Revista Brasileira de Ciência do Solo

Division - Soil, Environment and Society | Commission – History, Epistemology and Sociology of Soil Science

Toposequence: What are we talking about?

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ABSTRACT: The term toposequence, proposed to designate a lateral succession of soils on a slope due to the influence of topography, began to be used differently over time, distancing itself from its original concept. Here, we discuss how this concept has been used since its inception. We carried out bibliometric analyses of publications in the database available on the Web of Science since 1900. Three main approaches and related concepts, explicit or not, one at a regional scale and two others at a local scale were identified. From this analysis, we suggest: a) when the approach is regional, the term geomorphic surface or position in the landscape should be used to address the spatial distribution and genetic implications of soils at this scale; b) when dealing with series/sequences of soils on slopes for mapping purposes or discontinuous profiles that emphasize taxonomic classification, the term catena should be used; c) when the determining factor of the soil sequence is climatic, biotic, lithological, chronological, the corresponding term climo-, bio-, litho- or chronosequence should be used; d) when dealing with a lateral succession of horizons in the continuum on slopes, resulting from the influence of topography on soil formation, which may reflect the soil contribution to the model evolution, only in this case should the term toposequence be used, returning to its original concept.

Keywords: soil sequence, geomorphic surface, catena, soil structural analysis, topography.

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Received: November 04, 2023

Approved: February 05, 2024

How to cite: Alves GB, Oliveira FS, Silva AHN, Souza Junior VS. Toposequence: What are we talking about? Rev Bras Cienc Solo. 2024;48:e0230137. https://doi.org/10.36783/18069657rbcs20230137

Editors: José Miguel Reichert and Déborah de Oliveira.

INTRODUCTION

The importance of topography in soil formation and differentiation was recognized even before the systematization of pedology as a modern science. Around 62 ethnopedological soil classification systems use topography as one of the key criteria (Barrera-Bassols and Zinck, 2003), many of them practiced by indigenous groups in times before the 19th century, which highlights the importance of soil position in the landscape (Krasilnikov and Tabor, 2003). Dokuchaev (1893) created the first scientific notation on the relief role in pedogenesis when he postulated soil was much more than a simple weathered geological material, as admitted until then from an agrogeology perspective (Legros, 2011). Dokuchaev's studies on the Chernozem of the Russian steppes represent a historic milestone for Pedology (Espindola, 2010). Later, relief role was reaffirmed in the systematization of the soil formation function proposed by Jenny (1941), which is strongly inspired by the work developed by Russian pedology.

Besides Dokuchaev and Jenny, a study was conducted that specifically highlighted the role of relief in the formation and distribution of soils. This study was carried out by Milne (1935a) and defended the existence of a regular succession of soil profiles in association with a certain slope topography, a phenomenon that should be highlighted through a specific concept, proposing the term catena. As initially proposed by the author, catena has become a concept widely used in soil surveys, with two types recognized: i) a catena where the soil source material is uniform and ii) a catena in which the materials of origin are different. In both cases, differences between soils result from the lateral movement of materials, both on the surface and in the subsurface, mainly through the erosion-sedimentation process.

Milne's ideas and concept of catena influenced the subsequent generation of researchers, especially those in tropical regions (Vidal-Torrado et al., 2005). Borden et al. (2020) highlighted that the concept was quickly assimilated by pedology and other areas of knowledge, such as ecology, in several places around the world, which led to changes in its original definition or even to the proposition of different types, being more coherent to talk about "catenas" nowadays.

Among the studies that most influenced changes in the catena concept are those proposed by Bushnell (1943) with the collaboration of Milne, who applied it in soil surveys in Indiana-USA, and by Greene (1946, 1947) studying the genesis of soils in sub-Saharan Africa, including Sudan and South Africa. Bushnell (1943) suggested the use of catena as a taxonomic unit, including series of soils with similar characteristics due to climate and vegetational factors, and lateral variations of original material, but which differ in relation to drainage and relief conditions. In turn, Greene (1946, 1947) demonstrated the connection between different soils along sequences is the result of water movement and that material transport did not occur only vertically, but also laterally, which was later a determining factor in the recognition of the importance of the pedogenetic role in the balance between evapotranspiration, surface runoff, lateral subsurface flow, and vertical percolation.

Diffusion and modifications of catena concept led to the proposition of new terms, among which the term toposequence stands out. According to Hall (1983), its bases can be found in Bushnell (1943) through the term topographic-denudational-hydrologic sequence. However, its pioneering use appears to be in Jenny (1946), as the author proposed the terms toposequence, lithosequence, climosequence, biosequence, and chronosequence were used to recognize soil series organized in response, respectively, to the topographic formation factors, source material, climate, organisms, and time. In fact, the term toposequence has become widely used in the United States, alternately with catena, to designate soils genetically linked along topography (Winters, 1949). Toposequence concept was also adopted in studies carried out in Africa by the French at the end of the 1950s (Bocquier et al., 1959; Vieillefon, 1959), receiving a definition that was not exactly the one adopted by pedologists in England and the United States. This definition supported the proposal of specific methodologies to study soils, such as those systematized around 30 years later by Boulet et al. (1982a,b,c). Thus, similar to the concept of catena, toposequence has spread as an imprecise term, with multiple conceptual and methodological approaches, which is why it has been used in different ways until nowadays, although it has kept the meaning of lateral succession of soils in topography in common.

The use of the term toposequence occurs mainly in studies on the relationship between soil and landscape, soil and relief, but also in studies on genesis, characterization, survey, and classification of soils, and in some cases, on management and conservation. The lack of conceptual clarification on the term motivated this bibliometric research to understand its use over time and systematize how the term toposequence has been used from a theoretical, methodological, and operational viewpoint. This study presents considerations for the most appropriate use of the term toposequence and how some of its definitions could be replaced by more appropriate concepts equally established in the literature.

MATERIALS AND METHODS

Toposequence concept has been used in the scientific literature with different meanings, which hinders its understanding and the use of appropriate methodology for each scale of treatment intended in the studies. In this study, we sought to identify the most used approaches, the studies that coined the term and gave it new meanings, according to the survey scale, and quantify the different approaches through a bibliometric analysis. We started with the first publications on the topic, seeking to identify the first authors and how they defined the term, according to the abovementioned approaches. We used Google Scholar and articles that are considered classic and established on the topic.

After defining the object of study and the search terms, we carried out bibliometric searches and data mining for analysis. We considered all databases available on the Web of Science (WOS) platform, namely: Web of Science Core Collection, Current Contents Connect, Derwent Innovations Index, KCI-Korean Journal Database, Preprint Citation Index, and SciELO Citation Index. The time frame of publications was from 1900 to 2022 available on July 3, 2023, on the Capes Periódicos Platform (https://www-periodicos-capes-gov-br) through remote access via CAFe (Federated Academic Community) from the University of São Paulo.

We used the Boolean operators AND, OR, and * to search for publications. We used the following fields for the terms defined for the search: Title, Abstract, and Keywords. The most cited articles on the topic were evaluated based on quantification. Furthermore, we downloaded the results in txt format to analyze trends in the data obtained on the WOS platform to be filtered in the VOSviewer software in version 1.6.16 (Van Eck and Waltman, 2010). In this program, the text file was used to create clouds of words by identifying the terms in titles and abstracts. We considered the fields “title” and “abstract” for binary counting, which considers the presence or absence of words, thus defining the minimum number of occurrences of each term to ensure each cloud presented around 35 terms as a result, considering the most relevant 60 %. This number of terms allows the presentation of a cloud of words with good density and readability. We defined the following terms for the search:

General Search (soil* AND (Toposequence OR toposequences OR Toposequence))

The search generated 1,045 publications with 25,359 terms. We selected the minimum occurrence of 58 times, which corresponded to 60 occurrences and 36 terms, among the 60 % most relevant for constructing the cloud of words. From this search and analysis of the results, we defined a few more terms for a more refined search to identify the different approaches adopted for the term, namely:

1) ***Regional Scale Search*** (soil* AND (Toposequence OR toposequences OR Toposequence) AND (regional OR geomorphic surface OR landscape))

It presented 324 publications with 10,471 terms. We defined the minimum occurrence of 25 times, which corresponded to 57 occurrences and 34 terms, among the 60 % most relevant for constructing the cloud of words.

2) Slope Scale Searches

a) Discontinuous Profiles (soil* AND (Toposequence OR toposequences OR Toposequence) AND (*slope OR pedon OR profile))

It presented 624 publications with 15,472 terms. We defined the minimum occurrence of 38 times, which corresponded to 61 occurrences and 37 terms, among the 60 % most relevant for the construction of the cloud of words.

b) Catena (soil* AND (Toposequence OR toposequences OR Toposequence) AND (catena))

It presented 74 publications with 2,854 terms. We defined the minimum occurrence of 5 times, which corresponded to 61 occurrences and 37 terms, among the 60 % most relevant for constructing the cloud of words.

c) Continuum Soils (profiles) (soil* AND (Toposequence OR toposequences OR Toposequence) AND (continuum OR Lateral OR Structural analysis OR Soil cover))

It presented 215 publications with 7,358 terms. We defined the minimum occurrence of 13 times, which corresponded to 65 occurrences and 39 terms, among the 60 % most relevant for constructing the cloud of words.

The graphs were generated in Excel version 2305 software through Microsoft 365. These graphs, along with the clouds of words, were evaluated. We also considered the analysis of classic articles, the most cited among those available in the database, and those published between 2019-2023. This entire analysis provided an analytical overview of how the term toposequence has been used and the approaches that have been adopted.

RESULTS AND DISCUSSION

The term toposequence was proposed by Jenny (1946) and appears in 1,045 publications in the WOS database. The results show a significant increase in publications on the subject from 1990 onwards (Figure 1), and the number of citations was intensified in the following decade, reflecting the generality the term toposequence has acquired over time.

Studies present different approaches to the term toposequence and have been published mainly by Brazilian (22.6 %), American (21.6 %), and French (10.7 %, with 112 publications) researchers (Figure 2). These approaches differ, especially in relation to the concept of toposequence adopted and the soil analysis methodology used concerning landforms.

