

Division - Soil in Space and Time | Commission - Soil Genesis and Morphology

# Genesis and Classification of Soils from Subtropical Mountain Regions of Southern Brazil

**Denilson Dortzbach<sup>(1)</sup>, Marcos Gervasio Pereira<sup>(2)\*</sup>, Lúcia Helena Cunha dos Anjos<sup>(2)</sup>, Ademir Fontana<sup>(3)</sup> and Eduardo de Carvalho Silva Neto<sup>(2)</sup>**

<sup>(1)</sup> Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, Centro de Informações de Recursos Ambientais e de Hidrometeorologia, Florianópolis, Santa Catarina, Brasil.

<sup>(2)</sup> Universidade Federal Rural do Rio de Janeiro, Departamento de Solos, Seropédica, Rio de Janeiro, Brasil.

<sup>(3)</sup> Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos, Rio de Janeiro, Rio de Janeiro, Brasil.

**ABSTRACT:** Soils formed in high mountainous regions in southern Brazil are characterized by great accumulation of organic matter (OM) in the surface horizons and variation in the degree of development. We hypothesized that soil properties and genesis are influenced by the interaction of parent materials and climate factors, which differ depending on the location along the altitudinal gradient. The goal of this study was to characterize and classify the soil, evaluate soil distribution, and determine the interactive effects of soil-forming factors in the subtropical mountain regions in Santa Catarina state. Soil samples were collected in areas known for wine production, for a total of 38 modal profiles. Based on morphological, physical, and chemical properties, soils were evaluated for pedogenesis and classified according to the Brazilian System of Soil Classification, with equivalent classes in the World Reference Basis (WRB). The results indicated that pedogenesis was strongly influenced by the parent material, weather, and relief. In the areas where basic effusive rocks (basalt) were observed, there was formation of extensive areas of clayey soils with reddish color and higher iron oxide contents. There was a predominance of *Nitossolos Vermelhos* and *Háplicos* (Nitisols), *Latossolos Vermelhos* (Ferralsols), and *Cambissolos Háplicos* (Cambisols), highlighting the pedogenetic processes of eluviation, illuviation of clay, and latosolization in conditions of year-long, large-volume, well-distributed rainfall and stability of land forms. In areas with acid effusive rocks (rhyodacites), medial or clayey soils were observed with lower iron oxide content, invariably acidic, and with low base content. For these soils, relief promoted substantial removal of material, resulting in intense rejuvenation, with a predominance of *Cambissolos Háplicos* (Cambisols) and lesser occurrence of *Nitossolos Brunos* (Nitisols) and *Neossolos Litólicos* (Leptosols). Soils formed from sedimentary rocks also tended to be more acidic, but with higher sand content, and the soils identified were *Cambissolos Háplicos* and *Húmicos* (Cambisols). Cluster analysis separated the soil profiles into three groups: the first and largest was formed by profiles originating from sedimentary rocks and rhyodacites; the second, smaller group was formed by four profiles in the *Água Doce* region (acidic rocks); and the third was formed by profiles derived from basalt. Discriminant analysis was effective in grouping soil classes. Thus, the study highlighted the importance of geology in the formation of soils in this landscape associated with climate and relief.

\* **Corresponding author:**

E-mail: mgervasiopereira01@gmail.com

**Received:** December 15, 2015

**Approved:** March 28, 2016

**How to cite:** Dortzbach D, Pereira MG, Anjos LHC, Fontana A, Silva Neto EC. Genesis and Classification of Soils from Subtropical Mountain Regions of Southern Brazil. Rev Bras Cienc Solo. 2016;40:e0150503.

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**Keywords:** geology, soil formation, taxonomic classification.

## INTRODUCTION

Soils formed in the high-altitude regions in the state of Santa Catarina (southern region of Brazil) are characterized by high accumulations of soil organic matter (SOM) in their surface horizons and variation in regard to pedogenetic development. This development is likely influenced by weathering conditions, which results from the nature of the parent material (rocks) and the climate (high altitude). In such environments, colder climates, together with higher levels of Al, contribute to reduce biological activity, and consequently there is slower decomposition and mineralization of SOM. The deposition and mineralization of SOM allows it to accumulate in surface horizons, resulting in formation of horizons with either an organic (histic) or a mineral (humic) composition (Almeida et al., 2000).

Several types of rocks can be found in this region and, depending on their mineral composition and/or particle size distribution, they can greatly affect the intensity of weathering and, in turn, soil composition, especially in regard to clay content, mineralogy, and the dominance of elements such as Al and Fe. Because of climate dynamics, SOM, and rock composition, soils with a brown or yellowish-brown color (associated with high SOM content) are predominant in high-altitude regions. High humidity and SOM content affect both the formation and the persistence of iron oxides, generally favoring goethite over hematite and thereby resulting in yellow soils (Schwertmann and Taylor, 1989; Almeida et al., 2000).

Along with climate and parent material, geographical relief directly affects water dynamics and indirectly the soil moisture regime, due to differences in the intensity of solar irradiance, temperature decline with increasing altitude, and the influence of relief on natural vegetation, which is also an important factor in soil formation. Soils from steep regions are subject to rejuvenation caused by erosion, and, consequently, profiles are shallower and pedogenetically less developed than soils from low relief landscapes, where higher infiltration rates result in the formation of deeper soils (Silva et al., 2009).

Thus, the soils developed in the environment of the present study area have peculiar attributes; however, knowledge regarding their properties is still limited. The acquisition of such information may contribute to monitoring changes that take place in the soils, as well as their response in agricultural use under different management systems, especially the cultivation of grapes for wine production. This knowledge is of great importance in the area under study because it has undergone continuous and rapid changes in landscape (Boldrini, 2009).

