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INTER-RELATIONSHIPS AMONG ERODIBILITY, SOIL TOLERANCE AND PYSICAL-CHEMICAL ATTRIBUTES IN NORTHWESTERN OF SÃO PAULO STATE

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Abstract: Erosive processes are major environmental problems for soil and constitute a great conservation planning challenge. Knowledge of erodibility and soil loss tolerance, as well as their interactions with the physical and chemical attributes of soil, may allow important diagnostics for sustainable management. More dexterous processes for obtaining such information can be very interesting solutions in large areas with strong climatic and environmental dynamics. The aim of this study was to determine soil erodibility (K) and soil loss tolerance (T) for 32 kinds of soil in the northwestern region of São Paulo State from indirect methods and to assess their linear and spatial correlations with soil physical-chemical attributes. The evaluated attributes were: textural relationship (TR), particle density (PD), bulk density (BD), total porosity (TP), macroporosity (MA), microporosity (MI), water capacity storage (WCS), organic matter (OM) and soil pH (pH). The results showed that the K factor ranged from 0.0094 to 0.0758 Mg ha h/ha MJ mm (surface depth), while T values ranged from 3.09 to 14.79 Mg/ha year. The erodibility and loss tolerance presented significant interactions with the physical and chemical soil attributes, especially WCS and TR which showed the best regression adjustments. From a geostatistical point of view, the erodibility and soil loss tolerance also showed considerable spatial correlations with most soil physical properties (especially interactions with the TP and TR), allowing for the best maps using the cokriging technique. This allowed us to conclude that the adopted simple and relatively low-cost approach was effective in obtaining K and T, showing its potential for implementation in large areas without complex surveys, in situ tests, and long term climate data series, which is a common situation in large areas in less developed countries.

Keywords: Soil conservation; sustainable management; soil erosion; geostatistics

INTRODUCTION

The knowledge of soil characteristics is important for conservationist planning, mainly when considering the erosive processes of ecosystems (Boardman 2006; Rapport and Maffi 2010). According to Bertoni and Lombardi Neto (2012), some problems with erosive processes can be closely related to their use and soil management. In this way, combating the erosive processes requires the detailed knowledge of soil.

Human activities, especially farming, pasteurizing, urban expansion, and industry growth, cause more losses in ecosystem services (Millennium Ecosystem Assessment 2005; Goldman et al. 2008; Eigenbrod et al. 2009), specifically when associated with large water resource usage (Pires 2004; Montes and Ruiz 2008; Schewe et al. 2014; Costa et al. 2015; WWAP 2015; Dorici et al. 2016; Torres et al. 2016).

Soil erosion fosters particle removal and nutrient loss, accelerating the silting of hydric bodies and compromising the water resource quality (Uri and Lewis 1998; Ravenga 2005; Sala et al. 2000; Tundisi and Matsumura-Tundisi 2010; Minoti et al. 2011; Demarchi and Zimback 2014; Galharte et al. 2014).

When considering soil degradation, erosion results in the most significant environmental, social and economic losses (Pimentel et al. 1995; Uri and Lewis 1998; Environment Agency 2002; Wilkinson 2005; Vente et al. 2008; FAO 2011; Bayon et al. 2012; Vrieling et al. 2014; Reusser et al. 2015).

Although hydric erosion processes represent a global problem, in a tropical environment, they express large magnitude and area distribution (El-Swaify 1982; Morgan 2005; Florenzano 2008; Bertoni and Lombardi Neto 2012).

In the southeastern region of Brazilian, most economic activities (55.4% of the economy and 42.6% of people - IBGE 2010) occur in the Paraná Basin, where geological, pedological, climatological, relief, and land use/land cover conditions induce erosion processes (Valentin 2005; Florenzano 2008; Lollo and Sena 2013; Dorici et al. 2016; Zhou et al. 2016).

Soil erodibility is an important factor for conservationist planning, because it represents soil susceptibility to rain erosivity (Silveira and Pejon 2007; Arraes et al. 2010). Thus, several technical studies have been performed in Brazil to assess this factor, including the works of Demarchi and Zimback (2014) in São Paulo State, Castro et al. (2011) in Goiás, Vieira (2008) in Santa Catarina, and Nunes and Cassol (2008) in Rio Grande do Sul State.

Several recent studies have shown that erodibility can vary significantly in tropical environments as a consequence of other factors. Land use/land cover changes are one of these factors, with properties that change with soil hydrology and erosion (Abdulkareem et al. 2017; Thomaz 2018a; Nampak et al. 2019). Land use/land cover changes and their association with management factors can provoke significant changes in soil dynamics (Thomaz 2018a; Thomaz 2018b).

Strong climate changes can also modify soil physicochemical properties and associated degradation processes (Ahmad et al. 2018; Vijith and Dodge-Wan 2018). Studies also shown that some land use changes can act to reduce soil erosion (Deng et al. 2016; Abdulkareem et al. 2017).

Considering this context, authors have proposed alternative techniques for obtaining indirect soil erodibility (Markose and Jayappa 2016; Barbosa et al. 2019; Nampak et al. 2019).

Thus, considering that soil behaviour (e.g., erodibility) changes are induced by other environmental changes (i.e., land use/land cover and climate changes), reduced cost and quicker manners of erodibility are needed. This paper tests and validates the use of soil physical properties for determining erodibility; obtaining a quick, low-cost solution in large areas; and reflecting recent environmental changes.

According to Arraes et al. (2010), soil erodibility can also be measured indirectly based on regression equations that consider soil attributes as variables of influence. This method represents a fast and general diagnostic method with a low operational cost. Therefore, many studies have adopted these methods (Lima et al. 2007; Arraes et al. 2010; Anache et al. 2015).

Among these methods, this method highlights the precursor proposed by Wischmeier et al. (1971) for the US Midwest. On the other hand, Brazilian researchers have been developing and improving methods for different Brazilian soils (Lima et al. 1990; Marques et al. 1997). However, many studies (Mannigel et al. 2002; Demarchi and Zimback 2014) have adopted a simple methodology, as given by Bouyoucos (1935).

The soil loss tolerance also offers an important soil diagnostic. According to Bertoni and Lombardi Neto (2012), this term can be defined as the land quantity that can be eroded each year, preserving soil, with the aid of appropriate management techniques and a high level of productivity for a long time. Many studies have been conducted to assess loss tolerance (Manningel et al. 2002; Nunes et al. 2012), which has shown significant interactions with soil attributes.

According to Lima and Andrade (2001), texture, organic matter, and mineralogy influence soil erodibility. However, the physical attributes of the mass/volume relationship deserve focus because they are easily changed by management, directly linked to the dynamics of soil infiltration (Figueiredo et al. 2009) and can present interactions with erodibility.

Geostatistics, as an auxiliary tool to classic statistics, have been largely applied to analyse soil data, helping to comprehend spatial variability. This applicability considers that the samples of one variable are spatially dependent (Molin et al. 2015). The geostatic technique has been presenting increasing application in the study of soil erodibility (Arraes et al. 2010; Miqueloni et al. 2015), allowing for the interpretation of results based on natural variability.

Therefore, assuming that interactions of physical-chemical soil properties with erodibility and soil loss tolerance exist, the "São José dos Dourados" river basin (CBH-SJD 2012) indicated the concentration of erosive processes in the northwest region of São Paulo State. This study aims to assess erodibility and loss tolerance for 32 soil types and the analyse linear and spatial correlations between such parameters and the physical-chemical soil attributes.

