EROSION FACTORS AND MAGNETIC SUSCEPTIBILITY IN DIFFERENT COMPARTMENTS OF A SLOPE IN GILBUÉS- PI, BRAZIL

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ABSTRACT: The erosion is the degradation of soil with effects on crop productivity and pollution of the environment. To understand the spatial variability of this phenomenon, geostatistical techniques and concepts of soil-landscape can be used to identify landscape compartments with different potential of erosion. The aim of this study was to understand the factors of erosion in landscape compartments and the relations with the magnetic susceptibility (MS) of the soils in a slope in Gilbués, state of Piauí (PI), Brazil. Sampling meshes were set in compartments I and II with 121 points and in compartment III with 99 points spaced every 10 meters. There was significant difference to erodibility (K) and risk of erosion (RE); the spatial variability of MS was lower than the factors of soil erosion. The soil losses (A), the natural erosion potential (NEP), the RE and the MS had spatial relation with the topographic factor, indicating dependence of the erosion with the relief. We concluded that losses of soil, natural erosion potential and risk of erosion have spatial relation with the topographic factor, showing the dependence of the erosion factors with the relief. The soil magnetic susceptibility can be used as an auxiliary variable in the indirect quantification of the erodibility factor and the risk of soil erosion.

KEYWORDS: indirect quantification, geostatistics, conservation planning, compartments, topography, relief, landscape.

FATORES DE EROSÃO E SUSCETIBILIDADE MAGNÉTICA EM DIFERENTES COMPARTIMENTOS DE UMA VERTENTE DO MUNICÍPIO DE GILBUÉS-PI

RESUMO: A erosão é a forma de degradação do solo com efeitos na produtividade das culturas e na poluição do meio ambiente. Para compreender a variabilidade espacial desse fenômeno, técnicas geoestatísticas e conceitos da relação solo-paisagem podem ser utilizados para identificar compartimentos da paisagem com diferentes potenciais de erosão. O objetivo deste trabalho foi estabelecer elementos para a compreensão dos fatores de erosão em compartimentos da paisagem e das relações com a suscetibilidade magnética (SM) dos solos de uma vertente no município de Gilbués - PI. Foram montadas malhas de amostragem nos compartimentos I e II, com 121 pontos, e compartimento III, com 99 pontos, espaçados a cada 10 m. Houve diferença significativa para erodibilidade (K) e risco de erosão (RE); a variabilidade espacial da SM foi menor do que a dos fatores de erosão do solo. As perdas de solo (A), potencial natural de erosão (PNE), RE e SM tiveram relação espacial com o fator topográfico, indicando dependência da erosão ao relevo. Concluiu-se que as perdas de solo, o potencial natural de erosão e o risco de erosão apresentaram relação espacial com o fator topográfico, comprovando a dependência dos fatores de erosão ao relevo. A suscetibilidade magnética do solo pode ser utilizada como variável auxiliar na quantificação indireta do fator erodibilidade e do risco de erosão do solo.

PALAVRAS-CHAVE: quantificação indireta, geoestatística, planejamento conservacionista, compartimentos, topografia, relevo, paisagem.

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INTRODUCTION

The erosion, in many different ways, is seen as the most important stage of degradation, with consequent negative effects on crop productivity and environmental pollution. The knowledge of soil erosion rates is important for both understanding the evolution of relief as to assess the impact of human activity on these rates (PARSONS et al., 2010).

Statistics show that the physical loss of soil by erosion worldwide reaches billions of hectares of fertile land. In Brazil, this loss reaches 840 million tons per year and in semiarid regions, at least 10% are attained. The city of Gilbués, in the state of Piauí (PI), Brazil, presents as the city that has the largest continuous area degraded in this state, totaling 631 km^2 (SEMAR, 2008).

