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Geo-Sciences

Geomorphological characterization of soils with high organic carbon contents in southern Brazil

Caracterização geomorfológica de solos com elevados teores de carbono orgânico no sul do Brasil

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ABSTRACT

Soil organic carbon plays a crucial role in soil fertility, water retention, and overall ecosystem health. Understanding the geomorphological characteristics of environments where soils with high organic carbon content occur is essential for sustainable land management and conservation efforts. In this context, the objective of this study was to characterize the geomorphology of environments where soils with high organic carbon content occur in southern Brazil. The study collected 135 soil samples to determine organic carbon content, soil classification, and geomorphological variables derived from the digital elevation model SRTM 30m. The investigation found that the environments where Organosols occur have higher altimetry values than the places where Cambisols predominate. The analysis also observed variations in the maximum values of slope between the environments of occurrence of the Organosols and Cambisols evaluated. The results demonstrate the potential of environmental variables related to geomorphology to characterize and identify environments that are more favorable to the occurrence of soils with high levels of organic carbon in southern Brazil, remotely and with reduced costs associated with collecting data in the field and in hard-to-reach areas.

Keywords: Cambisols; Organosols; Remote Sensing; SRTM

RESUMO

O carbono orgânico do solo desempenha um papel crucial na fertilidade do solo, na retenção de água e na saúde geral do ecossistema. Compreender as características geomorfológicas dos ambientes onde ocorrem solos com alto teor de carbono orgânico é essencial para o manejo sustentável do solo e estratégias de conservação. Nesse contexto, este estudo teve como objetivo caracterizar a geomorfologia de ambientes onde ocorrem solos com elevados teores de carbono orgânico no Sul do Brasil. Foram coletadas 135 amostras de solos para determinar o teor de carbono orgânico, a classificação do solo e variáveis geomorfológicas derivadas do modelo digital de elevação SRTM 30m. A análise constatou que os ambientes onde ocorrem os Organossolos apresentam valores de altimetria mais elevados do que os locais onde predominam os Cambissolos. Além disso, houve variações nos valores máximos de declividade entre os ambientes de ocorrência dos Organossolos e Cambissolos avaliados. Esses resultados demonstram o potencial de variáveis ambientais relacionadas à geomorfologia para caracterizar e identificar ambientes mais favoráveis à ocorrência de solos com elevados teores de carbono orgânico no Sul do Brasil, de forma remota e com custos reduzidos associados à coleta de dados em campo e em áreas de difícil acesso.

Palavras-chave: Cambissolos; Organossolos; Sensoriamento Remoto; SRTM

1 INTRODUCTION

Remote sensing is a valuable tool for soil characterization, particularly in situations where resources are scarce or local soil data is lacking (Arruda et al., 2013). It allows for the collection of data on soils through the use of environmental variables obtained remotely. Elevation, slope and aspect have been identified as the most effective variables for medium-scale soil surveys (Chagas et al., 2013). In the study developed by Ziadat (2005) the author used slope, profile curvature, plan curvature, aspect and contribution area to predict soil attributes, with significant correlation found between soil depth, water storage capacity and soil texture.

In the states of Santa Catarina and Rio Grande do Sul, there are significant amounts of Humic Cambisols, Histic Cambisols and Folic Organosols (Streck et al., 2008; Santos et al., 2018). These soils are preferably located on the edges of the Serra Geral Formation scarp, in regions where altitudes above 1000m predominate. Due to the high contents of organic carbon, concentrated in the superficial horizons, these soils play an essential role in carbon immobilization and regulation of water fluxes.

In many cases, these areas are of permanent preservation (Simas et al., 2005; Benites et al., 2007; Scheer et al., 2011). At the national level, Law 12,651/2012 designates forests and other forms of vegetation located on the tops of hills, mountains or mountain ranges and at altitudes above 1800 meters as a permanent preservation area. These areas are predominantly covered by Campos and the Mixed Ombrophilous Forest, with inclusions of nebular forests on the tops and rupicolous vegetation in places with steeper declivity. This law is part of the legal framework for sustainable mountain management (Romeo et al., 2022).

The Mixed Ombrophilous Forest, according to the IBGE classification (2012), can be divided into three distinct classes based on their position in the relief: i) Submontane, which is below 400m; ii) Montana, which is located between 400 and 1000m and characterized by the presence of Araucaria angustifolia, Ocotea pulchella, Ocotea porosa, Matayba eleagnoides among others; and iii) Altomontana, which is located at altitudes above 1000m and predominates shallow soils on the slopes of hills. The Altomontana Mixed Ombrophilous Forest is of considerable environmental importance, as its occurrence is exclusively restricted to the states of Santa Catarina and Rio Grande do Sul.