MATERIAL AND METHODS

The present study was conducted based on technical data from a taxonomic assessment of the "Vale do Paraná" sugar and alcohol plant collected at 41 farms under agricultural production systems (Alves et al. 2009). The samples were representative of a quadrant area (**Fig. 1**) located within the following coordinates: UTM-Long 51º: 470432 East – 7730532 South; 516860 East – 7753257 North (20º19'6.8"S - 50º50'18.5"W; 20º31'25.5"S - 51º17'1.0"W).

The samples also included the western region of the low São Jose dos Dourados river basin, which is northwest of São Paulo State and encompasses the counties of Ilha Solteira, Suzanápolis, Santana da Ponte Pensa, Rubinéia, Nova Canaã Paulista, Aparecida D'Oeste, Três Fronteiras, Pereira Barreto, Santa Fé do Sul, Marinópolis and Palmeira D'Oeste (approximately 1,055 km^2). Altogether, 93 samples were analysed from individual trenches and divided into 32 types, comprising 5 soil orders: Ultisols, Inceptisols, Oxisols, Entisols and Nitisols. This geological and pedological context is representative of large areas in the Paraná Basin (southeastern Brazil).

For the determination of physical-chemical attributes, soil samples with preserved structures and changed structures were collected, prepared and analysed according to the methodology cited in Embrapa (2009; 2011). The physical soil attributes derived from the changed structure samples included the particle size, which was obtained by the pipette method using the dispersant NaOH 1 mol/L, and particle density (PD), which was obtained by volumetric flask with ethyl alcohol as the penetrating liquid. The physical soil attributes derived from the preserved structure samples obtained by the core cutter method were bulk density (BD) and the soil porosity system [including macroporosity (MA), microporosity (MI) and total porosity (TP)]. The water capacity storage (WCS) was also obtained, as in van den Berg et al. (2000), and the textural relationship (TR) was obtained by grain size methods, which considers the average percentage distribution of clay in Horizon B and Horizon A, as provided by Demarchi and Zimback (2014).

The chemical attributes analysed by the modified structural samples included the content of organic matter (OM), which was obtained indirectly by the organic carbon content, and the soil pH (pH), which was assessed by the potentiometric method in soil/water suspension at the proportion 1:2.5.

The soils for the survey were collected up to more than 2 meters deep to characterize Horizons A and B. Sampling was performed superficially in shallow soils, including the Horizon C characterization. In this way, for the present study, the data were tabulated and organized in a representative form for Horizon A (surface depth) and Horizon B (sub-superficial depth). Thus, the Horizon A samples for Ultisols had an average depth of 0.42 m, Oxisols had an average depth of 0.36 m, Inceptisols had an average depth of 0.38 m, Entisols had an average depth of 0.36 m, and Nitisols had an average depth of 0.32 m.

The soil erodibility is given by the Bouyoucos expression (Mannigel et al. 2002):

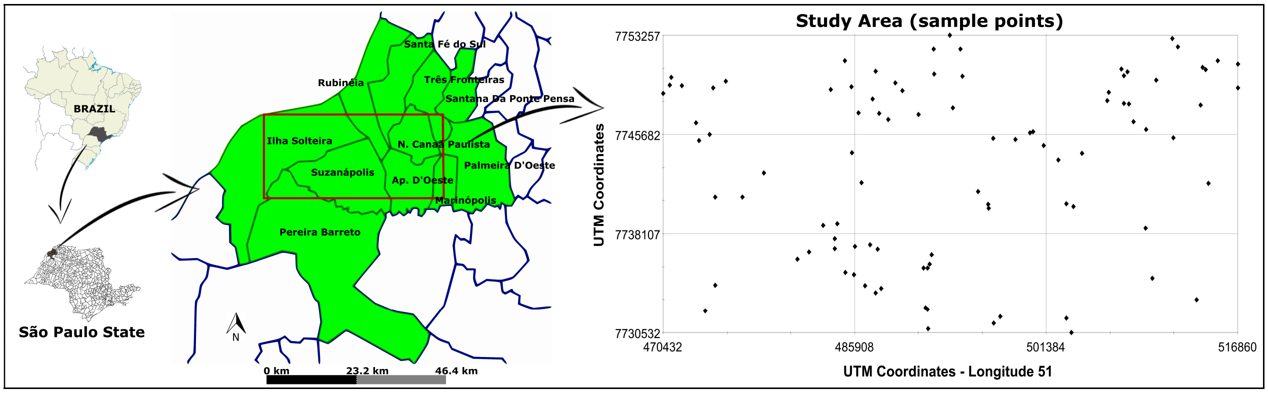

Fig. 1 Location of the study area (sample points)

$$K = [\%\text{sand} + \%\,\text{silt}) \;/\, (\%\text{clay})]/100 \quad (1)$$

where: K represents the soil erodibility factor (Mg ha h/ha MJ mm) and % sand, % silt and % clay represent the percentages of the respective grain size fractions.

The soil loss tolerance (T) was determined by the techniques used in Demarchi and Zimback (2014) using soil weight (W), according the following expression:

$$W = th\,.BD\,.f \quad (2)$$

where: W = soil weight (Mg/m); th = thickness of horizon considered (m); BD = bulk density (Mg/m); and f = conversion factor inherent to the textural relationship.

Descriptive statistical analyses were performed for each studied attribute using an Excel data sheet. Then, a Pearson's regression matrix was set up to choose the candidates of interest for modelling regression given the combinations every two studied attributes.

Multiple regression tests with a 5% probability were performed between 1) erodibility (i.e., the dependent variable), as a function of the other soil attributes (such as the dependent variables) and the 2) loss tolerance (dependent) as a function of the other soil attributes researched (i.e., the independent variables). For this proposal, SAS software was used (Schlotzhaver and Littell, 1997).

In the geostatistical approach, the spatial dependency of each attribute was analysed by the simple semivariogram calculation using the *Gamma Design* Software GS+ 7.0 (Robertson 2004). After this step, the cross semivariogram adjustments were tested between erodibility and loss tolerance with the other physical-chemical attributes to evaluate the spatial correlation.

The semivariogram adjustments (simple or cross) were made by observing the initial selection of: (a) the smaller amount of the sum of residual squares (SRS), (b) the largest spatial determination coefficient (r^2), and (c) the largest spatial dependency evaluator (SDE). The cutting values proposed were: (a) SDE ≤ 25% = variable was poorly dependent; (b) 25% < SDE ≤ 75% = variable was moderately dependent, and (c) SDE > 75% = variable was highly dependent (Robertson 2004). The final decision of the model that represented the adjustment was made through cross-validation and based on the definition of the number of neighbours generating the best map.

RESULTS AND DISCUSSION

The values of the loss tolerance and soil erodibility factor for the samples collected in the extreme northwestern region of São Paulo State are indicated in **Table 1**. By analysing the quantity of soils evaluated, it was observed that the values of loss tolerance ranged from 3.04 - 14.79 Mg/ha year. This result is consistent with the values presented by Mannigel et al. (2002) and Demarchi and Zimback (2014), with soil tolerance values of 2.8 - 14.7 Mg/ha year and 3.1 - 15.9 Mg/ha year, which are on the same soil orders evaluated in this study. In general, the studied Oxisols, Entisols and Nitisols stand out, as they present the highest values of tolerance in the study area.