Among the various proposals for the study of rates of soil erosion, those that come closest to conservation planning are the proposals made by IZIDORIO et al. (2005), SOUZA et al. (2005) and MARTINS FILHO (2007). These studies used geostatistical techniques and concepts of soil-landscape relation, involving compartments of the landscape, to create future scenarios of erosion in spatial and temporal scale. However, despite the geostatistical techniques and landscape compartments reveal itself promising to develop new concepts and/or technologies for understanding the processes of erosion and soil management practices (BARBIERI et al., 2008; SANCHEZ, 2009); they are techniques with short use in conservation planning.

The effect of erosion in crop production is often confused with that relative to the position of the landscape. Thus, the study of landscape and erosion should not be excluded. Compartmentalizing the landscape, CAMPOS et al. (2008) found significant results in the study of spatial variation of soil loss by erosion. These compartments are mappable, and identify its limits in the field may help to understand the spatial variability of soil variables and therefore the understanding of erosion. However, most studies emphasize the aspects of temporal variability and almost do not highlight the spatial variation of soil variables related to erosion (WANG et al., 2003; MELLO et al., 2006, PÉREZ-RODRIGUEZ et al., 2007; SILVA et al., 2000). Thus, the quantification of soil erosion associated with the compartmentalization of the landscape and the geostatistical techniques present themselves as effective tools to establish cause and effect relations of the soil erosion process. This combination of tools can assist in the transfer of information to locals with similar compartments, as proposed by MARQUES JUNIOR (2009) and SIQUEIRA et al. (2010a).

Another important aspect related to the study of erosion rates are indirect quantitative methods. There are a large number of studies using these models to quantify indirect taxes (SILVA et al., 2000; VENTURA JR. et al., 2001). Among the methods used in these studies, there is the magnetic susceptibility (MS). MS is a variable that expresses the mineralogical composition of the soil (MATHE et al., 2006; TORRENT et al., 2007) and is susceptible to be associated with the erodibility factor, as this factor depends on the constitution of the soil (SHERIDAN et al., 2000). The mapping of the MS has stood out as one of the more indirect methods used for agricultural studies (SIQUEIRA et al., 2010b) and environmental characterization (GRIMLEY et al., 2004). Some studies reported the relation between MS and the loss of soil by erosion (HANESCH & SCHOLGER, 2005; VENTURA JR. et al., 2001; PARSONS et al., 2010) and the identification of areas with different erosion potentials (ROYALL, 2001) .

Thus, the MS can aid in quicker acquisition of information about different erosion potentials along a slope. The aim of this study was to understand the factors of erosion in landscape compartments and the relations with soils magnetic susceptibility (MS) of a slope in Gilbués - PI.

MATERIAL AND METHODS

Location and characterization of the study area

The study area is located in Gilbués-PI. The geographical coordinates are 09º49' south latitude and 45°20' west longitude, with an average altitude of 481m above the sea level (Figure 1). The temperature varies between 25º and 36 ºC, and semi-humid and warm climate, pluviometric precipitation around 800 to 1,200 mm and the rainy season extends from November to December and from April to May (VIEIRA et al., 2007). The relief varies from flat to wavy with declivity of 0.9 to 20%.

In an area of 140 hectares, a transection was established from the slope ridge in the direction to the softer declivity of the slope at an approximate distance of 2,750 meters from the top of the landscape to the lowest level. It was identified three compartments, using topographic criteria, based on visual perceptions and in places where there are discontinuities or "breaks" of the degree of inclination, beyond the digital elevation model (DEM).