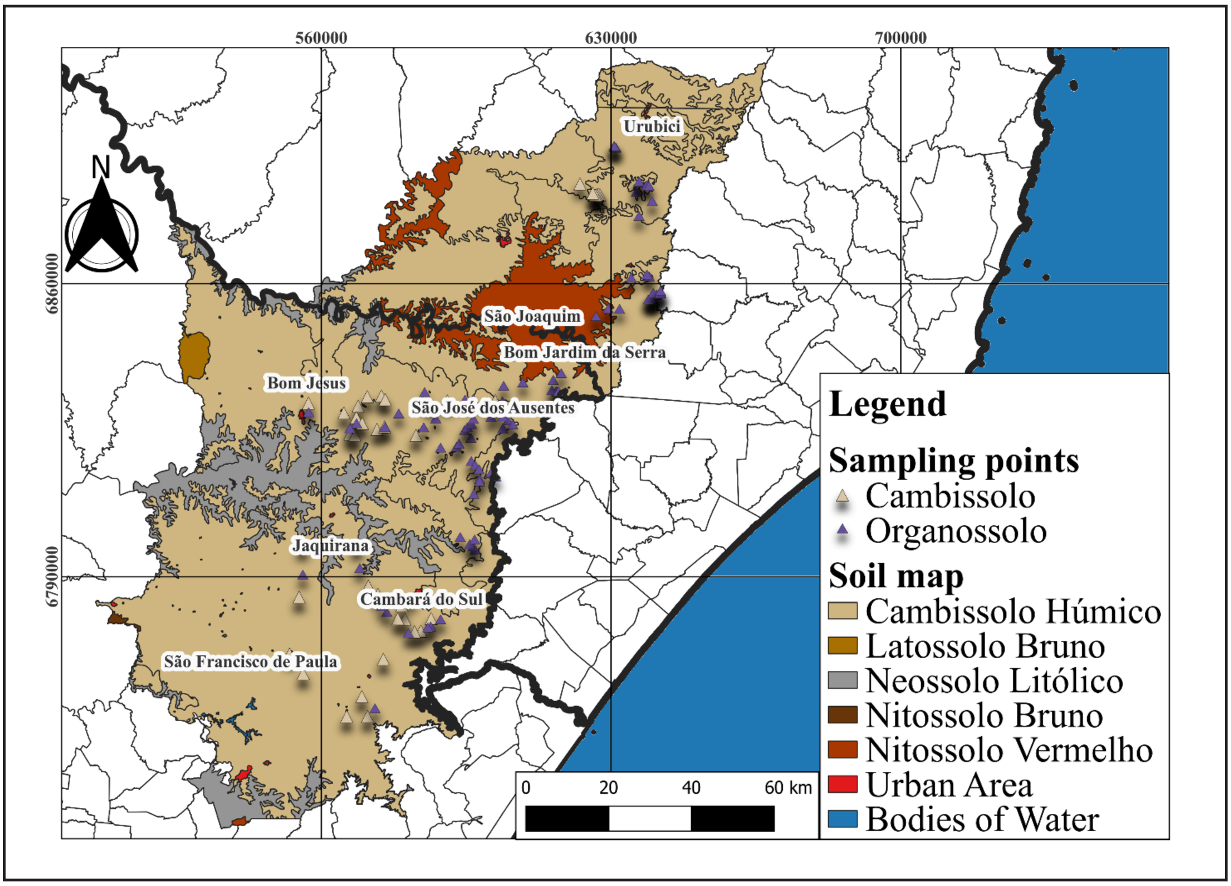
In high montane environments, the cold and humid climate and the high montane vegetation lead to a reduction in biological activity, resulting in the accumulation of organic matter in the soil (Benites et al., 2007; Ebeling et al., 2008; Valladares et al., 2008). Characterization works show that the soils in these areas are poorly developed, extremely acidic, with low base saturation and high saturation by exchangeable aluminum (Santos Junior; Almeida, 2021). Similar results are observed in studies developed in soils from other high montane regions of Brazil, from the rupestrian grasslands of the Southeast to the cloud forests in the Aparados da Serra Geral (Falkenberg, 2003; Benites et al., 2007; Soares, 2015).

Information on soils from high montane environments in southern Brazil is limited to studies carried out in small areas or environments protected by law, with most studies focusing on characterizing soils under altomontane forests. However, information on altomontane grassland soils in southern Brazil is scarce (Vashcenko et al., 2007; Scheer et al., 2011). Therefore, the present study aimed to carry out a geomorphological characterization of the environments in which soils with high contents of organic carbon occur in southern Brazil, filling a gap in the current knowledge of soils in this region.

2 MATERIAL AND METHODS

The study was carried out in the mesoregions of Campos de Cima da Serra in the state of Rio Grande do Sul and Planalto Serrano in the state of Santa Catarina (Figure 1). The study area covers the municipalities of São Joaquim, Urubici and Bom Jardim da Serra in the state of Santa Catarina and São José dos Ausentes, Bom Jesus, São Francisco de Paula, Jaquirana and Cambará do Sul in the state of Rio Grande do Sul.

Figure 1 – Soil map with spatial distribution of the sampling points



Source: adapted from IBGE (2015) and IBGE (2016)

The region is characterized by altitudes above 800m and relief ranging from smooth-wavy to wavy (Buckup, 2010; Santos Junior; Almeida, 2021). The climate is classified as Cfb, being the coldest region in the country with average winter temperatures of less than 10.5ºC and rainfall distributed evenly throughout the year, ranging from 1500 to 1700 mm (Alvares et al., 2013).