Regarding soil erodibility (**Table 1**), with a focus on the A Horizon, the factor K varied between 0.0131 and 0.0758 Mg ha h/ha MJ mm for LVAe(ti)3 and PVd(ab)1/2, respectively. By comparing these results with the values obtained by Demarchi and Zimback (2014) and Mannigel et al. (2002), the erodibility of Ultisols, Oxisols, Inceptisols, Entisols and Nitisols presented coherent values for both authors.

Soil erodibility can be classified based on its potential. Thus, according to Castro et al. (2011), the classes are represented as follows: $K < 0.0090$ (very low); $0.0090 < K \leq 0.0150$ (low); $0.0150 < K \leq 0.0300$ (moderate); $0.0300 < K \leq 0.0450$ (high); $0.0450 < K \leq 0.0600$ (very high); and $K > 0.0600$ (extremely high). Therefore, the soils that presented the highest erodibilities were the Ultisols (**Table 1**), which had a higher representation in the studied area and in the entire western plateau of São Paulo State (Oliveira et al. 1999).

Ultisols have a natural tendency to be more susceptible to erosive processes, which is mainly due to their textural relationship (EMBRAPA 2013). Therefore, this directly implies the infiltration rate between superficial and sub-superficial horizons. However, the moderate textured Ultisols present a smaller TR, giving a better condition for the porosity system and consequently good infiltration, reducing erodibility problems. In **Table 1**, the erodibility values (extremely high) range from 0.0647 Mg ha h/ha MJ mm [PVe(ti)1/2] to 0.0758 Mg ha h/ha MJ mm [PVe(ti)2/3]. In the same manner, the Inceptisols [CXe(la)2] also presented extremely high erodibility, with a value of 0.0691 Mg ha h/ha MJ mm.

Such data are shown to be higher than the average (0.0425 Mg ha h/ha MJ mm), as pointed out by Silva and Alvares (2005), who developed a database on the erodibility of soils occurring in São Paulo State. However, according to these authors, in the surveys conducted, 78% of Ultisols presented high erodibility, similar to the average Ultisols erodibility for Horizon A in the present study, which was equal to 0.0576 Mg ha h/ha MJ mm (**Table 1**). For Oxisols, the second class was more significant in the region, with an average that indicated high erodibility, while Silva and Alvares (2005) indicated moderate erodibility.

Table 1. Erodibility and soil loss tolerance in the extreme northwestern region of São Paulo State.

Id.[SiBCS]	Order		Tolerance	Erodibility		TR
			Mg / ha year	Mg ha h / ha MJ mm		
	Ultisols[Soil Taxonomy] (Acrisols[WRB])	n.	H1m.	H.A.	H.B.	H.B/A
PVAe(ab)1/2	RED-YELLOW ULTISOL Eutrophic abrupt texture sandy/medium	2	9.01	0.0551	0.0282	1.73
PVAe(ar)1/2	RED-YELLOW ULTISOL Eutrophic sandy texture sandy/medium	1	9.09	0.0583	0.0367	1.86
PVAe(ti)1/2	RED-YELLOW ULTISOL Eutrophic typical texture sandy/medium	1	9.18	0.0547	0.0248	1.86
PVAe(ti)2	RED-YELLOW ULTISOL Eutrophic typical texture medium	1	8.84	0.0521	0.0258	1.73
PVAe(ti)2/3	RED-YELLOW ULTISOL Eutrophic typical texture medium/loamy	1	8.85	0.0412	0.0177	1.85
PVe(ab)1/2	RED ULTISOL Eutrophic abrupt texture sandy/medium	12	4.32	0.0755	0.0255	2.42
PVe(ab)1/3	RED ULTISOL Eutrophic abrupt texture sandy/loamy	2	3.09	0.0685	0.0169	2.92
PVe(ab)2/3	RED ULTISOL Eutrophic abrupt texture medium/loamy	3	6.13	0.0508	0.0173	2.23
PVe(ar)1/2	RED ULTISOL Eutrophic sandy texture sandy/medium	2	7.54	0.0702	0.0281	2.12
PVe(ti)1/2	RED ULTISOL Eutrophic typical texture sandy/medium	7	9.05	0.0647	0.0311	2.12
PVe(ti)2	RED ULTISOL Eutrophic typical texture medium	4	9.04	0.0529	0.0276	1.68
PVe(ti)2/3	RED ULTISOL Eutrophic typical texture medium/loamy	2	8.67	0.0352	0.0159	1.75
PVd(ab)1/2	RED ULTISOL Dystrophic abrupt texture sandy/medium	7	6.32	0.0758	0.0307	1.82
PVd(ab)1/3	RED ULTISOL Dystrophic abrupt texture sandy/loamy	2	3.09	0.0690	0.0170	2.52
PVd(ab)2/3	RED ULTISOL Dystrophic abrupt texture medium/loamy	1	6.09	0.0525	0.0176	2.27
PVd(ar)1/2	RED ULTISOL Dystrophic sandy texture sandy/medium	1	8.14	0.0669	0.0324	1.81
PVd(ti)1/2	RED ULTISOL Dystrophic typical texture sandy/medium	2	8.73	0.0581	0.0276	1.82
PVd(ti)2	RED ULTISOL Dystrophic typical texture medium	2	8.91	0.0537	0.0274	1.70
PVd(ti)2/3	RED ULTISOL Dystrophic typical texture medium/loamy	3	8.86	0.0399	0.0178	1.81
Id.	Inceptisols[Soil Taxonomy] (Cambisols[WRB])	n.	H1m.	H.A.	H.B.	H.B/A
CXe(ti)2/3	INCEPTISOL HAPLIC Tb Eutrophic typical texture medium/loamy	1	8.71	0.0283	0.0104	1.88
CXe(la)2	INCEPTISOL HAPLIC Tb Eutrophic latosolic texture medium	1	8.33	0.0691	0.0324	1.87
CXef(la)3	INCEPTISOL HAPLIC Tb Eutroferric latosolic texture loamy	1	13.48	0.0094	0.0078	1.09
Id.	Oxisols[Soil Taxonomy] (Ferralsols[WRB])	n.	H1m.	H.A.	H.B.	H.B/A
LVAd(ag)2	RED-YELLOW OXISOL Dystrophic argisolic texture medium	1	9.11	0.0451	0.0263	1.52
LVAd(ti)2	RED-YELLOW OXISOL Dystrophic typical texture medium	1	14.79	0.0342	0.0311	1.08
LVe(ti)2	RED OXISOL Eutrophic typical texture medium	12	11.34	0.0571	0.0369	1.42
LVef(ti)3	RED OXISOL Eutrophic typical texture loamy	1	10.86	0.0131	0.0088	1.23
LVd(ti)2	RED OXISOL Dystrophic typical texture medium	12	12.26	0.0460	0.0333	1.29
Id.	Entisols[Soil Taxonomy] (Arenosols[WRB])	n.	H1m.	H.A.	H.B.	H.B/A
RLe(fr)2	ENTISOL LITOLIC Eutrophic fragmentary texture medium	3	13.75	0.0440	0.0349	1.17
RLe(fr)3	ENTISOL LITOLIC Eutrophic fragmentary texture loamy	1	14.62	0.0179	0.0163	1.06
Id.	Udox[Soil Taxonomy] (Rhodic Nitisols[WRB])	n.	H1m.	H.A.	H.B.	H.B/A
NVef(ti)2/3	RHODIC NITISOL Eutroferric typical texture medium/loamy	1	11.94	0.0210	0.0119	1.41
NVef(ti)3	RHODIC NITISOL Eutroferric typical texture loamy	1	11.97	0.0178	0.0089	1.47
NVef(ti)3/4	RHODIC NITISOL Eutroferric typical texture loamy/very loamy	1	10.47	0.0148	0.0072	1.44

Id. = identifier of the soil class based on Brazilian Soil Classification System[SiBCS]; Order = general identification of the type of soil based on the American Classification[Soil Taxonomy] and International Classification[WRB]; n. = number of individual samples representative of the average value; TR = textural relationship; (H.A.), (H.B.), (H1m.) and (H.B/A) refers to the assessment profile, being respectively: A Horizon, B Horizon, profile corresponding to 1 meter depth, and the relationship between A and B Horizons.

