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Field Perception of the Boundary Between Soil and Saprolite by Pedologists and its Differentiation Using Mathematical Models

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ABSTRACT: Saprolite plays a central role into hydrologic and nutrient cycles. Despite that, saprolite research is scattered and uses heterogeneous, sometimes conflicting, methods and concepts. During field work, it is difficult to assign the boundary between soil and saprolite. This paper aimed to identify the subjacent logic that pedologists use to assign to a regolith volume its soil or saprolite nature. To achieve this goal, a tree algorithm was used to build a hierarchy of physical and chemical properties of a set of regolith profiles. Such hierarchization expose the inner, subjective criteria used by researchers during the assignment of a certain profile zone as saprolite or soil. The following variables were measured: total porosity (TP); bulk density (Bd); particle density (Pd); total Fe_2O_3, Al_2O_3, CaO, MgO, K_2O, Na_2O, P_2O_5, and TiO_2; selective extraction of iron by ditionite-citrate-bicarbonate (Fe_{DCB}) and ammonium oxalate (Fe_{OA}); and the Fe_{DCB}/Fe_{OA} ratio. These measurements were done in a set of 25 regolith profiles (137 horizons and layers), located in the Southeast region and Northeast region of Brazil. The decision tree algorithm was applied using the recursive partition method to identify which of the measured property was most strongly associated with the field assignment of the pedologists to a certain profile zone as saprolite or soil. The Bd, Fe_{DCB}/Fe_{OA}, MgO, CaO, TP, and P_2O_5 explained 93 % of the pedologists choice, being Bd responsible for 81 %.

Keywords: regolite, subsolum, weathering, classification system.

INTRODUCTION

Recent approaches such as Critical Zone and Planetary Boundaries (Rockström et al., 2009) shed light on the importance of the whole regolith to sustain ecosystems and the human societies (Brantley et al., 2007).

The regolith is the section of the lithosphere column changed by weathering, being further divided into soil and saprolite (O'Brien and Buol, 1984). In shallow soils, saprolite is close to the surface and may become a nutrient source and water reservoir to plant development (Melo et al., 1995; Pedron et al., 2009; Santos et al., 2017), but also as a shortcut for surface pollutants to reach underground water.

As a natural resource, characterization and mapping of saprolites are needed for their better use and management. Despite its importance, the concepts and definitions of saprolite are quite diverse, even controversial.

Conceptualization, definition, and characterization are standard operations to allow the registering, organization, classification, and mapping of saprolites. The establishment of a common procedure worldwide would provide the basis to share knowledge and collaborate towards a global understanding of this natural body.

Establishment of a sharp limit between soil and saprolite is debatable. However, classification systems require a definition of the object being classified. In this regard, the operational definition of saprolites should avoid overlapping the soil, that is, the same material should not be classified simultaneously into two classification systems.

At present, two saprolite classification systems were proposed in the soil science community. The Saprolite-Regolith Taxonomy - SRT (Buol, 1994) defines the saprolite as "regolith material that have unconfined compressive strength less than 100 MPa, and are either not penetrated by plants roots, except at intervals greater than 0.10 m, or occur more than 2.00 m below the soil surface, whichever is shallower". The Subsoil Reference Groups - SRG defines "saprolithic material is little affected by pedogenetic process and represents in situ weathering product of the original rock" (Juilleret et al., 2016), and classifies the materials below the lower soil limit of the World Reference Base - WRB (IUSS Working Group WRB, 2015).

This paper is based on the perception of two pedologists in describing regolith profiles and assigning the soil-saprolite boundary disregarding any classification system. The study aimed to identify the criteria pedologists use to assign to a certain regolith volume its nature as soil or saprolite, by comparing the saprolite and soil sets made by the algorithm to those made by the pedologists. By doing so, we could identify the laboratory measurements that correlate with other field perception.

MATERIALS AND METHODS

Obtaining the data

The data were collected from 25 regolith profiles (P1 to P25) described by Guerra (2015) and Santos (2015) in their thesis, summing up to 137 horizons and layers, developed from: granite, syenite, gneiss, schist, sandstone, and siltstone (Table 1).

These profiles encompass the Caatinga, Savanna, and Atlantic Forest biomes (Figure 1), subjected to semiarid, tropical, and semitropical climates (Figure 2).