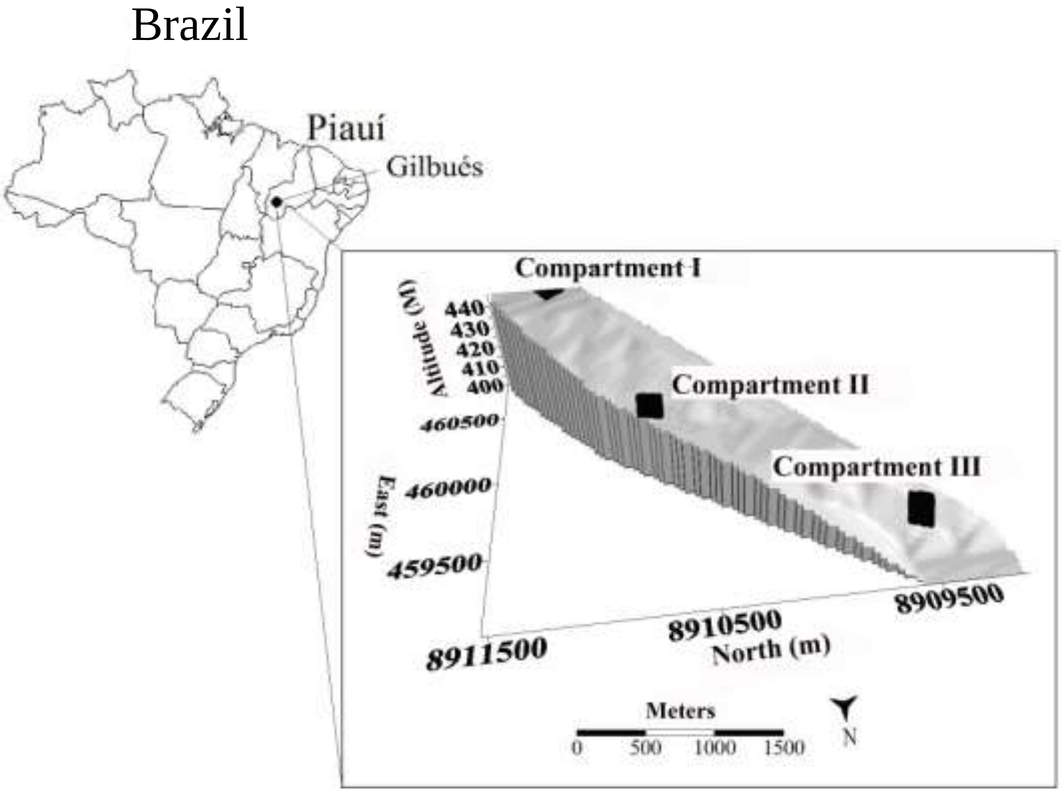

FIGURE 1. Area and sampling mesh within each compartment of the landscape represented in the digital elevation model (DEM).

It was made a sampling mesh in each compartment. Compartments I and II with 121 points and compartment III with 99 points regularly spaced at 10 meters. Samples were collected at the crossing points of the meshes in depth from 0.00 to 0.20 m. In the compartment I the relief is plan. The soil found is the Quartzarenic Neosol (Endsol) originated from arenite of the Urucuia Formation. The vegetation is sparse, without, however, denote a vegetative cover. The compartment II is a transition compartment with higher clay content and it is located at an inclined and bare plane. The occurrence soil is the Red Yellow Argisol (Ultisols), being a transitional compartment with higher clay content.

The compartment III lies in a curled plane toward the watercourse, without vegetation. In this compartment, Quartzarenic Neosol of sedimentary origin is found, with predominantly siltstone outcrops, by the force of erosive action, corresponding to areas of latest dissection.

Evaluation of variables of soil and erosion

The samples were air dried and sieved with a mesh of 2mm diameter for soil gradation and chemical analysis of soil profiles, following the methodology proposed by EMBRAPA (1997). The available exchangeable calcium, magnesium, potassium and phosphorus contents were extracted using the method of ion exchange resin by RAIJ et al. (1987). Based on the results of chemical analysis, it was calculated the sum of basis (BS), the cation-exchange capacity (CEC) and basis saturation (V%). The pH was determined in $CaCl_2$. The Fe_2O_3 (%) was obtained according to the method described by EMBRAPA (1997). The sand fraction was divided into five sub fractions separated by sieves of different openings: very coarse sand (VCS) in mesh sieve with 2-1mm; coarse sand (CS), in mesh with 1 to 0.5 mm; medium sand (MeS), in mesh with 0.5 to 0.25 mm; fine sand (FS), in mesh with 0.25 to 0.10 mm and very fine sand (VFS), in mesh sieve with 0.10-0.05 mm. The clay fraction was separated by sedimentation according to Stokes' Law, being the silt fraction determined by difference (EMBRAPA, 1997).