As noted by Demarchi and Zimback (2014), the Bouyoucos method loses accuracy, overestimating the value of erodibility when applied to extremely sandy soils. Thus, by virtue of some soils in the present work being substantially sandy (**Table 1**), it was observed that some values found presented above average values, as identified by Silva and Alvares (2005). On the other hand, it is important to consider that such a database presented numerous sources from different regions of São Paulo State, each with its unique characteristics. Therefore, given a quick and general diagnosis, our data meet the objective of this study mainly by overestimating an index, which indicates the need for greater care with the management of these soils and not the opposite.

Based on **Table 1** and by considering the tendency to potentiate the erosive process of Ultisols, it can be inferred that in western São Paulo State, in the lower region of the São Jose dos Dourados basin, the most environmentally sensitive soils are PVe(ab)1/2, PVe(ab)1/3, and PVd(ar)1/2.

This occurs not only because they have extremely high erodibility but also because these soils have the lowest loss tolerance values.

This fact shows that the grain size and textural gradient have a high interaction with the soil behaviour in relation to erodibility. However, the grain size is not modifiable attribute by soil management actions. In this way, land uses and their management, are appropriated based on the textural class. On the other hand, management easily changes some chemical attributes and physical attributes of the mass/volume relationship. Even according to Figueiredo et al. (2009) and Vitte and Mello (2007), these attributes show a strong interaction with erodibility for the dynamic water influence in soil.

Therefore, to assess the interactions among physical attributes and between loss tolerance and soil erodibility, a descriptive statistical analysis and Pearson´s correlation matrix between the attributes researched are reported in **Tables 2** and **3** respectively.

Table 2. Descriptive statistical analysis of the soil attributes studied in the extreme northwestern region of São Paulo State.

Soil Attributes$^{(a)}$	Measures Descriptive Statistics							
	Mean	Median	Value		Standard Deviation	Coefficient		
			Minimum	Maximum		Variation (%)	Kurtosis	Skewness
Dependent attributes								
$K_{H.A.}$ (Mg ha h / ha MJ mm)	0.0553	0.0554	0.0094	0.0924	0.018	32.5	-0.264	-0.411
$K_{H.B.}$ (Mg ha h/ ha MJ mm)	0.0275	0.0279	0.0071	0.0426	0.009	32.7	-0.339	-0.334
$T_{1m.}$ (Mg / ha year)	8.992	9.009	2.999	15.310	3.299	36.6	-0.440	-0.070
Independent attributes								
$TR_{H.B/A}$	1.772	1.740	1.061	3.117	0.465	26.2	-0.281	0.493
$WCS_{H.A.}$ (mm cm^{-1})	0.811	0.745	0.670	2.130	0.202	24.9	20.918	4.069
$WCS_{H.B.}$ (mm cm^{-1})	0.967	0.873	0.753	2.490	0.287	29.6	12.721	3.321
$PD_{H.A.}$ (kg dm^{-3})	2.553	2.567	2.435	2.620	0.036	1.4	1.809	-0.865
$PD_{H.B.}$ (kg dm^{-3})	2.550	2.567	2.330	3.330	0.091	3.8	56.223	6.381
$BD_{H.A.}$ (kg dm^{-3})	1.530	1.545	1.080	1.710	0.102	6.7	3.215	-1.213
$BD_{H.B.}$ (kg dm^{-3})	1.468	1.468	1.323	1.590	0.050	3.4	-0.147	0.006
$TP_{H.A.}$ (m^{3} m^{-3})	0.397	0.400	0.315	0.580	0.043	10.8	2.406	0.848
$TP_{H.B.}$ (m^{3} m^{-3})	0.419	0.416	0.353	0.489	0.026	6.2	0.272	0.292
$MA_{H.A.}$ (m^{3} m^{-3})	0.081	0.073	0.040	0.200	0.029	35.8	4.141	1.679
$MA_{H.B.}$ (m^{3} m^{-3})	0.086	0.083	0.053	0.150	0.019	22.1	1.270	1.030
$MI_{H.A.}$ (m^{3} m^{-3})	0.316	0.315	0.260	0.390	0.030	9.5	-0.145	0.456
$MI_{H.B.}$ (m^{3} m^{-3})	0.332	0.327	0.277	0.420	0.027	8.1	0.598	0.558
$OM_{H.A.}$ (g dm^{-3})	16.20	15.00	8.00	60.00	7.225	44.6	14.698	3.073
$OM_{H.B.}$ (g dm^{-3})	5.77	5.33	3.00	16.00	1.960	33.9	9.600	2.708
$pH_{H.A.}$	5.94	5.90	4.90	7.60	0.453	7.6	1.554	0.912
$pH_{H.B.}$	5.79	5.70	4.62	7.63	0.653	11.3	-0.717	0.259

$^{(a)}$soil attributes, where: K = soil erodibility factor, T = soil loss tolerance, TR = textural relationship, WCS = water capacity storage, PD = particle density, BD = bulk density, TP = total porosity, MA = macroporosity, MI = microporosity, OM = organic matter, pH = soil pH; attribute preceded of $_{(H.A.)}$, $_{(H.B.)}$, $_{(H1m.)}$ and $_{(H.B/A)}$ refers to the assessment profile, being respectively: A Horizon, B Horizon, profile corresponding to 1 meter depth, and the relationship between A and B Horizons.

The data variability can be classified by the magnitude of its variation coefficient (VC). Thus, according to Pimentel-Gomes and Garcia (2002), the classes are represented as follows: low when (VC ≤ 10%); moderate when (10% < VC ≤ 20%); high when (20% < VC ≤ 30%); and very high when (VC > 30%). In **Table 2** is possible to observe that VC of the physical soil attributes was classified between low and very high. The particle density presented low data variability, because it is an attribute almost inalterable for the management. For the other hand, the soil density, although being an attribute of easy alteration by the management, also presented low VC, besides the values of minimum and maximum, mainly in Horizon A (min. 1.08; max. 1.71), corresponding to distinct physical conditions. For the soil porous system (**Table 2**), was observed larger data variability in comparison with the BD and PD, with highlight to macroporosity (MA) responsible to aeration and to influence the drainage capability and infiltration, presenting high VC for the Horizons A and B. The water capacity storage (WCS) indicated high data variability in both horizons assessed. For the soil chemistry, the organic matter presented VC very high (both depths) and the pH presented low VC (surface depth) and medium VC for the sub-surfacelayer (**Table 2**). Therefore, by virtue of the wide range of soils analyzed and the evident variability of the physical-chemical conditions existents, the interactions observed in the correlation matrix (**Table 3**) represents distinct field conditions. In this way, when a strong tendency is observed in the correlations (**Table 3**), it can be considered that it occurred under different field conditions, represented by 93 samples collected in the northwestern region of São Paulo State.

