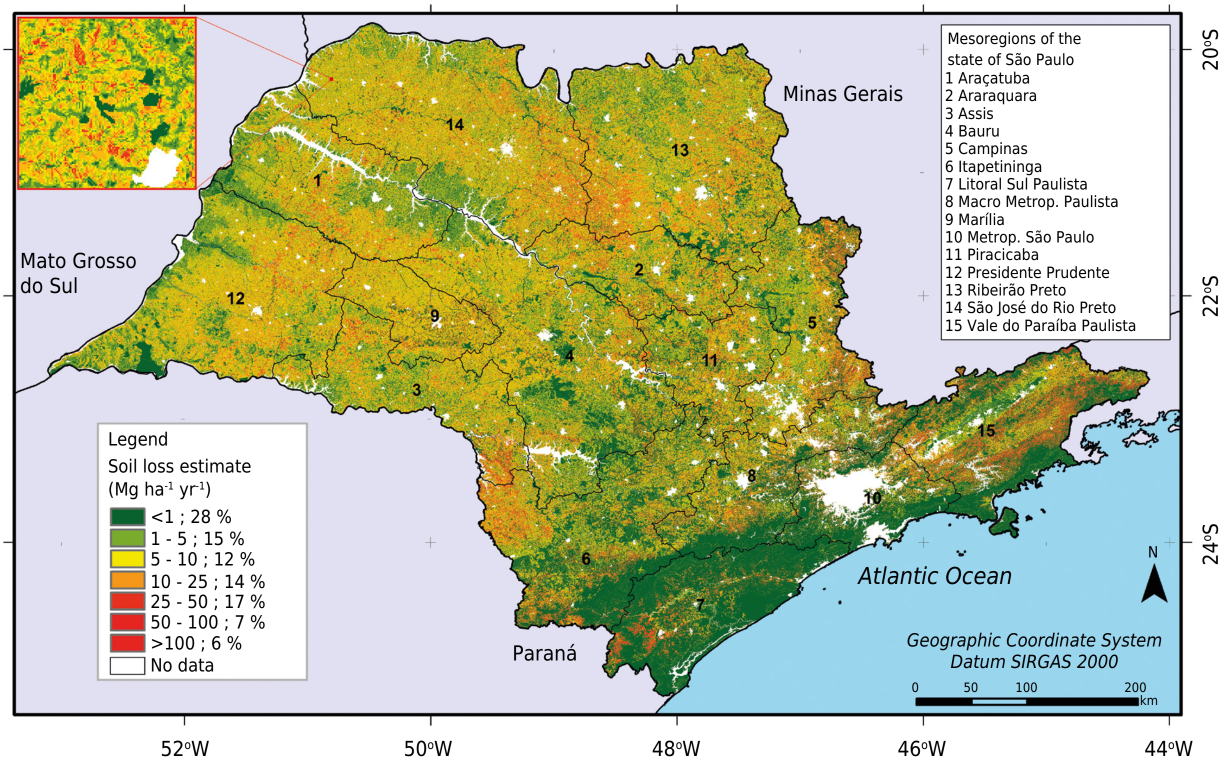

Figure 10. Map of estimated annual rates of soil loss of the state of São Paulo.

