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Espodossolos in Brazil: A review of the criteria and conceptualization of the spodic B horizons

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ABSTRACT: The absence of quantitative limits for the diagnostic attributes that define spodic B horizons in the Brazilian Soil Classification System (SiBCS) allows the inclusion of soils in the *Espodossolos* (the equivalent of Spodosols or Podzols) classes that contradict the classical concepts that define the podzolization process, by including horizons with low organic carbon (C_{org}) content, and with alkaline pH, high sum of bases and sodic or solodic characteristics. This study aimed to propose quantitative criteria and limits to identify spodic B horizons and to contribute to the hieraquical structure of SiBCS. Morphological, physical and chemical attributes were defined after analyzing a large set of spodic B horizons of profiles classified as *Espodossolos* in the SiBCS available in the literature. In total, 385 spodic B horizons were identified. From this total, they were identified as following: 93 as Bs(m), 127 as Bh(m) and 165 as Bhs(m). In terms of color, the main hues were 7.5YR and 10YR, while the value and the chroma were ≥4 in Bs(m), <4 in Bh(m) and a wide variation in Bhs(m). The means and medians of the C_{org} contents are 7.5 and 6.7 g kg^{-1} for Bs(m), 19.8 and 15.1 g kg^{-1} for Bh(m), and 19.0 and 14.5 g kg^{-1} for Bhs(m). When the limit of C_{org} content is established as ≥3.0 g kg^{-1}, 90 % of the spodic horizons are included in this group, with 85 % of the horizons for C_{org} ≥4.0 g kg^{-1} and 81 % of the horizons for C_{org} ≥5.0 g kg^{-1}. The pH(H_2O) had 94 % of the spodic B horizons with values ≤5.9. Around 48 % of the spodic B horizons have Al_o and Fe_o data and, by calculating the equation $Al_o + 0.5\ Fe_o$, around 47 % of the horizons have a value ≥0.25 %. The evaluation highlighted the potential for adopting the minimum C_{org} ≥5.0 g kg^{-1} and pH(H_2O) ≤5.9 as quantitative limits for defining the spodic B horizon in the SiBCS. It is also suggested to apply a lower requirement for the C_{org} content in spodic horizons with very low clay content that is sand texture classes, using the values of C_{org} ≥3.0 or ≥4.0 g kg^{-1} as limits. Otherwise, the minimum C_{org} value proposed is 5.0 g kg^{-1} and the types of spodic B horizons could be differentiated using a second limit of C_{org}, distinguishing the Bs with a content of C_{org} between 5.0 and 15.0 g kg^{-1} and Bsh ≥15.0 g kg^{-1}.

Keywords: podzolized soils, diagnostic horizons, SiBCS.

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INTRODUCTION

To contextualize the distribution of soils with spodic horizons in the world, they are most commonly found in cold and humid regions, particularly in boreal and/or temperate climates (Soil Survey Staff, 2022; IUSS/FAO, 2022). In these environments, materials of any nature and vegetation, predominantly conifers and Ericacia trees, add acidic organic material to the soil. Less frequently, these soils are present in subtropical and/or tropical climate regions in quartzose materials such as sedimentary and metamorphic rocks rich in quartz or unconsolidated sediments derived from them (Soil Survey Staff, 2014).

In Brazil, spodic horizons are commonly formed from sandy sediments or from the alteration of felsic rocks such as quartzite or sandstone, in both temperate and tropical climates, and with vegetation that provides acidic humified material during their transformation. Therefore, these spodic horizons have greater acidity and low content of exchangeable bases in the exchange complex. It is possible to see these characteristics in the analysis of an extensive database of *Espodossolos* (Spodosols or Podzols) in different Brazilian pedoenvironments, carried out by Menezes et al. (2018), including the *restingas* (coastal tropical and subtropical broadleaf forest included in the Atlantic Forest biome), the *muçunungas* (sandy areas of the Coastal Tablelands), the highland fields, the Pantanal and the *campinaranas* (unique vegetation in the Amazonian biome occurring in white-sand soils).

However, in both conditions (in the Northern Hemisphere or in Brazil), the genesis of the spodic B horizon is based on the pedogenetic process of podzolization, in which some conditions that favor the humification of organic matter and its translocation in the soil profile are required, such as a mean of high permeability, the recharge of the water table, a low content of polyvalent cations and exchangeable bases (Mckeague et al., 1978; De Coninck, 1980; Lundström et al., 2000; Schaetzl, 2002; Sauer et al., 2007; Kämpf and Curi, 2012).

Regarding the criteria for the taxonomic classification of the diagnostic spodic B horizon, the Soil Taxonomy (Soil Survey Staff, 2022) and the World Reference Base for Soil Resources – WRB (IUSS/FAO, 2022) apply quantitative limits for some essential attributes, combined or not with the morphological characteristics. For the WRB, the criteria are: thickness, pH(H_2O), Al_o (aluminum extracted by acid ammonium oxalate), organic carbon or color by chroma, color by the hue combined or not with chroma and value, $Al_o + 0.5 \times Fe_o$ (iron extracted by acid ammonium oxalate). For the Soil Taxonomy, the criteria are: thickness, pH(H_2O), organic carbon (C_{org}) or chroma, color by hue combined or not with value and chroma, $Al_o + 0.5 \times Fe_o$ and optical density of the oxalate extract (ODOE).

In Brazil, the quantitative criteria considered in the Brazilian Soil Classification System – SiBCS (Santos et al., 2018) for spodic B horizons are: the minimum thickness, hue combined or not with value and chroma and $Al_o + 0.5 \times Fe_o$. These criteria are derived from the Soil Taxonomy (Soil Survey Staff, 2022), the World Reference Base for Soil Resources – WRB (IUSS Working Group WRB, 2022) and The Australian Soil Classification (Isbell, 1996).

In SiBCS (Santos et al., 2018), the types of spodic horizons are differentiated based on the dominant illuvial compounds as follows: i) Bs, which has bright colors with high chroma and accumulation of amorphous material, mainly Al and Fe combined with low levels of organic matter; ii) Bhs, there is a significant accumulation of organic matter combined with Al and Fe and it contains significant levels of Fe and Al extracted by acid ammonium oxalate (Fe_o and Al_o); and; iii) Bh, there is accumulation of organic matter and Al, with little or no evidence of Fe and presents dark colors (low value and chroma). Also, it is considered the consistency to differentiate other types of spodic B: i) Ortstein (Bsm, Bhsm or Bhm), which represents the consolidated form, presenting itself as continuous or practically continuous, strongly cemented by organometallic complexes, the consistency varies from very firm to extremely firm regardless of humidity; ii) Placic, which is a thin horizon, between black and dark red in color and apparently cemented by Fe or manganese and organic matter.

Notably, due to the lack of limit values for the diagnostic attributes of spodic B horizons, such as C_{org} content and pH values, there are descriptions and classifications in the literature that contradict the precepts of the podzolization process, i.e., horizons with low C_{org} content, alkaline pH, high sum of bases, and sodic or solodic characteristics (Cunha, 1980; Schiavo et al., 2012; Cardoso et al., 2012; Menezes et al., 2022). Considering this pedo-taxonomic inconsistency between diagnostic attributes and pedogenesis concepts, it is essential to review and adjust the taxonomic criteria for the spodic B horizon of the SiBCS.

There is a considerable number of pedological surveys, theses, dissertations, articles, technical bulletins, field guides, and other types of publications in the literature with the descriptions of *Espodossolos* (Spodosols) in many Brazilian environments, and they have already been partially analyzed in the study of Menezes et al. (2018). In this list there are studies such as: Lemos et al. (1960), Camargo et al. (1962), Silva et al. (1970), IPEAAOc (1972), Jacomine et al. (1972, 1975, 1977), Brasil (1974, 1975, 1977a,b, 1978a,b, 1980, 1983a,b), Melo et al. (1978); Panoso et al. (1978), Camargo and Rodrigues (1979), Cunha (1980), Palmieri and Santos (1980), Freitas et al. (1978), Mélo Filho et al. (1982), IAA and UFRRJ (1983a,b), Campos et al. (1997), Gomes et al. (1998), Benites (1998), Rossi (1999), Araújo Filho et al. (1999, 2003), Cunha et al. (2000), Mafra (2000), Ipaam and Embrapa (2001), Lumbreras et al. (2001), Gomes (2002, 2006), Schaefer et al. (2002), Dias et al. (2003), Santos et al. (2004), Mendonça-Santos et al. (2005), Ribeiro Filho et al. (2005), Simas et al. (2005), Moreau et al. (2006), Coelho (2008), Oliveira et al. (2010), Cardoso et al. (2012), Schiavo et al. (2012), Silva et al. (2013), Secretti (2013), Carvalho et al. (2013), Anjos et al. (2013) and Batista et al. (2018).

