ORIGINAL ARTICLE

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Geomorphic surface and estimation of soil erosion on a sandstone-basalt substratum of a toposequence in Jardinópolis, São Paulo state, Brazil

Superfícies geomórficas e erosão do solo estimada em toposseqüência desenvolvida sobre arenito-basalto na região de Jardinópolis, SP

ABSTRACT: Superficial processes involving erosion, transport and deposition of materials, as well as internal pedogenic processes play a role in soil differentiation on the landscape, and are influenced largely by the relief. In this study, we aimed to identify relationships among geomorphic surfaces, hillslope segments, soil erosion and soil attributes of a toposequence in the municipality of Jardinópolis, São Paulo state, Brazil. Three geomorphic surfaces and five hillslope segments were identified and characterized: top, scarp, shoulder, stocking lean and inferior lean. Six trenches were opened along the hillslopes for soil horizon identification, morphologic description and soil classification. We observed soils of sandy texture in geomorphic surface I going to soils of clayey texture in geomorphic surface III. The soil values of SB, CEC and V% increase from G.S. I to G.S. III according to the sandstone-basalt lythosequence. Soil erodibility (K) decreases from geomorphic surface I to III, while losses (A and A*) show contrary behavior, increasing from geomorphic surface I to III, that is, from soils developed in sandstone to basaltic soils.

RESUMO: *Processos superficiais envolvendo erosão, transporte e deposição de materiais, como também processos internos, pedogenéticos, atuam na diferenciação dos solos na paisagem, condicionados em grande parte pelo relevo. Neste trabalho, objetivou-se identificar as relações das superfícies geomórficas e dos segmentos de vertentes com a erosão e os atributos dos solos, em Jardinópolis-SP. Foram identificadas três superfícies geomórficas e cinco segmentos da vertente: topo (arenito), ombro (arenito/basalto), meia encosta (arenito/basalto), escarpa (basalto) e encosta inferior (basalto). Foram abertas seis trincheiras a partir do espigão da vertente no sentido do declive mais suave das vertentes, para a identificação dos horizontes, a descrição morfológica e a classificação dos solos. Observaram-se solos com textura arenosa da superfície geomórfica I passando para a textura argilosa na superfície geomórfica III. Verificaram-se solos com valores crescentes de SB, CTC e V%, partindo da S.G. I para a S.G. III, em função da litologia de arenito transicionando para basalto. A erodibilidade (K) dos solos diminui da superfície geomórfica I para a III, enquanto que as perdas (A e A*) apresentam comportamento contrário, aumentando da superfície geomórfica I para a III, ou seja, de solos desenvolvidos sob arenito para solos de origem basáltica.*

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227

1 Introduction

The use of the geomorphic surface concept in studies of soil landscape represents an important milestone for the development of soil sciences because allows interrelationship among various branches of earth sciences such as geology, geomorphology and pedology (DANIELS; CAMBLE; CADY, 1971). This association enhances the understanding of spatial soil distribution through landscape, pointing out the behavior of soil attributes, which are mainly related to stratigraphy, water flow and relief forms (BOCKHEIM et al., 2005).

Relationships between soils and geomorphic surfaces allows the understanding of landscape structure and assists prediction of distribution of soils, vegetation and erosion, providing an important tool for soil survey and management (KRASILNIKOV et al., 2005). Moreover, Campos et al. (2007) point out that, although the erosional and depositional concept is implicit in the concept of geomorphic surface there are few studies that relate this information with soil erosion rates.

Topographic factors are the main conditioners of erosive processes because they control hydrological and pedological agents (CAMPOS et al., 2008). On the other hand, erosion presents spatial distribution in the landscape, which occurs due to the prevailing pedological and environmental processes (BOCKHEIM et al., 2005). Thus the classical models of landscape evolution incorporate the assumption of a simple linear relationship between the forms of relief and soil erosion, because the higher the slopes, the more severe the erosive action (MONTGOMERY, 2003). Nevertheless, most research on the relief x erosion relationship is quantitative and not associated with soil development and erosion.

In Brazil, there is some research focusing on soil-geomorphology relationships in studies of soil erosion, such as those developed by Souza et al. (2003), Cunha et al. (2005) and Campos et al. (2007) in soils under sandstone-basalt transition. These studies showed that the forms of relief condition water flow on ground surface and control erosion. Water, in turn, shapes the landscape while it is the causative agent of spatial variability of soil attributes.