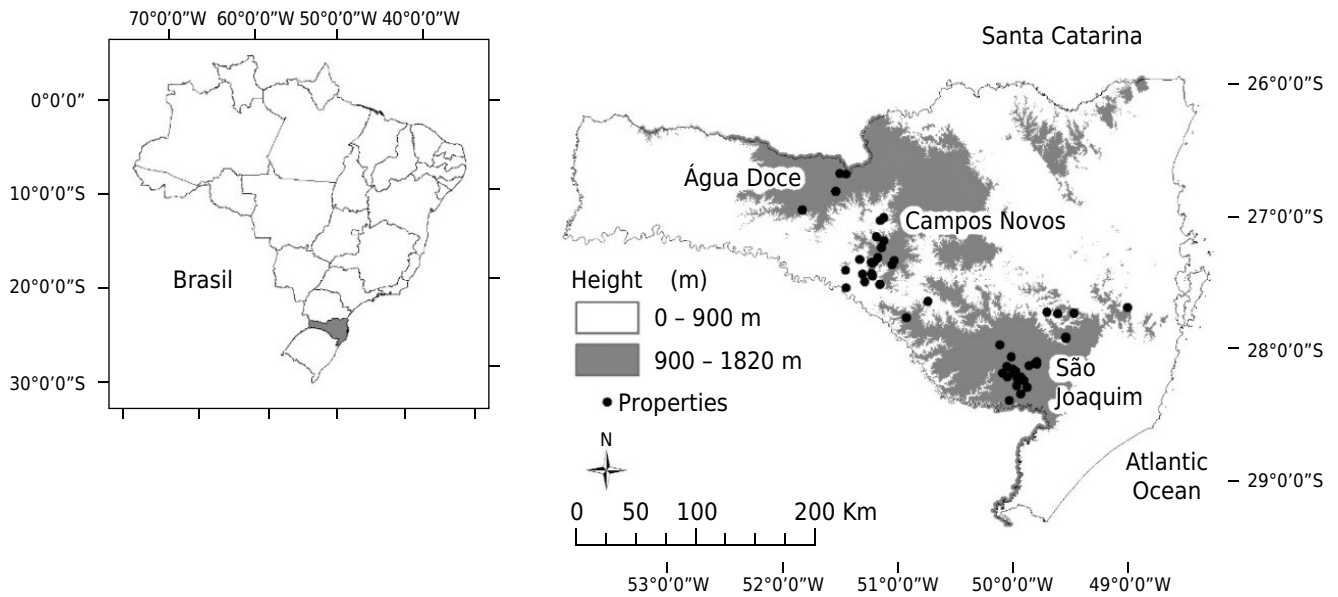
The hypothesis of this study is that the occurrence and genesis of the soils considered here are affected by the interaction between parent material and climatic factors, which differ along the altitude gradient. Therefore, the objective of the study was to characterize and classify the soils, to evaluate their distribution and determine the interactive effects among the soil formation factors in the subtropical mountain regions of the state of Santa Catarina, Brazil.

## MATERIALS AND METHODS

### Study area

The study was conducted in the municipalities of *Água Doce*, *Campos Novos*, and *São Joaquim*. These regions are the main producers of fine wines from high-altitude regions in the state of Santa Catarina (Figure 1).

The geology of the area consists of rocks from the *Serra Geral* formation, above the Paraná River Basin, as well as Paleozoic sedimentary rocks from the Paraná River Basin. The region's primary characteristic is its heterogeneity caused by geological



**Figure 1.** Altitude regions of the state of Santa Catarina, Brazil, and distribution of the soil profiles collected.

depositions in the form of traps (Leinz and Amaral, 1985). Different magma cooling conditions acted on the textural and mineralogical composition of each deposition (Leinz and Amaral, 1975). Therefore, there is a succession of rocks with different levels of resistance to weathering (Sartori and Gomes, 1980). The main rock is basalt, but there are also other types of rocks, with varying chemical and textural composition, such as andesites, rhyolites, dacites, and rhyodacite-felsite, with high Si content and low Fe and Mg content (Horbach et al., 1986). The Gondwana sedimentary cover is associated with deposition of materials, such as mudstones, sandstones, siltstones, and shale, as well as conglomerates with intermediate to high vulnerability to denudation (Santa Catarina, 1986). This is of special importance for the *Passa Dois* Group, found in the Rio do Rastro and Terezina formations.

Regarding geomorphology, two geomorphological units occur, the *Planalto dos Campos Gerais* that is distributed in the landscape as isolated blocks, and the *Planalto Dissecado Rio Iguaçu/Rio Uruguai* (Santa Catarina, 1986). The topography in the regions of basaltic volcanic rocks is flatter since lower slopes result in moderate transporting energy. In regions of acidic volcanic rocks, land forms are usually more rolling.

According to the Köppen climate classification system, because of the altitude, the climate type in all areas where soil was collected is Cfb (subtropical with mild summers). The hottest month has an average temperature lower than 22 °C. The Köppen climate classification system as modified by Braga and Guellere (1999) identifies the regions as part of the Mild Mesothermal Domains (2 and 3), which are moderate and temperate climates (3, 4, and 5 types), subtypes 3A, 4A, 4B, and 5, with average temperature in the coldest months (June/July)  $\geq 0$  °C and  $< 15$  °C (Table 1).

Subtropical forests, especially the araucaria forest (mixed broadleaf forest), transect the coastal mountains, extending over the Santa Catarina plateau, and usually occur at altitudes above 500 m where rainfall is well distributed and the average frequency of frosts is between 10 and 25 days per year. These forests are typically more resistant to low temperature, have lighter color, and are sparser and less lush than tropical forests (Lago, 1968). The plateaus (high-altitude fields) appear as isolated areas, intermingled with the araucaria forest, and coincide with altitudes from 900 to 1,400 m. The vegetation is predominantly composed of low and midsize grasses, as well as species of the Cyperaceae, Verbenaceae, Leguminosae, and Compositae families (Santa Catarina, 1986).

**Table 1.** Soil profiles according to region, and general characteristics of the sampling points in the high mountain regions in the state of Santa Catarina, Brazil

Profile	Elevation	Municipality	Parent material	Climate type	Regional topography
m					
Region I					
1	902	<i>Bom Retiro</i>	Silty-clay sediments	4A	Rolling to strongly rolling
2	864	<i>Bom Retiro</i>	Silty-clay sediments	4A	Rolling to strongly rolling
3	1,144	<i>Urubici</i>	Arenite, pelite, and shales	5	Strongly rolling
4	1,059	<i>Urubici</i>	Arenite, pelite, and shales	5	Strongly rolling
Region II					
5	1,258	<i>São Joaquim</i>	Rhyodacite	4A	Strongly rolling
6	1,282	<i>São Joaquim</i>	Rhyodacite	4A	Strongly rolling
7	1,259	<i>São Joaquim</i>	Rhyodacite	4A	Strongly rolling
8	1,359	<i>São Joaquim</i>	Rhyodacite	4A	Strongly rolling
9	1,259	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
10	1,304	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
11	1,274	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
12	1,240	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
13	1,227	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
14	1,302	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
15	1,301	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
16	1,270	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
17	1,328	<i>São Joaquim</i>	Rhyodacite and andesite	4A	Rolling to strongly rolling
18	1,112	<i>São Joaquim</i>	Rhyodacite and andesite	4A	Rolling to strongly rolling
19	1,146	<i>São Joaquim</i>	Rhyodacite	5	Rolling to strongly rolling
20	1,109	<i>Urupema</i>	Rhyodacite	4A	Rolling to strongly rolling
21	1,217	<i>São Joaquim</i>	Rhyodacite	4A	Rolling to strongly rolling
Region III					
22	900	<i>Campo Belo do Sul</i>	Basalt and diabase	3A	Rolling to strongly rolling
23	989	<i>Cerro Negro</i>	Basic vesicular basalt	3A	Rolling to strongly rolling
24	869	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
25	976	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
26	877	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
27	852	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
28	949	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
29	880	<i>Campos Novos</i>	Basalt and diabase	3A	Slightly rolling to rolling
30	912	<i>Tangará</i>	Basalt and diabase	3A	Rolling to strongly rolling
31	1,162	<i>Tangará</i>	Basalt and diabase	3A	Rolling to strongly rolling
32	1,055	<i>Tangará</i>	Basalt and diabase	3A	Rolling to strongly rolling
33	919	<i>Videira</i>	Basalt and diabase	3A	Rolling to strongly rolling
34	849	<i>Videira</i>	Basalt and diabase	3A	Rolling to strongly rolling
Region IV					
35	1,183	<i>Vargem Bonita</i>	Riolite, andesite, and rhyodacite	4B	Rolling
36	1,330	<i>Água Doce</i>	Volcanic acidic rocks	4B	Rolling
37	1,260	<i>Água Doce</i>	Volcanic acidic rocks	4B	Rolling
38	1,260	<i>Água Doce</i>	Volcanic acidic rocks	4B	Rolling

## Sample collection and laboratorial analyses

Soil sampling pits were opened to collect 38 modal profiles (Table 1), as described by Santos et al. (2013a). Soil samples from all horizons were dried, ground, and passed through a 2-mm sieve, resulting in fine air-dried soil (FADS).

