Chapter 19
Using Soil Depth Functions to Distinguish Dystric from Xanthic Ferralsols in the Landscape

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Abstract The soil texture is a key parameter and is widely used as input in predictive models to estimate other soil properties. The general goal was creating numerical parameters to describe the variability of soil particle size (sand, silt, and clay) components using continuous depth functions to characterize Ferralsols from Guapi-Macacu watershed in Rio de Janeiro State (Brazil). The profile collection comprises fifteen profiles, seven classified as Haplic Ferralsols (Dystric) and eight as Haplic Ferralsols (Xanthic). The analysis was performed in the R software through "aqp" package (Algorithms for Quantitative Pedology) and using equal-area quadratic spline function. A numerical aggregation of soil texture components was used to build a mean, a median, and spline depth functions, fitting the dataset to six predefined depths (GlobalSoilMap project) and to most-likely horizon depths. The analysis revealed sand and silt content with decreasing values with soil depth and the opposite trend for clay. The topsoil layer (0–30 cm) had

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dominantly a clay loam texture (32–40 % clay; 49–53 % sand; and 15–20 % silt). The most-likely diagnostic B-horizon (45–150 cm depth) presented clayey texture (43–47 % of clay and 40–55 % of sand). Ferralsols usually have low silt contents; and the silt range was from 10 to 20 % in the soil profile collection. The organized data can be useful to many purposes, including profile database harmonization and soil classification.

Keywords Soil depth functions · Soil texture components · Digital mapping of soil properties · Spline · Algorithm for quantitative pedology

19.1 Introduction

Ferralsols have a large distribution in Brazil covering almost one-third of the territory and are important for agriculture and pasture production (Dick et al. 2005). The mineralogy of these soils is mainly composed of low activity clays (kaolinite) and Fe and Al-oxides (hematite, goethite and gibbsite); thus, they have a low cation exchange capacity (Sposito 1989; Santos et al. 2013). The soil profiles are in general deep and they have a well-developed soil structure, showing yellowish and reddish colors indicating good drainage conditions.

The soil texture, or composition of mineral particle size, is a highly variable soil physical characteristic, which has an essential role for growing crops, engineering projects, and land protection and conservation. The effects of the soil texture on land capability, storage of water and nutrients, distribution and composition of vegetation are well known globally (Klingebiel 1963; Jenny 1980; Silver et al. 2000; Fernandez-Illescas et al. 2001). The soil texture information is a key parameter widely used as input in predictive models to estimate hydrologic parameters (Thompson et al. 2012). Due to those facts, digital soil mapping (DSM) efforts have been made to obtain information about soil particle size fraction distribution (Moore et al. 1993; Arrouays et al. 1995; McBratney et al. 2000).

Field evaluation of a soil profile and the description of horizons/layers are usually performed according to morphological characteristics related to pedogenetic processes (alteration of parental material, eluviation/illuviation of clay, organic matter and salts distribution, hydromorphic features, iron content, among others). In the soil surveys, the information and data from soil evaluation are related to narrative, tabulated, or presented in sketches drawings. However, the lack of data standardization and quantitative parameters turns it difficult to transmit the information to other users (Beaudette et al. 2013).

The organized data can be useful to many purposes; however, the analysis of large soil profile collections is affected by changes in soil classification over time and among taxonomic systems, regardless of standard soil data issues and differences of analytical procedures. Addressing the issue of variability of soil properties along profile depths, the global consortium of soil survey (GlobalSoilMap project) proposed standard intervals to compound the database of soil properties (Hartemink et al. 2010). The six predefined depths correspond to the following layers: 0–5, 5–15, 15–30, 30–60, 60–100, and 100–200 cm (Arrouays et al. 2014).

The general goal was creating numerical parameters to describe the variability of soil particle size (sand, silt, and clay) components using continuous depth functions to characterize Ferralsols from Guapi-Macacu watershed in Rio de Janeiro State (Brazil). The analysis comprised soil depth functions (spline and slicewise aggregation) and relations among soil texture components and diagnostic horizons. To accomplish the proposed goal, a numerical approach, fitting the dataset to predefined depths (GlobalSoilMap project) and according to most-likely inferred horizon depths, was applied aiming to set the representative functions and characterize the texture of soils studied in the watershed.

19.2 Materials and Methods

19.2.1 Study Area

The Guapi-Macacu watershed is located at southeast region of Brazil, in Rio de Janeiro State (Fig. 19.1). The climate is classified as tropical rainy with dry winter (Aw) according to Köppen classification (Köppen 1948). The mean temperature is 23 °C, with low temperatures in winter. The average annual rainfall exceeds