The organic matter determination was performed according to RAIJ et al. (1987). The magnetic susceptibility (MS) of samples was measured using an analytical balance as described by SIQUEIRA (2010b). The apparatus consists of an analytical balance, a magnet, a magnet support and a sample port. The interaction of minerals with magnetic expression, present in the soil sample, with the magnet generates a weight force on the scale. This weight force is then converted into MS using a standard curve. Table 1 lists the characteristics of the soils of the study area, at two depths.

TABLE 1. Soil gradation and chemical characterization of soils found in the area.

Compartments	Deep	pH	OM	P	BS	CEC	V	TS	Silt	Clay	Fe_2O_3
	m	$CaCl_2$	g dm^{-3}	mg dm^{-3}	mmol$_c$ dm^{-3}		%	------g kg^{-1}	---------		g kg^{-1}
I	0.00 - 0.15	4.6	18	5.0	24.4	58.4	42	583	70	347	9
	0.35 - 0.45	3.9	5	2.0	8.7	39.7	22	559	326	115	5
II	0.00 - 0.15	4.8	17	4.0	68.9	102.9	67	332	300	368	19
	0.30 - 0.40	4.8	10	2.0	74.8	108.8	69	320	296	384	27
III	0.00 - 0.20	5.2	14	6.0	66.4	94.4	70	518	269	213	20
	0.20 - 0.40	5.4	12	7.0	71.0	99.0	72	543	257	200	18

OM - organic matter; BS - sum of basis; CEC - cation-exchange capacity; V - basis saturation; TS - total sand; MS - magnetic susceptibility

To estimate the erosion, it was used the Universal Soil Loss Equation (USLE).

$$A = R\ K\ LS\ C\ P \quad (1)$$

In which,

R - erosivity, MJ mm ha^{-1} h^{-1} year^{-1};
K - erodibility, t ha^{-1} MJ^{-1} mm^{-1} h ha;
LS - topographic factor;
C - vegetation cover factor, and
P - pratice of soil conservation factor.

The location of rainfall erosivity was estimated to be 6340 MJ mm ha^{-1} h^{-1} year^{-1}, as the method proposed by LOMBARDI NETO et al. (2000). The erodibility was estimated using the equation proposed by DENARDIN (1990). To determine the topographic factor, we used the equation proposed by WISCHMEIER & SMITH (1978). The C factor value was adopted depending on the size of low to creeping vegetation, partially covering the terrain. For the P factor, were adopted values proposed by WISCHMEIER & SMITH (1978), depending on the declivity of the terrain. The soil loss tolerance (T) was estimated using the method proposed by BERTOL & ALMEIDA (2000). The natural erosion potential (NEP) was determined as proposed by WISCHMEIER & SMITH (1978). The risk of erosion (RE) was determined and classified according to LAGROTTI (2000).

Statistical analysis of data

The erosion factors, RE, NEP and MS of the soil were analyzed using descriptive statistics, calculating the average, median, variance, coefficient of variation, asymmetry coefficient and coefficient of kurtosis. For the statistical analysis, it was used the Tukey test. We also made the

Pearson correlation between the MS and the erosion factors in each compartment. Spatial dependence was analyzed using geostatistics. The exponential, Gaussian and spherical models of the semivariograms were adjusted using the GS + software, version 7.0.

RESULTS AND DISCUSSION

The descriptive statistics of erosion factors and MS is presented in Table 2. All compartments showed statistical difference in the K factor, the RE and the MS attribute, with higher values observed in compartment III. The rising value of the RE of the compartment I to the compartment III may be explained by the integration of agents: rugged relief, shallower soils, lack of vegetable cover and high pluviosity.