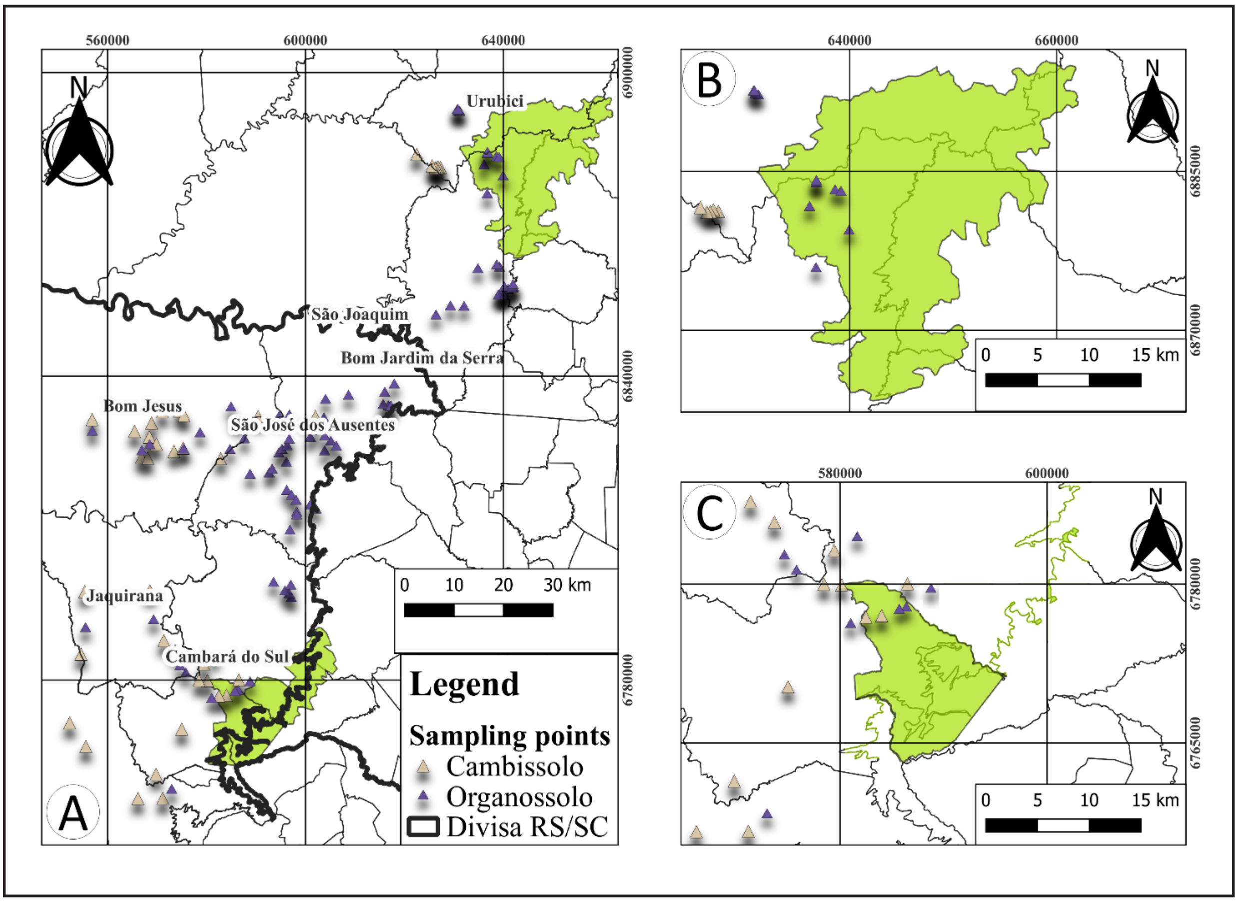
Regarding vegetation, angiosperms are the most diverse group of plants, occurring in all types of vegetation, while gymnosperms have a much smaller diversity, with a predominance of species such as *Podocarpus lambertii* e *Araucaria angustifolia* (Buckup 2010; IBGE 2012). The region also has endemic plant species with limited distribution to specialized habitats due to geographic or reproductive isolation mechanisms (Behling; Pillar, 2007). The constant fog that covers the region for a long period of the year favors the formation of vegetation called Nebular Forests (Buckup 2010), with lower branched, rounded trees and dark leaves such as *Mimosa sp*, *Fuschsia regia* e *Tibouchina sellowiana*.

2.1 Soil samples

For soil characterization, 135 soil samples were collected and georeferenced in an irregular grid at a depth of 0 to 20 cm (Figure 2). Most of the soil samples were collected in areas of considerable environmental importance, such as the São Joaquim National Park, Aparados da Serra National Park and Serra Geral National Park. Authorizations were requested from the supervisory institution (SISBIO – ICMBio nº 61131-1 e 61880-1).

All soil samples collected were air-dried, ground and sieved through a sieve with a 2.0mm opening to determine the organic carbon contents according to the ignition loss method (Santos et al. 2018). For soil classification, sampling was carried out using a Dutch auger until the lithic contact (parent material) and then compared to the representative profiles described by Santos Junior; Almeida (2021).

Figure 2 – Spatial distribution of the sampling points in the study area. A. highlighted the soil samples collected in the São Joaquim National Park. B. highlighted the soil samples collected in the Aparados da Serra and Serra Geral National Park



Source: adapted from IBGE (2015) and IBGE (2016)

2.2 Geomorphological variables

The geomorphological variables elevation, slope, topography wetness index - TWI, plan curvature and profile curvature were derived from the SRTM digital elevation model, which is provided free of charge by United States Geological Survey. The data have a resolution of 1" or 30m, Universal Transverse Mercator projection and Datum SIRGAS2000 Zone 22S. All geomorphological variables were processed using ArcGIS® v. 10.4 software.

The values of geomorphological variables were extracted directly from the SRTM digital elevation model for each sample point evaluated using the Extract Values to

Points tool in the Spatial Analyst module of ArcGIS software. To determine the slope, a 3x3 matrix centered on each point of the data grid was used to estimate the first derivative of Z with respect to aspect, resulting in a slope raster according to the Horn (1981) polynomial.