Chemical (pH in water,  $Mg^{2+}$ ,  $K^+$ ,  $Na^+$ , P, and  $Al^{3+}$ ) and physical (particle density - Pd and particle size distribution - sand, silt, and clay) properties were evaluated (Donagema et al., 2011), and the following parameters were calculated: sum of bases (SB), cation exchange capacity (CEC) at pH 7.0, clay activity ( $T_{clay}$ ), and degree of flocculation (DF). The levels of  $SiO_2$ ,  $Al_2O_3$ , and  $Fe_2O_3$  were determined after acid digestion (sulfuric acid attack method) and used to calculate the ki index (silica to aluminum ratio) and kr index (silicate to oxide ratio) (Camargo et al., 1986).

Based on the morphological attributes and the physical and chemical properties, the soil profiles were classified according to the Brazilian System of Soil Classification (*Sistema Brasileiro de Classificação de Solos* - SiBCS) (Santos et al., 2013b).

## Data analysis

The soil profiles were grouped into four regions according to their geology, and identified by the municipality of origin: I - region of sedimentary rocks - profiles 1 to 4 (*Bom Retiro* and *Urubici*); II - region of acidic igneous rocks - rhyodacite - profiles 5 to 21 (*São Joaquim*); III - region of igneous rocks - basalt - profiles 22 to 34 (*Campos Novos*); and IV - region of acidic igneous rocks - *Palmas* type - profiles 35 to 38 (*Água Doce*).

Theoretical inferences regarding pedogenesis were made based on combined analyses of the associated morphological, chemical, physical, and mineralogical attributes related to soil formation factors and pedogenetic processes.

To support decision making, the attributes were subjected to descriptive statistics, and similarities between the soil profiles were evaluated by multivariate analysis. Quantitative data were used to estimate the Euclidian distance, which generated a dissimilarity matrix, and the Nearest Neighbor Hierarchical Clustering method was applied, based on the presentation of a similarity dendrogram (Johnson and Wichern, 2007). The physical and chemical attributes of the subsurface soil horizons were used for analyses.

Discriminant analysis was used for distinction and characterization of soils, for separating different groups (according to physical and chemical attributes), and for establishing previously defined groups (soil classes), enabling visualization of the groups in a multidimensional space and indicating the contribution of the original variables to each discriminant function. All variables evaluated from the A and B horizons were individually used for this analysis. When more than one B horizon occurred, the horizon with the greatest expression in the soil profile was used.

All analyses were carried out using the software SPSS (Statistical Package for Social Sciences) version 20.0.

## RESULTS AND DISCUSSION

### Characterization and distribution of soils in the regions

In region I, among the soil formation factors, the parent material was the determining factor for the coarser particle size of the profiles compared with the other regions. The influence of the parent material associated with the cold and humid climate resulted in formation of soils with low sum of bases (SB) and base saturation (V), high levels of  $Al^{3+}$  (above  $4.0 \text{ cmol}_c \text{ kg}^{-1}$ ), an alytic character (Santos et al., 2013b) (P1, P3, and P4), and high activity clays ( $T_{clay} \geq 27.0 \text{ cmol}_c \text{ kg}^{-1} \text{ clay}$ ). The climate also contributed



to high C levels, such as in the B horizon of profile 4, which had 19 g kg<sup>-1</sup> C (Table 2), resulting in the classification of humic (P3 and P4) and prominent (P2) surface horizons (Santos et al., 2013b).

The low V, with values ranging from 3 to 30 %, indicated that the soils from region I were intensively weathered, leading to high Al saturation (above 80 %). The relatively low ki (from 0.42 to 0.48) and kr (from 0.30 to 0.36) values in the B horizon revealed an advanced state of weathering and indicated a predominantly oxidic mineralogy. The Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> levels increased from the top to the base of the profiles, and the opposite pattern was observed for the SiO<sub>2</sub> levels, which decreased with depth. Therefore, the low V of these soils may be caused by previous weathering of the parent material and the continuous lixiviation of the soil in such an environment with a highly humid climate.

The topography varied from rolling to strongly rolling, causing substantial removal of material and subjecting the soils to an intense process of rejuvenation. The continuity of rock fragments, gravel, and pebbles in the profiles indicated that erosion, transport, and deposition processes had a strong effect on soil formation, associated with resistance of the rock to weathering. The profiles revealed a low degree of pedogenetic development and no specific pedogenic process was observed. The subsurface diagnostic horizon was consequently characterized as incipient (Bi). Thus, all soils were classified as Cambisols, in which profiles 3 and 4 were classified as *Cambissolos Húmicos Alíticos típicos* and profile 1 as *Cambissolo Háplico Alítico típico*. The main variations in the region I group were associated with profile 2, which was classified as *Cambissolo Háplico Ta Distrófico léptico*, and the occurrence of the humic surface diagnostic horizon in profiles 3 and 4.

Regions II, III, and IV were formed by igneous rocks, but were constituted of different parent materials because volcanism in the state of Santa Catarina did not occur homogeneously, resulting in the presence of rocks ranging from an acidic to basic nature. All profiles presented high levels of clay, varying in the B horizon from 350 to 570 g kg<sup>-1</sup> in region II, from 450 to 743 g kg<sup>-1</sup> in region III, and from 489 to 613 g kg<sup>-1</sup> in region IV, indicating that the essential minerals, such as plagioclase, pyroxene, and alkali feldspar of the rhyodacites (Clemente and Azevedo, 2007) and plagioclase, pyroxene, and olivine of basalts (Corrêa, 2003) were completely weathered, forming clay minerals and pedogenic oxides.