This study assumes that, with a comprehensive data set, it is possible to identify the patterns of diagnostic attributes of spodic horizons under Brazilian tropical conditions, thus supporting the establishment of coherent and robust taxonomic criteria to be adopted in the SiBCS. This study aimed to propose quantitative criteria and limits to identify spodic B horizons and to contribute to the hieraquical structure of SiBCS.

MATERIALS AND METHODS

Gathering of data on soils with spodic B horizons

Based on bibliographic research in scientific articles, pedological surveys, field guides, thesis, and dissertations, 189 profiles classified as *Espodossolos* (Spodosols) were selected and classified according to the Brazilian Soil Classification System – SiBCS (Santos et al., 2018). The profiles necessarily contain the following pieces of information: i) organic carbon (C_{org}) content of all horizons that make up the soil profile; ii) initial and final depth of the spodic B horizon; and iii) morphological characterization. Profiles sampled by auger were not considered since it affects the quality of morphological information.

A consistency analysis of the morphology data was performed to verify the coherence of the subsurface horizon identified by organic matter accumulation according to the spodic B criteria, aiming to eliminate the possible presence of A or organic (O or H) horizons that could be buried and, therefore, lead to errors in the interpretation of the C_{org} contents. Also, it was verified in each profile the possibility of variation of C_{org} in depth due to other processes, such as the deposition of sediments (fluvic character).

The data related to the profiles were compiled in an electronic spreadsheet containing a general description of the environment, morphology, physical and chemical attributes. The horizon nomenclature was adjusted according to the recommendations of Santos et al. (2015), since there was a large number of studies prior to this publication, and the original morphological description was kept. Profiles were reclassified according to the SiBCS (Santos et al., 2018). Thus, 154 profiles were selected after this screening, and the total number of spodic horizons was 385, with complete data on thickness, morphology, and C_{org}.

Analysis of the diagnostic attributes

Using the spreadsheet, the spodic B horizons were separated into three groups, defined according to the SiBCS: i) Bs(m), horizon with high chroma color(s) and accumulation of amorphous material, mainly aluminum and iron combined with low levels of organic matter; ii) Bhs(m), horizon with significant accumulation of organic matter combined with aluminum and iron; iii) Bh(m), horizon with accumulation of organic matter and aluminum, with little or no evidence of iron (Santos et al., 2018). The (m) representation indicates that each group contains spodic B horizons with and without the cementation (m), i.e., they were not separated in the data set.

Considering the different types of spodic B horizons, the following attributes were evaluated: depth of occurrence, moist soil color, textural class, structure, granulometry, organic carbon, pH(H_2O), sorption complex, iron (Fe_o) and aluminum (Al_o) extracted by acid ammonium oxalate. All horizons were maintained in the data set regardless of whether or not they possessed all these attributes. To evaluate the hydromorphic criteria it was used the identification of drainage class or field observation about the height of the water table at the time of sampling, and the profiles were separated according to the Great Group level in the SiBCS into: i) hydromorphic, profiles classified as *Hidromórficos*, composing a total of 19 profiles and 46 horizons (Santos et al., 2018); ii) non-hydromorphic, profiles classified as *Hiperespessos*, *Hidrohiperespessos* and *Orticos*, composing a total of 135 profiles and 339 horizons.

Data dispersion and frequency distribution were performed, as well as descriptive statistics (mean, mode and median, standard deviation, minimum and maximum, count) for the different types of spodic B horizons, as well as the horizons of profiles classified as hydromorphic and non-hydromorphic.

To define the limit values of C_{org} (minimum), the mode was used, which defines the value that occurs the most (highest frequency). The median was used to define the limit value between the types of spodic B since it equally divides the number of spodic B horizons. The limit value of the types of spodic B was obtained in the data set of the horizons that met the proposed minimum C org contents.

RESULTS AND DISCUSSION

Morphological characteristics (sequence of horizons, thickness, color, texture class and structure)

In general, soil profiles classified as *Espodossolos* (Spodosols) present a sequence of horizons A-E-B. However, there are profiles that, depending on the soil environment, especially those of *restinga* and high-altitude fields, have the sequence A-B, O-B or H-B, and may or may not have an A horizon underlying the O or H horizon. This variation in the sequence of horizons, with the presence of overlying organic horizons and with or without an E horizon, denotes the influence and dependence of the intensity of processes that occur in the surface horizons in forming the spodic B horizon. Therefore, these results are in accordance with the conclusion that the variation in the sequence of horizons in the profile is a relevant criterion for the definition of the spodic B and the classes of *Espodossolos* (Spodosols or Podzols), at the various taxonomic levels in the SiBCS.

Regarding the initial depth of the spodic B horizons, there is great variation, ranging from 0.11 to 4.00 m from the soil surface. However, 97 % of the profiles described in the literature have the occurrence of the spodic B horizon up to 2.00 m from the soil surface (Figure 1). The values of the mean and median of the initial depth of the spodic B horizons of profiles classified as hydromorphic were 0.823 and 0.800 m, respectively, and they are lower in relation to the profiles classified at the Great Groups *Orticos* (mean of 0.941 m and median of 0.940 m) and *Hidrohiperespessos* and *Hiperespessos* (mean of 2.83 m and median of 2.46 m). In addition, there is only one hydromorphic *Espodossolo* (Spodosol) profile with the spodic B horizon starting at a depth greater than 1.50 m.

The lower initial depth of spodic horizons identified as Bs in the profiles with hydromorphism is consistent with the presence of the water table near the soil surface, acting as a physical barrier to the illuviation of organic matter at higher depth and consequently limiting the development of the spodic horizon (Vidal-Torrado and Ferreira, 2017). On the other hand, under free drainage conditions in tropical pedoenvironments, the intense illuviation of organic matter and polyvalent cations by the action of water infiltrated in the profile favors the formation of a thick eluvial (E) horizon, sometimes thicker than 1.0 m (Palmieri and Santos, 1980; Reunião Brasileira de Classificação e Correlação de Solos, 2012, 2015; Carvalho et al., 2013).

Commonly, the color of spodic B horizons has a greater participation of yellow compared to red hues, so 60 % of the horizons evaluated present a hue of 7.5YR or more yellow (n = 232). The remaining spodic B horizons present color with a hue redder than 7.5YR (17 %, n = 66), variegated colors (13 %, n = 51), neutral colors (1 %, n = 4), or the information was not available (8 %, n = 31).

The color pattern in its different types of spodic horizons (Figure 2) is as follows: Bs(m), regardless of the hue, the value ≥5, exceptionally 4 when the chroma is ≥4; Bh(m), value and chroma ≤3 for any hue; Bhs(m), intermediate colors compared to the Bs(m) and Bh(m) horizons, with the value from 2 to 5 and chroma from 0 to 6. The variegated color horizons present value and chroma according to the pattern observed for the non-variegated horizons.