The approach in the United States is centered on relief influence on soil attributes, using topographic information to model the thickness of horizons, organic matter, and pH, among others (Moore et al., 1993). In this sense, toposequence can also appear under the name catena (Gessler et al., 1995; Flynn et al., 2019; Acree et al., 2020; Chipomho et al., 2020). Toposequence can also be used as a unit of analysis for different elements (McGill and Cole, 1981); thus, soils are considered in different positions on the slope and can be used for different studies, such as evaluation of nutrient distribution and ecosystems (Giblin et al., 1991; Fisk et al., 1998; Stieglitz et al., 2003; Vitousek et al., 2003; Ajiboye et al., 2019; Silva et al., 2019), or soil microbial communities

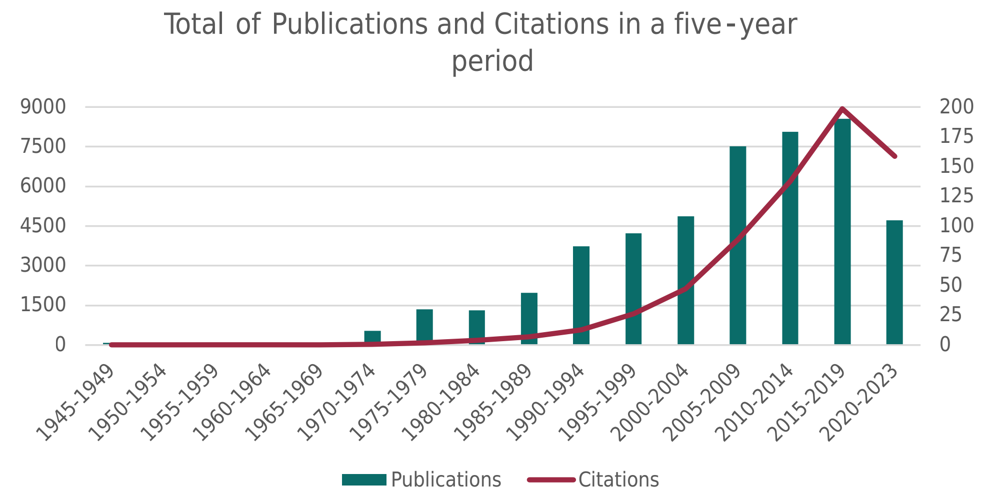

Figure 1. Publications and citations with the term toposequence for five years from 1945 to 2023. Base: WOS, 2023.

(Rogers and Tate, 2001). Some examples regard studies that use toposequences for soil successions associated with different source materials (Schimel et al., 1985; Aguilar et al., 1988), or different relief compartments (Yonker et al., 1988; Flynn et al., 2019).

In France, studies correlating toposequence with mineralogy and geochemistry stand out. Toposequence, in some cases, means soils in different positions on the slope, in which water circulation plays a preponderant role in the geochemical redistribution of elements (Becquer et al., 2003; Chardot et al., 2007; Prietzel et al., 2007; Guedron et al., 2009; Tano et al., 2020) and mineralogy (Revel and Bourgeat, 1985; Schwertmann and Latham, 1986; Verrecchia and Coustumer, 1996) and may even consider the influence of slope shape and groundwater conditions (Gruau et al., 2004). There are also studies using the term toposequence, but they use different source materials (Becquer et al., 2006; Kübler et al., 2021) or relief and vegetation compartments (Righi and Lorphelin, 1987; Masseroli et al., 2021; Sadiq et al., 2021), or even soil chronosequence (Wojcik et al., 2020).

French school goes further in showing the influence of topography on soils and was the first to highlight the influence of soils on the elaboration of the model (Bocquier, 1971), originating a new approach to toposequence through the Structural Analysis of Pedological Cover (Boulet et al., 1982a,b,c). These studies aimed to discuss the landscape evolution based on the toposequence analyses, which spread from the 1980s onwards, driven by French researchers (Bravard and Righi, 1988, 1989; Fritsch, 1988; Boulet et al., 1998; Dubroeucq and Volkoff, 1998) and later by Brazilians, under the influence of the former. This type of study began to gain prominence after the 1990s, mainly in Brazil (Queiroz Neto, 2012; Nakashima et al., 2017; Castro, 2021), while in France, there was a trend toward research with geochemistry at the landscape scale (Beauvais and Tardy, 1991; Beauvais, 1999; Momo et al., 2016), while research on toposequence started to lose importance, which once moved ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer).

Among the studies abovementioned with researchers from the United States and France, much of the work was carried out in other countries, mainly tropical countries. Tropical regions tend to have soils whose differentiation is primarily due to the influence of topography, as they are mostly well-developed soils subjected to different climate conditions over time, homogenizing the soil characteristics and distancing them from the source material (Silva et al., 2021a), except for areas with a semi-arid climate, where relief rejuvenation led to the development of new soils, more correlated to the original material (Alves, 2019; Câmara et al., 2021; Silva et al., 2021a).

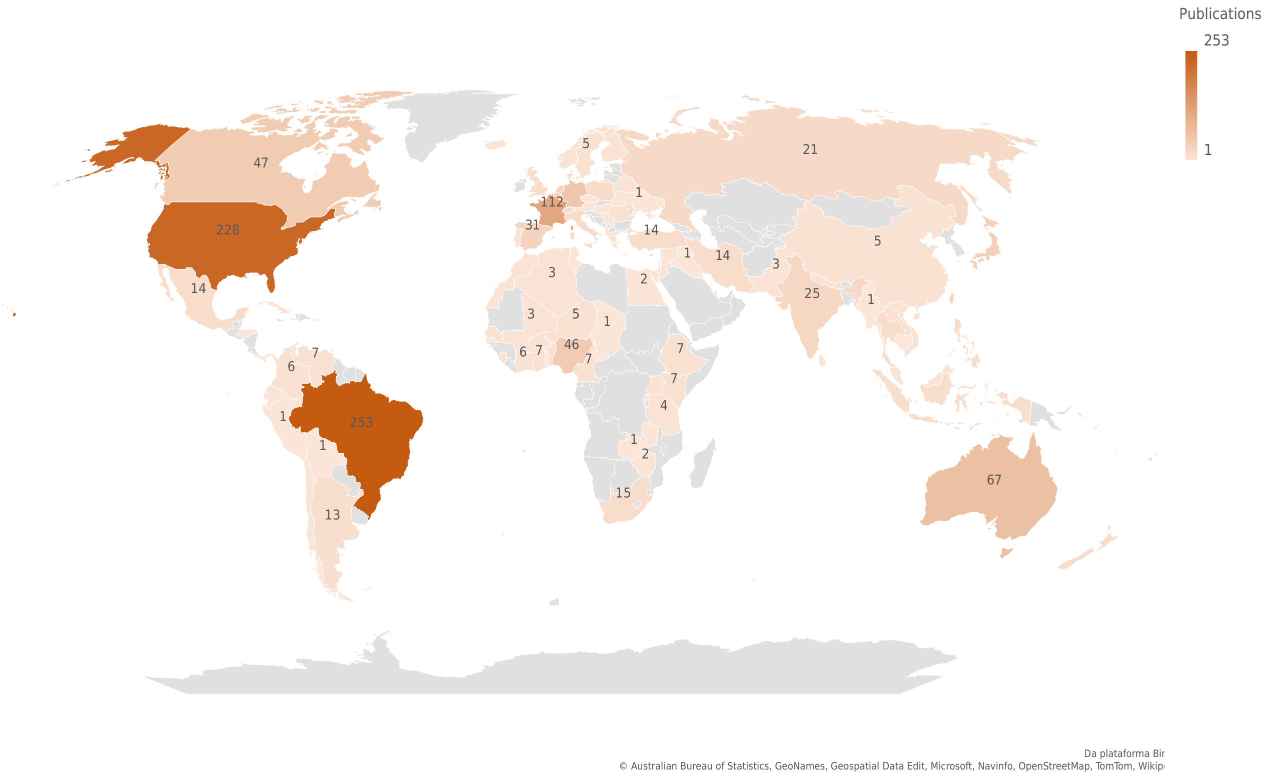

Figure 2. Publications that used the term toposequence by countries of authors and co-authors. In gray, countries without authorship or co-authorship of publications in the Web of Science database. Base: WOS, 2023.

We found the term toposequence used by Brazilian researchers tends to be used for studies carried out in the Brazilian territory, as we can see in the articles cited below. We also highlight Brazil has emerged as a leader in producing articles on this topic in recent years (Figure 3). Brazil received scientific influence from both the United States and France regarding the use of the term toposequence; however, it also created its own trajectory, given the extension and peculiarity of the national territory. In Brazil, as in the countries mentioned above, toposequence can only be used to indicate soil profiles are arranged in different slope compartments with attributes that respond to these positions (Curi and Franzmeier, 1984, 1987; Sobieraj et al., 2002; Araújo et al., 2004; Ghidin et al., 2006; Sarcinelli et al., 2009; Schiavo et al., 2010; Lopes et al., 2019). This type of study is also used to refine digital soil mapping (Demattê and Terra, 2014; Mendes et al., 2019; Poppiel et al., 2019). Some authors used the term toposequence to work on large areas (Reatto et al., 2008) and with materials of different biological origins and occupations (Demattê et al., 2004; Michel et al., 2006), or even to identify the influence of soil uses in properties (Pinheiro Junior et al., 2019; Vanacker et al., 2019). We can also recognize the line of studies on landscape evolution through soils (Roulet et al., 1998; Nascimento et al., 2004; Furquim et al., 2017).

Considering studies using toposequence, the associated terms that mostly stand out can be divided into three clusters (Figure 4). The most frequently occurring terms are in red: formation factors, increase, difference, organic carbon, erosion, vegetation, and relationship. The second cluster, in green, shows a relationship with processes such as weathering, genesis, chemistry, development, and formation. The third cluster, in blue, presents only the low slope and top.