In region II, soils originated from rhyodacites and were located at altitudes from 1,109 to 1,325 m. The climate was a very important soil formation factor because of low temperatures (among the lowest in Brazil) and high humidity. These characteristics, associated with the parent material, resulted in high levels of clay, which was reflected

**Table 2.** Physical and chemical properties of A and B horizons of soil profiles from region I (sedimentary rocks), located in the municipalities of Urubici and Bom Retiro, SC, Brazil

P	Hor.	Clay	Sand	DF	TOC	pH(H <sub>2</sub> O)	SB	Al <sup>3+</sup>	CEC	T <sub>clay</sub>	V	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	ki	kr
		— g kg <sup>-1</sup> —		%	g kg <sup>-1</sup>		cmol <sub>c</sub> kg <sup>-1</sup>		— % —		— % —		g kg <sup>-1</sup>				
1	A	360	319	30	24.2	4.7	2.8	3.2	18.4	51.1	16	53	36.4	97.4	67.1	0.64	0.44
	B	470	308	45	7.4	4.3	0.8	5.3	28.6	60.9	3	87	34.7	122.8	70.2	0.48	0.35
2	A	310	359	36	22.3	4.1	7.3	1.4	33.8	109.0	21	16	31.9	67.3	56.0	0.81	0.53
	B	490	350	53	8.7	4.4	13.0	2.0	43.9	89.6	30	13	35.0	128.7	73.6	0.46	0.34
3	A	296	343	76	19.8	4.2	1.4	7.0	27.8	93.9	5	83	43.8	94.0	48.7	0.79	0.60
	B	360	303	58	3.4	4.2	1.2	5.7	15.2	42.2	8	83	38.1	154.8	90.5	0.42	0.30
4	A	200	456	42	22.4	4.4	2.9	2.2	12.4	62.0	25	43	22.3	78.6	34.2	0.48	0.38
	B	200	438	54	18.6	4.3	0.5	5.2	15.3	76.5	3	91	29.0	111.5	42.4	0.44	0.36

P: profile; Hor.: horizon; DF: degree of flocculation; TOC: total organic carbon; pH(H<sub>2</sub>O): pH in water; SB: sum of bases; CEC: Cation Exchange Capacity; T<sub>clay</sub>: clay activity; V: base saturation; m: aluminum saturation; ki (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) and kr (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>). All analyses were performed according to Donagema et al. (2011).

in the formation of soils with low values of SB (1.2 to 3.6  $\text{cmol}_c \text{kg}^{-1}$ ) and V (11 to 39 %), high  $\text{Al}^{3+}$  content in most of the profiles, an alytic character in profiles 9, 10, 14, and 21, and highly active clay (P6, 9, 10, 11, and 21), as shown in table 3.

In this region, the cold, humid climate typical of high altitudes favored the leaching of bases, and contributed to an increase in the levels of  $\text{Al}^{3+}$ , resulting in chemically acidic soils (Almeida et al., 2000). Such climatic conditions favored low OM mineralization rates, providing high levels of organic C in the soil, reaching up to 39.0  $\text{g kg}^{-1}$  in the surface horizon of profiles 10 and 14. Therefore, the influence of the climate and organisms factors are of great importance to the accumulation of C in the surface horizons.

**Table 3.** Physical and chemical properties of A and B horizons of soil profiles (P) from region II (igneous acidic rocks), located in the municipalities of São Joaquim and Urupema, SC, Brazil

P	Hor.	Clay	Sand	DF	TOC	pH(H <sub>2</sub> O)	SB	Al <sup>3+</sup>	CEC	T <sub>clay</sub>	V	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	ki	kr
		— g kg <sup>-1</sup> —	%	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	%	%	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>
5	A	350	239	42	31.9	4.9	12.0	0.8	20.2	57.7	60	6	41.4	137.2	90.2	0.51	0.48
	B	540	186	89	12.4	4.7	3.6	3.0	12.1	22.4	30	45	43.2	165.8	93.1	0.44	0.48
6	A	560	104	66	17.3	5.3	4.3	2.2	18.6	33.2	23	34	43.2	148.7	91.5	0.49	0.49
7	A	496	122	54	25.8	5.0	7.5	0.8	17.4	35.1	43	10	42.8	163.2	82.7	0.45	0.54
	B	565	76	20	8.4	4.7	1.6	2.1	12.3	21.8	14	57	55.1	150.3	86.8	0.62	0.66
8	A	470	148	43	27.2	5.4	8.7	0.9	22.9	48.7	38	9	167.0	51.4	144.2	5.52	1.20
	B	530	113	30	18.8	5.2	3.0	1.5	13.0	24.5	24	33	167.8	80.4	90.7	3.35	1.92
9	A	453	147	27	11.4	5.1	9.2	1.6	14.8	32.7	63	15	32.2	154.7	90.9	0.35	0.37
	B	494	127	35	9.5	4.5	2.7	5.3	21.1	42.7	13	66	33.6	150.3	88.2	0.38	0.40
10	A	439	258	28	39.2	5.0	5.3	1.8	9.4	21.4	60	25	38.9	144.9	94.1	0.46	0.43
	B	450	155	42	18.7	4.7	4.0	5.3	19.5	43.3	20	57	40.2	154.5	93.3	0.44	0.45
11	A	323	173	75	33.4	5.3	7.1	2.6	18.7	57.9	38	27	40.4	110.3	92.8	0.62	0.45
	B	452	155	20	17.2	4.9	2.5	3.2	12.3	27.2	20	56	47.2	144.9	92.3	0.55	0.53
12	A	303	257	35	30.1	5.1	7.6	0.6	15.1	49.8	50	7	40.8	118.7	96.8	0.58	0.44
	B	500	146	44	15.8	4.5	1.8	3.8	8.4	16.8	24	68	44.3	150.2	96.2	0.50	0.48
13	A	400	258	44	284	5.5	6.7	0.0	10.3	26.8	68	0	129.1	55.9	76.4	3.93	1.75
	B	570	139	27	20.2	4.7	1.2	3.1	7.4	13.0	17	72	298.0	163.4	120.3	3.10	2.57
14	A	318	116	65	39.1	5.5	6.6	0.9	19.6	61.6	33	12	46.4	118.4	97.8	0.67	0.49
	B	428	113	16	16.9	5.2	2.5	2.4	11.1	25.9	21	49	38.5	78.3	94.2	0.84	0.42
15	A	230	370	27	25.0	6.5	16.4	0.0	18.2	79.1	91	0	36.5	87.7	138.3	0.71	0.27
	B	350	204	38	9.5	5.3	22.3	2.3	26.6	76.0	83	9	44.9	175.8	136.5	0.43	0.34
16	A	457	111	61	21.3	5.2	12.1	0.5	21.8	47.7	56	4	71.4	34.4	73.9	3.53	1.00
	B	536	100	57	10.2	4.4	3.5	2.3	12.9	24.1	28	40	67.1	33.3	74.2	3.43	0.94
17	A	417	105	40	23.7	5.1	5.9	1.2	17.2	41.2	34	17	30.2	142.1	33.4	0.36	0.94
	B	560	80	21	10.0	4.5	2.2	3.5	12.4	22.1	19	61	22.2	150.0	95.8	0.25	0.24
18	A	462	91	63	35.4	5.2	11.0	0.5	23.0	49.8	48	4	41.2	120.7	98.7	0.58	0.43
	B	527	62	35	10.4	5.3	6.0	1.2	12.4	23.5	48	1	40.8	142.6	93.2	0.49	0.45
19	A	451	98	31	34.6	5.5	9.1	0.6	14.2	31.5	68	6	84.8	38.3	73.1	3.76	1.20
	B	565	41	95	6.4	5.7	3.9	1.1	9.3	16.5	43	22	87.4	29.2	80.0	5.09	1.13
20	A	543	146	89	30.8	5.5	6.7	1.7	18.6	34.3	35	20	141.1	65.8	112.6	3.65	1.30
	B	570	110	74	14.2	5.3	1.8	3.7	10.9	19.1	16	67	144.8	70.1	123.1	3.51	1.22
21	A	330	259	36	23.8	4.5	5.5	2.5	17.7	53.6	31	31	34.9	170.5	95.3	0.35	0.38
	B	520	223	32	4.5	4.3	1.2	5.3	18.8	36.2	6	82	36.0	250.2	90.5	0.24	0.41

P: profile; Hor.: horizon; DF: degree of flocculation; TOC: total organic carbon; pH(H<sub>2</sub>O): pH in water; SB: sum of bases; CEC: Cation Exchange Capacity; T<sub>clay</sub>: clay activity; V: base saturation; m: aluminum saturation; ki (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) and kr (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>). All analyses were performed according to Donagema et al. (2011).