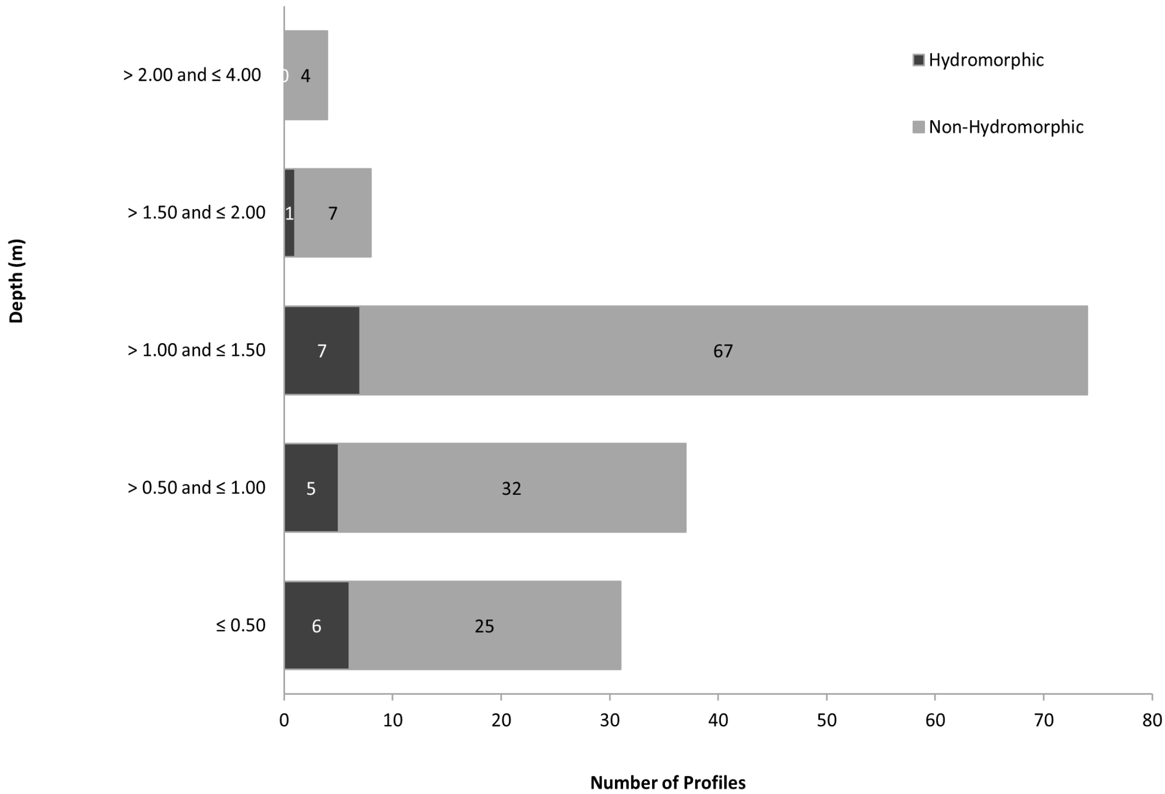

Figure 1. Initial depth frequency of *Espodossolos* profiles in hydromorphic and non-hydromorphic conditions.

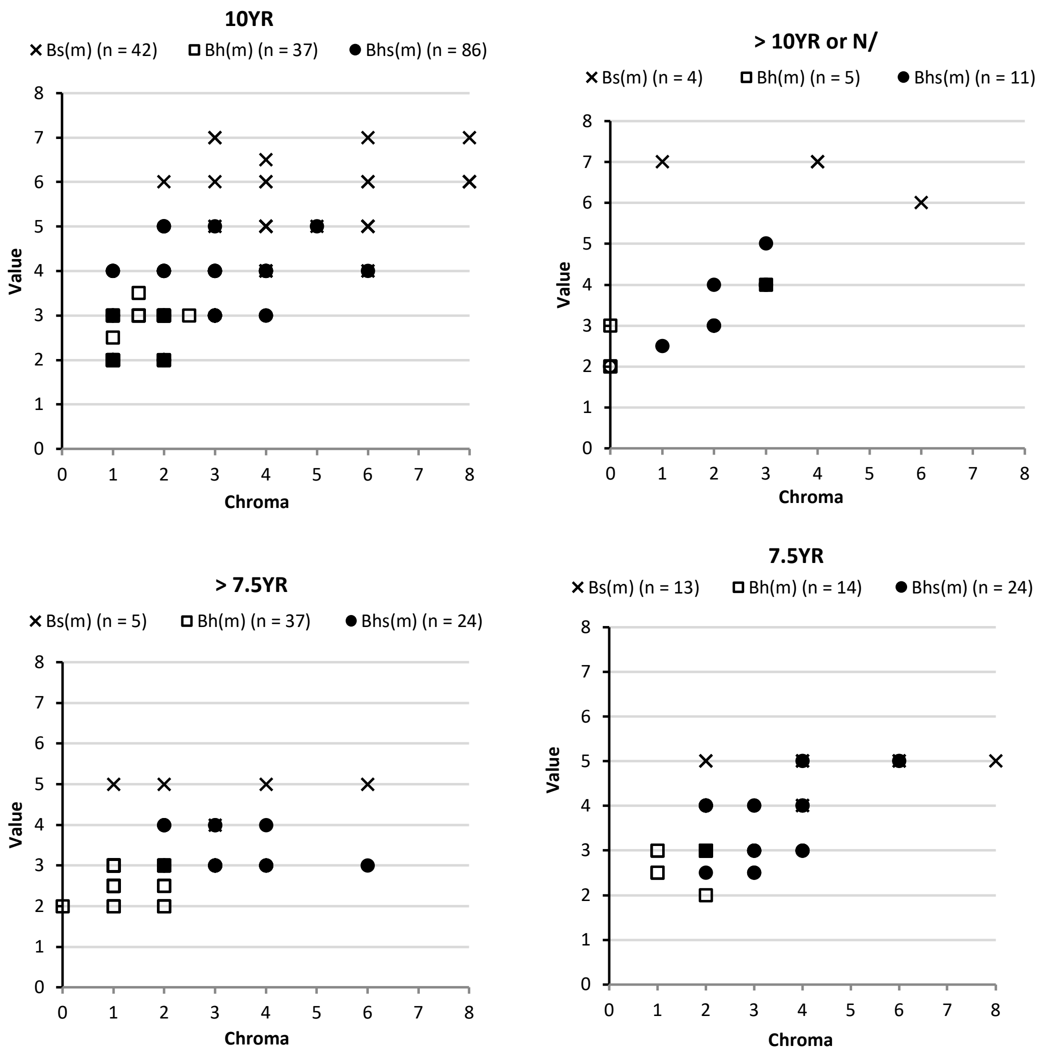

Figure 2. Value and chroma in different hue of spodic B horizons types (Bs, Bh, and Bhs, including with and without m subscript) without variegated color.

Approximately 12 % of the spodic B horizons (n = 46) from 30 profiles present mottling, in which the hue ranged from 5YR to 2.5Y or they were of a neutral color. Out of these spodic B horizons, only 4 are from profiles classified as hydromorphic (n = 3). The mottling colors are associated with illuviation (value and chroma between 3 and 4) or degradation of organic matter (value ≥5 and chroma ≤3), manganese precipitation (value <3 and chroma ≤2) and iron oxide precipitation (value and chroma ≥4) (Araújo Filho et al., 1999, 2003; Coelho, 2008; Carvalho et al, 2013; Batista et al., 2018).

The predominant textural classes in the spodic B horizons are: sand (56 %, n = 216), sandy loam (25 %, n = 96) and sandy loam (16 %, n = 62), which highlights the essentially sandy nature of the parent materials of Brazilian *Espodossolos* (Spodosols). Only 2 % of the spodic B horizons evaluated belong to other textural classes (n = 8), namely sandy clay loam and sandy clay, and 1 % of the assessed horizons did not present information on the textural class (n = 3).

Due to the sandy matrix, spodic B horizons often lack aggregates and have a massive structure (56 %, n = 216) or single grain (16 %, n = 62). In the case of spodic B horizons with aggregates – angular blocks (3 %, n = 12), subangular blocks (6 %, n = 23), granular (1 %, n = 3) and laminar (1 %, n = 3) – the degree of development of the structure varied from weak and moderate in almost all of them; there were only two records of Ortstein horizons with a structure with a strong degree of development (Gomes, 2006;

Oliveira et al., 2010). Approximately 17 % of the horizons evaluated had no description of soil structure (n = 66).

Most spodic B horizons (60 %) do not have cementation identified by the “m” or “x”subscript notation. However, the association of the subscripts “m” (extremely cemented) or “x” (apparent or reversible cementation) denotes the need for a revision of their concept and application in spodic B horizons since, even if to a smaller extent, the “x” condition is relevant for indicating limitations to water flow and root development.

Chemical attributes (C_{org}, pH, sorption complex and Fe and Al oxides)

One of the main chemical attributes used to identify spodic B horizons in the international soil classification systems is the organic carbon (C_{org}) content. In the data set of *Espodossolos* (Spodosols) evaluated, there is a large dispersion in the different types of spodic B horizons in the SiBCS, with no clear distinction between them (Figure 3). However, the Bs(m) horizons have C_{org} <20.0 g kg^{-1}, while the other types of spodic B horizons, such as Bh(m), reach values as high as 70.0 g kg^{-1} and Bhs(m) of 99.2 g kg^{-1} (Table 1).

It is important to mention that there are two horizons with C_{org} content higher than 80.0 g kg^{-1} (Jacomine et al., 1977; IAA and UFRRJ, 1983a) (Figure 3). This value is used in SiBCS as a quantitative criterion to define soil material of an organic nature. However, these horizons do not meet the qualitative criterion that defines the organic horizon; that is, they are not the result of accumulation of plant residues in varying degrees of decomposition, nor do they present signs of disturbance or morphology of a buried organic horizon.

There is a wide range of C_{org} in the spodic B horizons, from 0.2 to 99.2 g kg^{-1} (Table 1). Therefore, when testing the minimum value proposition for the spodic B horizons, it is observed that for the C_{org} content limit ≥3.0 g kg^{-1}, around 90 % of the horizons evaluated meet this criterion, for C_{org} ≥4.0 g kg^{-1} it is around 85 %, and for C_{org} ≥5.0 g kg^{-1} it is around 81 % (n = 312) (Figure 4).