Thus, for the correlations of Horizon A, although other significant correlations are presented in **Table 3**, the emphasis is on the following pairs: erodibility *vs* water capacity storage ($K_{H.A.}$ *vs* $WCS_{H.A.}$), erodibility *vs* organic matter ($K_{H.A.}$ *vs* $OM_{H.A.}$) and erodibility *vs* textural relation ($K_{H.A.}$ *vs* $TR_{H.B/A}$). In the first case, an indirect interaction occurred, which pointed out that erodibility has a strong interaction with the dynamics of soil mass/volume attributes because erodibility increased with decreasing WCS or decreasing soil density and porosity since they presented high correlations, even in Horizon B. This fact consolidates the hypothetical idea of the tendency that attributes

Table 3. Linear correlation matrix between erodibility and soil loss tolerance with some physical and chemical attributes of soils in the extreme northwestern region of São Paulo State.

Atr.$^{(a)}$	Correlation coefficient$^{(b)}$																		
	K_{HA}	K_{HB}	T_{lm}	$TR_{HB/A}$	WCS_{HA}	WCS_{HB}	PD_{HA}	PD_{HB}	BD_{HA}	BD_{HB}	TP_{HA}	TP_{HB}	MA_{HA}	MA_{HB}	MI_{HA}	MI_{HB}	OM_{HA}	OM_{HB}	pH_{HA}
K_{HB}	0.514^{**}																		
T_{lm}	-0.673^{**}	0.245^{*}																	
$TR_{HB/A}$	0.664^{**}	-0.278^{**}	-0.960^{**}																
WCS_{HA}	-0.690^{**}	-0.522^{**}	0.376^{**}	-0.386^{**}															
WCS_{HB}	-0.606^{**}	-0.703^{**}	0.122^{ns}	-0.105^{ns}	0.887^{**}														
PD_{HA}	0.290^{**}	0.140^{ns}	-0.200^{ns}	0.259^{*}	-0.381^{**}	-0.352^{**}													
PD_{HB}	0.231^{*}	0.210^{*}	-0.101^{ns}	0.060^{ns}	-0.208^{*}	-0.299^{**}	0.086^{ns}												
BD_{HA}	0.404^{**}	0.211^{*}	-0.290^{**}	0.310^{**}	-0.424^{**}	-0.332^{**}	0.173^{ns}	0.128^{ns}											
BS_{HB}	0.405^{**}	0.243^{*}	-0.227^{*}	0.273^{**}	-0.301^{**}	-0.281^{**}	0.253^{*}	0.094^{ns}	0.421^{**}										
TP_{HA}	-0.396^{**}	-0.117^{ns}	0.351^{**}	-0.369^{**}	0.381^{**}	0.302^{**}	-0.166^{ns}	-0.197^{ns}	-0.902^{**}	-0.409^{**}									
TP_{HB}	-0.525^{**}	-0.468^{**}	0.192^{ns}	-0.221^{*}	0.449^{**}	0.460^{**}	-0.273^{**}	-0.236^{*}	-0.400^{**}	-0.775^{**}	0.407^{**}								
MA_{HA}	-0.292^{**}	-0.173^{ns}	0.192^{ns}	-0.218^{*}	0.233^{*}	0.195^{ns}	-0.087^{ns}	-0.071^{ns}	-0.708^{**}	-0.341^{**}	0.697^{**}	0.393^{**}							
MA_{HB}	-0.112^{ns}	-0.051^{ns}	0.058^{ns}	-0.069^{ns}	-0.080^{ns}	-0.114^{ns}	0.301^{**}	0.059^{ns}	-0.049^{ns}	-0.209^{*}	0.072^{ns}	0.306^{**}	0.394^{**}						
MI_{HA}	-0.276^{**}	-0.039^{ns}	0.271^{**}	-0.284^{**}	0.307^{**}	0.246^{*}	-0.150^{ns}	-0.209^{*}	-0.605^{**}	-0.263^{*}	0.721^{**}	0.232^{*}	0.033^{ns}	-0.258^{*}					
MI_{HB}	-0.425^{**}	-0.424^{**}	0.133^{ns}	-0.152^{ns}	0.482^{**}	0.520^{**}	-0.469^{**}	-0.275^{**}	-0.354^{**}	-0.595^{**}	0.351^{**}	0.738^{**}	0.093^{ns}	-0.407^{**}	0.428^{**}				
OM_{HA}	-0.547^{**}	-0.403^{**}	0.286^{**}	-0.310^{**}	0.554^{**}	0.545^{**}	-0.457^{**}	-0.069^{ns}	-0.463^{**}	-0.169^{ns}	0.399^{**}	0.327^{**}	0.266^{*}	-0.083	0.350^{**}	0.375^{**}			
OM_{HB}	-0.295^{**}	-0.214^{*}	0.189^{ns}	-0.161^{ns}	0.341^{**}	0.405^{**}	-0.141^{ns}	-0.147^{ns}	-0.313^{**}	-0.218^{*}	0.291^{**}	0.179^{ns}	0.189^{ns}	0.051^{ns}	0.238^{*}	0.124^{ns}	0.433^{**}		
pH_{HA}	-0.299^{**}	-0.332^{**}	0.054^{ns}	-0.068^{ns}	0.444^{**}	0.397^{**}	-0.235^{*}	-0.039^{ns}	-0.078^{ns}	0.071^{ns}	-0.014^{ns}	0.099^{ns}	-0.103^{ns}	-0.178^{ns}	0.091^{ns}	0.229^{*}	0.415^{**}	-0.011^{ns}	
pH_{HB}	-0.049^{ns}	-0.259^{*}	-0.143^{ns}	0.153^{ns}	0.310^{**}	0.341^{**}	-0.175^{ns}	-0.022^{ns}	0.046^{ns}	0.258^{*}	-0.166^{ns}	-0.040^{ns}	-0.150^{ns}	-0.107^{ns}	-0.091^{ns}	0.031^{ns}	0.272^{**}	-0.040^{ns}	0.616^{**}

$^{a)}$soil attributes, where: **K** = soil erodibility factor, **T** = soil loss tolerance, **TR** = textural relationship, **WCS** = water capacity storage, **PD** = particle density **BD** = bulk density, **TP** = total porosity, **MA** = macroporosity, **MI** = microporosity, **OM** = organic matter, **pH** = soil pH; attribute preceded of $_{\mathbf{(H.A.)}}$, $_{\mathbf{(H.B.)}}$, $_{\mathbf{(H1m.)}}$ and $_{\mathbf{(H.B/A)}}$ refers to the assessment profile, being respectively: A Horizon, B Horizon, profile corresponding to 1 meter depth, and the relationship between A and B Horizons; $^{(b)}$correlation coefficient, where: * = significant at 5% probability,** = significant at 1% probability; ^{ns} = not significant.

influence soil erodibility, as cited before by Castro et al. (2011).

Soil management easily changes the physical attributes to the detriment of other attributes, such as grain size and particle density, which are more stable. This information allows us to infer that anthropic actions on the soil structure can indirectly control soil erodibility. In this way, in practice, management that give better conditions for the soil system mass/volume is able to corroborate one high soil resistance to the erosive process, in order to increase its drainage and storage of water, and reduce the density and consequently its compaction.

The second case ($K_{H.A.}$ *vs* $OM_{H.A.}$ - **Table 3**) also presented a positive correlation, reflecting that which was debated earlier because the WCS depends on the organic matter content. Thus, OM plays a key role in improving the chemical quality and physical soil structure quality.