In this study, we aimed to identify relationships among geomorphic surfaces, hillslope segments, soil erosion and soil attributes of a sandstone-basalt toposequence in the municipality of Jardinópolis, São Paulo state, Brazil.

2 Materials and Methods

The study area is located in the municipality of Jardinópolis in the north-central region of São Paulo state with its central point at the following geographic coordinates: 21° 01' 04" S and 47° 45' 50" W. The climate, according to the Köppen classification, is rainy tropical with dry winters (Cwa), mesothermal, with temperatures ranging between 18 and 22 °C, average annual rainfall of 1580 mm concentrated between November and March. The region presents flat to smoothly undulating relief at 670 m above sea level in average. The study area is currently cultivated with sugarcane on all its extension. The lithology consists of basalt from the São Bento Group, Serra Geral Formation and of sandstone from the Bauru Group, Adamantina Formation. The study area is located in the transition between the Geomorphologic Provinces of Planalto Ocidental and Cuestas Basalticas (IPT, 1981) in the state of São Paulo.

We chose a representative area of the region with maximum coordinates approximately 780 m above sea level. Subsequently, we established a transect from the hillslope top towards the smoother slope at a distance of 2200 m from the top of the landscape, which now constitutes the basic study unit. The geomorphic surfaces were identified according to the criteria in Daniels, Camble and Cady (1971). Six trenches were opened along the slope to identify horizons and perform morphological description with sample collection. The soils were classified according to SiBCS (EMBRAPA, 2006).

Particle size analysis was performed by the pipette method using a solution of NaOH 0.1 N as chemical dispersant and mechanical stirring apparatus at low speed for 16 h, following the methodology proposed by Embrapa (1997). Exchangeable calcium, magnesium and potassium were extracted by the ion exchange resin method (RAIJ et al., 2001). The following attributes were calculated based on chemical analysis results: sum of bases (SB), cation exchange capacity (CEC), and base saturation (V%). pH was determined by potentiometry using a soil:water ratio of 1:2.5 and KCl (EMBRAPA, 1997). Organic matter content was also determined according to the methods by Embrapa (1997).

Si, Al and Fe were extracted by sulfuric acid attack and expressed as oxides (SiO_2, Al_2O_3 and $Fe_2O_3 - Fe_s$), they were determined after H_2SO_4 1:1 digestion according to Embrapa (1997). K_i and K_r indices were calculated from the relations between silicon and aluminum oxides, and silicon and aluminum plus iron oxides, respectively. Iron content (identified as free oxide - Fe_d) was also extracted with dithionite-citrate-bicarbonate (MEHRA; JACKSON, 1960) and ammonium oxalate (identified as less crystallized iron - Fe_o) according to Camargo et al. (1986). To analyze the mineralogy of the iron free clay fraction we used the HGZ device equipped with copper cathode and nickel filter with $1°2\theta$/min scan rate by the powder method. Kaolinite / (Kaolinite Gibbsite +) ratio was calculated using the areas of the reflexes of Ct (kaolinite) (001) and Gb (gibbsite) (002).

Erosion was estimated by the Universal Soil Loss Equation (USLE), proposed by Wischmeier and Smith (1978) and adapted by Bertoni and Lombardi Neto (1990), expressed by the formula (Equation 1):

$$A = RKLSCP \tag{1}$$

where R = erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$); K = erodibility (t h MJ^{-1} mm^{-1}); LS = topographic factor; C = vegetation cover and soil management factor; P = conservation practices.