Comparing with international soil classification systems and using the minimum C_{org} content of 5.0 g kg^{-1} (0.5 %) as an inferior limit, as adopted in the WRB (IUSS, Working Group WRB, 2022), 81 % of the spodic B horizons meet this criterion. On the other hand, 74 % of the spodic B horizons meet this criterion when the minimum content of 6.0 g kg^{-1} (0.6 %) is applied, practiced in the Soil Taxonomy (Soil Survey Staff, 2022).

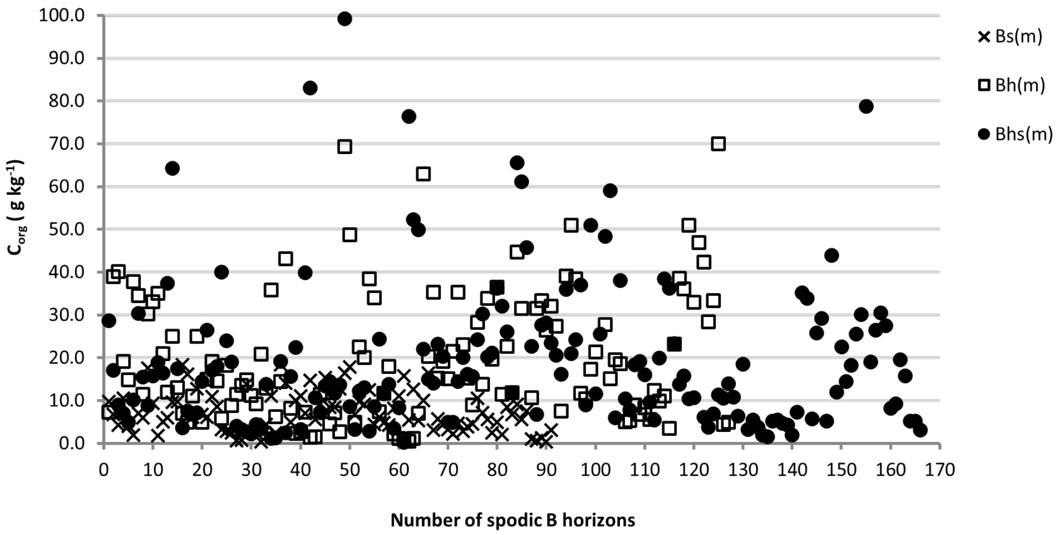

Figure 3. Distribution of organic carbon (C_{org}) content of spodic B horizons types (Bs, Bh, and Bhs, including with and without m subscript).

Table 1. Statistic of chemical attributes of spodic B horizons types (Bs, Bh, and Bhs, with and without m subscript), and hydromorphic and non-hydromorphic profiles

Statistic	pH(H_2O)	S	V	C_{org}	Al_o	Fe_o	Al_o + 0.5 Fe_o
		$cmol_c\ kg^{-1}$	%		$g\ kg^{-1}$		%
				Bs (m)			
Mean	4.9	0.50	14	7.5	3.6	1.4	0.4
Median	4.9	0.40	7	6.7	2.2	0.5	0.3
Mode	5.0	0.30	6	6.1	0.5	0.0	-
Standard deviation	0.6	0.36	18	4.9	6	2.3	0.7
Minimum	3.1	0.00	0	0.2	0.2	0.0	0.0
Maximum	6.9	2.12	88	19.0	40.2	11.3	4.5
Count	93	88	88	93	47	53	47
				Bh (m)			
Mean	4.6	0.80	12	19.8	3.4	0.2	0.3
Median	4.4	0.50	5	15.1	1.3	0	0.1
Mode	4.2	0.80	0	5	0.9	0	0.1
Standard deviation	1.1	1.14	23	15	4.5	0.5	0.5
Minimum	3.6	0.00	0	0.5	0.1	0	0.0
Maximum	9.7	6.91	100	70.0	16.8	3.4	1.7
Count	127	117	116	127	58	60	58
				Bhs (m)			
Mean	4.7	0.70	10	19.0	5.1	1.5	0.6
Median	4.7	0.41	4	14.5	2.4	0.2	0.3
Mode	4.8	0.30	-	5.0	0.9	0.1	0.1
Standard deviation	0.9	1.11	19	17.1	8.8	4.1	1.0
Minimum	2.4	0.01	0	1.2	0.2	0	0.0
Maximum	7.5	9.12	100	99.2	48.2	29	4.9
Count	165	155	155	165	80	95	80
				Hydromorphic			
Mean	4.6	0.61	10	15.5	0.8	0.6	0.1
Median	4.7	0.40	4	9.1	0.9	0.3	0.1
Mode	4.7	0.30	2	8.8	0.9	0	-
Standard deviation	1.0	0.75	18	19	0.3	0.8	0.0
Minimum	3.1	0.00	0	0.6	0.3	0	0.0
Maximum	7.4	4.50	88	99.2	1.4	3.1	0.2
Count	46	46	45	46	14	20	14
				Non-hydromorphic			
Mean	4.7	0.70	11	16.6	4.5	1.2	2.3
Median	4.7	0.44	4	12	2.4	0.1	0.7
Mode	4.4	0.30	4	7	0.6	0	0.5
Standard deviation	0.9	1.03	20	14.6	7.2	3.2	4.7
Minimum	2.4	0.00	0	0.2	0.1	0	0.0
Maximum	9.7	9.12	100	83	48.2	29	4.0
Count	339	314	321	339	171	188	171
				Total spodic B horizons			
Mean	4.7	0.67	11	16.7	2.9	0.9	0.3
Median	4.7	0.42	4	11.8	0.8	0.1	0.1
Mode	4.7	0.30	2	5	0	0	0.0
Standard deviation	0.91	0.99	19	15.2	5.9	2.8	0.8
Minimum	2.4	0.00	0	0.2	0	0	0.0
Maximum	9.7	9.12	100	99.2	48.2	29	4.8
Count	380	356	364	380	357	391	90

S: Sum of bases; V: Base saturation; C_{org}: Organic carbon; Al_o: Aluminum extracted by ammonium acid oxalate; Fe_o: Iron extracted by ammonium acid oxalate.

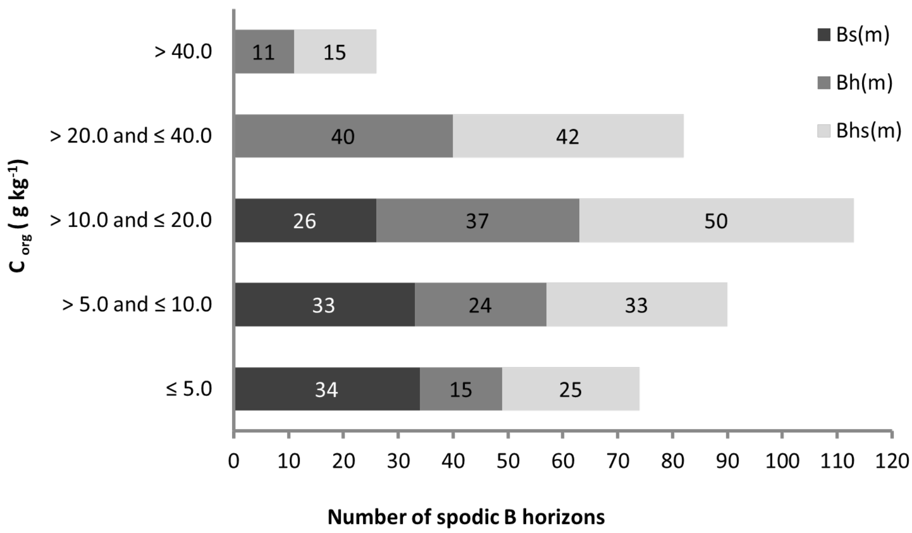

Figure 4. Distribution of organic carbon (C_{org}) frequency of spodic B horizons types (Bs, Bh, and Bhs, including with and without m subscript).

The mean and median C_{org} contents also indicate the lowest contents in the horizons Bs(m), 7.5 and 6.7 g kg^{-1}; Bh(m), 19.8 and 15.1 g kg^{-1}; and Bhs(m), 19.0 and 14.5 g kg^{-1} (Table 1). However, some horizons in the data set identified as Bh(m) and Bhs(m) do not present "significant accumulation of illuvial organic matter" according to their definitions in the SiBCS (Santos et al., 2018). This finding reinforces how the lack of C_{org} limit values for spodic B horizons makes it impossible to distinguish between their different types adequately.

Mean and median C_{org} contents of the spodic B horizons of the profiles classified as hydromorphic were respectively 15.5 g kg^{-1} and 9.1 g kg^{-1} (n = 46), and for the non-hydromorphic soils, they were 16.6 and 12.0 g kg^{-1} (n = 339) (Table 1). Thus, no relationship was observed between hydromorphism and the expression of the accumulation of illuvial organic matter, which is an essential component in the podzolization process.