In general, three large groups of articles can be recognized. Those treating toposequence at a regional level or those in which the variation that stands out is associated with another landscape element, such as source material or vegetation, although they use the term toposequence. Those using toposequence to refer to profiles located in different positions

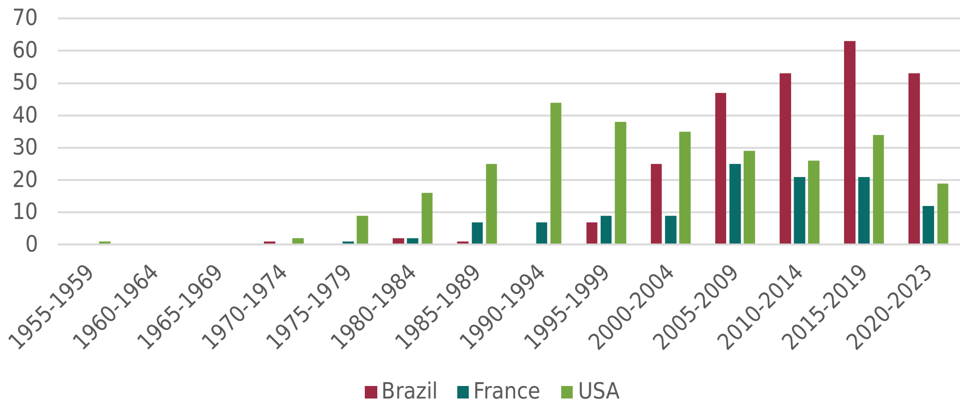

Figure 3. Articles with the term toposequence published by Brazilian, French, and American authors for a five-year period from 1955 to 2023. Base: WOS, 2023.

on the slope, in a discontinuous manner, or as a synonym for catena. There are also studies on toposequence that consider soils as a continuum and their lateral variation, in addition to their influence on the elaboration of the model. In general, we can correlate the red and blue clusters with the regional and slope/catena level approaches and the green cluster with the ground-level approach to understand landscape evolution. In the following sessions, we will detail these three approaches to contextualize the definition and the main studies according to the refinement of the searches.

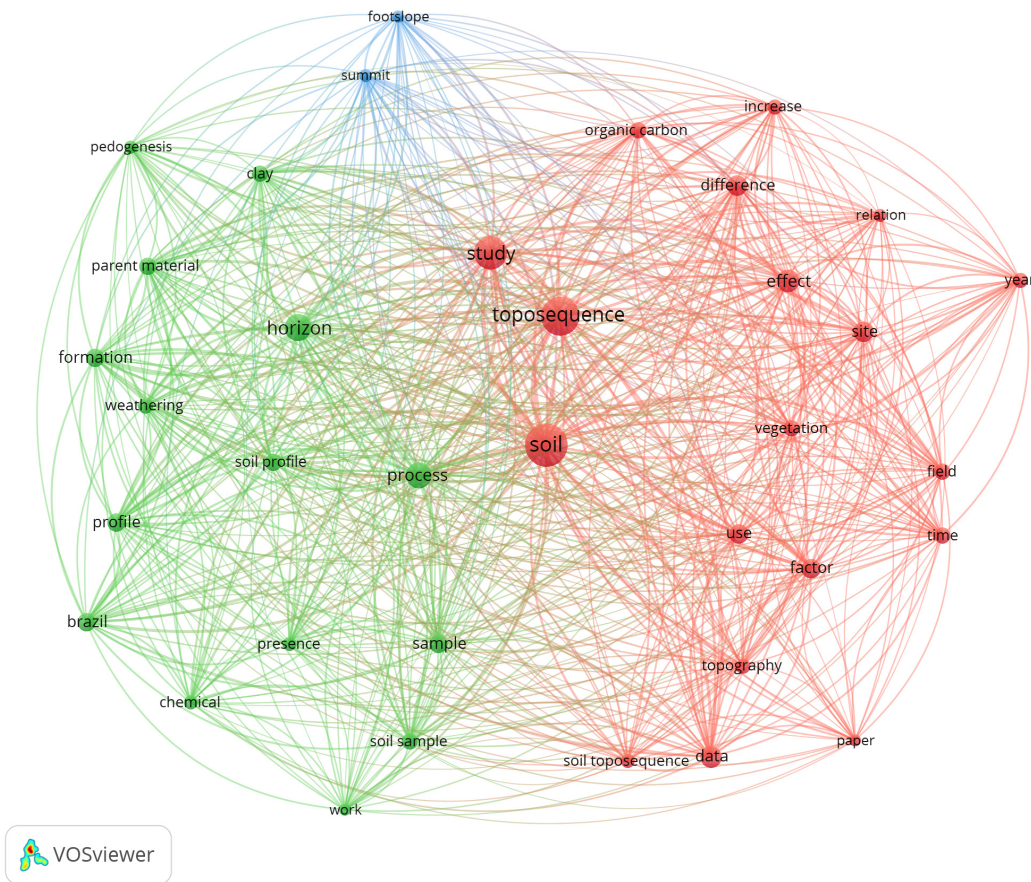

Figure 4. Articles with the term toposequence published by Brazilian, French, and American authors for a five-year period from 1955 to 2023. Base: WOS, 2023.

Toposequence as a variation of soils in distinct positions of the regional relief

Toposequence concept is related to an approach not restricted to the slope scale, but it considers any soil variation along the topography on a regional scale. In this concept, toposequence may involve soils collected along different relief units (Meng et al., 2022), or geomorphic surfaces, such as in planation surfaces and the top of plateaus (Zhu et al., 2019; Wang et al., 2021), or even in segments from the base to the top of mountain ranges (Molina et al., 2019), or along coastal strips (Fragoso-Servón et al., 2020), ranging from beach areas to coastal plateaus, or between different levels of terraces within a river valley, or even of the different erosion surfaces (Blancaneaux et al., 2007). This concept is often used as a guideline for sampling soils over large areas, with less interest in understanding the genetic relationship between the soils collected (Wang et al., 2021); thus, it is widely applied in exploratory scales in regional soil surveys. When the objective is to understand soil genesis, a relationship is usually made between the soils and the relief unit where they were sampled, including the adoption of paradigms, such as more developed and deeper soils are associated with higher and flatter reliefs, while shallower soils are associated to steeper areas, and so on. This concept gives rise to a series of assumptions about the relationship between soil and relief.

From a regional perspective, toposequence can also consider the distribution of soils throughout landscape units, approached as landscape segments, associating one or more soil types with a certain compartment since its definition typically had a significant landform influence, although not exclusive. Thus, the presence of certain soils is explained by factors acting in the landscape position, while some other components, such as vegetation, are explained by the presence of those soils in a systemic and solidary relationship (Queiroz Neto, 2000, 2012).

The search refinement for publications that used the term toposequence associated with other terms indicated in the methodology of the present study presents different configurations of words clouds. At regional scale, the importance of the terms landscape position, area, topography, or positions therein, in addition to profiles and horizons, is evident (Figure 5).

The approach to soil distribution in the landscape from a regional scale needs a deeper discussion to distinguish literature reports better, as the use mainly of a catenary approach is observed, and the term toposequence is used in some situations to explain or model the distribution of soils on a regional scale. In this context, we highlight studies on the distribution of soils in the Amazon basin (Quesada et al., 2011), using a taxonomic approach carried out in Brazil and neighboring countries. Roulet et al. (1998) address the regional geochemical distribution of mercury along a stretch of the Tapajós River in the Amazon region using a regional scale. Güntner and Bronstert (2004) present, in a semi-arid environment in Brazil, a way of structuring the landscape according to the terrain and soil attributes at different levels of the spatial scale, recognizing the occurrence of specific terrain and soil relationships that evolve through physical and biological processes.

In the United States, many studies seek to understand soil distribution on a regional scale, and studies addressing the application of the catena concept prevail, which are summarized in studies of a catenary soil distribution approach (Walker and Everett, 1991; Moore et al., 1993; Thompson et al., 1997; Gessler et al., 2000; Stieglitz et al., 2003) to be discussed in more detail below.

Toposequence used as a catena

Similar to catena, toposequence is used as a simple lateral variation of soil classes, taxonomically differentiated or not, associated with certain positions on a slope. In this concept, soil profile is mainly used as an analysis category, and the vertical organization

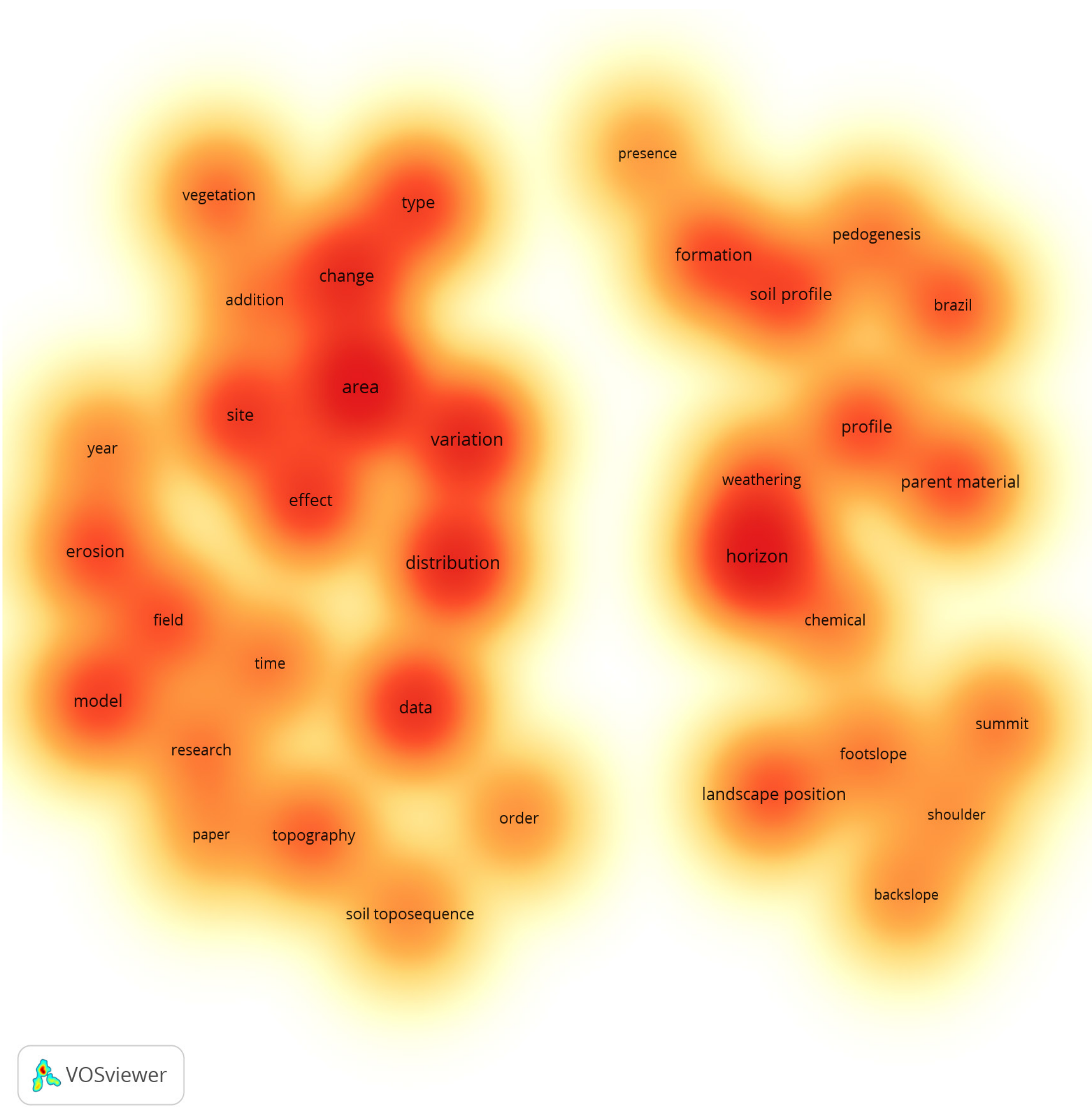

Figure 5. Terms with the highest recurrence that are associated with toposequence and regional level, according to the Web of Science database, and association by cluster according to bibliometric treatment in VOSviewer (Van Eck and Waltman, 2010).

of the horizons and their morphological, physical, chemical, and mineralogical attributes are used to define classes. The relationship between the soils occurs spatially and is associated with the vegetation cover and specific topographic compartments of the slope. This, in turn, is compartmentalized into units with different proposals (geomorphic surfaces, segments, and others), but almost always considering the top, mid-slope, and base positions (Borden et al., 2020). Sometimes, a genetic relationship can also be established between the soils, which are linked through processes associated with material movement along the slope due to erosion and sedimentation, as reported by Milne (1935a).