The topography factor, which ranged from rolling to strongly rolling, promoted considerable removal of material, resulting in intense rejuvenation in most of the profiles. There was no expression of a specific pedogenesis process, leading to characterization of 13 profiles as *Cambissolos*, and profile 6 as *Neossolo Litólico Distrófico típico* (Leptosol). In most cases, surface C levels were not high enough to characterize the A horizon as humic, which was also associated with the shallowness of the surface horizon.

In areas with lesser slope, which favored higher water infiltration into the soil profile, more pedogenically developed soils were observed. Some soils were formed by the specific pedogenetic process of illuviation/alluviation, as observed in profiles 5, 7, and 18. In these soils, there was translocation of clay from the A horizon to the B horizon, with highly evident expression of clay skins on the faces of the aggregates, which were well developed, reflecting the genesis of the mountainous nitric subsurface horizon and identifying the soil order as *Nitossolos* (Nitosols). At the Suborder categorical level, profiles 5 and 7 were classified as *Nitossolos Brunos*, a result of the climate, which led to browner colors, with hues ranging from 10YR to 7.5YR. The presence of goethite, which is usually the most abundant Fe oxide in soils of cold and humid regions, was relevant (Schwertmann and Taylor, 1989). The formation of hematite is suppressed by the accumulation of organic compounds that prevent the formation of ferrihydrite (hematite precursor) (Inda Junior, 2002). For the *Cambissolos*, the lack of any other distinctive characteristics classified them as *Háplicos* at the Suborder level.

At the third level, Great Group, profiles 9, 10, 14, and 21 were classified as altyic; profile 7 had an aluminic character (Al levels  $\geq 4$  cmol<sub>c</sub> kg<sup>-1</sup>, clay activity <20 cmol<sub>c</sub> kg<sup>-1</sup>, Al saturation (m)  $\geq 50$  %, and/or V <50 %). The other profiles were classified as dystrophic, with P11 having high activity clay ( $\geq 27$  cmol<sub>c</sub> kg<sup>-1</sup>) associated with low V. The other profiles exhibited low activity clay.

At the Subgroup level, profile 11 was identified as leptic, with lithic contact between 0.50 and 1.0 m from the surface, whereas P5 was classified as humic. Because of the lack of distinctive diagnostic attributes, the other profiles were classified as typic.

The low V, with values in the B horizon from 6 to 48 % (except for P15), indicated a high level of leaching in soils from the region II group, accompanied by high potential acidity (H+Al) and a large portion of the sorptive complex occupied by Al (Table 3). However, the values are below those observed for regions I and IV and similar to those of region III.

The clay levels were very high, and the total sand content very low. Despite a decrease in the SiO<sub>2</sub> levels, characterizing loss of silica due to the alteration of primary minerals, the resistance to weathering imposed by the mineralogy of the rhyodocite and the selection of larger fractions maintained high amounts of Si in the horizons relative to those found in the region III profiles (originating from basalt). These results indicated that the rhyodocite essential minerals (plagioclase, pyroxene, and alkali feldspar) were weathered and formed clay minerals and pedogenic oxides.

The high *k<sub>i</sub>* values, from 3.1 to 5.5 in profiles 8, 13, 16, 19, and 20 (Table 3), indicated that there is an evolution toward the formation of 2:1 minerals interlayered with 1:1 minerals in these profiles. In the areas surrounding *São Joaquim* and *Água Doce*, there was a predominance of rocks with a more acidic character (rhyodacites), which, unlike typical basalt, have higher silica content, reaching values close to or above 60 % (Teske, 2010).

In region III, soils developed from basalt and were located at latitudes lower than the other regions, from 832 to 1,128 m, and the parent material was responsible for the fine clayey texture (higher than 600 g kg<sup>-1</sup>), except for profiles 23, 30, 31, and 32, which exhibited a clayey texture in the B horizon (Table 4). Relief played an important role in the weathering of these soils because of lower slope (slightly rolling to rolling), allowing higher infiltration of water into the soil and resulting in deeper soils. This also explained the low sum of bases, with values below 3.0 cmol<sub>c</sub> kg<sup>-1</sup>, except for P23 and P32. The levels



of  $Al^{3+}$  varied greatly among profiles, ranging from 0.4 (P32) to 6.5 (P34). The same was true for V, which exhibited the extreme values of 2 % (P34) and 81 % (P32), whereas in the other profiles, it ranged from 8 to 28 % in the B horizon.

The climate and lower altitude associated with slightly rolling and rolling (less slope) topography resulted in conditions that favored the formation of hematite over goethite, resulting in reddish colors in the profiles, with hues of 5YR and 2.5YR. Hematite formation is favored in well-drained environments or those with low water activity, and the occurrence of this type of mineral is directly associated with a high degree of weathering (Schwertmann and Taylor, 1989).

These conditions are also reflected in the soil classification; in the areas with a higher slope, *Nitossolos Háplicos* (Nitosols) and *Cambissolos Háplicos* (Cambisols) occurred; whereas in areas of stability with lower slope, *Latossolos Vermelhos* (Ferralsols) and *Nitossolos Vermelhos* and *Háplicos* were observed.

The clay content observed in the *Nitossolos* reflected the high degree of pedogenetic development, which was lower than in the *Latossolos* because the former were located in more sloped topography where soil rejuvenation processes take place (Curcio, 2006).