We calculated two values for soil losses (A): a) A = soil loss by erosion considering the ramp length of each hillslope; b) A* = soil loss by erosion considering the presence of terraces every 50 m. The 50 m spacing corresponds to the mean value between terraces adopted by the local sugar mills for mechanized harvesting of sugarcane as a function of the average steepness of hillslopes (4%). Local rainfall erosivity (R) was estimated as 7645 MJ mm ha^{-1} h^{-1} $year^{-1}$ according to the method proposed by Lombardi Neto, Pruski and Teixeira (2000), considering the interpolation of R values from climatic stations in the state of São Paulo as a function of the ratio

between average monthly and annual rainfall. Erodibility (K) was estimated by means of the Equation 2 proposed by Denardin (1990), as follows:

$$K = 0.00000748\ M + 0.00448059\ P -$$
$$-0.06311750\ X27 + 0.01039567\ X32$$
(2)

where M is "new silt" (%) multiplied by the addition of "new sand" (%) and "new silt"; "new silt" = particles with diameters between 0.1 and 0.002 mm and "new sand" = particles with diameters between 2.0 and 0.1 mm; P is permeability encoded according to Wischmeier, Johnson and Cross (1971); X27 is the average weighted diameter of particles smaller than 2.0 mm, expressed in mm; and X32 is the ratio between organic matter content (OM) and "new sand" content determined by the pipette method (X32 = MO x "new sand"/100). All variables in Equation 2 were calculated at depths of 0.00-0.20 m below ground surface.

To determine the topographic factor (LS) we used the Equation 3 proposed by Wischmeier and Smith (1978):

$$LS = \left(\frac{\lambda}{22.13}\right)^m \left(65.41 sen^2\theta + 4.56 sen\theta + 0.065\right)$$
(3)

where λ is the ramp length (m); m is an exponent which is a function of steepness; θ is the angle in degrees of the slope.

The value of the C factor adopted for sugarcane was equal to 0.06, according to the value set by Campos et al. (2008). For the P factor, we adopted the values proposed by Wischmeier and Smith (1978), as a function of slope.

Tolerance of soil losses (T) was estimated using the method modified by Bertol and Almeida (2000) (Equation 4):

$$T = h.r_a.1.000^{-1}$$
(4)

where T = tolerance of soil loss (mm year^{-1}); h = effective soil depth (mm), limited to 1,000 mm; r_a = the relationship expressing, jointly, the effect of the textural relationship between A and B horizons and the clay content of A horizon; 1000 = the constant expressing the period of time required to erode a soil layer of 1.000 mm thickness, disregarding soil formation during this period.

Natural erosion potential (NEP) was determined considering only physical factors, corresponding to estimates of soil loss in areas devoid of vegetation and without any anthropic intervention, as described below (Equation 5):

$$PNE = RKLS$$
(5)

In this study, we used the NEP to establish the risk of natural erosion (e), which corresponds to the value of the C factor permissible (C$_{permissible}$) for use and management of an area, described in Equation 6.

$$e = C_{permissible} = \frac{T}{PNE\ P}$$
(6)

where T = losses tolerable to the soil area, t ha^{-1} year^{-1}; NEP = natural erosion potential, t ha^{-1} year^{-1}; P is the factor of conservation practices.

The values for risk of natural erosion (e) were classified and associated with a general indication of soil use and management for the area according to Nogueira (2000): 1)

very high, e <0.0010 (maintenance of natural cover), 2) high, 0.0011< e <0.0170 (pasture with grazing management and/or reforestation), 3) moderate, 0.0171< e <0.0880 (pasture without management), 4) low, 0.088 < e <0.2000 (perennial and semi-perennial management); 5) very low, e >0.2000 (annual crop).

The risk of erosion (RE) was determined and classified according to Lagrotti (2000) (Equation 7):

$$RE = \frac{A}{T}$$
(7)

where A = soil losses by erosion, t ha^{-1} year^{-1}; losses tolerable to the soil area, t ha^{-1} year^{-1}. Classification for RE was as follows: very low (<1), low (1-2), moderate (2-5), high (5-10), and very high (> 10).

3 Results and Discussion

We located and mapped three geomorphic surfaces in the study area, named geomorphic surfaces I, II and III (Figure 1), based on the model in Daniels, Camble and Cady (1971). Surface III was the largest with total area of 476.34 ha, surface II comprised 73.92 ha and surface I was the smallest with an area of 49.92 ha.

The first geomorphic surface (GS) is located 780 m above sea level, with occurrence of Typic Quartzipsamment/Orthic Arenosol, deep and well drained, with sandy texture and smoothly undulating to flat relief. The second surface (700-675 m above sea level) is located between geomorphic surfaces I and III, with occurrence of Typic Hapludox/Rhodic Ferralsol and Typic Hapludult/Euthropic Acrisol, with flat to smoothly undulating relief and texture ranging from very clayey to medium (Figure 1).