Analyzed variables

The variables measured into the lab and considered in the decision tree algorithm were chosen among the most affected by weathering and pedogenesis. Only samples analyzed by the same or similar procedures were considered.

Table 1. Regolith profiles used in the decision tree algorithm

Profile[1]	Lithology	Classification SiBCS[2]	Classification WRB[3]	Bd in saprolite as related to the upper Hz
P1	Schist	*Cambissolo Háplico Tb Distrófico típico*	Dystric Cambisol (loamic)	Increase
P2	Schist	*Argissolo Amarelo Distrófico típico*	Haplic Acrisol (siltic)	Decrease
P3	Schist	*Latossolo Vermelho Eutrófico cambissólico*[4]	Haplic Ferrasol (loamic)	Decrease
P4	Schist	*Argissolo Acinzentado Eutrófico típico*	Haplic Lixisol (loamic)	Decrease
P5	Gneiss	*Chernossolo Háplico* Órtico *típico*[4]	Haplic Phaeozem (loamic)	Increase
P6	Gneiss	*Latossolo Vermelho-Amarelo Distrófico argissólico*[4]	Haplic Ferrasol (loamic)	Increase
P7	Sandstone	*Cambissolo Háplico Alítico típico*	Dystric Cambisol (arenic)	Increase
P8	Sandstone	*Cambissolo Háplico Ta Distrófico típico*	Dystric Cambisol (loamic)	Increase
P9	Sandstone	*Cambissolo Háplico Ta Distrófico típico*	Dystric Cambisol (arenic)	Increase
P10	Siltstone	*Cambissolo Háplico Ta Eutrófico* típico	Eutric Cambisol (siltic)	Increase
P11	Siltstone	*Cambissolo Háplico Ta Eutrófico* típico	Eutric Cambisol (siltic)	Increase
P12	Siltstone	*Argissolo Vermelho-Amarelo Eutrófico* típico	Haplic Luvisol (loamic)	Decrease
P13	Gneiss	*Chernossolo Argilúvico* Órtico *típico*	Haplic Phaeozem (clayic)	Increase
P14	Gneiss	*Chernossolo Argilúvico* Órtico *típico*	Haplic Phaeozem (loamic)	Increase
P15	Gneiss	*Cambissolo Háplico Tb Distrófico léptico*	Leptic Cambisol (loamic)	Increase
P16	Gneiss	*Chernossolo Argilúvico* Órtico *típico*	Haplic Phaeozem (loamic)	Increase
P17	Granite	*Neossolo Regolítico Eutrófico solódico*	Sodic Regosol (loamic)	Increase
P18	Gneiss	*Neossolo Regolítico Eutrófico típico*	Eutric Regosol (arenic)	Increase
P19	Gneiss	*Planossolo Nátrico Sálico típico*	Salic Solonetz (loamic)	Increase
P20	Gneiss	*Neossolo Quartzarênico* Órtico *êutrico*	Eutric Arenosol (arenic)	Increase
P21	Syenite	*Cambissolo Háplico Tb Eutrófico* típico	Eutric Cambisol (loamic)	Increase
P22	Syenite	*Neossolo Litólico Eutrófico fragmentário*	Eutric Leptsol (loamic)	Increase
P23	Syenite	*Argissolo Vermelho-Amarelo Distrófico abrúptico cambissólico*	Abruptic Acrisol (loamic)	Increase
P24	Gneiss	*Luvissolo Crômico* Órtico *típico*	Chromic Luvisol (loamic)	Decrease
P25	Granite	*Neossolo Regolítico Eutrófico solódico*	Sodic Regosol (arenic)	Increase

[1] P01-P12 (Guerra, 2015) and P13-P25 (Santos, 2015); the order of the profiles presented here is not the same as the theses. Match (paper/theses). In Guerra (2015), P01 = P03, P02 = P02, P03 = P05, P04 = P06, P05 = P08, P06 = P09, P07 = P10, P08 = P11, P09 = P12, P10 = P13, P11 = P14, P12 = P15. In Santos (2015), P13 to P25 corresponds P01 to P13 in the thesis. [2] Santos et al. (2013). [3] IUSS Working Group WRB (2015). [4] Profile classification was corrected in relation to the thesis (Guerra, 2015).