Studies using isolated slope profiles consider toposequence as a synonym for catena, generally in the United States, aimed at identifying soils along slopes and for the distribution of soils in the landscape (Figure 6). In this sense, denominations of positions in the landscape/topography, horizon, and profile also stand out.

Toposequence concept presented here is close to the original concept of catena proposed by Milne and can be considered one of its derivations, although they are not synonymous. The first difference is that Milne did not establish the need for material of similar origin for the existence of a catena. On the contrary, the author recognized the possibility

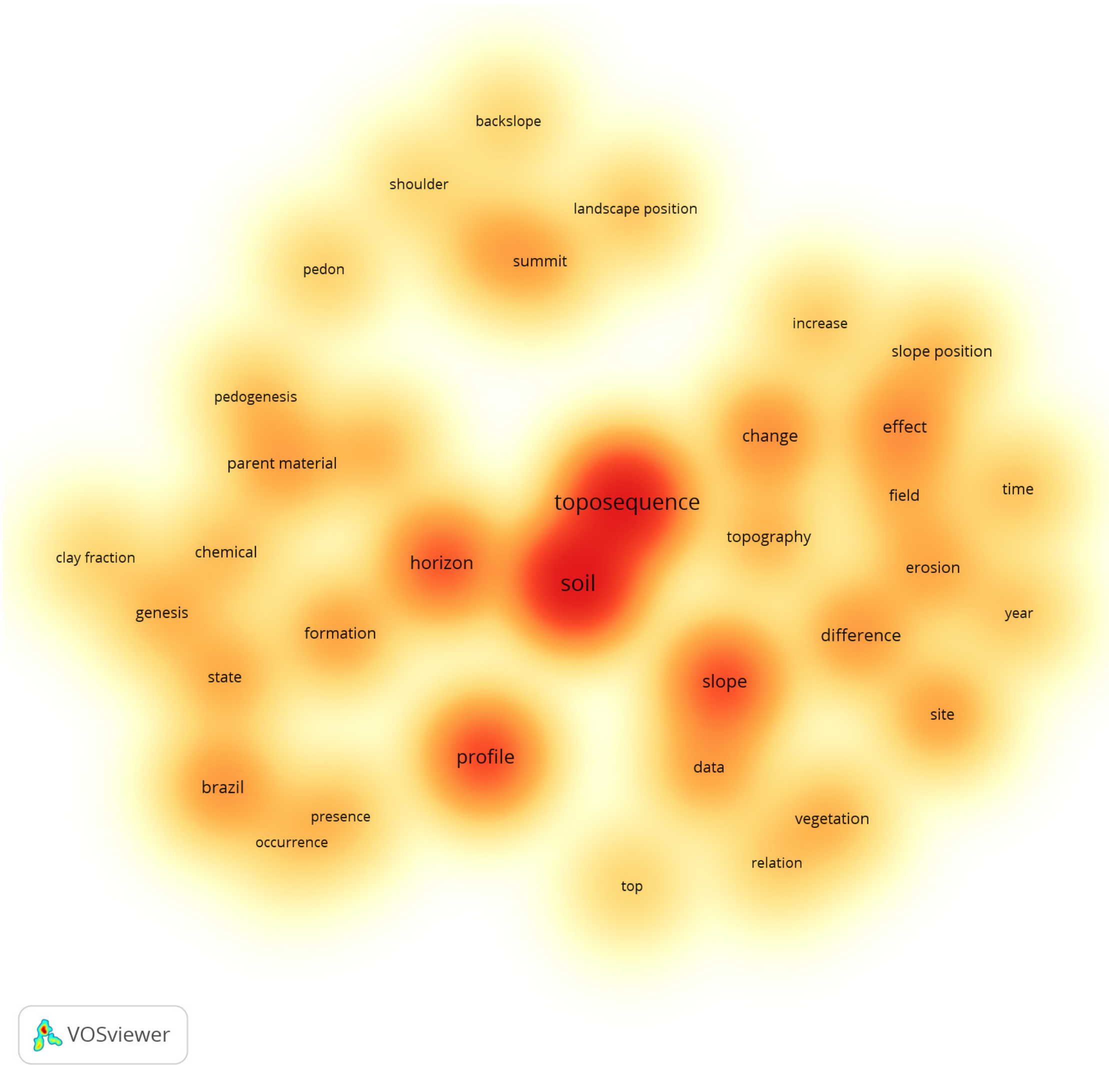

Figure 6. Terms with the highest recurrence that are associated to toposequence and slope level in discontinuous profiles, according to the Web of Science database, and association by cluster according to the bibliometric treatment in VOSviewer (Van Eck and Waltman, 2010).

of topography controlling soil formation even in conditions involving different source materials. However, the toposequence of this concept does not require recognizing the relief role in soils associated with similar source materials. This premise was strongly defended by researchers in the United States, which possibly led some to use the term toposequence and others to propose the approach as a catenary system (Bushnell, 1943), or systems of associated catenas (Figure 7). Furthermore, catenas are strongly adopted in soil mapping as well as in the initial proposal by Milne (1935a,b). Sommer and Schlichting (1997) consider catena synonymous with toposequence and propose types of catenas that take into account transformations, losses, and accumulations on slopes to differentiate them, helping to understand soils in the landscape.

According to our bibliographical survey, the use of the term catena seems to be negligible in Europe, possibly due to the ambiguity in the use of the terms catena and toposequence. The distribution of soils along slopes approached based on catena has been applied in pedogenesis studies to evaluate vertical and horizontal translocation of material involved in the podzolization (Sauer et al., 2007) and pedogenetic processes and mineral transformations (Bonifacio et al., 1997; Bócoli et al., 2023). This approach integrates slope gradient, elevation, and relative position of the soil in the landscape in a catenary sequence to predict soil thickness at a river basin scale (Catani et al., 2010; Armanto, 2019).

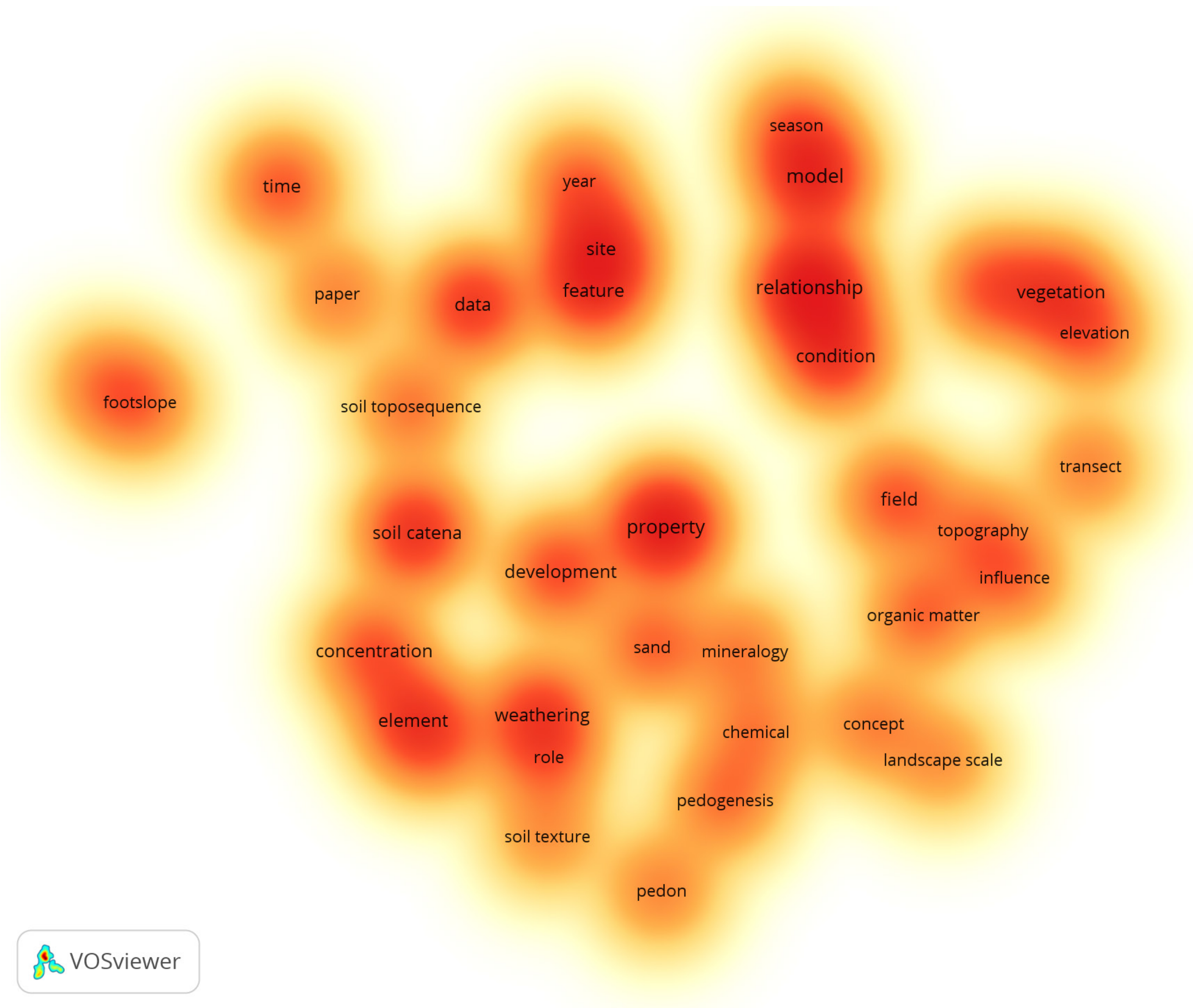

Figure 7. Terms with the highest recurrence that are associated with toposequence and catena, according to the Web of Science database, and association by cluster according to bibliometric treatment in VOSviewer (Van Eck and Waltman, 2010).