Geomorphic surface III is located between 600 and 680 m above sea level, with undulating relief and clayey texture. It is the youngest of the three surfaces and is characterized for being in constant renewal. The following soils are predominant is this surface: Typic Kandiudult/Eutroferric Latosolic, Typic Kandiudult/Eutroferric Typic and Typic Hapludox/Rhodic Eutroferric (Figure 1).

Hillslope segments were identified in each geomorphic surface (Figure 1). In geomorphic surface I, we identified the landscape top, a higher flat area. In geomorphic surface II, we located the shoulder on the higher quotas and the slope, in flat and transition relief between geomorphic surfaces II and III. In geomorphic surface III, corresponding to the rougher part of the terrain studied, four distinct forms were identified: shoulder, scarp, stocking lean and inferior lean. The shoulder, convexly shaped, connects relatively flat areas of geomorphic surface II to the scarp, which presents very steep relief and basalt outcrops.

These hillslope units are similar to those identified by Marques Júnior and Lepsch (2000) in geomorphic surfaces of the municipality of Monte Alto, and before that, by Salomão (1994) in the municipality of Baurú, both in São Paulo state. Soils were not sampled in the scarp segment because of the sharply steep relief and outcrops.

Sum of bases (SB), cation exchange capacity (CEC), and base saturation (V%) increase gradually as from the breaking of the top slope, area corresponding to geomorphic surface I, to the shoulder, which belongs to geomorphic surface II,
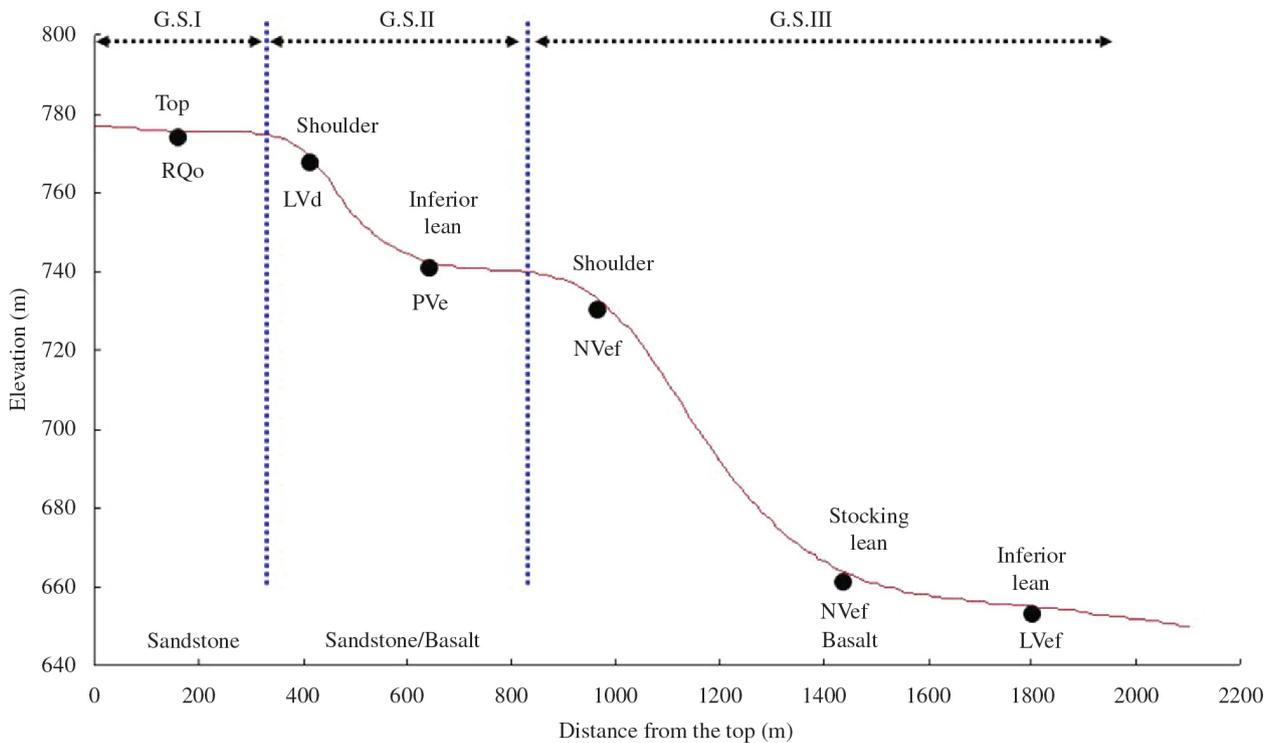
Figure 1. Topographic profile, geomorphic surfaces, hillslope segments and soil classes in a sandstone-basalt transition toposequence in the municipality of Jardinópolis, São Paulo state. Sandstone (RQo = Typic Quartzipsamment/Orthic Arenosol; LVe = Typic Hapludox/Rhodic Ferralsol; PAe = Typic Hapludult/Euthropic Acrisol; NVef = Typic Kandiudult/Eutroferric Latosolic; NVef = Typic Kandiudult/Eutroferric Typic; LVef =Typic Hapludox/Rhodic Eutroferric). GS I; GS II; GS III = Geomorphic Surfaces I, II, III.