The TWI considers the slope and area of contribution in the calculation (Beven; Kirkby, 1979). It expresses the distribution of areas with greater probability of soil water saturation, being useful to distinguish environments with contrasting characteristics such as plateaus and plains. The intervals proposed by Lin et al. (2006), are used in the TWI classification and interpretation (Table 1).

Table 1 – Classification of the Topographic Wetness Index (TWI) according to drainage classes

Drainage classes	Value range
Very well drained	5,4 – 7,8
Well drained	7,81 – 9,3
Moderately drained	9,31 – 11,7
Poorly drained	11,71 – 15,5
Very poorly drained	15,5 – 21,4

Source: Lin et al. (2006)

The plan curvature, or horizontal curvature, represents the curvature of the hypothetical contour line that passes through a specific cell (Zevenbergen; Thorne, 1987), which allows for the distinction between valleys and hilltops (Table 2).

Table 2 – Classification of landforms according to horizontal curvature ranges

Classes	Interval (°/m)
Convergent	< -0,038
Flat	-0,038 to 0,051
Divergent	> 0,051

Source: Valeriano (2008)

The curvature of the surface in the direction of steepest slope is represented by the curvature profile, or vertical curvature. This variable helps to identify environments that are more susceptible to erosion and deposition, in addition to influencing the speed of surface water flow (Table 3).

Table 3 – Classification of landforms according to vertical curvature ranges

Classes	Interval (°/m)
Concave	< -0,55
Straight	-0,55 to 0,55
Convex	> 0,55

Source: Valeriano (2008)

2.3 Data analysis

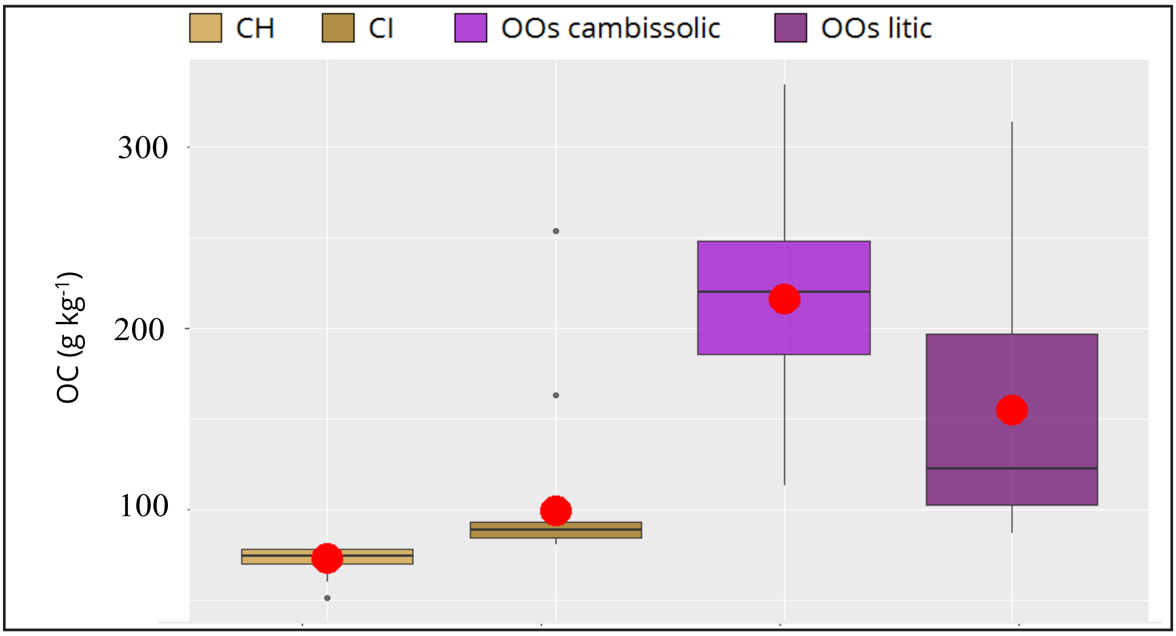
Data were analyzed using descriptive statistics, including minimum and maximum values, first and third quartiles, mean and median (Lopes, 1999), for the variables elevation, slope and TWI. For the categorical variables of plan and profile curvature, a data frequency distribution analysis was performed (Chig *et al*., 2008). All statistical analyses and graphs (boxplot) were developed using R v.4.0 software.

3 RESULTS AND DISCUSSION

The balance between organic carbon (OC) entry and exit from the ecosystem strongly influences the OC contents. While natural ecosystems maintain a steady state between OC inputs and decomposition, this relationship is observed less frequently in ecosystems under agricultural management due to changes in nutrient dynamics and decomposition rates, as noted by Wang et al. (2017).

The average OC contents in the 0-20cm depth of areas dominated by CH were 72.8g kg^{-1}, with a range of 51.0g kg^{-1} to 80.0g kg^{-1} (Figure 2). The average OC levels at the some depth were 88.0g kg^{-1} in areas where CI were present, with a range of 80.5g kg^{-1} to 98.7g kg^{-1}.

Figure 3 – Boxplot of OC contents in the 0-20cm layer in the samples of Cambisols (CH = Humic Cambisol and CI = Histic Cambisol) and Organosols (OOs cambissolic = Cambissolic Sapric Folic Organosol and OOs litic = Lithic Sapric Folic Organosol) evaluated.