**Table 4.** Physical and chemical properties of A and B horizons of soil profiles (P) from region III (igneous basic rocks), located in Campos Novos, SC, Brazil

P	Hor.	Clay	Sand	DF	TOC	pH(H <sub>2</sub> O)	SB	Al <sup>3+</sup>	CEC	T <sub>clay</sub>	V	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	ki	kr
		— g kg <sup>-1</sup> —	%	g kg <sup>-1</sup>	g kg <sup>-1</sup>		cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	cmol <sub>c</sub> kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	
22	A	543	90	56	33.8	5.2	11.8	0.2	19.2	35.4	62	2	17.2	120.2	97.4	0.24	0.16
	B	690	43	64	15.2	4.6	2.4	2.0	10.4	15.1	24	45	20.3	140.0	96.1	0.25	0.17
23	A	320	170	25	23.7	6.8	16.1	0.0	16.6	51.9	92	0	34.8	172.8	112.0	0.34	0.24
	B	450	153	41	15.3	4.5	4.7	5.3	30.2	57.1	16	53	34.7	95.5	124.6	0.62	0.34
24	A	455	121	38	38.2	6.1	15.6	0.3	15.7	34.5	98	2	9.4	120.9	101.1	0.13	0.09
	B	602	39	24	18.0	4.6	2.5	3.1	9.4	15.6	28	55	11.2	167.2	107.5	0.11	0.08
25	A	449	33	51	63.8	5.2	7.4	0.5	16.6	37.0	42	6	21.1	187.1	153.6	0.19	0.13
	B	657	27	30	28.2	4.5	1.5	4.0	11.2	17.0	13	73	46.6	212.3	150.6	0.37	0.26
26	A	663	23	47	26.7	5.3	8.4	0.6	18.0	27.1	46	7	25.5	140.7	93.0	0.31	0.22
	B	677	20	93	13.2	5.0	0.8	1.7	7.3	10.8	11	68	12.3	177.7	136.8	0.12	0.08
27	A	671	16	54	16.7	5.5	4.9	1.6	13.2	19.7	38	25	9.4	180.3	145.8	0.09	0.06
	B	743	11	99	12.4	5.2	1.5	0.6	6.4	8.6	25	29	12.2	173.8	142.3	0.12	0.08
28	A	422	50	34	26.7	4.5	10.0	0.6	16.7	39.6	58	6	41.7	203.4	158.7	0.35	0.23
	B	631	25	46	8.4	4.2	2.1	2.2	10.1	16.0	21	51	42.5	262.4	157.5	0.28	0.20
29	A	472	76	47	22.1	5.8	13	0.5	20.4	43.2	64	4	12.8	142.3	135.3	0.15	0.10
	B	687	31	24	17.4	4.5	1.9	2.7	10.8	15.7	17	59	18.0	164.5	134.2	0.19	0.12
30	A	415	39	30	19.0	5.0	8.6	0.3	20.2	48.7	44	3	30.3	127.5	93.4	0.40	0.28
	B	592	62	75	15.4	4.3	2.0	4.1	16.1	27.2	13	67	25.1	170.0	92.2	0.25	0.19
31	A	436	83	59	24.4	4.2	1.8	5.7	25.6	58.7	7	76	54.6	158.3	153.7	0.59	0.36
	B	456	89	52	14.8	4.5	2.2	3.0	14.2	31.1	16	58	44.5	58.4	126.8	1.30	0.54
32	A	427	30	44	23.9	5.0	8.2	0.6	16.6	38.9	48	67	44.0	114.4	98.1	0.65	0.42
	B	562	80	96	6.4	5.0	10.7	0.4	13.1	23.3	81	4	37.2	155.5	94.0	0.41	0.29
33	A	568	82	38	17.2	5.3	11.9	0.4	17.0	29.9	72	3	34.2	144.6	93.5	0.40	0.28
	B	635	55	99	6.3	4.3	2.9	2.4	10.5	16.5	26	45	34.8	162.9	94.3	0.36	0.27
34	A	539	17	37	20.1	4.8	4.8	2.9	16.9	31.4	28	38	31.2	150.2	93.4	0.35	0.25
	B	620	33	66	14.0	4.4	0.4	6.5	18.8	30.3	2	94	22.4	70.4	92.1	0.54	0.29

P: profile; Hor.: horizon; DF: degree of flocculation; TOC: total organic carbon; pH(H<sub>2</sub>O): pH in water; SB: sum of bases; CEC: Cation Exchange Capacity; T<sub>clay</sub>: clay activity; V: base saturation; m: aluminum saturation; ki (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) and kr (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>). All analyses were performed according to Donagema et al. (2011).

In addition, the low clay activity ( $T_{\text{clay}}$ ) reflected the advanced state of weathering of *Latossolos* compared with *Nitossolos*, which showed higher  $T_{\text{clay}}$  values.

Clay translocation from the A to the B horizon, with moderate development and frequent presence of clay skins and well-developed aggregates, indicated the pedogenetic process of clay eluviation and illuviation, reflecting the genesis of the nitric horizon characteristic of *Nitossolos*. With regard to *Latossols*, they had a fine clayey texture and a high degree of flocculation, reaching 93 and 99 % in the oxic horizon, indicating the specific pedogenetic process of latolization, responsible for considerable removal of silica and bases and a relative increase in Fe and Al oxides.

In the Suborder categorical level, profiles 22, 26, 27, 30, and 34 were classified as *Vermelhos* (located at lower altitudes), indicating the effect of climate and relief, allowing for higher expression of the Fe oxide hematite in the soil color. The other profiles, for their lack of distinctive characteristics, were classified as *Háplicos*. At the third level (Great Group), eight of the 13 profiles from region III were dystrophic, 2 (P25 and P30) had an aluminic character, two had an alytic character (P34 and P23), and one was eutrophic (P32). At the Subgroup level, all profiles were classified as typic.

The low V indicated that the soils from region III were highly leached and had high potential acidity (H+Al), although with values lower than those found in regions I and IV and similar to those of region II. In general, the  $\text{SiO}_2$  content was the lowest, compared to soils from the other regions. The  $\text{Fe}_2\text{O}_3$  level was generally higher in region III in comparison with the soils originating from rhyodacites and sedimentary rocks. However, most profiles in this region possessed moderate levels of Fe oxides. According to Santos et al. (2013b),  $\text{Fe}_2\text{O}$  levels between 80 and 180  $\text{g kg}^{-1}$  of soil define the mesoferric soil character, which was unusual for these soils originating from basalt, where high Fe content would be expected.

In studies with basaltic and acidic rocks, Levi and Melfi (1972) concluded that weathering was faster on basaltic rocks because of the occurrence of high levels of ferromagnesian minerals (olivine and piroxene), which are the first to be altered, resulting in a higher number of fissures, favoring drainage and, consequently, weathering. The acidic rocks were more compact and resistant to weathering because of the higher amount of quartz and aluminosilicated minerals.

Soils from region IV, originating from volcanic acidic rocks - *Palmas* type, were located at altitudes ranging from 1,252 to 1,330 m, with a slightly rolling and rolling topography. This topography favored the erosive process, retarding pedogenesis and rejuvenating the profiles, and the soils were classified as *Cambissolos Húmicos* (P35 and P36) and *Háplicos* (P37 and P38). Consequently, no specific pedogenetic process was observed for these soils.

The climate factor affected OM accumulation, with values of organic C up to 72  $\text{g kg}^{-1}$  in the surface layer (Table 5). With regard to color, the accumulation of OM was associated with higher soil moisture and favored the formation of goethite in detriment to hematite, resulting in soils with a typically brown or yellow color, with hues ranging from 10YR to 7.5YR. All profiles had an alytic character, therefore defining the third level (Great Group); at the Subgroup level, all profiles were classified as typic.