reaching the maximum value in geomorphic surface III, area with predominance of leans (Table 1). This growing trend occurs because of the presence of basalt in the GS III and sandstone in the GS I, as well as the relief itself, as highlighted by Montanari et al. (2010).

Geomorphic surfaces II and III present greater renewal, therefore less time of parent material alteration, which affects nutrient reserves (DANIELS; CAMBLE; CADY, 1971). Variations in chemical attributes are associated with parent materials, relief forms, and hillslope segments, where all soils of geomorphic surfaces II and III have adjacent lithology from sandstone to basalt, or purely basaltic (Table 1), corroborating the results found by Cunha et al. (2005), who observed variations in chemical attributes of soil parent material when studying soil-relief relations in a sandstone-basalt transition slope in the region of Jaboticabal, São Paulo state.

Clay contents increase from GS I to GS III (Table 1), confirming the results obtained by Campos et al. (2008), who claim that these variations occur as a function of parent material. Silt has limited relevance in these soils, in the horizons presented, and in soils formed by covers and allochthons, and even less by sediments. This relationship was developed for native soils and comparisons within the profile as from the C horizon and the rock.

The Ki index relation in the hillslopes ranged from 1.81 to 1.36, indicating predominance of kaolinite and gibbsite in the clay fraction of these soils (Table 2). Among the geomorphic surfaces, the lowest Ki values were observed in the soils

of geomorphic surface I when compared to the soils of the geomorphic surface III, agreeing with the results obtained by Daniels, Camble and Cady (1971) and Campos et al. (2007).

The distribution of values of poorly crystalline Fe (Fe_o) and total Fe (Fe_s) along the geomorphic surfaces shows that iron concentration is lower in surface geomorphic I, followed by geomorphic surfaces II and III, respectively; this fact is linked to the parent material of soils (Table 2). The Fe_o/Fe_d ratio indicates the degree of crystallinity of iron compounds, the values of this ratio vary from 0.05 to 0.17, and the lowest values were found at the top of the landscape, evincing presence of less crystalline iron compounds. Geomorphic surfaces I and II presented the highest Fe_d/Fe_s ratio values, corroborating the study developed by Cunha et al. (2005) on a sandstone-basalt toposequence in the Jaboticabal region, São Paulo state. Thus, the different Fe_d/Fe_s ratios of the three surfaces studied reinforce the fact that the oldest geomorphic surface also presents the most weathered soils. The Ct/(Ct+Gb) ratio decreased considerably from geomorphic surface I (the oldest) to the most renewed surface (GS III) (Table 2), coinciding with the results found by Cunha et al. (2005), justified by the sandstone-basalt transition.

The Ct/(Ct+Gb) ratio declined considerably form GS I to GS III (Table 2), corroborating the results verified by Campos et al. (2007) in a sandstone-basalt transition toposequence in the Pereira Barreto region, São Paulo state.

Soil erodibility (K) decreased from geomorphic surface I to III (Table 3), agreeing with the increase in contents of iron

Table 1. Physical and chemical attributes of some soil horizons of the geomorphic surfaces and hillslope segments in a sandstone-basalt transition toposequence in Jardinópolis, São Paulo state.