In the spodic horizons Bh(m) and Bhs(m), in which dark colors predominate (low value and chroma) according to the SiBCS definitions (Santos et al., 2018), no direct relationship is observed between color and C_{org} content (Figure 5). As an example, a spodic B horizon with a color value of 2 and zero chroma may have less than 5.0 g kg^{-1} of C_{org}, as well as more than 30.0 g kg^{-1}. It can be assumed that the dark colors of spodic B horizons are associated with the quality and degree of decomposition of organic matter to the detriment of quantity.

The pH(H_2O) of spodic B horizons is notably acidic, with the mean and median being 4.4 and 4.9 in their different types (Table 1). For spodic B horizons of hydromorphic profiles (n = 46), the mean and median are 4.6 and 4.7, while for non-hydromorphic ones (n = 339), both have a value of 4.7 (Table 1). This fact shows that regardless of the hydromorphic condition, the acidic pH in these horizons is diagnostic of the pedogenetic process of podzolization.

Although the pH(H_2O) of spodic B horizons shows a wide range, from 2.4 to 9.7, only 23 horizons (6 % of the total evaluated) have a pH higher than 6.0 (Figures 6 and 7). In this sense, a pH(H_2O) ≤5.9 has the potential to be used as a diagnostic criterion for spodic B horizons in the SiBCS, thus avoiding the classification of soils of a different nature and soil forming factors that differ significantly from those indicated as essential for podzolization.

In a study with soils from the Pantanal, whose question was based on the evaluation of the occurrence of the podzolization process in basic or alkaline soil solution environments, Menezes et al. (2022) highlight the contradictory and antagonistic condition for the formation of spodic B horizons, including the high pH and sum of bases, and the low C_{org} and Al contents. For the attribute pH(H_2O), both the WRB (IUSS Working Group WRB,

2022) and the Soil Taxonomy (Soil Survey Staff, 2022) apply the maximum limit of 5.9, as long as the soil has not received liming and/or fertilization.

Sum of bases of the spodic B horizons has a wide range, from 0 to 9.12 $cmol_c$ kg^{-1}. Despite the variation, 89 % of the values of the sum of bases are <2.00 $cmol_c$ kg^{-1} (n = 341) (Figure 8). Out of the 19 records of spodic B horizons with a sum of bases ≥2.00 $cmol_c$ kg^{-1}, 12 horizons have a sodic or solodic character. These aspects are related to the illuviation of organic matter, since the ion sodium acts in its dispersion. There is a low organic carbon content for the horizons with sodium saturation ≥6 % (n = 12), with an mean and median C_{org} content of 2.9 and 2.0 g kg^{-1}, respectively. Furthermore, from 12 horizons, only one presented a pH(H_2O) lower than 5.9, reinforcing the proposal of a limit of pH(H_2O) ≤5.9 to be adopted as a diagnostic criterion for spodic B horizons.

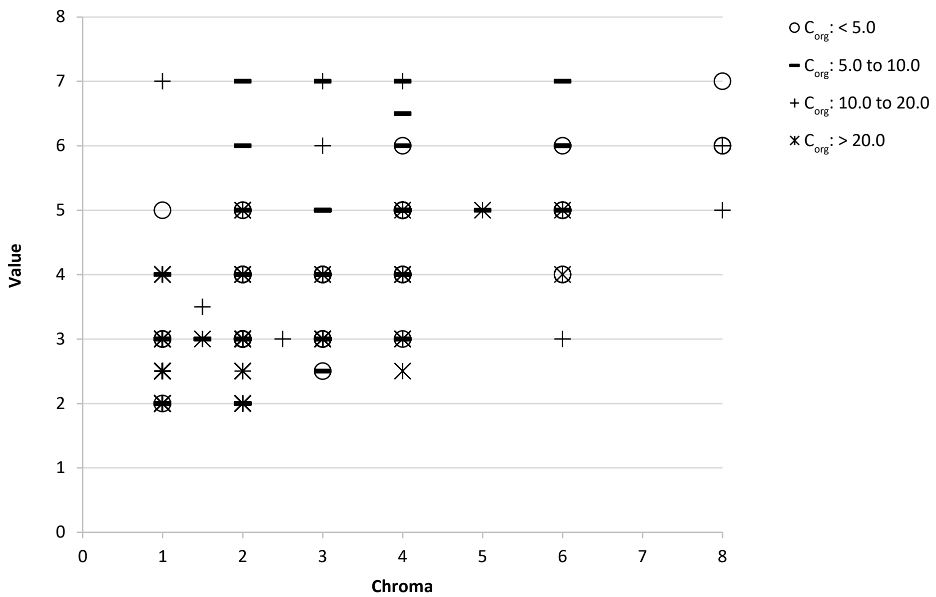

Figure 5. Color (value and chroma) of the spodic B horizons distributed in different ranges of C_{org} content (g kg^{-1}).

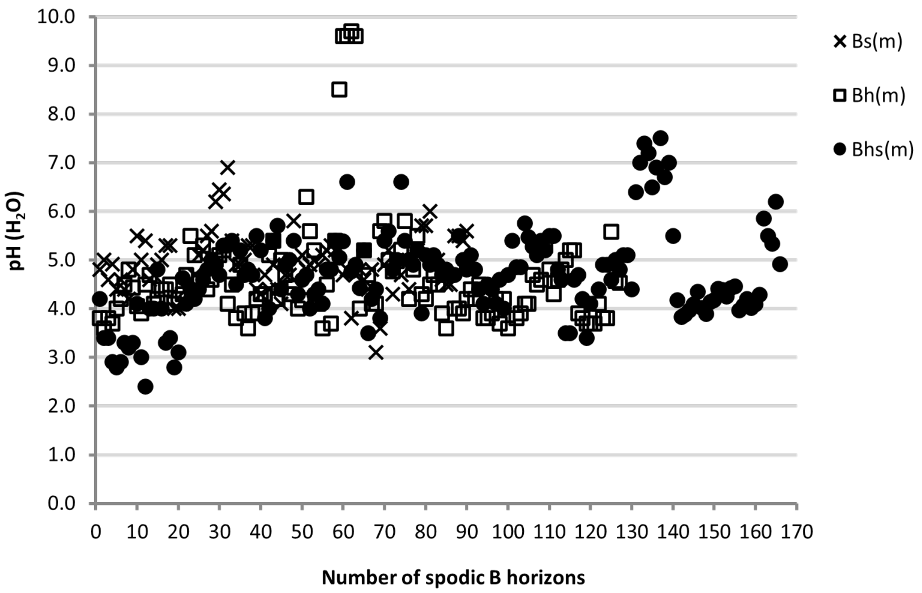

Figure 6. Distribution of pH(H_2O) of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

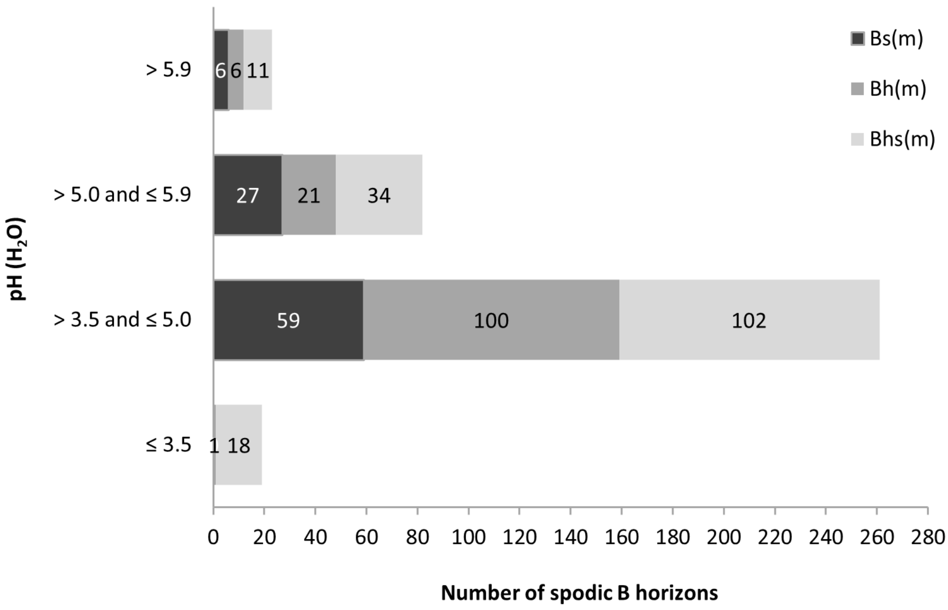

Figure 7. Frequency of values of pH(H_2O) of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