In short, catena studies sometimes deal with soils in the landscape or sometimes on the slope (Figure 7). Soil distribution throughout the landscape is used in various research on pedology, soil physics, ecology, plant production, nutrient cycling, among others. In this sense, we can mention the assessment of soil texture variation throughout the landscape and its influence on soil water retention, distribution of vegetation groups, and agricultural yield (Singh et al., 1998), or even resulting from agricultural practices (Sowiński et al., 2023). Regarding homogeneous lithology, soil development in a catena is recurrently presented as a product of how water moves across the landscape since terrain attributes can characterize the water flow routes and soil attributes (Moore et al., 1993; Howlett et al., 2022).

Catena is also used to discuss soil and landscape relationships in research on carbon dynamics at regional and global levels (Gessler et al., 2000; Stieglitz et al., 2003; Howlett et al., 2022), in addition to research on soil variation in floodplains, linked to variations in terrain attributes (Thompson et al., 1997). In Brazil, there is also ambiguity in the definition of catena and toposequence (Sobieraj et al., 2002; Santos et al., 2018), which use both terms to study soil attributes along different topographic positions in the landscape.

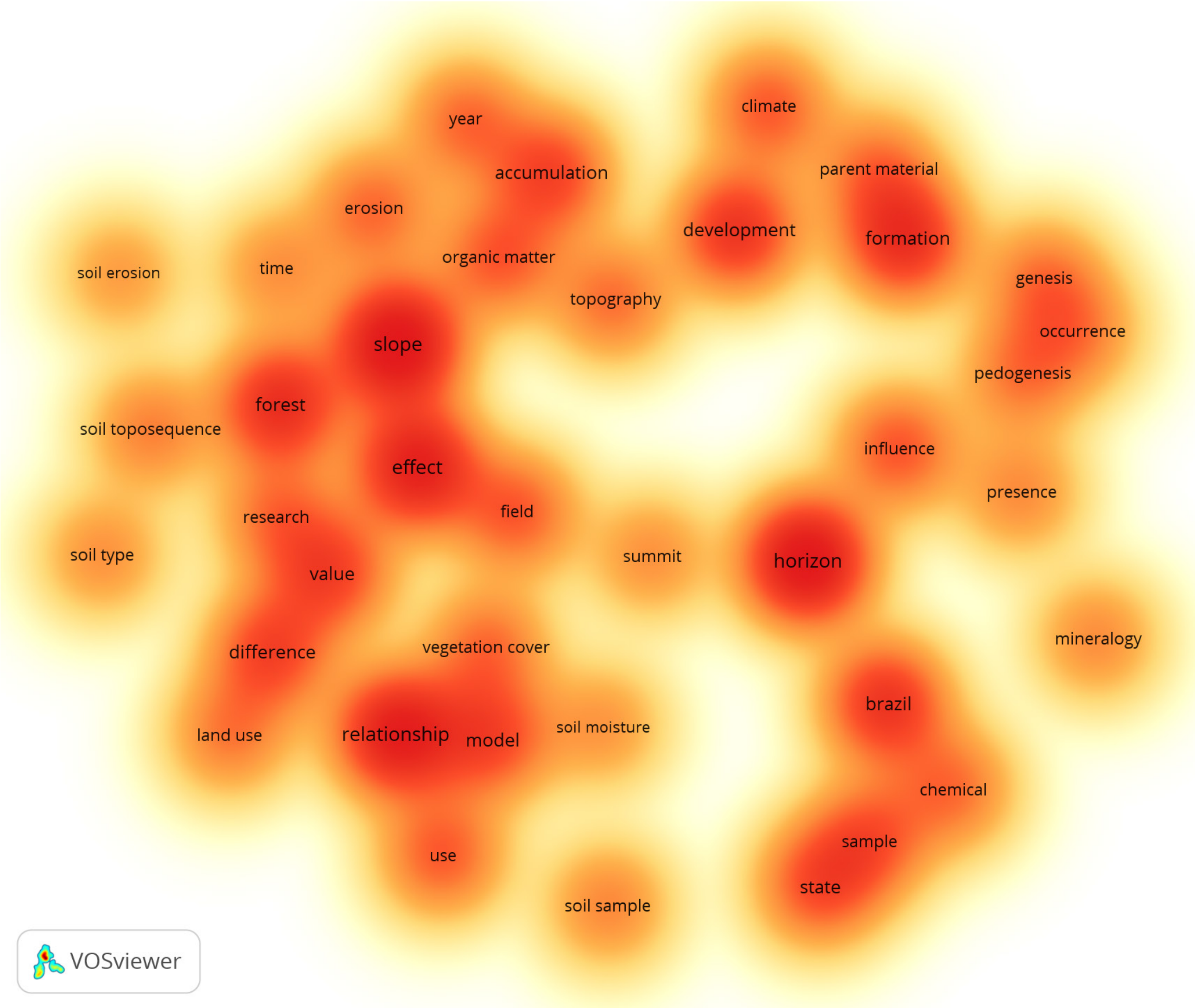

Figure 8. Terms with the highest recurrence that are associated with toposequence and the continuum, according to the Web of Science database, and association by cluster according to the bibliometric treatment in VOSviewer (Van Eck and Waltman, 2010).

Toposequence as pedological cover in the continuum along the slope

Toposequence is also approached as a product of pedological cover organization along the slope, considering the lateral distribution of horizons or pedological volumes (Figure 8). Boulet et al. (1982a) define toposequence as a longitudinal section of soils, that is, along the interfluves (from top to bottom of the valley), obtained through observation of vertical profiles of soils aligned on the topographic axis perpendicular to the contour lines, whose representation occurs on the continuum. This definition positions toposequence as a concept applied to the local distribution of pedological organizations in which lateral variations are linked to three main components: topography, slope shape, and position on the slope (Ruellan and Dosso, 1993). This concept is widely used in studies by French pedologists in tropical areas of the African and American continents, especially since the 1960s and 1970s.

Toposequence as the continuum of pedological cover has its origins associated with surface geochemistry studies in which several authors showed pedological variations along slopes are associated with the movement dynamics of matter and energy over time in side (lateral) transformation systems. This understanding dates back to the Soviet school of pedology, where Polynov excelled in describing in detail the migration relationships of elements and patterns in several important types of geochemical landscapes (Fortescue, 1992). However, geochemical landscapes kept a compartmentalized and vertical view of the landscape, later understanding geochemical relationships laterally on topography and after being associated with the regional evolution of landforms (Millot, 1977).

Delvigne (1965), for instance, showed the top positions export constituents and accumulate less mobile residual constituents, the intermediate positions are passing zones, and the foothills are receiving zones. They can involve mineral neoformation based on the availability and recombination of constituents in this environment. This and other studies supported Bocquier (1971) in proposing the biogeodynamic theory, which demonstrates the soil is a dynamic environment from which transformations occur on remounting fronts and with a strong participation of self-development mechanisms.

Several studies strengthened this interpretation of the lateral mobility of constituents (Millot, 1977) and the toposequence concept (Chauvel, 1977; Boulet, 1978), until Boulet and other authors systematized the procedure to investigate pedological cover based on its lateral representation in a continuum, known as the Structural Analysis of Pedological Cover (Boulet et al., 1982a,b,c). This approach goes beyond the idea of topography as a soil formation factor to the concept soil evolution and topography are joint, and soils are able to act as sculpting agents of forms at the slope scale (Queiroz Neto, 2012). The terms with the most recurrence confirm the prominence of research carried out in Brazil, in addition to the importance of relationships, variations, accumulation, development, and formation, which act on horizons and slopes, with the influence of water and climate, allowing pedogenesis to be observed.

We observed the importance of studies investigating soil evolution and relief (Dubroeucq and Volkoff, 1998; Rosolen and Herpin, 2008; Alves, 2014; Cerri et al., 2020; Masseroli et al., 2021), with emphasis on the dynamics of chemical weathering (Moniz et al., 1982; Vanacker et al., 2019) and the formation of horizons with contents of certain elements (Norton and Franzmeier, 1978; Dequincey et al., 2006), as well as influence on soil properties (Loba et al., 2020; Silva et al., 2021b). Some studies associate soil observation as a continuum with applied research to improve crops (Moormann et al., 1977) or even how pedogenesis influences the availability of chemical elements on water flux (Roulet et al., 1998).

CONCLUSIONS

Different approaches used for the term toposequence are related to the theoretical and methodological line, mainly regarding the soil concept used by the authors over time. In the analyzed studies, few authors discuss the origin and meaning of the term toposequence, which can be grouped into three main approaches: (i) Regional: discusses soil in the landscape, whose classes are distributed and spatially associated with different geomorphological compartments, geomorphic surfaces, or even different source materials and ecosystems; (ii) Catenary: considers lateral soil sequences as keys to mapping units to identify the limits between soil classes or pedological mapping indicators or differentiate soils based on some taxonomic classification, indicating changes in attributes along the slope or landscape; and (iii) Continuum: treats the soil as a pedological cover where the horizons can change along the slope under the influence of topography and subsequent water flows that condition the pedological processes, which, in turn, can even influence the modification of forms thus marking the coevolution of soil and relief or soil and landscape.

We suggest the use of the term geomorphic surface or position in the landscape in the regional approach. Catena is the most appropriate term for soil series/sequences as indicators of pedological mapping or discontinuous profiles that use taxonomic classification as a highlight. If the soil sequence is biotic, climatic, lithological, or chronological, the most appropriate terms should include the corresponding prefix, bio, climo-, litho- or chronosequence, respectively.