Hillslope Segment	Hor.	pH H_2O	pH KCl	ΔpH	MO g kg^{-1}	Ca^{2+}	Mg^{2+}	K^+	SB	CEC mmol$_c$ kg^{-1}	V %	Sand	Silt	Clay g kg^{-1}	[1]S/C
Geomorphic Surface I –Typic Quartzipsamment/Orthic Arenosol – Sandstone															
Top	A_1	5.4	4.3	–1.1	0.9	1.4	0.5	0.07	1.97	3.9	50	910	70	20	3.50
	C_1	5.5	4.5	–1.0	0.8	0.3	0.3	0.06	0.56	2.3	20	950	20	30	0.66
Geomorphic Surface II – Typic Hapludox/Rhodic Ferralsol – Sandstone/Basalt															
Shoulder	A_1	5.7	4.8	–0.9	7.5	1.3	0.5	0.12	1.92	3.5	55	900	30	70	0.42
	Bw_2	5.8	4.6	–1.2	6.8	0.8	0.3	0.06	1.16	2.4	47	870	20	110	0.18
Geomorphic Surface II – Typic Hapludult/Euthropic Acrisol – Basalt/Sandstone															
Inferior Lean	A_1	5.9	4.7	–1.2	9.0	6.7	2.1	1.44	10.24	13.6	75	360	200	230	0.86
	Bt_2	6.8	5.1	–1.7	7.9	2.9	1.1	0.19	4.19	5.3	78	310	170	520	0.32
Geomorphic Surface III –Typic Kandiudult/Eutroferric Latosolic - Basalt															
Shoulder	A_1	6.0	5.2	–0.8	18.1	6.0	4.0	0.41	14.1	13.2	79	217	263	520	0.50
	Bn_2	6.1	5.1	–1.0	9.2	4.8	1.5	0.14	6.44	8.0	80	200	220	580	0.37
Geomorphic Surface III –Typic Kandiudult/Eutroferric Typic - Basalt															
Stocking Lean	A_1	5.9	5.4	–0.5	14.3	11.0	5.0	0.40	16.4	31.4	57	120	300	580	0.52
	Bn_2	6.5	5.6	–0.9	6.5	10.0	1.8	0.20	12.0	14.2	85	70	320	610	0.52
Geomorphic Surface III –Typic Hapludox/Rhodic Eutroferric - Basalt															
Inferior Lean	A_1	6.1	4.8	–1.3	31.5	41.0	15.0	2.60	68.6	102.6	67	290	251	451	0.55
	Bw_2	6.4	5.6	–0.8	8.5	19.0	17.0	0.40	36.4	52.4	69	247	235	518	0.45

[1]S/C = silt/clay ratio.

Table 2. Kr and Ki indices, free Fe content (Fe_d), oxalate (Fe_o) and oxalate sulfuric acid attack (Fe_s), Fe_o/Fe_d, Fe_d/Fe_s and Ct/(Ct + Gb) ratios on the geomorphic surfaces and hillslope segments in a sandstone-basalt transition toposequence in Jardinópolis, São Paulo state.

Hillslope Segments	Horizon	Depth m	Kr	Ki	Fe_o	Fe_d	Fe_s -------------g.kg^{-1}-----------	Fe_o/Fe_d	Fe_d/Fe_s	Ct/(Ct + Gb)
Surface Geomorphic I –Typic Quartzipsamment/Orthic Arenosol – Sandstone										
Top	A_1	0.0-0.20	0.68	0.76	1.1	4.8	6.0	0.23	0.80	0.94
	C_1	0.60-1.00	0.93	1.10	1.0	5.6	6.6	0.17	0.85	0.93
Surface Geomorphic II –Typic Hapludox/Rhodic Ferralsol – Sandstone/Basalt										
Shoulder	A_1	0.0-0.18	0.49	0.68	2.07	32.7	40.1	0.06	0.81	0.80
	Bw_2	0.90-1.40	0.69	1.17	3.2	45.50	56.2	0.07	0.80	0.83
Surface Geomorphic II –Typic Hapludult/Euthropic Acrisol – Basalt/Sandstone										
Inferior Lean	A_1	0.0-0.17	0.69	0.87	5.2	112.7	135.1	0.04	0.83	-
	Bt_2	0.75-1.05	1.64	1.36	6.4	115.0	144.0	0.05	0.79	-
Surface Geomorphic III –Typic Kandiudult/Eutroferric Latosolic - Basalt										
Shoulder	A_1	0.0-0.26	0.56	1.79	20.1	155.9	218.1	0.12	0.71	0.68
	Bn_2	1.05-1.30	0.47	1.81	18.60	177.80	227.0	0.10	0.78	0.79
Surface Geomorphic III –Typic Kandiudult/Eutroferric Typic - Basalt										
Stocking Lean	A_1	0.0-0.16	0.69	1.87	22.7	168.3	221.1	0.13	0.76	0.47
	Bn_2	0.70-0.90	0.67	1.97	25.2	176.2	230.0	0.14	0.76	0.45
Surface Geomorphic III –Typic Hapludox/Rhodic Eutroferric - Basalt										
Inferior Lean	A_1	0.0-0.22	0.32	1.96	24.5	110.1	152.0	0.22	0.72	0.29
	Bw_2	0.85-1.35	0.37	1.89	25.9	218.6	330.0	0.12	0.66	0.25