The bulk density (Bd) was determined by the volumetric ring method. After measuring the dry mass (dm) and volume (dv) of the material, the bulk density (Mg m^{-3}) was calculated by equation 1:

$$Bd\,(Mg\,m^{-3}) = \frac{dm}{dv} \qquad \text{Eq. 1}$$

It is worth noting that for profile 21 (P21) there is no result of bulk density for saprolite.

The particle density (Pd) was determined in Santos (2015) by the alcohol volumetric method (Claessen, 1997) and in Guerra (2015) using the helium pycnometer method (Danielson and Sutherland, 1986). The total porosity (TP) was estimated from the values of the bulk density (soil or saprolite) and the particle density (Pd) by the equation 2:

$$TP\,(\%) = \left(1 - \frac{Bd}{Pd}\right) \times 100 \qquad \text{Eq. 2}$$

The selective extractions of iron were done with the dithionite-citrate-bicarbonate (Fe$_{DCB}$) and the ammonium oxalate (Fe$_{OA}$) methods described in Mehra and Jackson (1960) and
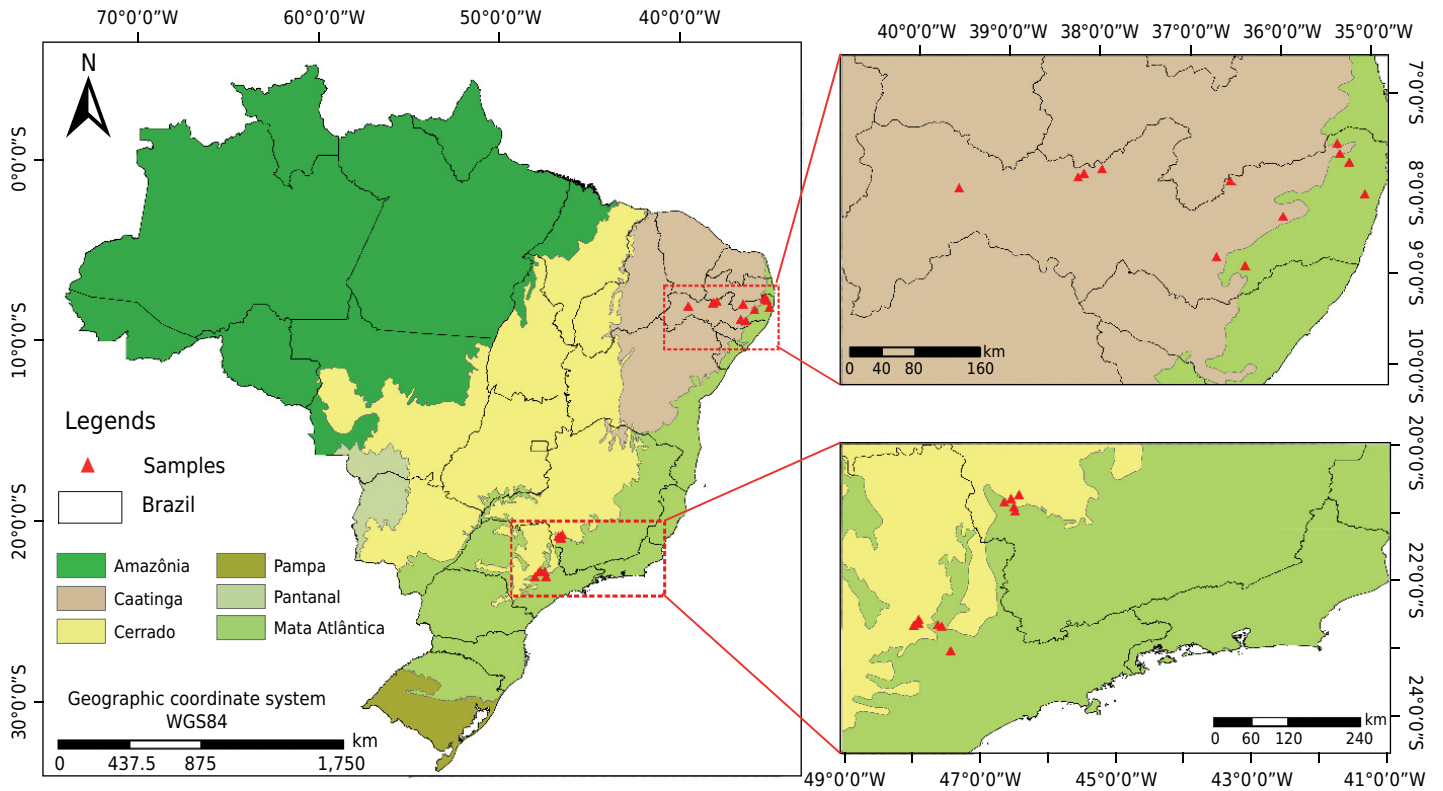
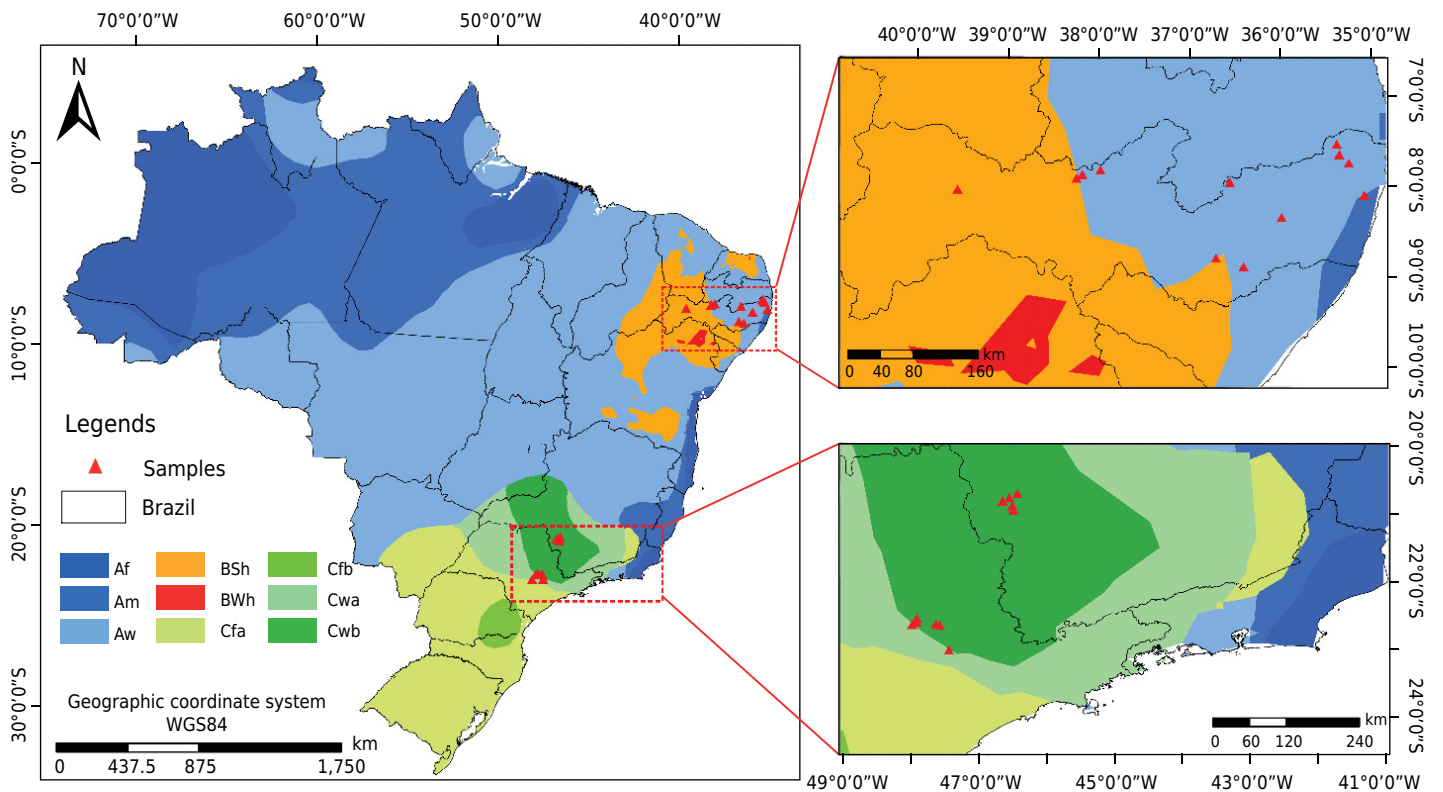**Figure 1.** Profile of the Brazilian biomes (IBGE, 2004).