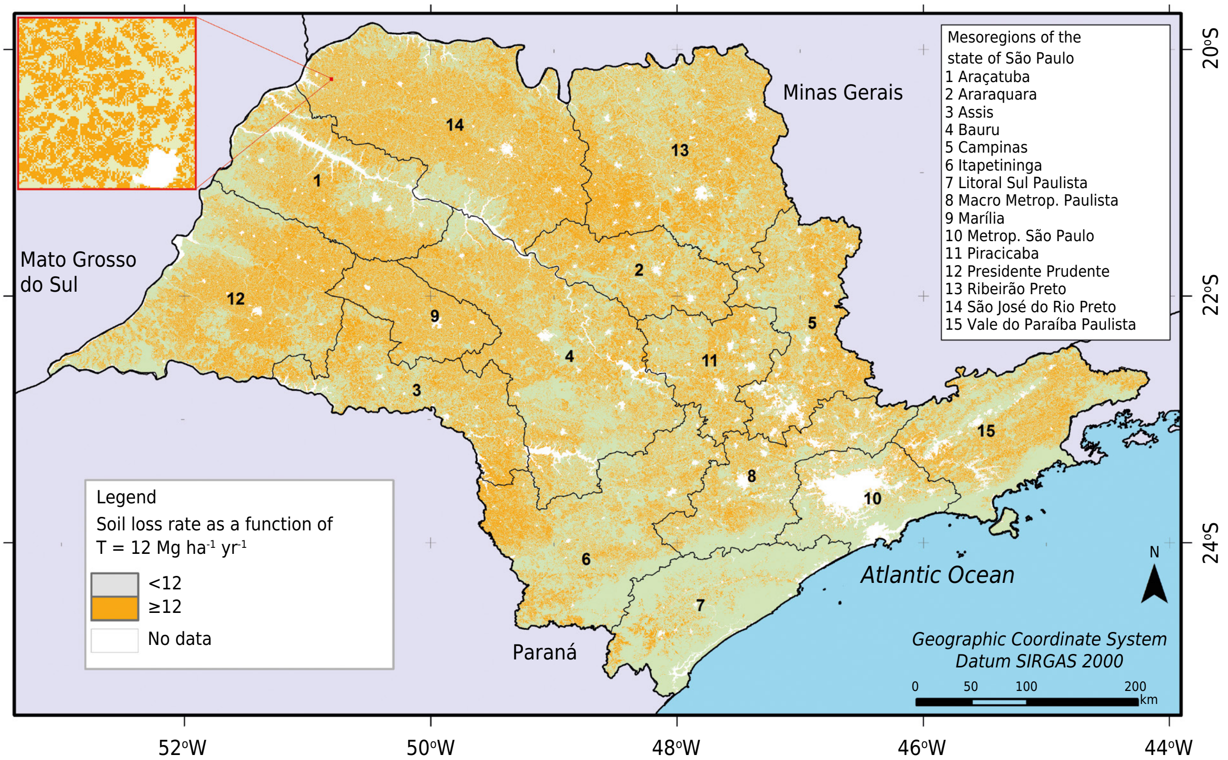

Figure 11. Map of soil conservation/degradation of the state of São Paulo based on average rate of tolerance to soil loss of 12 Mg ha^{-1} yr^{-1}.

Table 2. Quantity of areas with land use cover where the estimates of soil loss rates are greater than the average rate of soil loss tolerance of 12 Mg ha^{-1} yr^{-1}

Mesoregion	ID	Total area	Area with soil loss >12 Mg ha^{-1} yr^{-1}		Land use cover where soil loss rates are greater than 12 Mg ha^{-1} yr^{-1}			
					Predominant land use		Secondary land use	
		km^2	km^2	%		%		%
São José do Rio Preto	1	29545	14593	41	Pasture	66	Sugarcane	29
Ribeirão Preto	2	27569	13036	47	Sugarcane	60	Pasture	37
Araçatuba	3	16897	6572	39	Pasture	62	Sugarcane	34
Bauru	4	26809	10442	39	Pasture	70	Sugarcane	29
Araraquara	5	9483	4454	47	Sugarcane	47	Pasture	43
Piracicaba	6	9057	3839	42	Pasture	60	Sugarcane	33
Campinas	7	14229	6108	43	Pasture	74	Sugarcane	21
Presidente Prudente	8	24292	10488	43	Pasture	80	Sugarcane	16
Marília	9	7209	4205	58	Pasture	89	Sugarcane	8
Assis	10	12798	5673	44	Pasture	53	Sugarcane	46
Itapetininga	11	20224	6063	30	Pasture	72	Sugarcane	12
Macro Metrop. Paulista	12	12307	3679	30	Pasture	92	Sugarcane	7
Litoral Sul Paulista	13	13223	1229	9	Pasture	94	Permanent agricultural crop	4
Metropolitana de São Paulo	14	9300	1271	14	Pasture	94	Reforestation	4
Vale do Paraíba Paulista	15	16172	5337	33	Pasture	97	Reforestation	1

The highest average soil loss rate was associated with crop areas, similar to that reported by Weill and Sparovek (2008) and Lino (2010). The average estimated soil loss rates for annual, semi-perennial, and perennial crops were 118, 78, and 38 Mg ha^{-1} yr^{-1}, respectively, far above the accepted average rate of tolerance to soil loss of 12 Mg ha^{-1} yr^{-1}. These results suggest the need for implementing more effective soil management techniques and conservation practices in agricultural production areas in the state of São Paulo. Public policies can be defined in which land capability or suitability would be considered a primary factor for determining sustainable agricultural use of natural resources. For example, the Environmental Department of the state of São Paulo established technical guidelines for licensing in the sugar and alcohol sector in São Paulo (Resolução Estadual No. 88). This guideline is based on the State Agro-Environmental Zoning of the Sugarcane Sector, determined by the Instituto Agronômico de Campinas, which classifies regions of São Paulo into four suitability categories for sugarcane cultivation, namely: i) adequate, ii) limited suitability, iii) restricted suitability, and iv) inadequate. Thus, as of 2008, in areas classified as inadequate, environmental licenses were no longer granted for setting up or expanding existing enterprises in the sugarcane sector (São Paulo, 2008).