The third case was shown by the correlation $K_{H.A.}$ *vs* $TR_{H.B./A.}$ (**Table 3**), where the erodibility interacts positively with the increasing relative texture of soil, which was also observed by Mannigel et al. (2002). However, in the present study, this interaction was noted in a more consistent way than that observed by the author, as the data presented final correlations that were more significant. With regard to loss tolerance ($T_{1m.}$), it was evident that the influence exercised by the soil textural relation occurred indirectly. Demarchi and Zimback (2014) also noted such an influence recently. However, these authors observed an indirect tendency between the cause and effect for the set of attributes loss tolerance *vs* erodibility but did not presented any linear correlation. In contrast to this study, that study showed the increased significance for the set $K_{H.A.}$ *vs* T_{1m} ($r = -0{,}673^{**}$).

Based on the results, the best regression model was used to estimate the erodibility and loss tolerance in the northwestern region of São Paulo State, as shown in **Figs 2** and **3**.

In spite of these observations, a large number of the correlations of the soil attributes with the loss tolerance and erodibility exist (**Table 3**). The study revealed that $WCS_{H.A.}$ and $TR_{H.B./A}$ were the attributes that presented the best possible interaction for the conditions in the northwest highlands of São Paulo State and can, therefore, be considered the highest quality indicators for the studied soils when studying erodibility and soil loss tolerance, which can be performed by using the following equations:

$$K_{H.A.} = 0.0323 \times WCS_{H.A.}^{-2} \quad (r^2 = 0.764^{**};\ p < 0.01) \tag{3}$$

$$T_{1m} = 1.3702 \times TR_{H.B/A.}^{2} - 11.981 \times TR_{H.B/A.} + 25.629 \quad (r^2 = 0.934^{**};\ p < 0.01) \tag{4}$$

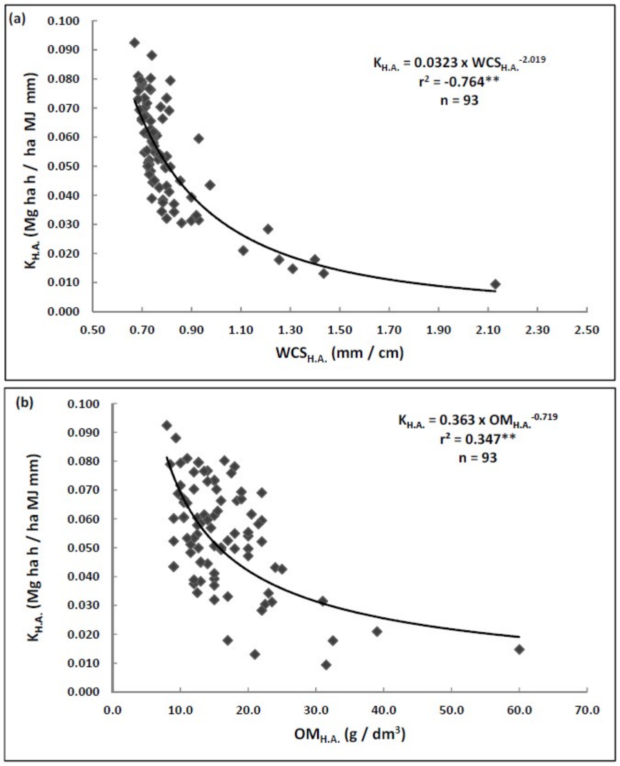

Fig. 2(a), (b). Regression curves of the soil erodibility factor (K) with the water capacity storage (WCS) and organic matter (OM) for Horizon A ($_{H.A.}$)

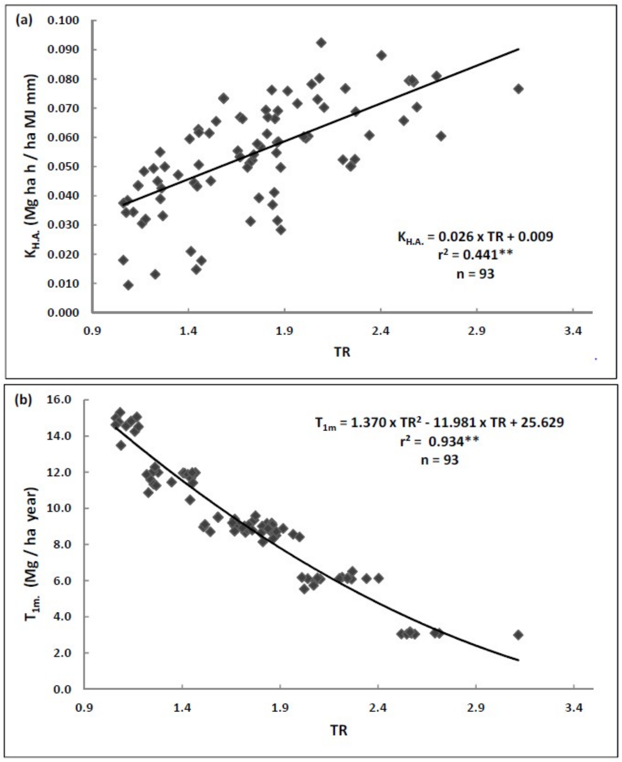

Fig. 3(a), (b). Regression curve between the soil erodibility factor in the surface layer ($K_{H.A.}$) and the textural relationship (TR) and regression curve between the soil loss tolerance (T_{1m}) and textural relationship (TR)

The multiple evaluation analysis indicated high and significant interactions among the studied variables. However, none of these variables exceeded the results given by the simple interactions.

The parameters of the simple semivariograms adjusted for erodibility, loss tolerance and other soil attributes [except the particle density ($PD_{H.A.}$ and $PD_{H.B}$) and the organic matter ($OM_{H.A.}$), that show the pure nugget effect (pne)], denoted spatial dependency (**Table 4**).

The semivariogram adjustments (**Table 4**) presented spherical models ($K_{H.A.}$, $T_{1m.}$, $WCS_{H.B.}$, $BD_{H.B.}$, $MA_{H.A.}$, $MI_{H.A.}$, $MI_{H.B.}$, $OM_{H.B.}$, $pH_{H.A.}$ and $pH_{H.B.}$), gaussian models ($WCS_{H.A.}$, $BD_{H.A.}$, $TP_{H.A.}$ and $TP_{H.B.}$), and exponential models ($K_{H.B.}$, $TR_{H.B/A}$, and $MA_{H.B}$), with ranges varying from 4,330 m ($OM_{H.B.}$) to 34,830 m ($K_{H.B.}$). These ranges represent a distance between 9.3% and 74.9% for the entire sample area. Soil erodibility, similar to most other attributes, showed spatial distribution that was not random. Arraes et al. (2010) also observed spatial dependence for the soil erodibility factor determined indirectly in a smaller area than the area of the present study, with a range of 8,020 m via gaussian adjustment.

Regarding the performance of the adjustment (**Table 4**) analysed by the respective coefficient of spatial determination (r^2), and with the exception of water capacity storage ($WCS_{H.A.}$ and $WCS_{H.B.}$) which did not present good performance, the other attributes showed appreciable performance, with r^2 values ranging from 0.676 ($OM_{H.B.}$) to 0.934 ($MI_{H.A.}$). The spatial evaluator dependence (SDE) was rated (Robertson 2004) as moderately dependent ($K_{H.A.}$, $K_{H.B.}$, TR, $BD_{H.A.}$, $TP_{H.A.}$, $TP_{H.B.}$, $MA_{H.A.}$, $MI_{H.B.}$, $pH_{H.A.}$, and $pH_{H.B.}$) and highly dependent ($WCS_{H.A.}$, $WCS_{H.B.}$, $MA_{H.B.}$, $MI_{H.A.}$, and $OM_{H.B.}$). These observed results allow for the estimation of the spatial distribution of attributes studied based on very appreciable statistical parameters. This fact is of great interest for management and soil conservation.