In summary, the term toposequence should be restricted to the approach seeking the morphological and morphodynamic representation of pedological horizons in the continuum on a given slope, which represents a landscape unit. In this sense, the objective of the toposequence study should aim to understand how the lateral succession of soils occurs and to characterize the indicators of its vertical and especially lateral transformation induced by topography or even revealing soil contribution to topography evolution, which are always in coevolution.

ACKNOWLEDGMENTS

The authors thank Professor Selma Simões de Castro for the review and contributions. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001."

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REFERENCES

Acree A, Weindorf DC, Paulette L, Van Gestel N, Chakraborty S, Man T, Jordan C, Prieto JL. Soil classification in Romanian catenas via advanced proximal sensors. Geoderma. 2020;377:114587. https://doi.org/10.1016/j.geoderma.2020.114587

Aguilar R, Kelly EF, Heil RD. Effects of cultivation on soils in Northern Great Plains Rangeland. Soil Sci Soc Am J. 1988;52:1081-5. https://doi.org/10.2136/sssaj1988.03615995005200040034x

Ajiboye GA, Oyetunji CA, Mesele SA, Talbot J. The role of soil mineralogical characteristics in sustainable soil fertility management: A case study of some tropical Alfisols in Nigeria. Commun Soil Sci Plan. 2019;50:333-49. https://doi.org/10.1080/00103624.2018.1563100

Alves GB. A formação das paisagens sertanejas no tempo e no espaço. In: Barros J, Prieto G, Marinho C, editors. Sertão, sertões: Repensando contradições, reconstruindo veredas. São Paulo: Editora Elefante; 2019. p. 98-113.

Alves GB. O estudo da cobertura pedológica e sua relação com a formação e evolução de depressões no sudoeste de Maracaí (SP) [thesis]. São Paulo: Universidade de São Paulo; 2014.

Araújo MSB, Schaefer CER, Sampaio EVSB. Soil phosphorus fractions from toposequences of semi-arid Latosols and Luvisols in northeastern Brazil. Geoderma. 2004;119:309-21. https://doi.org/10.1016/j.geoderma.2003.07.002

Armanto ME. Soil variability and sugarcane (*Saccharum officinarum* L.) biomass along Ultisol toposequences. J Ecol Eng. 2019;20:196-204. https://doi.org/10.12911/22998993/109856

Barrera-Bassols N, Zinck JA. Ethnopedology: A worldwide view on the soil knowledge of local people. Geoderma. 2003;111:171-95. https://doi.org/10.1016/S0016-7061(02)00263-X

Beauvais A. Geochemical balance of lateritization processes and climatic signatures in weathering profiles overlain by ferricretes in Central Africa. Geochim Cosmochim Ac. 1999;63:3939-57. https://doi.org/10.1016/s0016-7037(99)00173-8

Beauvais A, Tardy Y. Degradation features of iron duricrusts under tropical humid climate at the edge of the equatorial rain forest. CR Acad Sci II. 1991;313:1539-45.

Becquer T, Quantin C, Rotte-Capet S, Ghanbaja J, Mustin C, Herbillon AJ. Sources of trace metals in Ferralsols in New Caledonia. Eur J Soil Sci. 2006;57:200-13. https://doi.org/10.1111/j.1365-2389.2005.00730.x

Becquer T, Quantin C, Sicot M, Boudot JP. Chromium availability in ultramafic soils from New Caledonia. Sci Total Environ. 2003;301:251-61. https://doi.org/10.1016/S0048-9697(02)00298-X

Blancaneaux PW, Carvalho Junior PEF, Motta A, Carvalho Filho NR, Pereira C, Chagas S. Sistemas pedológicos no Cerrado de Goiás: Município de Silvânia, região Centro-Oeste do Brasil. Rio de Janeiro: Embrapa Solos; 2007.

Bócoli FA, Silva SHG, Mancini M, Inda AV, Teixeira AFDS, Andrade R, Silva FM, Santos WJRD, Pádua EJ, Curi N. Catena of Ultisols from southeastern Brazil: Assessing variation within and among pedons. Geoderma R. 2023;33:e00653. https://doi.org/10.1016/j.geodrs.2023.e00653

Bocquier G. Genése et évolutuion de deux toposéquences de sols tropicaux du Tchad: interprétation biogéodynamique. Bondy: Cah. ORSTOM; 1971.

Bocquier G, Boissezon P, Kaloga B. Reconnaissance pédologique de la zone de Mifitsinngui dans la boucle du Niari (région du Niari, République du Congo). Brazzaville: ORSTOM; 1959.

Bonifacio E, Zanini E, Boero V, Franchini-Angela M. Pedogenesis in a soil catena on serpentinite in north-western Italy. Geoderma. 1997;75:33-51. https://doi.org/10.1016/S0016-7061(96)00076-6

Borden RW, Baillie IC, Hallett SH. The East African contribution to the formalisation of the soil catena concept. Catena. 2020;185:104291. https://doi.org/10.1016/j.catena.2019.104291

Boulet R. Toposéquences de sols tropicaux en Haute-Volta : Équilibre et déséquilibre pédobioclimatique. Paris: ORSTOM; 1978. (Mémoires ORSTOM, 85).

Boulet R, Chauvel A, Humbel F-XX, Lucas Y. Analyse structurale et Cartographie en pédologie. I - Prise en compte de l'organisation bidimensionnelle de la couverture pédologique: Les études de toposéquences et leurs principaux apports à la connaissance des sols. Cah ORSTOM Pedol. 1982a;XIX:309-21.

Boulet R, Fritsch E, Filizola HF, Filho RFA, Leprun JC, Barreto F, Balan E, Tessier D. Iron bands, fragipans and duripans in the northeastern plateaus of Brazil - properties and genesis. Can J Soil Sci. 1998;78:519-30. https://doi.org/10.4141/S98-030

Boulet R, Humbel F-X, Lucas Y. Analyse structurale et Cartographie en pédologie. III Passage de la phase analytique A une cartographie génerale synthétique. Cah ORSTOM Pedol. 1982b;XIX:341-51.

Boulet R, Humbel F-XX, Lucas Y. Analyse structurale et Cartographie en pédologie. II - Une Méthode d'analyse prennant en compte l'organisation tridimensionnelle des couvertures pédologiques. Cah ORSTOM Pedol. 1982c;XIX:323-39.

Bravard S, Righi D. Geochemical differences in an Oxisol-Spodosol toposequence of Amazonia, Brazil. Geoderma. 1989;44:29-42. https://doi.org/10.1016/0016-7061(89)90004-9

Bravard S, Righi D. Characteristics of clays in an Oxisol - Spodosol toposequence in Amazonia (Brazil). Clay Miner. 1988;23:279-89. https://doi.org/10.1180/claymin.1988.023.3.05

Bushnell TM. Some aspects of the soil catena concept. Soil Sci Soc Am J. 1943;7:466-76. https://doi.org/10.2136/sssaj1943.036159950007000C0079x

Câmara ERG, Santos JCB, Araújo Filho JC, Schulze SMBB, Corrêa MM, Ferreira TO, Sousa JES, Souza Júnior VS. Parent rock–pedogenesis relationship: How the weathering of metamorphic rocks influences the genesis of Planosols and Luvisols under a semiarid climate in NE Brazil. Geoderma. 2021;385:114878. https://doi.org/10.1016/j.geoderma.2020.114878

Castro SS. Solo e relevo: pontos para um resgate histórico sobre o estudo das interrelações. WMD Rev Geomorf. 2021;2:1-36. https://doi.org/10.48025/ISSN2675-6900.v2n1.2021.138

Catani F, Segoni S, Falorni G. An empirical geomorphology-based approach to the spatial prediction of soil thickness at catchment scale. Water Resour Res. 2010;46:W05508. https://doi.org/10.1029/2008WR007450

Cerri RI, Rosolen V, Reis FAGV, Filho AJP, Vemado F, Giordano LC, Gabelini BM. The assessment of soil chemical, physical, and structural properties as landslide predisposing factors in the Serra do Mar mountain range (Caraguatatuba, Brazil). Bull Eng Geol Environ. 2020;79:3307-20. https://doi.org/10.1007/s10064-020-01791-1

Chardot V, Echevarria G, Gury M, Massoura S, Morel JL. Nickel bioavailability in an ultramafic toposequence in the Vosges Mountains (France). Plant Soil. 2007;293:7-21. https://doi.org/10.1007/s11104-007-9261-1

Chauvel A. Recherches sur la transformation des sols ferrallitiques dans la zone tropicale a saisons contrastées: evolution et réorganisation des sols rouges de moyenne Casamance (Sénégal). Paris: ORSTOM; 1977.

Chipomho J, Rugare JT, Mabasa S, Zingore S, Mashingaidze AB, Chikowo R. Short-term impacts of soil nutrient management on maize (*Zea mays* L.) productivity and weed dynamics along a toposequence in Eastern Zimbabwe. Heliyon. 2020;6:e05223. https://doi.org/10.1016/j.heliyon.2020.e05223

Curi N, Franzmeier DP. Effect of parent rocks on chemical and mineralogical properties of some Oxisols in Brazil. Soil Sci Soc Am J. 1987;51:153-8. https://doi.org/10.2136/sssaj1987.03615995005100010033x

Curi N, Franzmeier DP. Toposequence of Oxisols from the Central Plateau of Brazil. Soil Sci Soc Am J. 1984;48:341-6. https://doi.org/10.2136/sssaj1984.03615995004800020024x

Delvigne J. Pédogenèse en zone tropicale: La formation des minéraux secondaires en milieu ferrallitique. Paris: Dunod; 1965.

Demattê JAM, Campos RC, Alves MC, Fiorio PR, Nanni MR. Visible-NIR reflectance: A new approach on soil evaluation. Geoderma. 2004;121:95-112. https://doi.org/10.1016/j.geoderma.2003.09.012

Demattê JAM, Terra FS. Spectral pedology: A new perspective on evaluation of soils along pedogenetic alterations. Geoderma. 2014;217-218:190-200. https://doi.org/10.1016/j.geoderma.2013.11.012

Dequincey O, Chabaux F, Leprun JC, Paquet H, Clauer N, Larque P. Lanthanide and trace element mobilization in a lateritic toposequence: Inferences from the Kaya laterite in Burkina Faso. Eur J Soil Sci. 2006;57:816-30. https://doi.org/10.1111/j.1365-2389.2005.00773.x

Dokuchaev VV. The Russian steppes: Study of the soil in Russia, its past and present. St Peterburg: Department of Agriculture, Ministry of Crown Domains; 1893.