Despite the compartment I present soil loss (A) of 41.30 t ha^{-1} $year^{-1}$ and compartment III present 28.06 t ha^{-1} $year^{-1}$, there was no statistical difference by Tukey test between these values, possibly due to the high variability of soil variables. The same occurs for the NEP attribute. The results of the average test and C.V. indicate that there is no difference between the compartments studied. Some authors (SAUER et al., 2006) report that the average result is not a good analysis to be used to compare the compartments along the landscape. Other authors (SOUZA et al., 2007) reported that even inferring the variability by C.V., more detailed analysis are needed, using geostatistics to characterize the variability in different compartments of the landscape.

TABLE 2. Descriptive statistics of variables, erodibility - K (t h MJ^{-1} mm^{-1}), topographic factor - LS, natural potential erosion - NEP (t $ha^{-1}year^{-1}$), soil loss - A (t $ha^{-1}year^{-1}$), risk of erosion - RE and magnetic susceptibility - MS (m^3 kg^{-1}) among the compartments in depth from 0.00 to 0.20 m.

Statistic	Erosion Factors					MS (10^{-6})
	K	LS	NEP	A	RE	
Compartment I - 121 samples						
Average	0.043^{c}	1.51^{a}	413.00^{a}	41.30^{a}	2.07^{c}	1.25^{c}
Median	0.04	0.75	230.13	230.13	0.03	1.26
[1]C.V.(%)	11.80	117.04	111.75	111.75	131.60	26.82
Kurtosis	-0.67	7.86	5.47	5.47	8.87	0.85
Asymmetry	0.60	2.49	2.13	2.13	2.65	-1.61
Compartment II - 121 samples						
Average	0.048^{b}	1.06^{a}	322.29^{a}	32.23^{a}	6.28^{b}	1.78^{b}
Median	0.05	0.49	146.91	14.69	2.83	1.76
C.V.(%)	8.47	162.02	166.45	166.45	166.45	35.04
Kurtosis	0.82	17.85	20.75	20.75	20.75	5.12
Asymmetry	-1.29	3.86	4.10	4.10	4.10	-0.45
Compartment III - 99 samples						
Average	0.08^{a}	0.54^{b}	280.62^{a}	28.06^{a}	13.39^{a}	0.68^{a}
Median	0.08	0.32	164.62	16.46	7.85	0.64
C.V.(%)	9.35	117.50	119.98	119.98	119.97	77.66
Kurtosis	10.75	12.06	12.31	12.31	12.31	80.65
Asymmetry	-2.34	2.98	3.00	3.00	3.00	8.53

[1]C.V.% - coefficient of variation; Average followed by the same letters in the column do not differ significantly, $p<0{,}05$ of probability, by the Tukey test.

The RE values were higher in the compartment III, indicating that in the areas of the lowest topographical factor (LS) the amount of soil being lost is greater than that which is being formed (pedogenesis/erosion rate). The greater erosion of some places of the landscape is associated to the declivity and erodibility of the soils, among other factors. In the present study, even the compartment III presenting the lowest influence of the topographic factor, it has higher risk of erosion, possibly due to mineralogical characteristics that influence soil erodibility. Thus, it is necessary to use practices that can reduce this impact, such as increasing soil cover and build terraces (MARTINS FILHO, 2007). One way to change the soil loss is to modify the LS factor as demonstrated by CAMPOS et al. (2008), when reduced the distance between terraces, working with spatial variability in soil loss by erosion. Comparing the three compartments (Table 1), it was noted that the values of NEP decrease from compartment I to compartment III. This result corroborates the results of MELLO et al. (2006) which mentions that in the region where the terrain is more accentuated, more soil losses and erosion risk are estimated.

With the exception of the K factor, which showed low C.V., all the others showed high C.V. in all compartments. The compartment II had the lowest CV values for K and the highest values of C.V. for LS, NEP, and RE. SOUZA et al. (2003) and SOUZA et al. (2005) found similar values for the K factor, LS, NEP, and RE. SIQUEIRA et al. (2010a) reported that even inferring the variability by C.V., a more detailed analysis is needed, using geostatistics to characterize the variability in different compartments of the landscape.