As is the case for soils from other regions, the low V, the high H+Al levels, and m between 66 and 88 % are properties that indicate a high degree of leaching in the profiles.

### **Interaction between soil formation factors**

According to evaluation of grouping by similarity (Figure 2), it is possible to separate the soils into groups and confirm the influence of parent material on the soil attributes, highlighting the importance and the direct correlation between geology and soil formation in the high-altitude regions of Santa Catarina.

**Table 5.** Physical and chemical properties of A and B horizons of soil profiles (P) from region IV (igneous acidic rocks), located in Água Doce, SC, Brazil

P	Hor.	Clay	Sand	DF	TOC	pH(H <sub>2</sub> O)	SB	Al <sup>+3</sup>	CEC	T <sub>clay</sub>	V	m	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	ki	kr
		— g kg <sup>-1</sup> —		%	g kg <sup>-1</sup>			cmol <sub>c</sub> kg <sup>-1</sup>			%		g kg <sup>-1</sup>				
35	A	468	40	81	72.3	4.8	3.0	3.7	21.2	45.3	14	55	11.4	129.1	109.2	0.15	0.10
	B	515	46	15	36.4	4.3	1.6	4.5	13.2	25.6	12	74	21.7	209.0	131.9	0.18	0.13
36	A	484	35	38	37.9	4.9	0.9	5.1	14.9	30.8	6	85	27.2	135.2	81.4	0.34	0.25
	B	489	17	22	21.1	4.0	1.0	5.5	19.5	39.9	5	85	26.4	158.7	84.2	0.28	0.21
37	A	556	43	73	29.4	4.6	1.5	2.8	17.8	32.0	9	65	28.4	154.9	93.7	0.31	0.22
	B	613	12	38	10.2	4.7	2.1	4.1	11.2	18.3	19	66	34.9	177.3	26.6	0.33	0.31
38	A	316	193	56	26.6	4.3	12.8	5.5	19.4	61.4	7	30	23.8	130.2	22.8	0.31	0.28
	B	520	129	54	7.5	4.6	1.0	7.6	22.0	42.3	1	88	25.3	142.7	97.2	0.30	0.21

P: profile; Hor.: horizon; DF: degree of flocculation; TOC: total organic carbon; pH(H<sub>2</sub>O): pH in water; SB: sum of bases; CEC: Cation Exchange Capacity; T<sub>clay</sub>: clay activity; V: base saturation; m: aluminum saturation; ki (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) and kr (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>). All analyses were performed according to Donagema et al. (2011).

According to dendrogram analysis, the soils were divided into four homogeneous groups: i) the largest, formed by the soils from regions I (sedimentary rocks) and II (rhyodacites); ii) the smallest, composed only of profile 4; iii) the group made up of the four profiles from region IV (igneous acid rocks); and iv) the group formed by soils originating from basalt (region III).

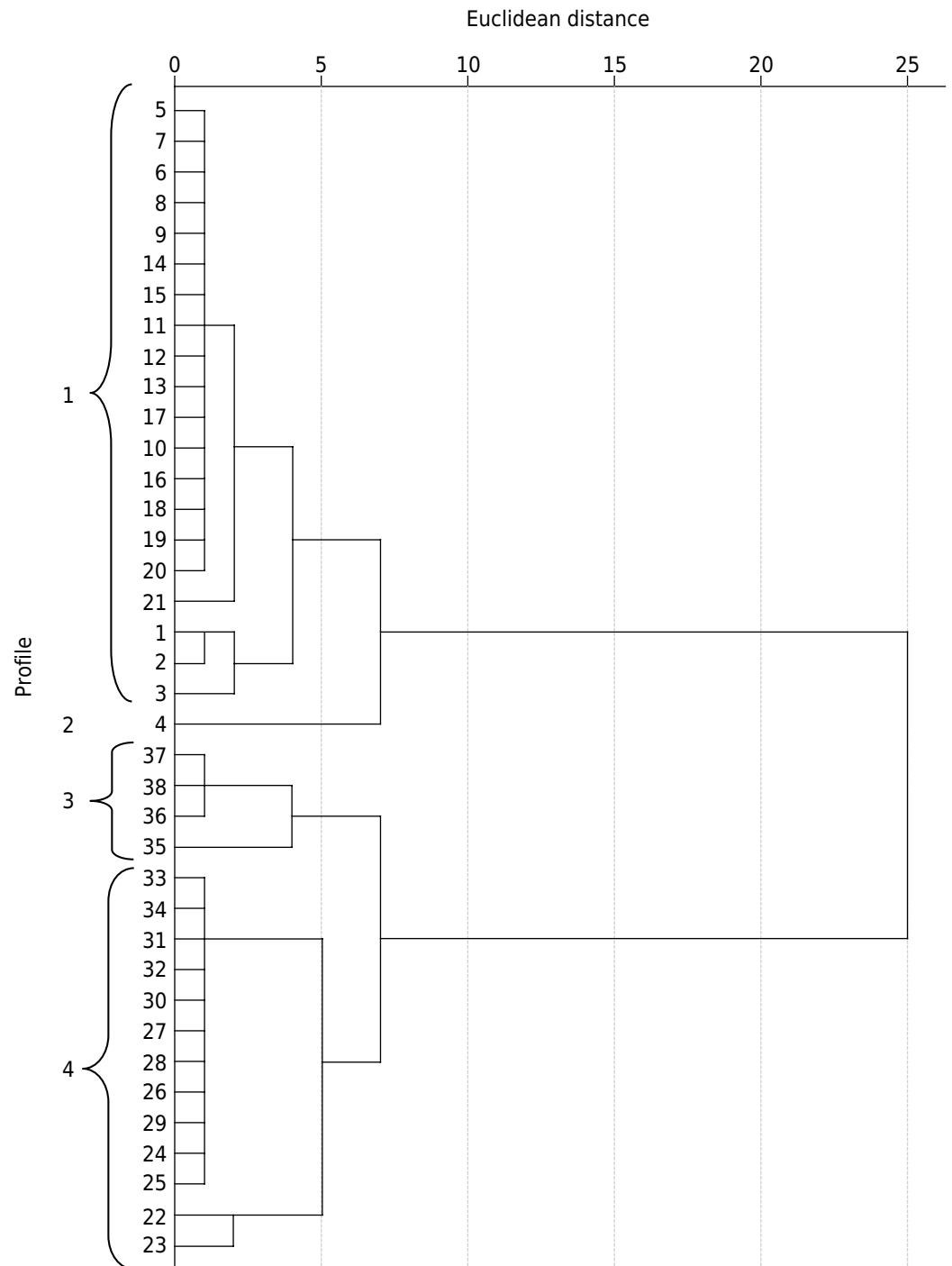
The dendrogram indicates the profiles originating from rhyodacite from region II in São Joaquim (profiles 5, 7, 6, 8, 9, and 14 to 21, in this sequence) as having the highest similarity to each other, indicated by the smaller Euclidian distance. This group also included the profiles from region I, from sedimentary rocks, with profile 1 exhibiting greater similarity to profiles 2 and 3. Conversely, profile 4 was similar to both soil groups, originating from rhyodacites and from sedimentary rocks, but with a higher Euclidian distance. This profile was unique primarily because of its lower levels of clay, with little or no variation between the A and B horizons.