Dubroeucq D, Volkoff B. From Oxisols to Spodosols and Histosols: Evolution of the soil mantles in the Rio Negro basin (Amazonia). Catena. 1998;32:245-80. https://doi.org/10.1016/S0341-8162(98)00045-9

Espindola CR. A pedologia e a evolução das paisagens. Rev Inst Geológico. 2010;31:67-92. https://doi.org/10.5935/0100-929X.20100005

Fisk MC, Schmidt SK, Seastedt TR. Topographic patterns of above- and belowground production and nitrogen cycling in alpine tundra. Ecology. 1998;79:2253-66. https://doi.org/10.1890/0012-9658(1998)079[2253:TPOAAB]2.0.CO;2

Flynn T, van Zijl G, Van Tol J, Botha C, Rozanov A, Warr B, Clarke C. Comparing algorithms to disaggregate complex soil polygons in contrasting environments. Geoderma. 2019;352:171-80. https://doi.org/10.1016/j.geoderma.2019.06.013

Fortescue JAC. Landscape geochemistry: retrospect and prospect-1990. Appl Geochem. 1992;7:1-53. https://doi.org/10.1016/0883-2927(92)90012-R

Fragoso-Servón P, Corona AP, Zúñiga FB, Hernández BP, Reyes NA. Soils in extreme conditions: the case of the catenas karst-marsh-coastline in the Mexican Caribbean. Bol Soc Geol Mex. 2020;72:A040619. https://doi.org/10.18268/BSGM2020v72n2a040619

Fritsch E. Morphologie des quartz d'une couverture ferrallitique dégradée par hydromorphie. Cah ORSTOM Pedol. 1988;XXIV:3-15.

Furquim SAC, Santos MA, Vidoca TT, Balbino MDA, Cardoso EL. Salt-affected soils evolution and fluvial dynamics in the Pantanal wetland, Brazil. Geoderma. 2017;286:139-52. https://doi.org/10.1016/j.geoderma.2016.10.030

Gessler PE, Chadwick OA, Chamran F, Althouse L, Holmes K. Modeling soil-landscape and ecosystem properties using terrain attributes. Soil Sci Soc Am J. 2000;64:2046-56. https://doi.org/10.2136/sssaj2000.6462046x

Gessler PE, Moore ID, Mckenzie NJ, Ryan PJ, Moore ID, Mckenzie NJ, Ryan PJ. Soil-landscape modelling and spatial prediction of soil attributes. Int J Geogr Inf Syst. 1995;9:421-32. https://doi.org/10.1080/02693799508902047

Ghidin AA, Melo VDF, Lima VC, Lima JMJC. Toposseqüências de Latossolos originados de rochas basálticas no Paraná. II - Relação entre mineralogia da fração argila e propriedades físicas dos solos. Rev Bras Cienc Solo. 2006;30:307-19. https://doi.org/10.1590/S0100-06832006000200011

Giblin AE, Nadelhoffer KJ, Shaver GR, Laundre JA, McKerrow AJ. Biogeochemical diversity along a riverside toposequence in Arctic Alaska. Ecol Monogr. 1991;61:415-35. https://doi.org/10.2307/2937049

Greene H. Soil formation and water movement in the tropics. Soil Fertil. 1947;10:253-6.

Greene H. Classification and use of tropical soils. Soil Sci Soc Am J. 1946;10:392-6. https://doi.org/10.2136/sssaj1946.03615995001000C00067x

Gruau G, Dia A, Olivié-Lauquet G, Davranche M, Pinay G. Controls on the distribution of rare earth elements in shallow groundwaters. Water Res. 2004;38:3576-86. https://doi.org/10.1016/j.watres.2004.04.056

Guedron S, Grangeon S, Lanson B, Grimaldi M. Mercury speciation in a tropical soil association; Consequence of gold mining on Hg distribution in French Guiana. Geoderma. 2009;153:331-46. https://doi.org/10.1016/j.geoderma.2009.08.017

Güntner A, Bronstert A. Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. J Hydrol. 2004;297:136-61. https://doi.org/10.1016/j.jhydrol.2004.04.008

Hall GF. Pedology and geomorphology. Dev Soil Sci. 1983;11:117-40. https://doi.org/10.1016/S0166-2481(08)70600-7

Howlett DS, Stewart JR, Inoue J, Saito M, Lee D, Wang H, Yamada T, Nishiwaki A, Fernández FG, Toma Y. Source and accumulation of soil carbon along Catena toposequences over 12,000 years in three semi-natural *Miscanthus sinensis* grasslands in Japan. Agriculture. 2022;12:88. https://doi.org/10.3390/agriculture12010088

Jenny H. Arrangement of soil series and types according to functions of soil-forming factors. Soil Sci. 1946;61:375-92.

Jenny H. Factors of soil formation: A system of quantitative pedology. New York: Dover Publications; 1941.

Krasilnikov PV, Tabor JA. Perspectives on utilitarian ethnopedology. Geoderma. 2003;111:197-215. https://doi.org/10.1016/S0016-7061(02)00264-1

Kübler S, Rucina S, Aßbichler D, Eckmeier E, King G. Lithological and topographic impact on soil nutrient distributions in tectonic landscapes: implications for Pleistocene human-landscape interactions in the southern Kenya Rift. Front Earth Sci. 2021;9:611687. https://doi.org/10.3389/feart.2021.611687

Legros J-P. A l'aube de la Science du sol. Acad Sci Lett Montpellier. 2011;42:1-19.

Loba A, Sykuła M, Kierczak J, Łabaz B, Bogacz A, Waroszewski J. In situ weathering of rocks or aeolian silt deposition: Key parameters for verifying parent material and pedogenesis in the Opawskie Mountains—a case study from SW Poland. J Soils Sediments. 2020;20:435-51. https://doi.org/10.1007/s11368-019-02377-5

Lopes DV, Schaefer CEGR, Souza JJLL, Oliveira FS, Simas FNB, Daher M, Gjorup DF. Concretionary horizons, unusual pedogenetic processes and features of sulfate affected soils from Antarctica. Geoderma. 2019;347:13-24. https://doi.org/10.1016/j.geoderma.2019.03.024

Masseroli A, Villa S, Mariani GS, Bollati IM, Pelfini M, Sebag D, Verrecchia EP, Trombino L. Reconsidering the compound effect of geomorphology, vegetation, and climate change on paleopedogenesis in sensitive environments (Northern Apennines, Italy). Catena. 2021;197:104951. https://doi.org/10.1016/j.catena.2020.104951

McGill WB, Cole CV. Comparative aspects of cycling of organic C, N, S and P through soil organic matter. Geoderma. 1981;26:267-86. https://doi.org/10.1016/0016-7061(81)90024-0

Mendes WDS, Medeiros Neto LG, Demattê JAM, Gallo BC, Rizzo R, Safanelli JL, Fongaro CT. Is it possible to map subsurface soil attributes by satellite spectral transfer models? Geoderma. 2019;343:269-79. https://doi.org/10.1016/j.geoderma.2019.01.025

Meng Q, Wang S, Fu Z, Deng Y, Chen H. Soil types determine vegetation communities along a toposequence in a dolomite peak-cluster depression catchment. Plant Soil. 2022;475:5-22. https://doi.org/10.1007/s11104-022-05308-5

Michel RFM, Schaefer CEGR, Dias LE, Simas FNB, Benites VM, Mendonça ES. Ornithogenic Gelisols (Cryosols) from Maritime Antarctica. Soil Sci Soc Am J. 2006;70:1370-6. https://doi.org/10.2136/sssaj2005.0178

Millot G. Géochimie de la surface et formes du relief. Présentation. Sci Géol Bull. 1977;30:229-33.

Milne G. Composite units for the mapping of complex soil associations. Trans 3rd Int Congr Soil Sci. 1935a;1:345-7.

Milne G. Some suggested units of classification and mapping, particularly of East African soils. Soil Res. 1935b;3:183-98.

Molina A, Vanacker V, Corre MD, Veldkamp E. Patterns in soil chemical weathering related to topographic gradients and vegetation structure in a high Andean tropical ecosystem. J Geophys Res Earth Surf. 2019;124:666-85. https://doi.org/10.1029/2018JF004856

Momo MN, Yemefack M, Tematio P, Beauvais A, Ambrosi JP. Distribution of duricrusted bauxites and laterites on the Bamiléké plateau (West Cameroon): Constraints from GIS mapping and geochemistry. Catena. 2016;140:15-23. https://doi.org/10.1016/j.catena.2016.01.010

Moniz AC, Buol SW, Weed SB. Formation of an Oxisol-Ultisol transition in São Paulo, Brazil: II. Lateral dynamics of chemical weathering. Soil Sci Soc Am J. 1982;46:1234-9. https://doi.org/10.2136/sssaj1982.03615995004600060023x

Moore ID, Gessler PE, Nielsen GA, Peterson GA. Soil attribute prediction using terrain analysis. Soil Sci Soc Am J. 1993;57:443-53. https://doi.org/10.2136/sssaj1993.03615995005700020026x

Moormann FR, Veldkamp WJ, Ballaux JC. The growth of rice on a toposequence - a methodology. Plant Soil. 1977;48:565-80. https://doi.org/10.1007/BF00145768

Nakashima MR, Alves GB, Barreiros AM, Neto JPQ. Dos solos à paisagem: Uma discussão teórico-metodológica. Rev ANPEGE. 2017;13:30-52. https://doi.org/10.5418/RA2017.1320.0003

Nascimento NRD, Bueno GT, Fritsch E, Herbillon AJ, Allard T, Melfi AJ, Astolfo R, Boucher H, Li Y. Podzolization as a deferralitization process: A study of an Acrisol-Podzol sequence derived from Palaeozoic sandstones in the northern upper Amazon Basin. Eur J Soil Sci. 2004;55:523-38. https://doi.org/10.1111/j.1365-2389.2004.00616.x

Norton LD, Franzmeier DP. Toposequences of loess-derived soils in southwestern Indiana. Soil Sci Soc Am J. 1978;42:622-7. https://doi.org/10.2136/sssaj1978.03615995004200040018x

Pinheiro Junior CR, Pereira MG, O Filho JS, Beutler SJ. Can topography affect the restoration of soil properties after deforestation in a semiarid ecosystem? J Arid Environ. 2019;162:45-52. https://doi.org/10.1016/j.jaridenv.2018.11.004