For analysing the correlation and spatial dependency between the studied attributes (**Table 5**), only the best cross semivariogram adjustments were presented. The analysis revealed that the erodibility and the soil loss tolerance presented good spatial correlations with the majority of the soil physical attributes, a fact that occurred only with pH (for the chemical attributes).

Table 4. Semivariogram analysis of the soil attributes studied in the extreme northwestern region of São Paulo State.

Attributes(a)	Parameters of Simple Semivariograms						
	Model(b)	C_0	C_0+C	A (m)	r^2	SRS(c)	SDE(d) %
			γ(h) Simple of Soil Attributes				
$K_{H.A.}$	shp	1.600×10^{-4}	3.710×10^{-4}	23590.0	0.746	3.184×10^{-8}	59.6
$K_{H.B.}$	exp	3.900×10^{-5}	8.900×10^{-5}	34830.0	0.696	1.801×10^{-9}	69.6
$T_{1m.}$	sph	5.430	1.269×10^{1}	9340.0	0.688	2.990×10^{1}	57.2
$TR_{H.B/A}$	exp	1.075×10^{-1}	2.590×10^{-1}	10710.0	0.724	8.069×10^{-3}	58.5
$WCS_{H.A.}$	gau	2.000×10^{-5}	5.570×10^{-3}	1628.1	0.381	2.126×10^{-5}	99.6
$WCS_{H.B.}$	sph	8.200×10^{-3}	4.720×10^{-2}	2910.0	0.285	1.746×10^{-3}	82.6
$PD_{H.A.}$	pne	1.328×10^{-3}	1.328×10^{-3}	-	-	-	-
$PD_{H.B.}$	pne	1.382×10^{-3}	1.382×10^{-3}	-	-	-	-
$BD_{H.A.}$	gau	4.220×10^{-3}	8.460×10^{-3}	12903.0	0.881	5.045×10^{-6}	50.1
$BD_{H.B.}$	sph	1.390×10^{-3}	2.870×10^{-3}	20760.0	0.811	1.144×10^{-6}	81.1
$TP_{H.A.}$	gau	7.400×10^{-4}	1.530×10^{-3}	9422.0	0.777	3.255×10^{-7}	51.6
$TP_{H.B.}$	gau	3.320×10^{-4}	7.230×10^{-4}	20559.0	0.777	1.165×10^{-7}	54.1
$MA_{H.A.}$	sph	3.070×10^{-4}	9.540×10^{-4}	25170.0	0.678	4.799×10^{-7}	67.8
$MA_{H.B.}$	exp	4.670×10^{-5}	3.444×10^{-4}	8100.0	0.907	6.744×10^{-9}	86.4
$MI_{H.A.}$	sph	2.790×10^{-4}	9.880×10^{-4}	10680.0	0.934	4.819×10^{-8}	81.8
$MI_{H.B.}$	sph	2.550×10^{-4}	7.900×10^{-4}	20710.0	0.735	1.964×10^{-7}	67.7
$OM_{H.A.}$	pne	3.508×10^{1}	3.508×10^{1}	-	-	-	-
$OM_{H.B.}$	sph	3.800×10^{-1}	3.905	4330.0	0.676	2.460	90.3
$pH_{H.A.}$	sph	9.900×10^{-2}	2.020×10^{-1}	28930.0	0.682	7.981×10^{-3}	51.0
$pH_{H.B.}$	sph	2.092×10^{-1}	4.524×10^{-1}	19670.0	0.729	4.220×10^{-2}	53.8

(a)soil attributes, where: K = soil erodibility factor, T = soil loss tolerance, TR = textural relationship, WCS = water capacity storage, PD = particle density, BD = bulk density, TP = total porosity, MA = macroporosity, MI = microporosity, OM = organic matter, pH = soil pH; attribute preceded of $_{(H.A.)}$, $_{(H.B.)}$, $_{(H1m.)}$ and $_{(H.B/A)}$ refers to the assessment profile, being respectively: A Horizon, B Horizon, profile corresponding to 1 meter depth, and the relationship between A and B Horizons; (b)adjustment models, where: gau = gaussian, exp = exponential, sph = spherical; pne = pure nugget effect; (c)SRS = Sum of Residual Squares; (d)SDE = Spatial Dependence Evaluator.

Table 5. Cross semivariogram analysis between erodibility and soil loss tolerance with some physical and chemical soil attributes in the extreme northwestern region of São Paulo State.

Attributes[(a)]	Parameters of Cross Semivariograms					
	Model[(b)]	C_0	C_0+C	A (m)	r^2	SRS[(c)]	SDE[(d)] %
$\gamma(h)$ Cross between erodibility with soil attributes							
$K_{H.A.}=f(T_{1m.})$	exp	-2.740×10^{-2}	-4.868×10^{-2}	24300.0	0.517	9.955×10^{-4}	57.4
$K_{H.A.}=f(TR)$	exp	1.840×10^{-3}	6.740×10^{-3}	20730.0	0.621	1.956×10^{-5}	72.7
$K_{H.A.}=f(WCS_{H.A.})$	gau	-5.510×10^{-4}	-1.232×10^{-3}	27314.0	0.692	4.966×10^{-4}	55.3
$K_{H.A.}=f(WCS_{H.B.})$	gau	-8.760×10^{-4}	-2.342×10^{-3}	22256.8	0.517	4.596×10^{-6}	62.6
$K_{H.A.}=f(BD_{H.A.})$	sph	1.000×10^{-6}	8.620×10^{-4}	26660.0	0.745	5.976×10^{-7}	99.9
$K_{H.A.}=f(BD_{H.B.})$	sph	1.330×10^{-4}	4.840×10^{-4}	18980.0	0.693	1.139×10^{-7}	72.5
$K_{H.A.}=f(TP_{H.A.})$	exp	-1.000×10^{-7}	-2.552×10^{-4}	16740.0	0.622	5.252×10^{-8}	99.9
$K_{H.A.}=f(TP_{H.B.})$	gau	-8.500×10^{-5}	-3.580×10^{-4}	22170.0	0.813	4.197×10^{-8}	76.3
$K_{H.A.}=f(MI_{H.B.})$	sph	-1.000×10^{-7}	-2.472×10^{-4}	22210.0	0.703	6.010×10^{-8}	99.9
$K_{H.A.}=f(pH_{H.A.})$	gau	-2.570×10^{-4}	-2.564×10^{-3}	24699.0	0.535	9.989×10^{-6}	90.0
$\gamma(h)$ Cross between soil loss tolerance with soil attributes							
$T_{1m.}=f(TR)$	sph	-5.910×10^{-1}	-1.727	9410.0	0.778	4.610×10^{-1}	65.8
$T_{1m.}=f(BD_{H.A.})$	gau	-1.000×10^{-4}	-1.122×10^{-1}	11414.0	0.777	3.433×10^{-3}	99.9
$T_{1m.}=f(BD_{H.B.})$	gau	-1.350×10^{-2}	-6.050×10^{-2}	18446.0	0.668	2.955×10^{-3}	77.7
$T_{1m.}=f(TP_{H.A.})$	gau	1.000×10^{-4}	5.500×10^{-2}	9560.0	0.726	2.328×10^{-3}	99.8
$T_{1m.}=f(TP_{H.B.})$	gau	5.450×10^{-3}	3.120×10^{-2}	22066.0	0.640	1.082×10^{-3}	82.5
$T_{1m.}=f(MI_{H.A.})$	gau	1.000×10^{-4}	3.290×10^{-2}	10981.0	0.697	7.155×10^{-4}	79.7
$T_{1m.}=f(MI_{H.B.})$	gau	1.000×10^{-5}	2.662×10^{-2}	24006.0	0.757	4.902×10^{-4}	99.9