Figure 2. Profiles location and climate types in the two regions sampled. Af – Tropical rainforest climates; Am – Tropical monsoon climate; Aw – Tropical savanna climate; BSh – Hot semi-arid climate; BWh – Hot desert climate; Cfa – Humid subtropical climate; Cfb – Oceanic climate; Cwa – Humid subtropical climate; Cwb – Subtropical highland climate (Peel et al., 2007).

McKeague and Day (1966), respectively. The total elements (Fe_2O_3; Al_2O_3; CaO; MgO; K_2O; Na_2O; P_2O_5; and TiO_2) were determined by digestion with acids (HNO_3 and $HClO_4$) and the elements were determined by mass spectrometry (ICP-MS) in the extract.

Data analysis

The decision tree algorithm used the recursive partition method and the Deviance function from the R software library (Ripley, 2016). The algorithm provided a cutting value to split the initial set of samples into two subsets, and a looping procedure further splits each sub-set into two sub-sub-sets and so on, until a limit value is reached or a single object remains in the set. Metaphorically, the method splits the data as a tree splits from the trunk towards the branches and leaves. At each step, the procedures identify a variable and a cutting value that maximize an impurity measurement (Rodrigues, 2005).

RESULTS AND DISCUSSION

The variables that contribute most to group the samples into subsets were Bd, Fe_{DCB}/Fe_{OA}, MgO, CaO, TP, and P_2O_5 (Figure 3).

Main variable

The most important variable was bulk density (Bd) which alone explained 81 % of the sample clustering, that is, bulk density was the variable that best fit the pedologists criteria to decide the place of the soil-saprolite boundary (Tables 2 and 3).

Saprolites usually have greater bulk density than soil (Oliveira, 2012) (Figures 3 and 4a), because saprolites tend to be less porous, have less organic carbon, and are also compressed by the weight of the overlaying soil. However, in the present paper, we found profiles in which the saprolite density was smaller than the soil density. In all cases, these profiles had a textural horizon (Table 2 and Figure 4b). The probable origin of the term "saprolite" dates back to the 19st century when Becker (1895) defined it as "the non-transported weathering product which has very little or none loss of volume as related to the original rock". By this concept, the solid phase saprolite is both the residual and neoformed material, and the associated porous system (Calvert et al., 1980; Kretzschmar et al., 1997), resulted from rock weathering. Since the volume is maintained (isovolume) the loss of mass during the alteration of minerals imply in a decrease in bulk density and increase in the porous system (Costa and Cleaves, 1984). The further loss of isovolume in saprolites may occur both by collapse of the saprolite volume due to the overgrowth of the porous system beyond its capacity to sustain the weight of its own weight and of the soil column above it; or by expansion due to the formation of peds and increase in organic carbon (Stolt et al., 1991).
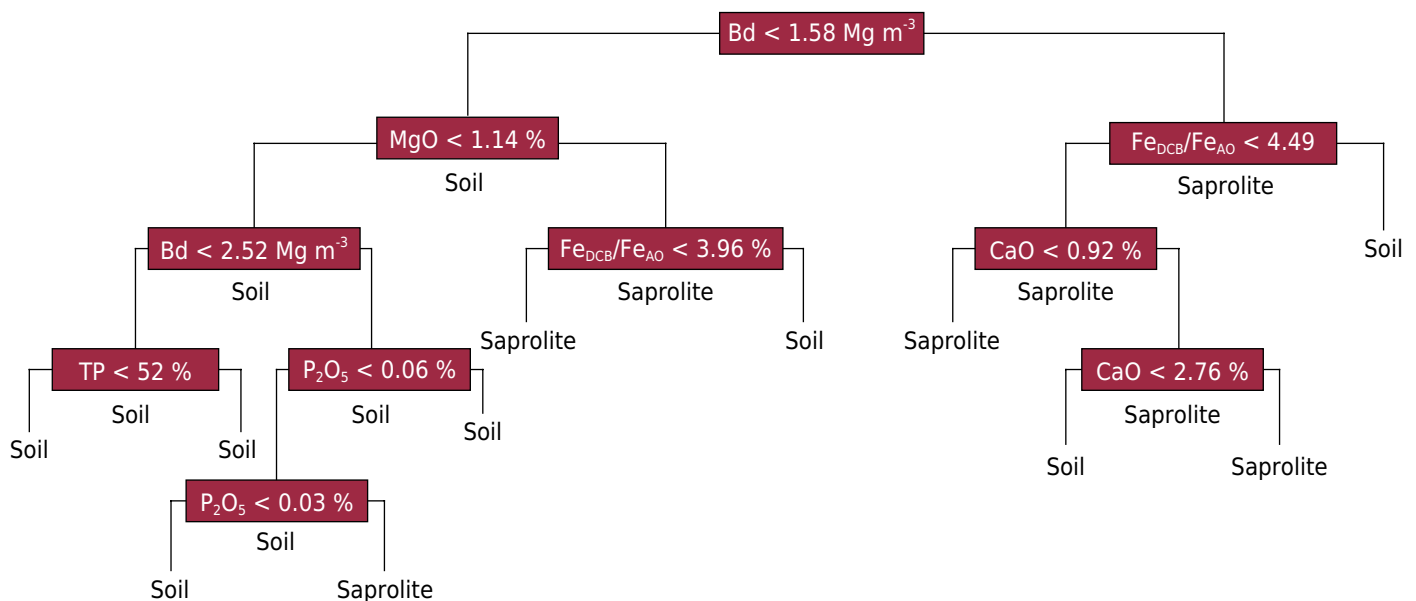