Source: Authors (2023)

Regarding the OOs lithic, they presented the highest average OC content in the 0-20cm depth, with an average of 205.0g kg^{-1}, a minimum of 102.0g kg^{-1} and a maximum of 333.8g kg^{-1}. The OOs cambissolic showed an average OC content in the 0-20cm layer of 156.6g kg^{-1}, with a minimum of 86.9g kg^{-1} and a maximum of 313.5g kg^{-1}. Table 4 shows the parameters related to the descriptive statistics of the geomorphological variables elevation, slope and TWI, categorized according to the different soils in the study area (Santos Junior; Almeida, 2021).

Table 4 – Descriptive statistics of geomorphological variables in the occurrence environments of soils with high organic carbon contents in Southern Brazil

Statistical parameter	**OC (g kg^{-1})**	**Elevation (m)**	**Slope (%)**	**TWI**
CH – Humic Cambisol (Cambissolo Húmico)				
Minimum	51.0	923	0.61	4.74
1st Quantile	70.0	1005	6.86	5.96
Median	74.0	1116	11.73	6.54
Mean	72.8	1157	15.47	6.85
3rd Quantile	78.0	1288	23.85	7.15
Maximum	80.0	1475	40.41	12.33
CI – Histic Cambisol (Cambissolo Hístico)				
Minimum	80.5	884	1.82	4.38
1st Quantile	83.9	946	6.10	5.85
Median	86.0	988	8.76	6.25
Mean	88.0	1050	10.39	6.53
3rd Quantile	92.6	1082	12.81	7.58
Maximum	98.7	1434	25.37	9.77
OOs litic – Lithic Sapric Folic Organosol (Organossolo Fólico Sáprico lítico)				
Minimum	102.0	1278	3.54	4.98
1st Quantile	162.3	1368	10.38	5.41
Median	210.9	1384	12.87	6.31
Mean	205.0	1385	14.96	7.19
3rd Quantile	247.7	1414	19.90	8.88
Maximum	333.8	1443	30.59	13.40
OOs cambissolic – Cambissolic Sapric Folic Organosol (Organossolo Fólico Sáprico cambissólico)				
Minimum	86.9	921	0.61	4.76
1st Quantile	102.3	1064	6.17	6.06
Median	125.9	1212	10.79	6.77
Mean	156.6	1223	13.05	7.23
3rd Quantile	200.7	1296	15.48	7.71
Maximum	313.5	1680	54.71	14.45

Source: Authors (2023)

In general, higher values of slope were observed in environments where OOs lithic occur. The lowest slope values were observed in the environments where CIs occur, showing the potential for accumulation of organic material to form the histic horizon (>80g kg^{-1}). In conditions of steeper slopes, the erosive process effects are more intense, resulting in greater soil loss in the superficial layers, which favors the occurrence of OOs lithic. The opposite is observed in areas of less accentuated relief, where the effect of erosive processes is reduced, and consequently, the loss of soil and sediments with accumulation of organic material in the superficial horizons decreases (Guerra et al. 2007; Brandão et al. 2009).

Compared to high-altitude environments, climatic conditions under medium elevation conditions (<1000m) are more favorable to the activity of organic matter decomposing organisms (Gerschlauer et al., 2019). In these places, temperatures are higher and precipitation is also lower when compared to cold and humid environments located at high altitudes (Becker; Kuzyakov, 2018; Borken; Matzner, 2009). As exposed by Calil et al. (2012) local relief conditions such as altitude, slope, aspect, curvature surface and drainage are considered the main topographic attributes that influence water dynamics and transport of particles and sediments.

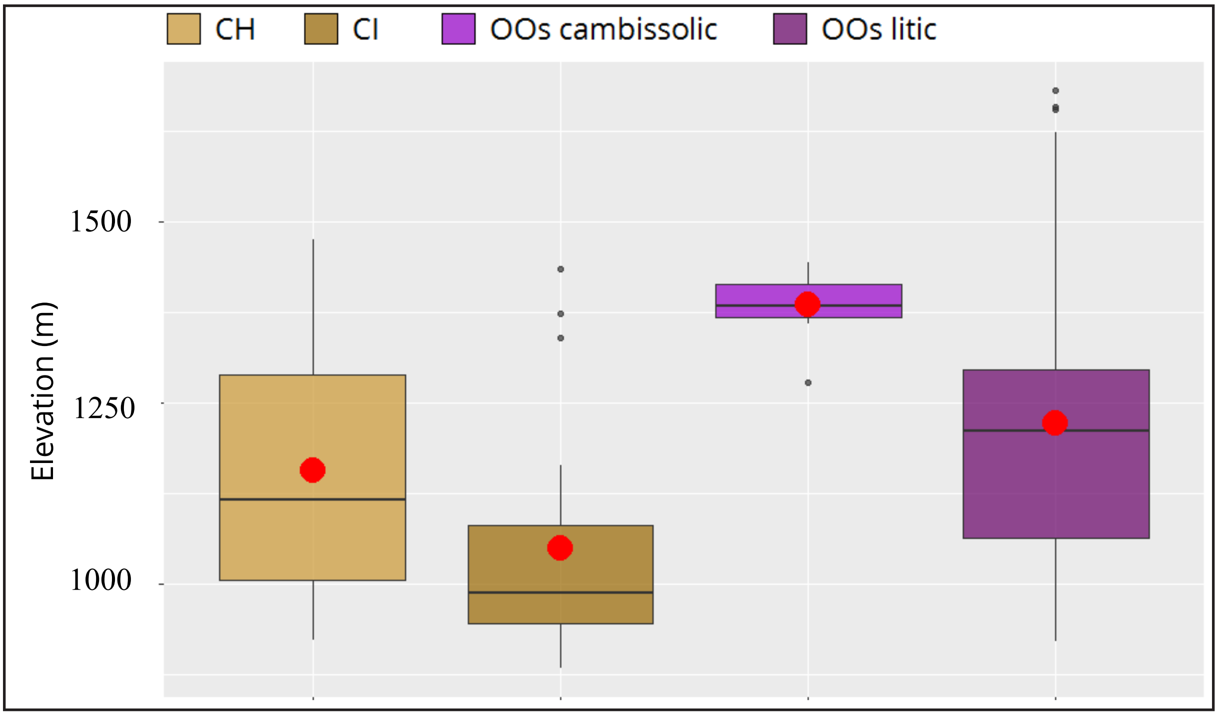
The environments of occurrence of the Organosolos evaluated (OOs cambisolic and OOs lithic) have higher altimetry values (Figure 3) when compared to environments where Cambisolos predominate (CH e CI). The OOs lithic occur in places with an average elevation of 1223m, ranging from 921 to 1680m, with a greater occurrence in the range between 1064 and 1296m. OOs cambisolic occur in environments with less variable elevations, being found at altitude conditions between 1278 and 1443m, with an average altitude of 1385m. The range of preferential occurrence of these soils is also lower, ranging from 1368 to 1414m.