The second group with soils from region IV exhibited higher similarity between profiles 37 and 38, with the latter showing similarity with all three profiles and, at a smaller scale, with profile 35. P35 was different from the other profiles because of its high C content (72 g kg<sup>-1</sup>) in the A horizon and lower ki value.

In the group with the lowest similarity among soils, region III, profiles 33, 32, 31, and 34 were closest to each other. Profiles 22 and 23 were similar to each other, but showed the greatest differences when compared with all the other profiles; that is, they had distinct variables from those found in the other soils.

Continuing with the analysis, the soils underwent discriminant analysis, which is an important tool in the evaluation of soil surveys and has shown the possibility for predicting soil classes and/or their separability in the terrain (Kravchenko et al., 2002; Demattê and Nanni, 2003). Therefore, discriminant analysis was performed based on the four soil classes. The results showed that for the A horizon, the first two canonical axes (CAN) explained 94 % of total variance, with CAN1 explaining 78.1 %; that is, it was the function that contributed most to the differences exhibited among the groups, whereas CAN2 explained 16.2 % of the variance. However, the Wilks Lambda evaluation, which tests the significance of the discriminant functions, indicated a p-value (0.455) higher than the significance level of 0.05 for CAN1, and it was therefore deemed not significant.

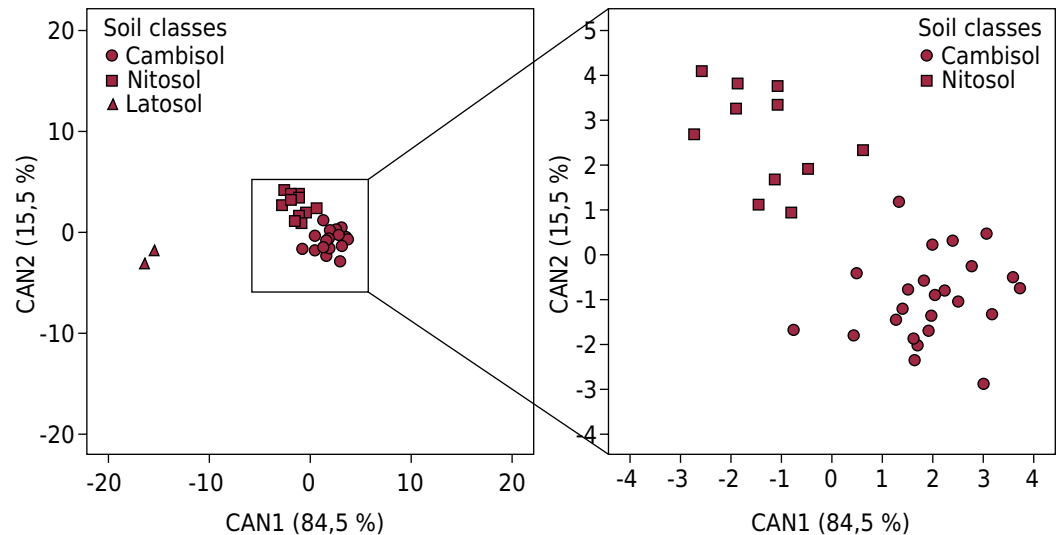
For the B horizon, 100 % of the data variance was explained by the first two canonical axes (Figure 3), where CAN1 explained 73.8 % and CAN2 explained 26.2 %. The low



**Figure 2.** Dendrogram of the soil profiles of similarity (I - 1-4; II - 5-21; III - 22-34; IV - 35-38) evaluated in different altitude regions of the state of Santa Catarina, Brazil.

Wilks Lambda value (0.000) for CAN1 indicated that the first function was better for discriminating, and the p-value (0.003) indicated that the first discriminant function was highly significant. Among the most relevant variables for the determination of CAN1 were K and P levels,  $k_r$ , soil particle density, Mg, and pH. They were evaluated through a structural matrix, which indicated the contribution of each variable to the function.

The analysis of all observations and the percentages of correct and incorrect fit into soil classes in the four groups determined by the canonical discriminant functions (Table 6) indicated that all soil samples from the B horizon (100 %) were correctly classified. This demonstrated the efficiency of the grouping technique to distinguish among soil classes and showed the correlation between the B horizon and the attributes that best express pedogenesis.



**Figure 3.** Dispersion of the canonical coefficients of the variables in relation to the soil classes in the B horizon.

**Table 6.** Sample classification into four soil classes (Neossolos, Cambissolos, Nitossolos, and Latossolos) as determined using the two discriminant functions on the A and B horizons

Original group	No. of profiles	Estimated groups (model)			
		Litholic Neosol	Cambisol	Nitosol	Latosol
A horizon (73.7 %)					
Neosol L.	1	0	0	1	0
		0	0	100 %	0
Cambisol	24	0	24	0	0
		0	100 %	0	0
Nitosol	11	0	0	2	9
		0	0	18.2 %	81.8 %
Latosol	2	0	0	0	2
		0	0	0	100 %
B horizon (100 %)					
Cambisol	24	0	24	0	0
		0	100 %	0	0
Nitosol	11	0	0	11	0
		0	0	100 %	0
Latosol	2	0	0	0	2
		0	0	0	100 %

These canonical discriminant functions results were in accordance with studies by Demattê and Garcia (1999) and Demattê et al. (2000), who reported a 100 % rate of classification exactness for the soil classes evaluated. For Nanni et al. (2004) and Fiorio et al. (2010), this rate was 80 %, and Kravchenko et al. (2002) had a 90 % rate.

Conversely, in the A horizon, only 73 % of soil classification was correctly associated with the classification model, which is explained by the fact that diagnostic attributes for most soil orders are based on subsurface horizons. Using attributes from the A horizon, the *Neossolo Litólico* was classified as a *Nitossolo*, nine *Nitossolos* were grouped with *Latossolos*, and all *Cambissolos* (24 profiles) had the same classification according to the model.



## CONCLUSIONS

The genesis of soils from the high mountain regions of Santa Catarina has been greatly affected by parent material, climate, and relief factors, which was reflected in the formation of soils with high clay content, low sum of bases and base saturation, and high aluminum and carbon content.

Most soils from the region were classified as *Cambissolos* (63 %). However, *Nitossolos* (29 %) and *Latosolos* (5 %) were also present, indicating the influence of topography and climate on the expression of pedogenetic processes. In addition, *Neossolos Litólicos* (3 %) were found in areas of strongly rolling land.

Combined analysis of the edaphic variables enabled classification of the soils into three groups. The first and largest group included the profiles originating from parent materials such as rhyodacite and sedimentary rocks; the second and smallest group was constituted by the four profiles from the *Água Doce* region (acidic rocks); and the third was formed by profiles originating from basalt.

Discriminant analysis based on variables from the B horizon was an efficient method for grouping of soil classes.

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