Figure 3. Decision tree scheme for the samples and cutting values of subsets.

Table 2. Bulk density along the regolith profiles in the Southeast (Guerra, 2015)

Profile	Horizon	Bd	Profile	Horizon	Bd	Profile	Horizon	Bd
		Mg m^{-3}			Mg m^{-3}			Mg m^{-3}
P01	A	1.19	P02	A	1.07	P03	A	1.35
	Bi	1.42		Bt	1.32		BA	1.63
	C	1.34		C	1.33		Bt	1.47
	CR	1.59		CR	1.06		C	1.37
	RC1	1.73					CR1	1.23
	RC2	1.73					CR2	1.10
P04	A	1.46	P05	A	1.38	P06	A	1.27
	BgA	1.53		BA	1.56		Bt1	1.48
	Btg1	1.70		Bt1	1.57		Bt2	1.37
	Btg2	1.73		Bt2	1.45		CBt	1.39
	CR1	1.55		C	1.47		C1	1.28
	CR2	1.51		CR1	1.58		CRC	1.19
	CR3	1.42		CR2	1.68		RC1	1.27
P07	A	1.46	P08	A	1.44	P09	A	1.46
	Bi	1.45		Bi	1.37		Bi	1.55
	C1	1.49		C	1.39		BC	1.60
	C2	1.63		CR	1.55		CR1	1.68
	C3	1.66					CR2	1.75
	CR	1.63					CR3	1.72
P10	A	1.25	P11	A	1.32	P12	A	1.38
	Bi	1.50		Bi	1.36		E	1.56
	C	1.47		CR	1.22		Bt	1.61
	CR	1.53		RC	1.37		BC	1.48
	RC	2.38					BC	1.52
							CR1	1.55

Bulk density determined by the method of the volumetric ring and paraffin-shaped fragment (Teixeira et al., 2017). Bd = bulk density.

For the sake of simplicity, soil materials were named "horizons" and saprolite materials, "layers". The 81 % agreement obtained using only Bd (first node of the decision tree) means that it missed 15 horizons and 11 layers, from a total of 88 horizons and 49 layers (Figure 5).

The use of the variables of the three first nodes (Bd, Fe_{DCB}/Fe_{OA}, and MgO) increased the agreement only by 4 %, that is, up to 85 %, missing 7 horizons and 5 layers (Figure 5). Using all the nodes/variables (Figure 3), the final percentage of agreement between the tree and the pedologists were 93 %.

Most of the samples in disagreement were from metamorphic rocks, particularly schists (Table 1). This suggests that it was more difficult for the pedologists to maintain their criteria when judging saprolite materials inherited from rocks with heterogeneous structure. As Price and Velbel (2003) pointed out, saprolitic materials evolved from heterogeneous rocks are also heterogeneous, entangling the judgement.

Despite these difficulties, the Fe_{DCB}/Fe_{OA} ratio and Bd, taken together, resulted in an error in only three samples, when considering the gneisses. These profiles have in common thinner soil-saprolite transitions, all at depths smaller than 1.00 m. This observation suggests that the contribution of the Fe_{DCB}/Fe_{OA} ratio depends on the degree of weathering/pedogenesis and the abundance of Fe in the parent material.