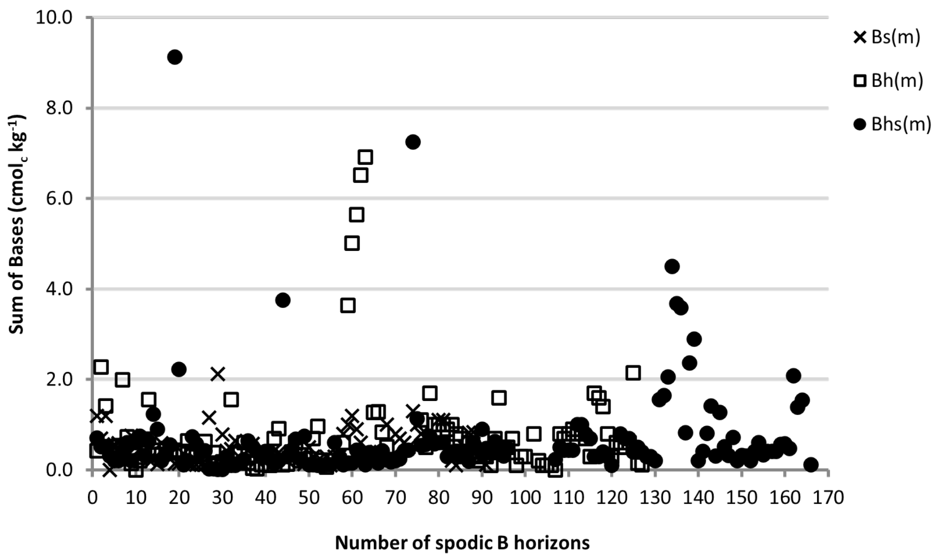

Figure 8. Distribution of sum of bases of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

Similar to the pH(H_2O), high levels of the sum of bases and the definition of the sodic or solodic character also reinforce the antagonistic condition to the classic podzolization process. This same condition was observed in the study on the influence of basic and alkaline soil solution as a restriction for the formation process of spodic B horizons in the Pantanal (Menezes et al., 2022). In the WRB, the spodic horizon cannot be part of a natric horizon, which, in SiBCS, shares one of the criteria that defines the sodic character (% Na saturation ≥15).

There is no distinction in the base sum values for the different types of spodic B horizons (Figure 9), as well as for the hydromorphic and non-hydromorphic profiles, with the mean and median for the Bs(m) (n = 88) horizons of 0.50 and 0.40 $cmol_c\ kg^{-1}$, Bh(m) (n = 117) of 0.8 and 0.50 $cmol_c\ kg^{-1}$, Bhs(m) (n = 155) of 0.70 and 0.41 $cmol_c\ kg^{-1}$; while the hydromorphic spodic B horizons (n = 46) show values of 0.61 and 0.40 $cmol_c\ kg^{-1}$, and the non-hydromorphic (n = 314) 0.70 and 0.44 $cmol_c\ kg^{-1}$ (Table 1).

Base saturation (V value) is low and there is no distinction between the types of spodic horizons, with the mean and median being 4 and 14 % (Table 1). Only 24 spodic horizons present base saturation above 50 %, and 17 of these horizons have concomitant $pH(H_2O)$ >5.9 and C_{org} <5.0 g kg^{-1}. Thus, the association of high base saturation and basic pH suggests a limiting condition for the accumulation of C_{org}. The mean and median values of spodic B horizons from hydromorphic profiles (n = 46) are similar to those of non-hydromorphic profiles (n = 339), with a mean value of 10 and 11 % and a median of 4 % (Table 1).

Although the SiBCS defines spodic B horizons by the accumulation of aluminum oxides (Al), and it is stated they may or may not contain iron (Fe), the lack of information on the contents of these elements, expressed as Fe_o and Al_o, limits the proposition of limit values. Only 54 and 48 % of the total spodic horizons have data for Fe_o (n = 208) and Al_o (n = 185), respectively. Furthermore, to evaluate the accumulation of Fe and Al oxides in the subsurface horizons, it is necessary to perform this analysis in the B spodic and in the overlying horizon. In this case, the percentages of profiles with spodic B horizons with extraction data for pedogenetic oxides in the overlying horizon are 42 and 38 % for Fe_o (n = 161) and Al_o (n = 146), respectively.

In the spodic B horizons with information on selective extraction of pedogenetic oxides, the mean and median Fe_o values (0.20 and 0.0 g kg^{-1}) of the Bh(m) horizons are lower when compared to the other types of spodic B horizons (means of 1.39 and 1.54 g kg^{-1} and medians of 0.20 and 0.45 g kg^{-1}) (Table 1; Figure 10). For the Al_o oxide contents, there is no distinction for the different types of spodic B horizons, with the mean ranging from 3.4 to 5.1 g kg^{-1} and the median from 1.3 to 2.4 g kg^{-1} (Table 1).

Spodic B horizons, by definition, must present Al accumulation, regardless of their type. However, the minimum Al_o content observed for spodic B horizons was 0.1 g kg^{-1}. Furthermore, the Bs(m) and Bhs(m) horizons must present Fe accumulation in addition to Al, and the minimum Fe_o value is 0.0 g kg^{-1}, i.e., not detected by the method used, contradicting their definitions in SiBCS (Table 1).

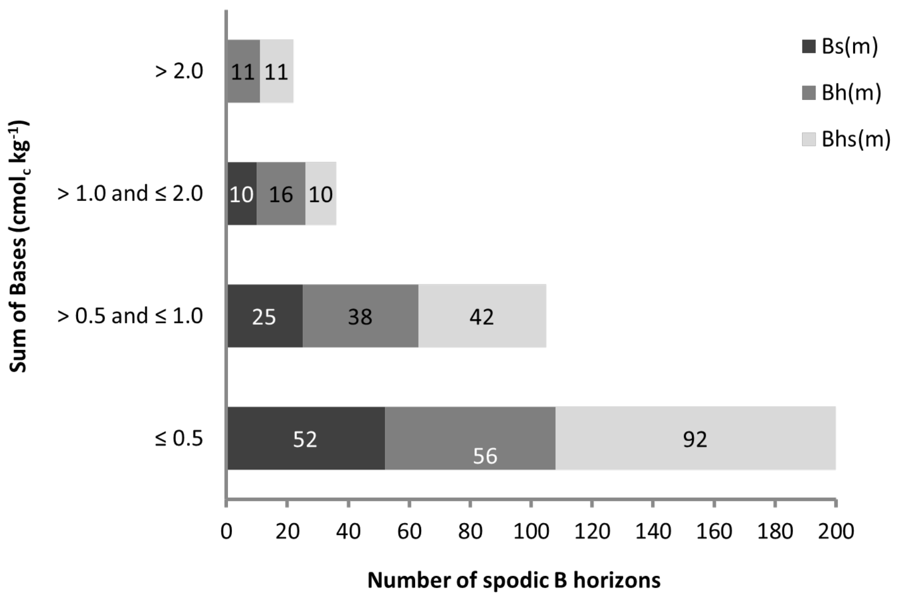

Figure 9. Distribution of sum of bases of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

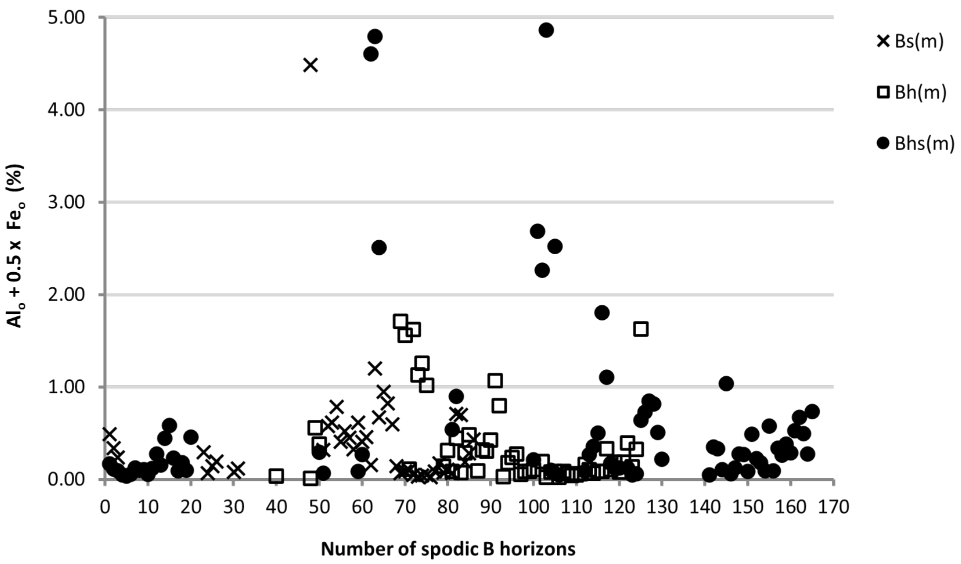

Figure 10. Distribution of $Al_o + 0.5\ Fe_o$ values of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

Comparatively, the spodic B horizons of *Espodossolos* in the data set identified as hydromorphic have a lower mean and median values for Al_o (0.8 and 0.9 g kg^{-1}) in relation to the other spodic B horizons, with a mean of 4.5 g kg^{-1} and median of 2.4 g kg^{-1} (Table 1). Under hydromorphic conditions, the accumulation of organometallic complexes is influenced by the high water table, which prevents the vertical loss of organic matter (Andriesse, 1969; Vidal-Torrado and Ferreira, 2017), whereas under free drainage conditions, the main mechanism of immobilization of the complexes is the saturation of the polar binding sites with Al and Fe (Buurman, 1985; Schnitzer, 1986).