Agricultural management practices such as soil preparation and harvesting intensify OC losses, with increased OM decomposition. This mainly occurs in places with hot climate and moderate drainage situated in the lower positions of the slope. According to Gerschlauer et al. (2019), the results demonstrate that OC contents are higher in cold and humid environments at high altitudes when compared to managed sites at low altitudes.

Combining topographic attributes and soil organic matter content, it is possible to map the variable in poorly sampled regions at low cost (Oliveira et al., 2012). In the study conducted by Gerschlauer et al. (2019), the authors evaluated semi-natural ecosystems on Mount Kilimanjaro and found an increase in OC contents with elevation, which is in agreement with results observed in mountain ecosystems in North America and Europe (Zhu et al., 2009; Zhou et al., 2011; Ortiz et al., 2016). This same relationship is observed in the conclusions of Oliveira et al. (2012) where the authors evaluated different vegetation classes and the greatest amount of biomass was observed in the highest positions, which may be related to the milder temperatures that predominate in these environments.

Variations in maximum slope were observed between the environments where Organosolos and Cambisolos were evaluated. The mean slope values were similar among the Organossolos, as seen in the preferential occurrence interval (Figure 4).

Figure 4 – Boxplot of OC contents in the 0-20cm layer in the samples of Cambisols (CH = Humic Cambisol and CI = Histic Cambisol) and Organosols (OOs cambissolic = Cambissolic Sapric Folic Organosol and OOs litic = Lithic Sapric Folic Organosol) evaluated



Source: Authors (2023)

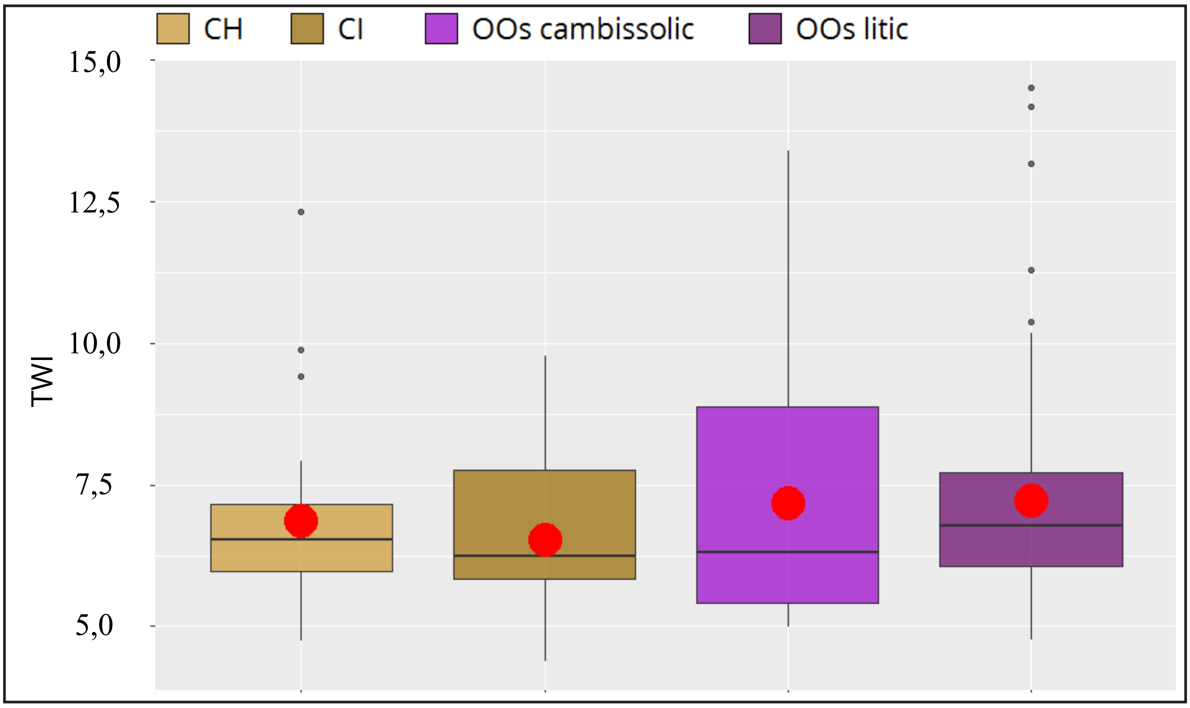
The results obtained by Razavi-Termeh et al. (2019) demonstrate that places with lower slopes have a greater correlation with water availability, while in situations with higher slopes, this relationship has less effect due to increased runoff in the higher parts (Moore et al., 1993). In order to assess the pedomorphogeological relationships and the distribution of soils in the landscape, the study developed by Lacerda; Barbosa (2012) identified the occurrence of Cambisolos in the steepest positions (>45%), while in areas with flat slopes (0-2%), hydromorphic soils predominate.