Table 3. Bulk density along the regolith profiles in the Northeast (Santos, 2015)

Profile	Horizon[1]	Bd	Profile	H/L	Bd	Profile	Horizon	Bd
		Mg m⁻³			Mg m⁻³			Mg m⁻³
P13	Ap	1.27	P14	Ap	1.29	P15	A	1.45
	A2	1.33		Bt	1.32		Bi	1.47
	Bt	1.30		Cr1/S	1.65		Sr1/SC	1.68
	C	1.69		Cr2/SR1	1.71		Sr2/S	1.71
	Cr1/SC	1.72		Cr3/SR2	1.82			
	Cr2/SR	1.81						
P16	Ap	1.31	P17	A	1.49	P18	A	1.55
	Bi	1.36		AC	1.38		AC	1.50
	Sr1/SC	1.42		C1	1.44		C1	1.55
	Sr2/S1	1.73		C2	1.47		C2	1.56
	Cr3/S2	1.76		C3	1.50		C3	1.52
				Cr1/Cr	1.56		Cr/CS	1.59
				Cr2/CS	1.61			
P19	Ap	1.75	P20	Ap	1.44	P22	Ap	1.57
	2Btn	1.73		AC	1.41		Cr1/S	1.72
	2Cn	1.78		CA	1.46		Cr2/SR	1.69
	2Crn1/Sn1	1.92		C1	1.45		Cr3/RS	1.74
	2Crn2/Sn2	1.89		C2	1.46			
				C3	1.47			
				Cr1/SC1	1.72			
				Cr2/SC2	1.76			
				Cr3/S	1.74			
P23	A	1.44	P24	A	1.41	P25	A	1.29
	Bt1	1.55		2Bt	1.44		AC	1.41
	Bt2	1.53		2BC	1.78		C1	1.42
	BC	1.56		2Cr1/CS	1.74		C2	1.49
	Cr/CS	1.62		2Cr2/SC	1.79		Crn1/Cm	1.53
							Crn2/CSn	1.55