Factors that accelerate erosion are mainly related to high intensity of land use, beyond agricultural potential, and to inadequate management of more fragile soils. Most areas with high estimated soil loss rates are located in regions where IPT (1995; 1997) and Kertzman et al. (1995) have reported high erosion susceptibility in ravines and gullies. Although the focus of these studies was not exclusively on water erosion, the conclusions of these authors were related to natural susceptibility. In an integrated analysis of land features, Kertzman et al. (1995) investigated water behavior and the occurrence of erosive processes (interpretation of aerial photographs) in relation to geological, geomorphological, and soil data. They concluded that these areas are highly susceptible to degradation since they have very favorable natural conditions for development of erosion, regardless of the forms of land use and occupation. These findings can be extrapolated to this study, confirming our results in areas where the estimated erosion rates were high.

Studies addressing soil erosion using detailed information on a regional scale are scarce. For the state of São Paulo, Lino (2010) estimated soil loss rates using the USLE and reported variations from 0 (zero) to 179 Mg ha^{-1} yr^{-1}. This author reported that in 35 % of the area of the state, estimated soil loss rates ranged from 0 to 9 Mg ha^{-1} yr^{-1}, in 50 % from 9 to 118 Mg ha^{-1} yr^{-1}, and in 15 % they exceeded 118 Mg ha^{-1} yr^{-1}. In comparison, for the same respective intervals, 53 %, 41 %, and 6 % were found in this study. This variation can be attributed to methodological differences, e.g., in the calculation of erosivity (R-factor), since the author used only the equation developed for the region of Campinas, and differences in the C-factor adopted for each category of land use. In an analysis of soil loss, Rocha (2013) also used the USLE for the entire Brazilian territory. Although there are also many methodological differences with regard to how the model factors were obtained and a quantitative comparison with our study would not be possible, there was an apparent qualitative agreement in regions with estimates of a high rate of soil loss.

However, taking into account only the soil loss tolerance criterion to interpret the intensity of soil erosion could be insufficient in view of the diversity of soil types, climatic conditions, and other aspects. Therefore, the relationship between the estimated soil loss rate, soil renewal rate, and erosion tolerance can be a guideline in determining the stages of degradation. In other words, soil loss tolerance should be understood as a dynamic concept in space and time since it is defined in terms of soil loss and renewal rates, a methodological approach followed in another study (Medeiros et al., 2016). In practice, scientific studies on the dynamics of erosion in lands conditioned by spatial-temporal variation on a regional scale are limited by the limited availability of data.

The results of this study contribute to diagnose the conservation status of the topography of the state of São Paulo and to feed - the now urgent - discussions on the implementation of conservation practices and land use policies, motivated by the threat of resource depletion if no soil protection practices are applied. The state of São Paulo has a history of agricultural activities that make it a protagonist in the economic scenario of the country and the world and, therefore, it is a strategic area from the perspective of food security and future energy and fiber demands. Consequently, continuous overuse of soils without consideration for their limits/suitability, as well as inadequate conservation and management practices, may cause humanity to slide into an even deeper state of environmental crisis in the coming decades and push the expansion of agricultural frontiers towards areas of social interest, compromising policies of preservation of biodiversity and water supply, for example.

In methodological terms, with regard to the inherent generalizations of local-regional adaptation, this study should be understood as an initiative to introduce Soil Science into an agenda of global discussions, as suggested by Hartemink (2008), Bockheim and Gennadiyev (2010), Camargo et al. (2010), and Bouma (2014). In other words, Soil Science in its original concept has not been effectively taken into consideration in the current discussions involving Earth System Sciences, but soil has been addressed mainly in terms of land use change (Land Use Cover Change - LUCC) and few references are made to it as a finite natural resource that if not properly managed, on a human time scale, may be exhausted.

CONCLUSIONS

The average soil loss rate estimated for the entire state of São Paulo was 30 Mg ha^{-1} yr^{-1}, which exceeds the average tolerance limit of 12 Mg ha^{-1} yr^{-1} adopted in this study.

In about 59 % of the study area, excluding surface water and urban areas, soil loss rates exceeded 12 Mg ha^{-1} yr^{-1}, and in those areas the predominant land uses were sugarcane, semi-perennial crops, and pastures.

The average soil loss rates in areas used for cultivation of annual, semi-perennial and perennial crops were 118, 78, and 38 Mg ha^{-1} yr^{-1}, respectively.

For the state of São Paulo, attention must be paid to soil conservation mainly in terms of soil suitability for agriculture and incentives for the implementation of appropriate management practices.

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