Poppiel RR, Lacerda MPC, Demattê JAM, Oliveira MP, Gallo BC, Safanelli JL. Pedology and soil class mapping from proximal and remote sensed data. Geoderma. 2019;348:189-206. https://doi.org/10.1016/j.geoderma.2019.04.028

Prietzel J, Thieme J, Eusterhues K, Eichert D. Iron speciation in soils and soil aggregates by synchrotron-based X-ray microspectroscopy (XANES, µ-XANES). Eur J Soil Sci. 2007;58:1027-41. https://doi.org/10.1111/j.1365-2389.2006.00882.x

Queiroz Neto JP. Geomorfologia e pedologia. Rev Bras Geomorf. 2000;1:59-76. https://doi.org/10.20502/rbg.v1i1.70

Queiroz Neto JP. Relações entre as vertentes e os solos: Revisão de conceitos. Rev Bras Geomorf. 2012;12:15-24. https://doi.org/10.20502/rbg.v12i0.255

Quesada CA, Lloyd J, Anderson LO, Fyllas NM, Schwarz M, Czimczik CI. Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences. 2011;8:1415-40. https://doi.org/10.5194/bg-8-1415-2011

Reatto A, Silva EM, Bruand A, Martins ES, Lima JEFW. Validity of the centrifuge method for determining the water retention properties of tropical soils. Soil Sci Soc Am J. 2008;72:1547-53. https://doi.org/10.2136/sssaj2007.0355n

Revel JC, Bourgeat F. Transformations of carbonates in soils of a sequence formed in marls in the Aquitain Basin, France. Geoderma. 1985;36:123-43. https://doi.org/10.1016/0016-7061(85)90033-3

Righi D, Lorphelin L. The soils of a typical slope in the Himalayas (Nepal): Their main characteristics and distribution. Catena. 1987;14:533-50. https://doi.org/10.1016/0341-8162(87)90004-X

Rogers BF, Tate RL. Temporal analysis of the soil microbial community along a toposequence in Pineland soils. Soil Biol Biochem. 2001;33:1389-401. https://doi.org/10.1016/S0038-0717(01)00044-X

Rosolen V, Herpin U. Expansão dos solos hidromórficos e mudanças na paisagem: Um estudo de caso na região Sudeste da Amazônia Brasileira. Acta Amaz. 2008;38:483-90. https://doi.org/10.1590/S0044-59672008000300013

Roulet M, Lucotte M, Saint-Aubin A, Tran S, Rhéault I, Farella N, Silva EDJD, Dezencourt J, Passos CJS, Soares GS, Guimarães JRD, Mergler D, Amorim M. The geochemistry of mercury in central Amazonian soils developed on the Alter-do-Chao formation of the lower Tapajos River Valley, Para state, Brazil. Sci Total Environ. 1998;223:1-24. https://doi.org/10.1016/S0048-9697(98)00265-4

Ruellan A, Dosso M. Regards sur le sol. Paris: Foucher; 1993.

Sadiq FK, Maniyunda LM, Anumah AO, Adegoke KA. Variation of soil properties under different landscape positions and land use in Hunkuyi, Northern Guinea savanna of Nigeria. Environ Monit Assess. 2021;193:178. https://doi.org/10.1007/s10661-021-08974-7

Santos LAC, Araujo JKS, Souza Júnior VS, Campos MCC, Corrêa MM, Souza RAS. Pedogenesis in an Archaeological Dark Earth – Mulatto Earth catena over volcanic rocks in western Amazonia, Brazil. Rev Bras Cienc Solo. 2018;42:e0170359. https://doi.org/10.1590/18069657rbcs20170359

Sarcinelli TS, Schaefer CEGR, Lynch LS, Arato HD, Viana JHM, Albuquerque Filho MR, Gonçalves TT. Chemical, physical and micromorphological properties of termite mounds and adjacent soils along a toposequence in Zona da Mata, Minas Gerais State, Brazil. Catena. 2009;76:107-13. https://doi.org/10.1016/j.catena.2008.10.001

Sauer D, Sponagel H, Sommer M, Giani L, Jahn R, Stahr K. Podzol: Soil of the year 2007. A review on its genesis, occurrence, and functions. J Plant Nutr Soil Sc. 2007;170:581-97. https://doi.org/10.1002/jpln.200700135

Schiavo JA, Pereira MG, Miranda LPM, Neto AHD. Caracterização e classificação de solos desenvolvidos de arenitos da formação Aquidauana-MS. Rev Bras Cienc Solo. 2010;34:881-9. https://doi.org/10.1590/S0100-06832010000300029

Schimel DS, Coleman DC, Horton KA. Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota. Geoderma. 1985;36:201-14. https://doi.org/10.1016/0016-7061(85)90002-3

Schwertmann U, Latham M. Properties of iron oxides in some new caledonian Oxisols. Geoderma. 1986;39:105-23. https://doi.org/10.1016/0016-7061(86)90070-4

Silva DLA, Camêlo DL, Araújo Filho JC, Santos JCB, Souza Junior AJ, Souza Junior V, Corrêa MM. Genesis of clay skins in tropical eutric soils: A case study from NE-Brazil. Catena. 2021b;202:105236. https://doi.org/10.1016/j.catena.2021.105236

Silva FM, Weindorf DC, Silva SHG, Silva EA, Ribeiro BT, Guilherme LRG, Curi N. Tropical soil toposequence characterization via pXRF spectrometry. Soil Sci Soc Am J. 2019;83:1153-66. https://doi.org/10.2136/sssaj2018.12.0498

Silva JP, Alves GB, Ross JLS, Oliveira FS, Nascimento MAL, Felini MG, Manosso FC, Pereira DI. The geodiversity of Brazil: Quantification, distribution, and implications for conservation areas. Geoheritage. 2021a;13:75. https://doi.org/10.1007/s12371-021-00598-0

Singh JS, Milchunas DG, Lauenroth WK. Soil water dynamics and vegetation patterns in a semiarid grassland. Plant Ecol. 1998;134:77-89. https://doi.org/10.1023/A:1009769620488

Sobieraj JA, Elsenbeer H, Coelho RM, Newton B. Spatial variability of soil hydraulic conductivity along a tropical rainforest catena. Geoderma. 2002;108:79-90. https://doi.org/10.1016/S0016-7061(02)00122-2

Sommer M, Schlichting E. Archetypes of catenas in respect to matter - A concept for structuring and grouping catenas. Geoderma. 1997;76:1-33. https://doi.org/10.1016/S0016-7061(96)00095-X

Sowiński P, Smólczyński S, Orzechowski M, Kalisz B, Bieniek A. Effect of soil agricultural use on particle-size distribution in young glacial landscape slopes. agriculture. 2023;13:584. https://doi.org/10.3390/agriculture13030584

Stieglitz M, Shaman J, McNamara J, Engel V, Shanley J, Kling GW. An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. Global Biogeochem Cy. 2003;17:1105. https://doi.org/10.1029/2003gb002041

Tano BF, Brou CY, Dossou-Yovo ER, Saito K, Futakuchi K, Wopereis MCS, Husson O. Spatial and temporal variability of soil redox potential, ph and electrical conductivity across a toposequence in the Savanna of West Africa. Agronomy. 2020;10:1787. https://doi.org/10.3390/agronomy10111787

Thompson JA, Bell JC, Butler CA. Quantitative soil-landscape modeling for estimating the areal extent of hydromorphic soils. Soil Sci Soc Am J. 1997;61:971-80. https://doi.org/10.2136/sssaj1997.03615995006100030037x

Van Eck N, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010;84:523-38

Vanacker V, Ameijeiras-Mariño Y, Schoonejans J, Cornélis J-T, Minella JPG, Lamouline F, Vermeire M-L, Campforts B, Robinet J, Van De Broek M, Delmelle P, Opfergelt S. Land use impacts on soil erosion and rejuvenation in Southern Brazil. Catena. 2019;178:256-66. https://doi.org/10.1016/j.catena.2019.03.024

Verrecchia EP, Coustumer MNL. Occurrence and genesis of palygorskite and associated clay miner in a Pleistocene calcrete complex, Sde Boqer, Negev Desert, Israel. Clay Miner. 1996;31:183-202. https://doi.org/10.1180/claymin.1996.031.2.04

Vidal-Torrado P, Lepsch IF, Castro SSD. Conceitos e aplicações das relações pedologia-geomorfologia em regiões tropicais úmidas. In: Vidal-Torrado P, et al. Tópicos em ciência do solo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2005. v. 4. p. 145-92.

Vieillefon J. Notices sur les cartes d'utilisation des sols: 6. Feuilles d'Imady. Tananarive : IRSM; 1959.

Vitousek P, Chadwick O, Matson P, Allison S, Derry L, Kettley L, Luers A, Mecking E, Monastra V, Porder S. Erosion and the rejuvenation of weathering-derived nutrient supply in an old tropical landscape. Ecosystems. 2003;6:762-72. https://doi.org/10.1007/s10021-003-0199-8

Walker DA, Everett KR. Loess ecosystems of northern Alaska: regional gradient and toposequence at Prudhoe Bay. Ecol Monogr. 1991;61:437-64. https://doi.org/10.2307/2937050

Wang Y, Huang L, Jia X, Zhu Y, Shao M. Distribution characteristics and controls of soil organic carbon at different spatial scales in China's Loess Plateau. J Environ Manage. 2021;293:112943. https://doi.org/10.1016/j.jenvman.2021.112943

Winters E. Interpretative soil classification: Genetic grouping. Soil Sci. 1949;67:131-40.

Wojcik R, Donhauser J, Frey B, Benning LG. Time since deglaciation and geomorphological disturbances determine the patterns of geochemical, mineralogical and microbial successions in an Icelandic foreland. Geoderma. 2020;379:114578. https://doi.org/10.1016/j.geoderma.2020.114578

WOS. Web of Science database. 2023. Available from: https://www-webofscience.ez67.periodicos.capes.gov.br/wos/woscc/basic-search

Yonker CM, Schimel DS, Paroussis E, Heil RD. Patterns of organic carbon accumulation in a semiarid shortgrass steppe, Colorado. Soil Sci Soc Am J. 1988;52:478-83. https://doi.org/10.2136/sssaj1988.03615995005200020032x

Zhu M, Feng Q, Zhang M, Liu W, Qin Y, Deo RC, Zhang C. Effects of topography on soil organic carbon stocks in grasslands of a semiarid alpine region, northwestern China. J Soils Sediments. 2019;19:1640-50. https://doi.org/10.1007/s11368-018-2203-0