[(a)] soil attributes, where: K = soil erodibility factor, T = soil loss tolerance, TR = textural relationship, WCS = water capacity storage, BD = bulk density, TP = total porosity, MA = macroporosity, MI = microporosity, OM = organic matter, pH = soil pH; attribute preceded of $_{(H.A.)}$, $_{(H.B.)}$, $_{(H1m.)}$ and $_{(H.B/A)}$ refers to the assessment profile, being respectively: A Horizon, B Horizon, profile corresponding to 1 meter depth, and the relationship between A and B Horizons; [(b)]adjustment models, where: gau = gaussian, exp = exponential, sph = spherical; pne = pure nugget effect; [(c)]SRS = Sum of Residual Squares; [(d)]SDE = Spatial Dependence Evaluator.

For the correlations between soil attributes and erodibility, such as the loss tolerance (**Table 5**), there were relations in accordance with the observed correlations given by Pearson's matrix (**Table 3**). In this way, the soil erodibility presented a positive spatial correlation with the textural relation (TR) and bulk density ($BD_{H.A.}$ and $BD_{H.B.}$), indicating that the places that showed low values for these attributes, also showed lower rates of erodibility. On the other hand, soil erodibility presented a negative correlation with the soil loss tolerance ($T_{1m.}$), water capacity storage ($WCS_{H.A.}$ and $WCS_{H.B.}$), total porosity ($TP_{H.A.}$ and $TP_{H.B.}$) and microporosity ($MI_{H.B.}$), indicating that the places where these attributes presented higher values also presented a lower erodibility index.

The soil loss tolerance (**Table 5**) exhibited a positive correlation with the total porosity ($TP_{H.A.}$ and $TP_{H.B.}$) and microporosity ($MI_{H.A.}$ and $MI_{H.B.}$), while it exhibited a negative correlation with the textural relation (TR) and bulk density ($BD_{H.A.}$ and $BD_{H.B.}$). In general, the cross semivariogram analysis presented adjustments with height in gaussian, spherical and exponential models, ranging between 9,410 m [$T_{1m.}=f(TR)$] and 32,164 m [$K_{H.A.}=f(MA_{H.B.})$], and the coefficient of spatial determination (r^2) ranged between 0.621 [$K_{H.A.}=f(TR)$] and 0,813 [$K_{H.A.}=f(TP_{H.B.})$], showing significant cross adjustments.

Finally, considering the spatial dependency of the studied attributes (**Table 4**), those of greatest interest (i.e., erodibility and soil loss tolerance) presented significant spatial correlations with the other physical attributes of soil (**Table 5**). These results are shown in **Fig. 4** by the spatial distribution maps of erodibility and soil loss tolerance, as estimated by the cokriging technique, which surpassed the statistical performance obtained by the kriging technique. Therefore, in **Fig. 4a**, the best adjustment considering the performance of the spatial determination coefficient (r^2) was $K_{H.A.}=f(TP_{H.B.})$, and for **Fig. 4b**, the best adjustment was $T_{1m.}=f(TR)$.

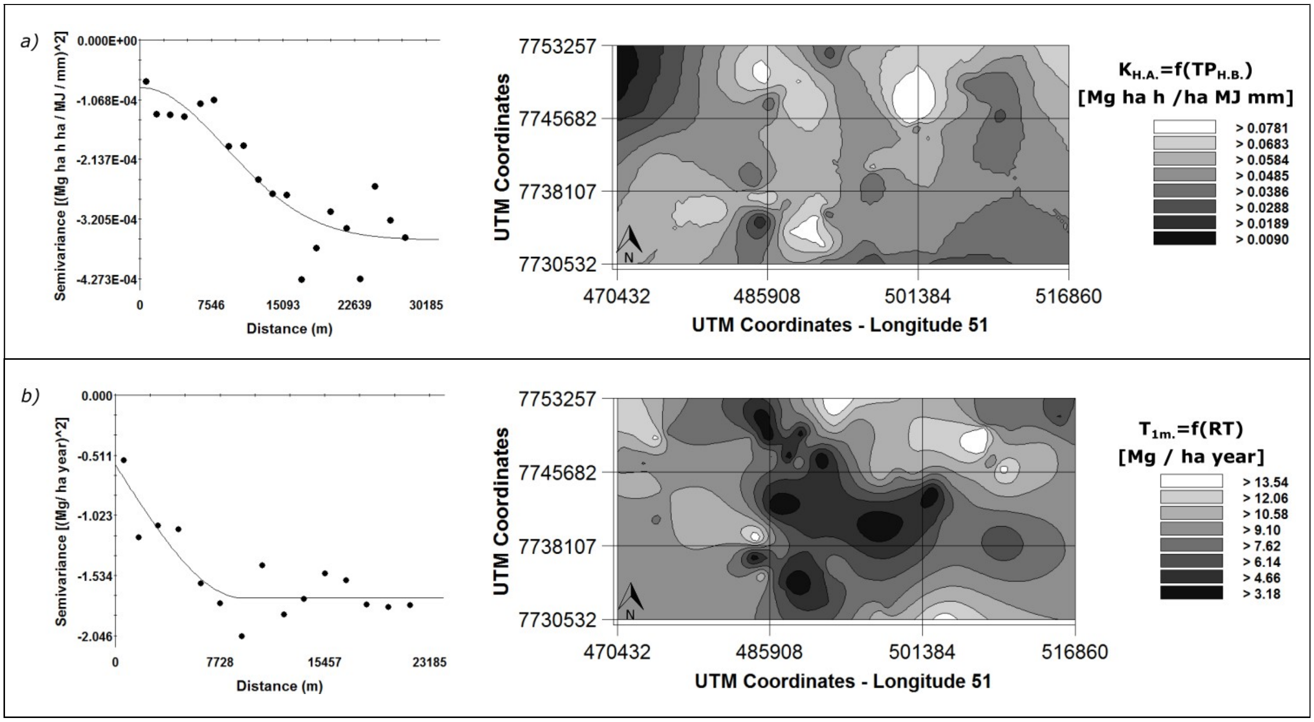

Fig. 4$_{(a),(b)}$. Cross semivariograms and cokriging maps of the erodibility factor and soil loss tolerance in the northwestern highland region of São Paulo State.

CONCLUSIONS

Among the studied soils, the red Ultisols had higher risks of soil erosion by rainfall, because they presented the highest erodibility and lowest loss tolerance.

Both loss tolerance and erodibility have strong interactions with soil physical attributes and may be measured in accordance with WCS and TR, as derived from equations with high statistical probability.

From a geostatistic point of view, the erodibility and the loss tolerance also presented significant spatial correlations with most soil attributes, but the most significant spatial correlations were mainly with total porosity and TR, allowing for better mapping by the cokriging technique.

The results of this work and its discussion involving classic studies on soil erodibility show that this proposal can be a very interesting approach for preliminary soil erodibility zoning in large areas with warm climates and soil profile similarities sparing high cost, complex surveys and long-term climate data series.

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