The $Al_o + 0.5\ Fe_o$ values range from 0.0 (non-detected) to 4.9 % and, based on the dispersion and frequencies, no differentiation is observed between the Bs(m), Bh(m) and B(hs) horizons (Figure 11). Of the horizons with $Al_o + 0.5\ Fe_o$ data, only 25 % have a value ≥0.5 %. On the other hand, it is observed that 47 % (n = 87) of the spodic horizons with $Al_o + 0.5\ Fe_o$ data have a value ≥0.25 %, a limit that has the potential to be used as a criterion for differentiation between the types of Bs(m) and Bhs(m) horizons from the Bh(m) horizons.

Proposal of quantitative criteria for the definition of spodic B horizons

The proposal includes a broad evaluation of data from spodic B horizons of *Espodossolos* (Spodosols) classified according to the SiBCS (Santos et al., 2018), covering all the main pedoenvironments in Brazil and in a representative manner (Menezes et al., 2018). The criteria are based on easily obtainable and quantifiable attributes consistent with the podzolization process that defines these soils in the SiBCS.

In the general definition of spodic B horizons, the inclusion of the pH(H_2O) is proposed as evidence of the conditions of greater acidity in which the podzolization process occurs. This attribute is used as a criterion and has a similar value in the WRB (IUSS Working Group WRB, 2022) and the ST (Soil Survey Staff, 2022).

Regarding the minimum C_{org} content, the essence of the formation process of spodic B horizons stands out through the accumulation of illuvial organic matter. Minimum contents are defined based on the evaluation of all spodic B horizons and by the descriptive statistics "mode" (all spodic B horizons) (Table 1).

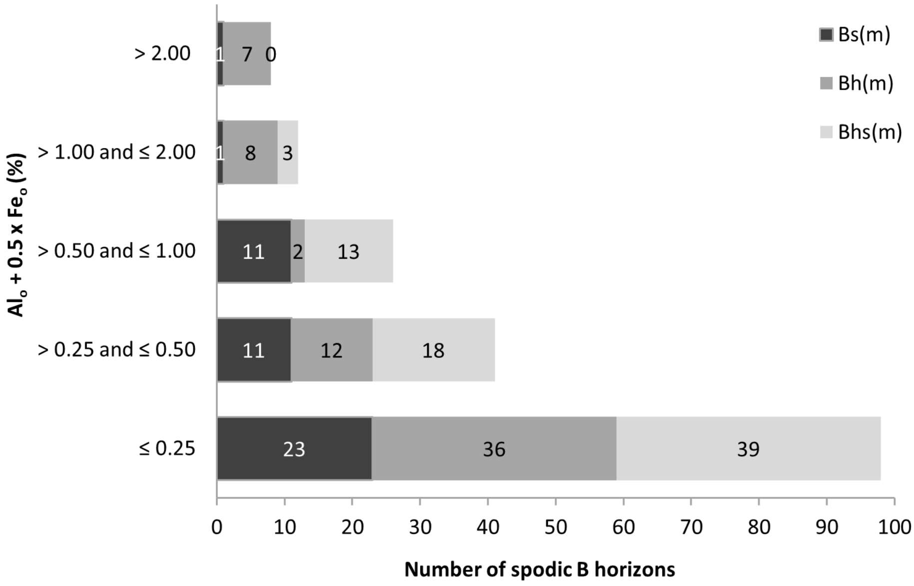

Figure 11. Frequency of Al_o + 0.5 Fe_o values of spodic B horizons types (Bs, Bh, and Bhs, included with and without m subscript).

For profiles in which the E horizon does not occur, the inclusion of the C_{org} criterion and its limits is necessary to evidence the significant increase in organic matter in the spodic B horizons, considering the absence of other evidence of the eluviation process. Thus, in profiles with a sequence of A-B, O-B or H-B horizons, it is not feasible to define this increase based solely on the color of the spodic horizon, which also does not characterize a horizon of organic matter accumulation in itself. This group of soils includes especially the *restinga* and high-altitude field profiles (Menezes et al., 2018, 2022).

In the definition of the types of spodic B horizons proposed in this study, the color criterion by value and chroma was excluded. When observing the current definitions in SiBCS (Santos et al., 2018), there is an overlap of colors between them, and no distinction was observed between the types of spodic B horizons when evaluated using the dispersion graph of C_{org} (Figure 5). In other words, there is no clear relationship between the expression of the organic matter accumulation process and the color of the spodic B horizons, according to their distinction in the current version of the SiBCS (Santos et al., 2018).

Fulvic acid and humic acid fractions of soil organic matter have a yellow-brown and dark-to-black coloration, respectively (Stevenson, 1994). In this way, the soil color, expressed by hue, value, and chroma, has a low capacity to distinguish the types of spodic B horizons in soils originated from sandy matrix material (quartz) due to the strong influence of the components of humified organic matter over the mineral fraction.

The lack of relationship between the denomination of spodic B horizons and the humic and fulvic acid contents is evident by the lack of a standard in the evaluation of the ratio between these fractions (C-FAH/C-FAF), as reported by Fontana et al. (2010). Furthermore, there is no distinction between the types of spodic B when applying the proposed classification based on the C_{org} contents for Bs and Bsh (proposed below) (Figure 12).

Furthermore, the criterion for Al_o and Fe_o oxides was not corroborated by the data set statistics and was therefore excluded from the definition. One factor contributing to this, is the lack of data, which may reflect the absence of laboratory conditions, in routine analyses, for the determination of these forms of Fe and Al. However, even so, considering the existing information, due to the dispersion of the $Al_o + 0.5 \times Fe_o$ values, there is no pattern of distinction between the types of spodic B horizons (Figure 11 and Table 1), except when hydromorphic and non-hydromorphic soils are grouped (Table 1). Furthermore, as for soil color (chroma and value), there is no distinction between the proposed types of spodic B (Bs and Bsh - see below) (Figure 13).

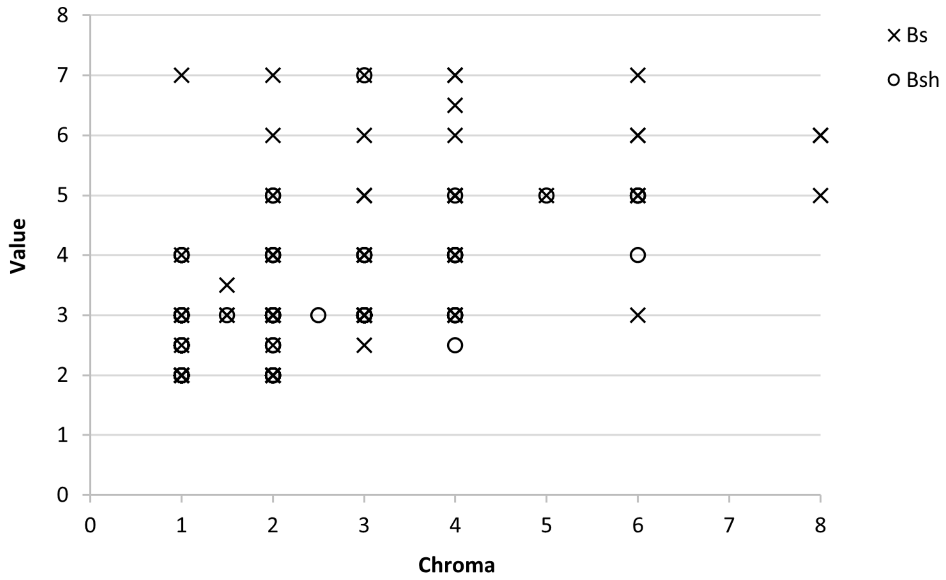

Figure 12. Distribution of color (value and chroma) of proposed spodic B horizon types (Bs and Bsh).