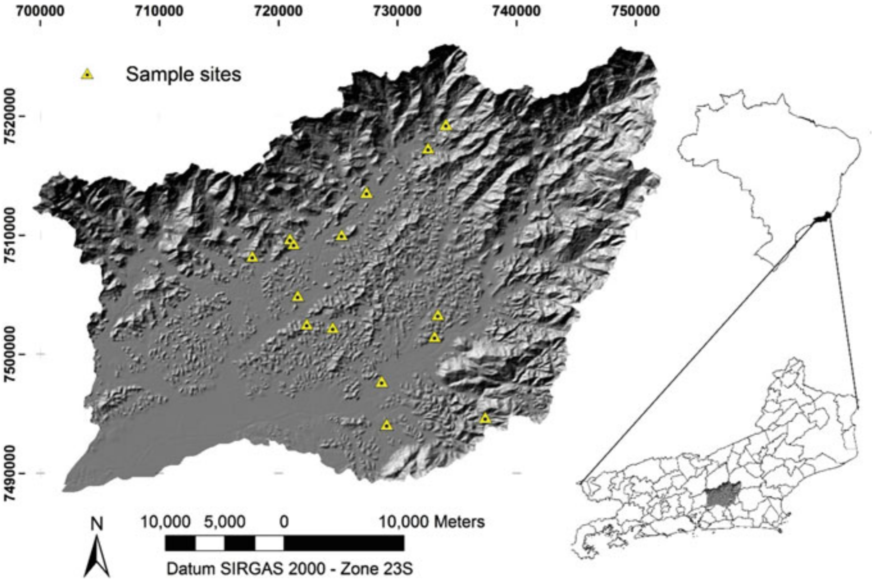

Fig. 19.1 Location of Ferralsols profiles in the Guapi-Macacu watershed, Rio de Janeiro (Brazil)

1200 mm, and it can reach 2600 mm in the watershed divisors (Projeto Macacu 2010; Dantas et al. 2008). The region is part of the Atlantic rainforest biome, with different types of natural vegetation, such as the altitude grasslands, dense forests, mangroves, swamps, and estuaries (Pedreira et al. 2009).

The maximum altitudes are observed in the escarpments of the "Serra do Mar," with gneiss/granite rocks as the predominant lithology. The transition area between the escarpment and the coastal plains, at sea level, comprises of a series of hills and slopes with elevations below 1000 m. Geologically, the region is located in the central portion of the Guanabara Graben, classified as Macacu Sedimentary Basin, formed by several depositional sequences from tectonic events in the early Tertiary (Ferrari 2001). The consequences of geological events that gave rise to the Guanabara Graben induced geomorphological features related to depositional events, such as alluvial fans and fluvial and lacustrine deposits.

The soils were surveyed in 2011 and 2012, and approximately one hundred soil profiles were described and collect. For this study, fifteen profiles of Ferralsols were selected from the collection. Figure 19.1 shows the location of Ferralsols profiles in the Guapi-Macacu watershed in Rio de Janeiro State, Brazil.

Total sand, silt, and clay contents were measured according to Embrapa (1997) procedures. The analytical results of particle size, corresponding to the depths described in the soil survey (genetic horizons), were used to identify the diagnostic horizons, and the soil classification was performed according to the Brazilian System of Soil Classification—SiBCS (Santos et al. 2013) and correspondent criteria in the World Reference Base for Soil Resources—WRB (IUSS Working Group 2014).

19.2.2 Soil Profile Data and Depth Functions

The dataset selected to perform the analysis comprises fifteen Ferralsols: seven profiles classified as Haplic Ferralsols (Dystric) and eight as Haplic Ferralsols (Xanthic). The statistical procedures were implemented in the R software (R Development Core Team 2013). The R program is an open source and free software. Operating procedures in this program are conducted by command lines (scripts) and require the prior installation of packages to read certain types of data and run specific analysis.

The analysis of the soil profile data comprises aggregation of profiles by soil texture properties by slicewise aggregation algorithm (Beaudette et al. 2013) and harmonization of soil depth by equal-area spline function (Ponce-Hernandez et al. 1986). The analysis by slicewise aggregation was performed using Algorithm for Quantitative Pedology (AQP) package, developed by Beaudette et al. (2013). The "aqp" stable version of the package is available on CRAN (http://cran.r-project.org/web/packages/aqp/). The aggregation algorithm allows the estimative of central tendency according to each depth slice (1 cm) and computing statistic for each segment, reconstructing the profile data at predefined depths, as a single "representative depth function" (Beaudette et al. 2013). Slicing the soil profiles in layers with 1 cm thickness allows calculating the average and median values of each layer as a vector of segment boundaries, allowing reassemble the average profile and the median, through the syntax below:

$$\text{slab}\ (\text{data},\ \sim\text{clay}\ +\ \text{silt}\ +\ \text{sand},\ \text{slab.fun} = \text{mean/median},\ \text{na.rm} = \text{TRUE})$$

A function to summarize soil texture data according certain depths can be extracted from the dataset created by slicing the soil profile in 1 cm layers. The aggregation of continuous data was based on the distribution of soil particle size fractions (sand, clay, and silt) at the predefined depths (0–5, 5–15, 15–30, 30–60, 60–100, 100–200 cm) and most-likely inferred horizon depths.