Table 3. Factors of soil erosion on the geomorphic surfaces and hillslope segments in a sandstone-basalt transition toposequence in Jardinópolis, São Paulo state.

Hillslope Segments	λ	d%	R	K	LS	C	P	LS*	NEP	A	A*	T	e	Class e	RE	Class RE	RE*	Class RE*
	m	%	MJ mm ha⁻¹ year⁻¹	t. h .MJ⁻¹ mm⁻¹							t ha⁻¹ year⁻¹							
Surface Geomorphic I – Typic Quartzipsamment/Orthic Arenosol - Sandstone																		
Top	240	0.41	7645	0.022	0.137	0.06	0.60	0.100	22.7	0.8	0.6	3.4	0.250	Very low	0.24	Very low	0.18	Very low
Surface Geomorphic II – Typic Hapludox/Rhodic Ferralsol – Sandstone/Basalt																		
Shoulder	210	5.23	7645	0.012	1.483	0.06	0.50	0.724	134.0	4.0	2.0	7.4	0.110	Low	0.54	Very low	0.27	Very low
Surface Geomorphic II – Typic Hapludult/Euthropic Acrisol – Basalt/Sandstone																		
Inferior Lean	250	3.00	7645	0.022	0.539	0.06	0.50	0.334	89.2	2.7	1.7	4.4	0.099	Low	0.61	Very low	0.38	Very low
Surface Geomorphic III – Typic Kandiudult/Eutroferric Latosolic - Basalt																		
Shoulder	315	8.09	7645	0.018	3.237	0.06	0.55	1.290	446.6	14.7	5.9	4.7	0.019	Moderate	3.14	Moderate	1.25	Low
Surface Geomorphic III – Typic Kandiudult/Eutroferric Typic - Basalt																		
Stocking Lean	580	5.00	7645	0.019	2.334	0.06	0.50	0.685	346.9	10.4	3.1	3.9	0.022	Moderate	2.67	Moderate	0.78	Very low
Surface Geomorphic III – Typic Hapludox/Rhodic Eutroferric - Basalt																		
Inferior Lean	475	2.30	7645	0.013	0.513	0.06	0.55	0.261	52.8	1.7	0.9	2.9	0.100	Low	0.60	Very low	0.31	Very low

λ = ramp length; d% = steepness; R = rainfall erosivity; K = soil erodibility; LS = topographic factor; C = vegetation cover and soil management factor; P = conservation practices; LS* = topographic factor for λ equals 50 m; NEP = natural erosion potential; A = soil loss by erosion considering the ramp length of each hillslope segment; 2) A* = soil loss by erosion considering the presence of terraces every 50 m; T = soil loss tolerance; e = risk of natural erosion; RE = risk of erosion; RE* = risk of erosion for λ equals 50 m.