In the study conducted by Gomes et al. (2019), the authors evaluated different environmental variables to predict carbon stocks in soils of Brazil and slope was used as a predictor variable in all evaluated layers. In the topographic attributes evaluated by Chagas et al. (2013) the slope was also an effective variable to distinguish Argissols in the State of Rio de Janeiro. In the study developed by Sirtoli et al. (2008) to evaluate relief attributes and their relationships with soils, the authors concluded that slope was the attribute that presented the best relationship with the soil units.

Soils with hydromorphic character occur predominantly in a slope of less than 3%, Latossols on slopes of up to 8% and Cambisols preferably on slopes of up to 20%. The conclusions obtained by Silva et al. (2005) confirm the strong negative correlation between slope and soil organic carbon content. Under conditions of higher slopes, there is a reduction in organic carbon contents, which agrees with the results observed in the present study.

It is possible to observe the occurrence of IC (Figure 5) in places with TWI up to 9.77 (moderately drained) while CH and Organosols (OOs cambisolic and OOs lytic) are found in environments with TWI above 12.33 (poorly drained).

Figure 5 – Boxplot of TWI categorized by soil, in the environments where soils with high organic carbon occur in Southern Brazil



Source: Authors (2023)

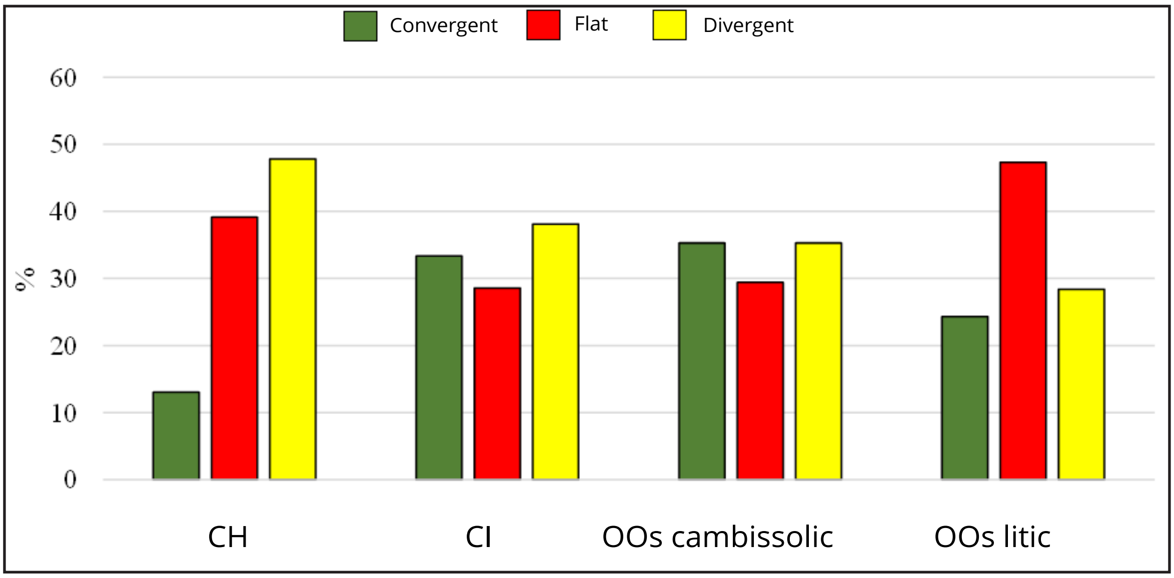
The distribution of water in landscapes has a significantly impact on soil organic carbon dynamics (Gessler et al., 2000). In higher areas, moisture conditions are influenced by soil depth, structural degree and permeability (Lin et al. 2006). In high-altitude environments with a cold climate (Cfb), the orographic effect contributes to maintaining high levels of humidity and the constant presence of cloud cover, as demonstrated by the observed difference in the TWI (Figure 5). The results obtained support the findings of Pei et al. (2010) that the TWI index had the strongest correlation with topographic attributes and organic matter for mapping purposes in Heilongjiang Province in China.

Li et al. (2017) evaluated seven quantitative terrain indices to develop an approximate model for predicting the spatial pattern of soils in a simple, acceptable, effective and low-cost way. Among these indices, elevation, orientation, relative slope position and TWI were identified as the most important variables in the model.

Kokulan et al. (2018) conducted a study to investigate the relationship between relief-related variables and physical-chemical parameters. The authors found that elevation and relative slope position were the most significant variables in explaining the spatial variability of the physical and chemical parameters evaluated. Additionally, the study found that variables such as TWI, plan and profile curvatures were also correlated with physical-chemical parameters.

The environments of CH and OOs lithic occurrence showed greater differences in horizontal curvatures (Figure 6). No preferential classes of horizontal curvature were identified among the evaluated OOs cambisololic, as observed in areas where CI predominates. This soil was found to occur in areas with divergent (35%), convergent (35%) and planar (30%) reliefs.