Comparing the values of MS with the K factor and RE, it was noted that in compartments where the highest values were observed for K and RE, were also observed higher values of MS. MS is a variable that expresses indirectly the mineralogical composition of the soil (TORRENT et al., 2007). The main minerals of magnetic expression in soils are the iron oxides. Several studies report about the relation between mineralogy of iron oxides with soil physical properties, such as stability of aggregate (SCHWERTMANN & KAMPF, 1985; CAMARGO et al., 2008). Other studies conclude that the aggregation process is not affected by the type of iron oxide, but by the dimension of it (BARBERIS et al., 1991), which also affects its magnetic expression (magnetic anisotropy) (DUNLOP & ÖZDEMIR, 1997) . Thus, understanding that a relation exists between the aggregate and the stability of erodibility (SHERIDAN et al., 2000), the MS may be used to infer the erodibility (K) at different locations in the landscape.

Table 3 presents the coefficients of the experimental semivariogram adjusted to the erosion factor, RE and MS in depth from 0.00 to 0.20 m. The factor and the MS showed spatial dependence in the different compartments.

In the compartment I, the most frequent model was exponential, in the compartment II, the Gaussian model, and in the compartment III, there was a tendency of higher nugget effect. This indicates that in the compartment III will be an abrupt transition between the classes formed on a map of isolines of mesh I. In the compartment I, the adjusted model showed a smooth transition, and in the compartment II, an intermediate transition. An abrupt transition may be associated with the occurrence of fewer numbers of distinct classes in the map of isolines of the area, so it is recorded lower variability, while a smooth transition indicates the presence of a larger number of classes, indicating greater variability. CAMPOS et al. (2008) and SANCHEZ (2009) also adjusted the exponential and spherical models in their study of the spatial variability of soil erosion factors.

The value of C_0 (nugget effect), unexplained variance (error due to sampling, laboratory analysis, interpretation, etc.), was lower for MS than for the other factor of erosion, RE. This result shows that the error of representing the spatial variability of the MS was lower than the factors of soil erosion. SIQUEIRA (2010) reports that the MS presented a 33% lower error in the spatial representation of a set of variables at depth from 0.00 to 0.20 m.

However, a tendency is observed for pure nugget effect (PNE) in compartment III, confirming the hypothesis that younger compartments (compartment III) have greater variability (SANTOS et al., 2011; CAMPOS et al., 2012). For being a younger compartment, with greater variability, there is greater difficulty in adjusting to a model of semivariogram.

TABLE 3. Estimation of the coefficients of semivariogram models adjusted for the variables, K - soil erodibility, LS - relief, NEP - natural erosion potential, A - soil loss, RE - risk of erosion, MS - magnetic susceptibility between the geomorphic surfaces in depth from 0.00 to 0.20 m.

Variables	Models	C_0	$C_0 + C_1$	SDD	Reach (m)	R^2	CVRC	
							B	Y
Compartment I - 121 samples								
K	Gaussian	0.00	0.000017	0.00	10.02	0.66	0.83	0.00
LS	PNE	-	-	-	-	-	-	-
NEP	Exponential	559.00	202700	0.28	42.00	0.60	0.64	156.02
A	Exponential	1.00	1865	0.05	15.90	0.30	0.35	27.22
RE	Gaussian	0.0029	0.0446	6.50	33.98	0.85	0.95	0.00
MS	Exponential	0.000	0.000	0.00	18.60	0.35	1.07	-0.01
Compartment II - 121 samples								
K	Gaussian	0.00	0.000012	0.00	9.00	0.67	0.85	0.01
LS	Gaussian	0.00	1.932	0.01	14.02	0.68	0.58	0.42
NEP	Gaussian	100	173500	0.06	14.02	0.66	0.53	138.31
A	Gaussian	18	1712	1.06	10.77	0.59	0.68	9.49
RE	Gaussian	0.60	63.71	0.94	10.77	0.59	0.68	1.83
MS	Gaussian	0.00	0.00	0.00	80.02	0.84	1.08	-0.01
Compartment III - 99 samples								
K	Exponential	0.000001	0.000072	1.39	64.80	0.81	0.66	0.03
LS	PNE	-	-	-	-	-	-	-
NEP	PNE	-	-	-	-	-	-	-
A	PNE	-	-	-	-	-	-	-
RE	Gaussian	36.80	283.90	12.96	16.28	0.38	0.54	5.95
MS	Spherical	0.00	0.00	0.00	85.70	0.60	0.80	0.01