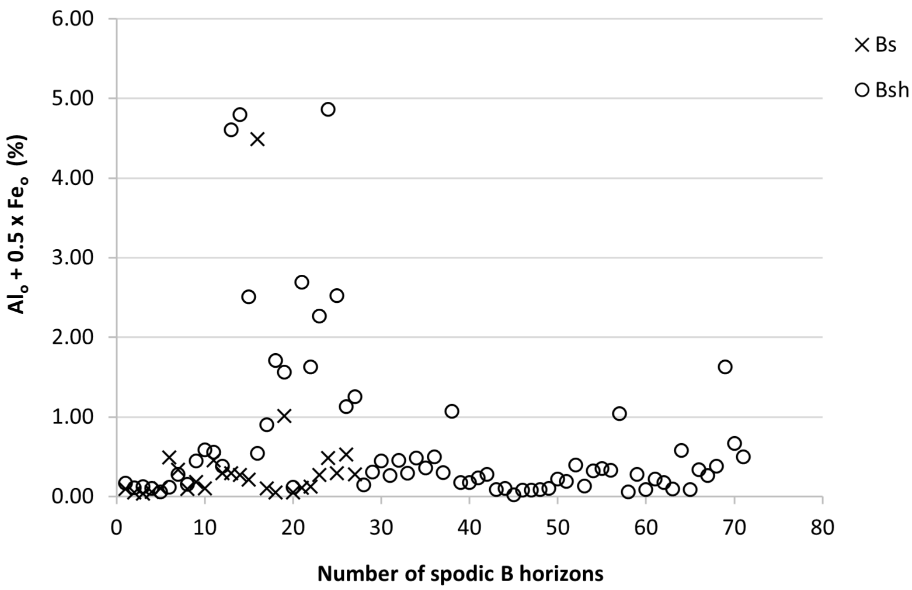

Figure 13. Distribution of Al_o + 0.5 Fe_o values according to the proposed spodic B horizons types (Bs and Bsh).

Organic carbon content is presented as the main quantitative criterion for distinguishing the types of spodic B horizons, in addition to morphology. Organic carbon content for distinguishing Bs and Bsh is taken as a basis for all horizons with contents greater than or equal to 5.0 g kg^{-1}, which have a median value of 15.0 g kg^{-1}, thus characterizing two groups equally in the set of data evaluated.

The inversion of the suffixes from Bhs to Bsh in relation to the current version of SiBCS is due to the essence that both (Bs or Bsh) have potential accumulation of Al and/or Fe (although limited quantification, as pointed out above), which suggests, as the best differentiation criterion, the higher or lower content of C_{org} (feasible and possible of routine quantification in pedology works). As for the exclusion of Bh, the dark color has greater pigmentation power in soils originated from sandy matrix materials (quartz), which strongly reduces the efficiency of the separation between Bhs and Bh in Brazilian soils, where there is a predominance of these materials in the various pedoenvironments

(Menezes et al., 2018). As observed in figure 2, there is no distinction between the Bh and Bhs horizons by the chroma and value of the types of spodic B horizons without variegated color.

Based on the preponderant attributes of the podzolization process and the characterization of spodic B horizons in Brazilian pedoenvironments, the general definition and types of spodic B horizons are presented according to the following criteria:

a) General definition

Horizon B underlying horizon E must meet the following:

i) accumulation of illuvial organic matter combined with Al, which may contain Fe;

ii) thickness ≥2.5 cm or >0.5 cm and <2.5 cm when placic;

iii) $pH(H_2O)$ ≤5.9;

iv) C_{org} ≥5.0 g kg^{-1} (the option of limits of 3.0 or 4.0 g kg^{-1} can be evaluated, depending on the sandy texture class).

Horizon B underlying the superficial horizons O or H, with or without horizon A, in addition to the previous criteria, must meet the following:

i) ratio of the mean C_{org} content of the spodic B horizons to the mean C_{org} content of the histic (O or H) horizons or any type of A ≥0.6;

Horizon B underlying the surface horizon A, in addition to the previous criteria, must meet the following:

i) ratio of the mean C_{org} content of spodic B horizons to the mean C_{org} content of any type of A horizon ≥0.4.

Spodic B horizons are those above a lithological discontinuity or polygenetic profile (i.e., the most superficial profile and horizons, disregarding the buried A and E horizons).

b) Symbols for representations of spodic B horizons

Bs – horizon of accumulation of illuvial organic matter combined with Al, which may or may not contain iron and with a C_{org} content between 5.0 and 15.0 g kg^{-1};

Bsh – horizon of accumulation of illuvial organic matter combined with Al, which may or may not contain iron and with a C_{org} content ≥15.0 g kg^{-1};

"*m*" – *applied to all types when present and according to the definition currently used in the SiBCS.*

The proposed quantitative limits based on the two types of spodic B horizons resulted in the equitable distribution of the profiles in the data set, excluding few profiles, both by $pH(H_2O)$ and by C_{org} content. The profiles not classified by these criteria can be classified in the fourth level as having a spodic character, following the same criteria of several other classes considered as intermediate in the SiBCS.

Regarding the B horizons, from the total of 383, 22 are excluded due to $pH(H_2O)$ values higher than the proposed limit and 83 due to C_{org}, resulting in a total of 310 spodic B horizons that fit the criteria. Also, 157 spodic B horizons have C_{org} content ≥ 15.0 g kg^{-1} and 153 horizons show values between 5.0 and 15.0 g kg^{-1}, again highlighting the equitable distribution of generic horizons in the types of diagnostic spodic B horizons (taxonomic) and the validity of the criteria.

In terms of soil profiles, out of 154, based on the pH(H_2O), only eight profiles are excluded from the classification of *Espodossolos* (Spodosols) because all B horizons have a value of pH(H_2O) higher than the proposed limit, 5 of them have at least one horizon that matches the minimum limit of C_{org} content. By the criterion of C_{org} ≥5.0 g kg^{-1}, 17 (11 %) profiles have all B horizons with contents lower than the proposed minimum. Thus, 137 profiles have at least one horizon classified as B spodic. Out of these, 67 profiles (49 %) have a spodic B horizon with a content of ≥15.0 g kg^{-1}, with the remaining 70 profiles (51 %), which also shows the importance of this criterion to differentiate suborders of *Espodossolos* (Spodosols), although this is not the objective of this work.

CONCLUSION

The absence of limit values for the main diagnostic attributes for the definition of the spodic B horizon in the SiBCS allows the identification of horizons that do not meet the pedogenetic premises of podzolization and compromises the differentiation of the various types of spodic B and the *Espodossolo* order in the SiBCS.

It is proposed to include in the definition of the spodic B horizon the minimum content of C_{org} ≥5.0 g kg^{-1}, in addition to the pH(H_2O) ≤5.9. Due to the lack of relationship between the morphological criterion of color and the accumulation of illuvial organic matter and Al and Fe oxides, which would allow to define better criteria to distinguish the Bs, Bhs and Bh horizons, it is proposed to review the nomenclature using the C_{org} content as a quantitative criterion indicating the expression of the organic matter illuviation, thus identifying two horizons, Bs with C_{org} between 5.0 and 15.0 g kg^{-1} and Bsh ≥15.0 g kg^{-1}.

Soil color, identified by hue and combined or not with distinctive chroma and value, is an important aspect of the spodic B horizons. It should be applied in the definition of the genetic horizon and recognized by the respective notation in the soil profiles whenever occurring.

In this proposal, in addition to the inclusion of limits and quantitative criteria for types of spodic B horizons, adding to those already existing for classifying the *Espodossolos* such as the sequence of horizons, the podzolization process is better expressed and the identification of the Order in the SiBCS is simplified.

DATA AVAILABILITY

The data will be provided upon request.

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AUTHOR CONTRIBUTIONS

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Data curation: Ademir Fontana (supporting) and Andressa Rosas de Menezes (lead).

Formal analysis: Ademir Fontana (equal) and Andressa Rosas de Menezes (equal).

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Methodology: Ademir Fontana (equal) and Andressa Rosas de Menezes (equal).

Project administration: Ademir Fontana (lead).

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Validation: Ademir Fontana (equal), Andressa Rosas de Menezes (equal) and Lúcia Helena Cunha dos Anjos (equal).

Visualization: Ademir Fontana (equal), Andressa Rosas de Menezes (equal) and Lúcia Helena Cunha dos Anjos (supportting).

Writing – original draft: Ademir Fontana (equal), Andressa Rosas de Menezes (equal) and Lúcia Helena Cunha dos Anjos (supportting).

Writing – review & editing: Ademir Fontana (equal), Andressa Rosas de Menezes (equal) and Lúcia Helena Cunha dos Anjos (equal).

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