Figure 6 – Frequency of distribution (%) of horizontal curvature classes (Convergent, planar and divergent), categorized by soil, in the environments where soils with high organic carbon occur in Southern Brazil

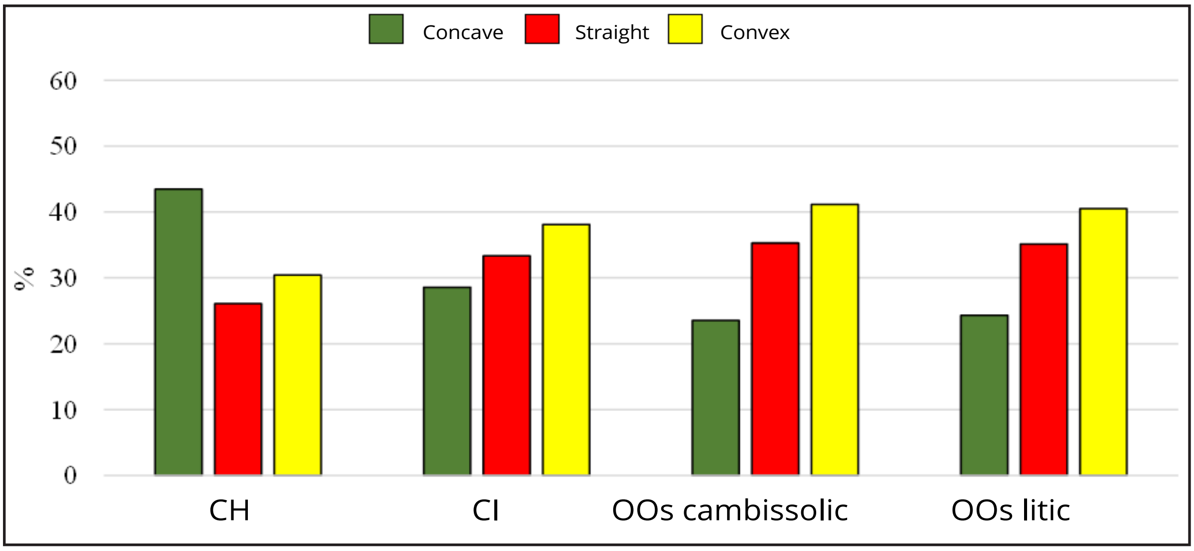


Source: Authors (2023)

The places where CHs occur show the greatest differences between the soils, with a preferential for environments with concave (44%), convex (30%) and straight (26%) profiles curvature (Figure 7). The environments where CI, OOs cambisolic and

OOs lithic occur share similar characteristics in terms of profile curvature, with a higher proportion of convex curvatures and a lower proportion of concave curvatures.

Figure 7 – Frequency of distribution (%) of vertical curvature classes (Concave, straight and convex), categorized by soil, in the environments where soils with high organic carbon occur in Southern Brazil



Source: Authors (2023)

As explained by Vidal-Torrado et al. (2005), relief forms have a significant influence on water dynamics, which affects the pedogenetic processes and consequently leads to the formation of soils with different characteristics. In conditions of concave reliefs, the flow and transport of particles reach higher speeds, with enough energy to displace surface particles from the soil to lower points of the landscape (Vidal; Silva Neto, 2020). Under convex curvature conditions, the flow and dispersion processes of particles and sediments are intensified, which limits the development of the surface horizon in these soils (Montanari et al., 2005). Another factor that contributes to the low proportion of OO lithic in concave and straight curvature profiles is due to the increased infiltration under these conditions, which favors the development of thicker surface horizons (Gessler et al., 2000; Kokulan et al., 2018).

According to Menezes et al. (2016), the highest organic carbon contents were observed in convex relief situations. This reflects the combination of increased weathering, low natural fertility, low temperatures and limited activity of microorganisms. These factors may have contributed to the greater accumulation of organic carbon in this position of the landscape.

In the evaluation of soils that occur in the altomontane fields of Paraná, soils with thicker histic horizons predominate in places with convex-divergent curvature, with emphasis on Fibric Folic Organosols and Sapric Folic Organosols. Under conditions of strong undulating relief and concave-converging curvatures, the formation of mineral horizons is favored through the combined action of morphogenetic (colluvium) and pedogenetic processes (Scheer et al., 2011).

4 CONCLUSIONS

The altimetry values of the environments where Organosols occur are higher then those where CH and CI predominate in southern Brazil. Variations in the maximum slope values were observed between the environments of occurrence of the Organosols and Cambisols. However, among the Organosols evaluated, the values of mean slopes and preferential occurrence interval were similar.

In areas dominated by OOs cambisolic, the preferential range of TWI showed the greatest variation. Moreover, the range of variation in the index was higher in environments where CIs occur, compared to those where CH predominates.

The plan and profile curvature classes did not show any significant differences in distinguishing between the environments where the evaluated soils occur.

The study presented highlights the potential of using environmental variables related to geomorphology, such as elevation, slope and TWI, to characterize and identify soil occurrence environments with high organic carbon contents in southern Brazil. The use of remotely obtained environmental variables reduces the costs associated with collecting data in the field, such as transport vehicles, displacements and labor.

Additionally, it provides information on difficult-to-access environments such as hilltops, lower slope positions and hydromorphic environments.

This approach is a promising alternative to traditional field inventory methods and can account for the spatial and temporal variations of soil properties based on soil information and related environmental variables. With the increasing availability of remote sensing data, this method can be used to map soils of the Brazilian territory in much more detail than the existing methods, contributing to soil governance and management.

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