oxides in this direction (Table 2). According to Cunha et al. (2005), the different amounts of water of the hillslope interfere with the forms and distribution of iron oxides. These different properties of iron oxides, in turn, influence soil erodibility (DUIKER et al., 2003). The highest K values were found in the soils of geomorphic surfaces I and II compared with geomorphic surface III (Table 3), this fact is due to the lower clay contents of the first geomorphic surface, associated with a reduced aggregation of these ambiences (DUIKER et al., 2003). Soils losses by erosion estimated by the USLE considering the ramp length of each hillslope presented the highest values in the shoulder and stocking lean segments of GS III. The top of GS I and the inferior lean of GS III were the segments that presented the lowest results of soil losses by erosion (Table 3). These results showed expressive decrease when soil losses were estimated with the presence of terraces spaced every 50 m (normally used in sugarcane crop), but the trend of soil loss by erosion continued along the slope. Geomorphic surfaces I and II showed greater stability regarding erosion rates; the opposite occurred in geomorphic surface III, as observed by Krasilnikov et al. (2005).

The lowest natural erosion potentials (NEP) and risk of erosion (**e**, RE e RE*) were verified at the landscape top of GS I and on the inferior lean of GS III. Risk of natural erosion (**e**), equivalent to factor C$_{permissible}$, was classified in surfaces I and II as very low to low, indicating that the C factor for sugarcane is lower than the **e** values according to criteria by Nogueira (2000). The same did not occur in surface III (except for the inferior lean) where the C factor was always higher than the values of risk of natural erosion **e** (Table 3). Therefore, soils with greater NEP are located in the shoulder and the stocking lean of GS III. Thus, the topographic aspects of landscape are the main conditioning factors of erosive processes (MONTANARI et al., 2010). This occurs because of the ramp length and especially the steepness of terrain, associated with texture, structure and texture gradient, which reduce water infiltration in the soil and increase volume and speed of runoff (MONTGOMERY, 2003).

Typic Hapludox/Rhodic Ferralsol found in GS II was the soil that presented the highest estimate of soil loss tolerance (T = 7.4 t ha^{-1} year^{-1}), while Typic Hapludox/Rhodic Eutroferric found in GS III was the one that showed the lowest tolerance (T = 2.9 t ha^{-1} year^{-1} (Table 3).

We observed that the same soil class presents different values of soil loss tolerance, demonstrating the importance of studying relief and hillslope segments in the understanding of erosion processes. Results allowed to verify that there is a negative correlation (r = –0.48) between T and erodibility (K), which corroborates the observations by Campos et al. (2008). The difference in erodibility of distinct soils occurs because of the intrinsic characteristics of these soils given by the physical, chemical and mineralogical attributes; however, there are differences in these attributes depending on the geomorphic surface (CUNHA et al., 2005). Having said that, soil losses by erosion (A and A*) and T enabled the analysis of results in terms of risk of erosion (RE). Typic Kandiudult/Eutroferric Latosolic and Typic Kandiudult/Eutroferric Typic were the soil that presented moderate risk of erosion according to the classification by Lagrotti (2000) in the shoulder and stocking

lean positions in GS III (Table 3). Very low risk of erosion was found at the top and on the shoulder of GS II (Table 3).

We observed that Typic Kandiudult/Eutroferric Latosolic (NVef) was the soil with the highest loss and mean erodibility; while Typic Hapludox/Rhodic Eutroferric (LVef) was the one that showed the lowest rates of loss and mean erodibility. These results are associated mainly with the concepts of geomorphic surfaces, intrinsic characteristics of soil (texture, structure and soil water infiltration), and with soil positions in the landscape. The level of erosion in NVef and LVef (geomorphic surface III), represented by d% x K, can be classified as strong and quick according to the classification by Pereira and Lombardi Neto (2004). According to Marques Junior and Lepsch (2000), the use of quantitative attributes should be taxonomically understood within a context of natural body considering the soil-relief relationships. While studying a toposequence in the region of Jaboticabal, São Paulo state, Souza et al. (2003) stated that geomorphic processes impose complexity to the soils in landscapes and that the factors connected to parent material and form of relief are decisive in the distribution of soil types over a given toposequence.

4 Conclusions

We observed soils with sandy texture in geomorphic surface I going to clayey texture in geomorphic surface III;

The soil values of BS, CEC and V% increase from G.S. I to G.S. III according to the sandstone-basalt lythosequence;

Soil erodibility (K) decreases from geomorphic surface I to III, while losses (A and A*) show contrary behavior, increasing from geomorphic surface I to III, that is, from soils developed in sandstone to basaltic soils.

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