C_o - nugget effect; $C_o + C_1$ - level, R^2 - coefficient of model determination; PNE - pure nugget effect; SDD (C_o/ $C_o + C_1$)*100 - spatial dependence degree; D.P - spatial dependence; B - angular coefficient; CVRC - cross validation regression coefficient; y - intercepted. Nugget effect - 100% of the level; SDD 25 < moderate < 75%, weak > 75% and strong≤ 25%.

With the exception of the LS variables in the compartment I and LS, PNA and A in the compartment III, the remaining variables showed strong spatial dependence degree (SDD). The use of geostatistical techniques allows better detail of the spatial variation of soil losses.

We emphasize the proximity of the parameter reach with the A factor in compartment I, and with A attribute in compartment III. These results, comparing the soil loss with spatial variability of MS are scarce in literature. According to BECEGATO et al. (2005), geophysical researches in agricultural soils are still very incipient in Brazil. In this sense, the author emphasizes the importance of using MS as a promising tool to investigate the spatial variability of other soil variables in the context of soil-landscape relation, providing better understanding of the pedology-geomorphology relations. This reinforces the studies of MARQUES JUNIOR (2009) and SIQUEIRA et al. (2010a), which report that the geostatistical techniques should be used with the soil landscape relation concepts in the transfer of information to similar locations. This transfer is based on the concept that the landscape compartments may be used to infer the variability.

Table 4 shows the significant correlations between MS values and the values of the study factors of soil erosion in depth from 0.00 to 0.20 m. The MS values presented positive correlation with the values of RE in compartment I, and negative correlation with the values of the K factor in compartment III. The RE results are consistent with those in Table 1, showing that the larger the MS the higher the RE.

SADIKI et al. (2009) used the magnetic susceptibility to assess the degradation of tropical soils. Thus, studies that relate the variability of erosion with MS may contribute to the development of strategies aimed at sustainable land use.

TABLE 4. Coefficient of linear correlation among MS - magnetic susceptibility, K - erodibility of the soil, LS - relief, NEP - natural potential of erosion, A - soil loss, RE - risk of erosion, in depth of 0.00 - 0.20 m.

K	LS	NEP	A	RE
		Compartment I – 121 samples		
0.096	-0.0149	-0.156	-0.156	0.245**
		Compartment II – 121 samples		
0.056	-0.123	-0.119	-0.119	-0.119
		Compartment III – 99 samples		
-0.329**	0.025	0.006	0.006	0.007

The correlations found in this study between MS and erosion factors are specific for this type of soil, which means that to use the MS in prediction of other variables new studies are needed for each particular region or soil type. Thus, assuming that current agricultural practices require knowledge of the variability of soil variables on a detailed scale (1:10.000) and ultra-detailed (1:5.000 or greater), it is extremely important new studies on the relation of cause and effect between MS and erosion. The results of this type of study when associated to technical and economic impact of the loss of soil and nutrients by erosion, as proposed by DE ANDRADE (2011), may promote the emergence of a new management tool for the use, management and conservation of soil and water in commercial areas.

CONCLUSIONS

Soil losses, natural erosion potential and risk of erosion presented spatial relation with the topographic factor, proving the dependence of erosion factors to relief.

The magnetic susceptibility of the soil can be used as an auxiliary variable to indirect quantify the erodibility factor and the risk of soil erosion.

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