[1] The horizons of the saprolite were denominated according to the proposal of the studies by Gullà and Matano (1997), Pedron (2007), and Borrelli et al. (2014). R - unchanged rock; RS - little altered rock; SR - moderately altered rock; S - intermediately altered rock; SC - very altered rock; CS - extremely altered rock; Cr - completely altered rock. Bulk density (Bd) determined by the method of the volumetric ring and paraffin-shaped fragment (Teixeira et al., 2017).
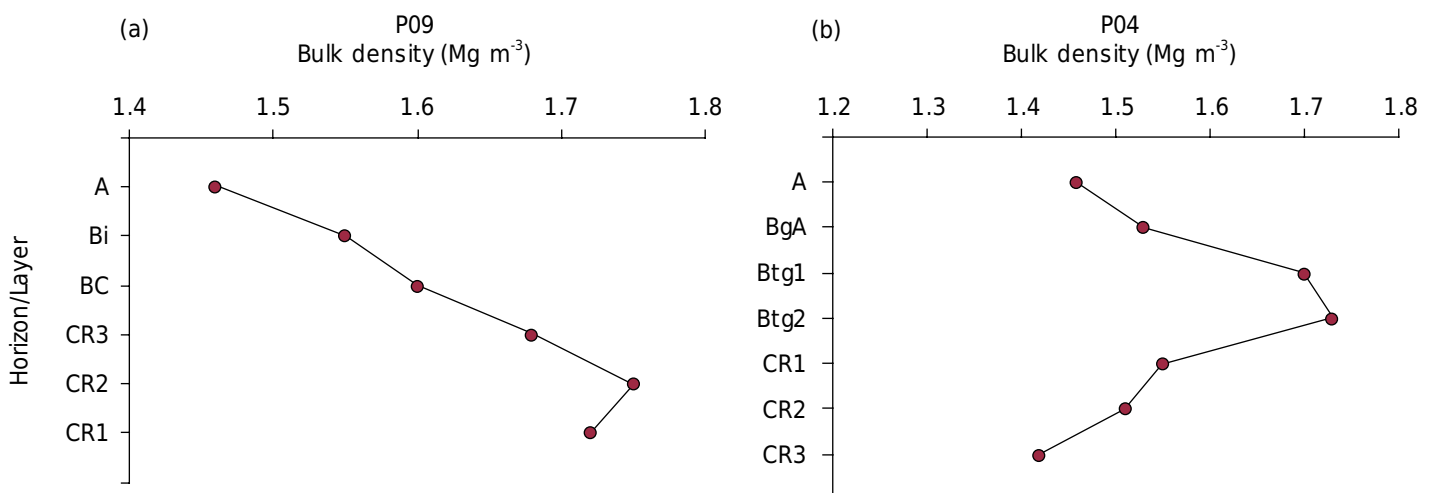
Figure 4. Representative of the group of profiles where the density increases at the soil-saprolite boundary (a) and profiles where the density decreases at the soil-saprolite boundary (b).
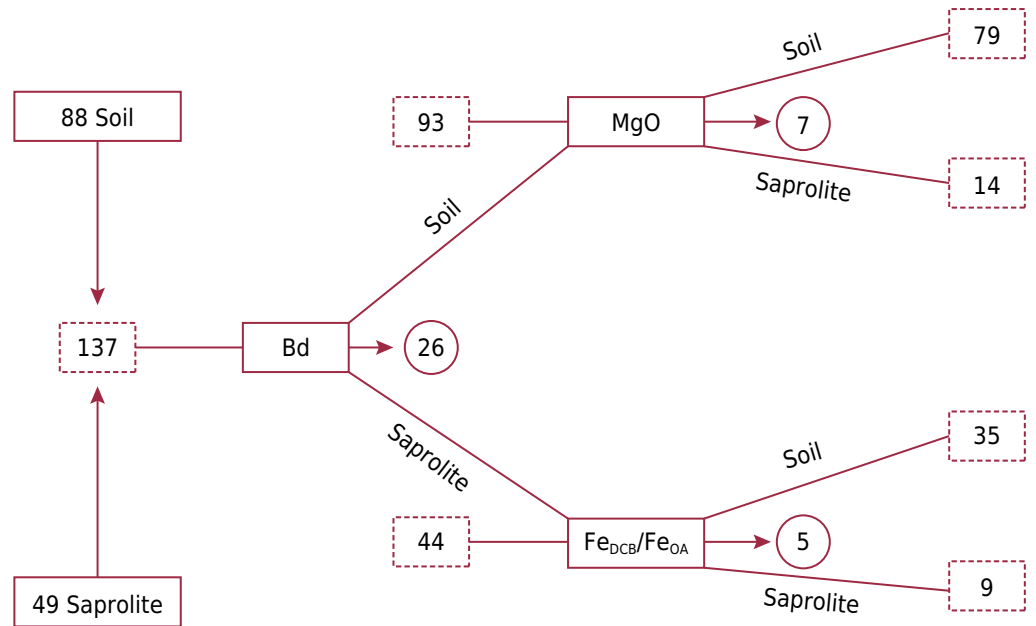
Figure 5. The decision tree output: total number of horizons/layers considered at each node (shaded rectangles), variable considered in the node (continuous rectangles) and number of horizons/layers in disagreement (circles).

Secondary variables

The variables other than Bd were considered secondary due to the much smaller contribution they did to the overall agreement between the pedologists and the decision tree (Figure 3).

The total magnesium content (MgO) and the Fe_{DCB}/Fe_{OA} ratio increased only 4 % the agreement between pedologists and the decision tree (from 81 to 85 %), figure 4. The use of variables, such as MgO, is very dependent on the parent material composition. On the other hand, because the ammonium oxalate (Fe_{OA}) solubilize preferentially the less crystalline oxides (Schwertmann, 1973), and the DCB (Fe_{DCB}) the pedogenic ones (Mehra and Jackson, 1960), the ratio between the two is less dependent of the total amount of iron.

The fast precipitation of iron during the weathering of iron bearing minerals at the weathering front tends to produce less crystalline oxides, which further, during the pedogenesis, tend to reorganize themselves in more crystalline forms. Therefore, the Fe_{DCB}/Fe_{OA} ratio tends to increase as the profile evolves (Stolt et al., 1991; Pedron et al., 2015).

CONCLUSIONS

The decision tree methodology allowed to estimate the best variable to separate soil from saprolite under the conditions of the present study was the bulk density of materials. This variable alone explained 81 % of the grouping of materials (soil/saprolite) performed by pedologists. The improvement brought by all the variables studied in this mathematical model resulted in 93 % agreement with the logic adopted by pedologists.

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