Soil depth functions were applied to fit the data to the proposed intervals, which act as coefficients for a spline function. The spline function proposed by Ponce-Hernandez et al. (1986) represents a nonparametric function, called an equal-area spline, appropriated to model soil attributes (Bishop et al. 1999; Malone et al. 2009). The function equal-area spline considers each horizon as the predefined interval and the knots of each horizon lie between horizon boundaries, with one inflexion in each interval. The knots should lie as near as possible to the inflexion and as far of boundaries as possible, which in essence, preserve the mean value of the soil property. In this sense, the area at left of the fitted curve above the horizon mean value is the same than the area at the right of the spline curve, below the horizon mean (Odgers et al. 2012). This mechanism provides continuous values to soil properties varying according to the depth in a soil profile, which allows compose a database where all points can have a value in a certain depth.

The slicewise aggregation algorithm was applied to create a new dataset from the original profile collection to support soil depth functions analysis, allowing to distribute the data by one-centimeter layers and posteriori aggregation by horizons/layers. This algorithm is based on the premise: "*a representative depth function for some soil property (e.g., clay content) can be generated from a collection of soil profiles by summarizing this property along depth slides*" (Beaudette et al. 2013). In this sense, depth-slice probabilities were generated based on data frequency by major horizon (most-likely horizon depth), revealing quantitative trends of the soil texture components according Ferralsols profiles horizons. The probabilities for each slice (1 cm) are syntax:

$$S_{k.i} = \text{frequency}\ (S_{k.i})/j;$$

where "$S_{k.i}$" corresponds to the inferred value of the soil property to each 1 cm slice, and "k" is the class of the categorical variable (sand, silt, and clay), "i" is the slice counter and "j" is the number of profiles contributing to the calculation.

19.2.3 Similarity Between Soil Profiles

The pairwise similarity between soil profiles was based on soil classification diagnostic criteria, where a quantitative comparison between soil profiles must account the variability of diagnostic horizons thickness associated with soil properties (Webster and Oliver 1990). The regular layer slices of the dataset allow calculating the dissimilarity between profiles, comparing then through a dissimilarity matrix for each depth slice (Beaudette et al. 2013). A dissimilarity between Ferralsols was computed using "profile compare ()" function considering sand, clay, and content to a maximum depth and depth-weighting coefficient of 0.01. The contributing fraction values returned for each depth slice describe the number of soil profiles used in the computation and that value can be understood as an aggregate measure of soil depth probability.

A function to rendering soil profiles in simple sketches was applied using "profile plot ()" function, turning the visualization and comparison between taxonomic relationships based on the soil profiles' properties easier to observe and analyze (Beaudette et al. 2013).

19.3 Results and Discussion

19.3.1 Characterization of Ferralsols and Soil Texture Data

The Guapi-Macacu watershed presented substantial variability of soils, predominantly Ferralsols (28 %), Acrisols (24 %), Cambisols (18 %), and Gleysols (15 %). Haplic Ferralsols (Xanthic)—FRxa and Haplic Ferralsols (Dystric)—FRdy represent the Ferralsols, which showed a wide distribution with 58 and 41 % of the soil observations in the watershed (Pinheiro et al. 2013). The main taxonomic difference between these classes is expressed by the color criteria, which reflect differences in the clay mineralogy and moisture regime, where Xanthic soils have greater content of hydrated Fe-oxides (goethite), and Dystric soils have more hematite and better soil drainage. These differences are generally related to landscape features, hydrological conditions, and parental material.

Haplic Ferralsols (Dystric) are largely observed under pasture and Atlantic rainforest, in varied slope conditions but predominantly in less hilly areas. In the mountainous areas, these soils occur in association with regosols and cambisols. Haplic Ferralsols (Xanthic) commonly occupy the footslopes of the watershed. Such soil sequence is typical in the east and south of the watershed, along a band of NE-SW-oriented gneiss rocks of Precambrian age. Besides their occurrence at the lower part of hills with granite/gneiss parental material, Haplic Ferralsols (Xanthic) were also observed related to sedimentary rocks, in the Southeast areas of the watershed. The Haplic Ferralsols (Xanthic) land coverage is usually of grassland, secondary forest vegetation, and urban areas.

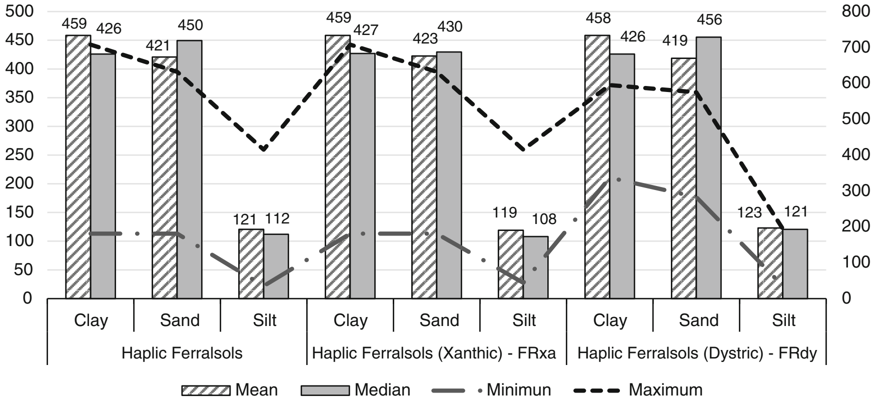

Fig. 19.2 Distribution of minimum, maximum, mean, and median values of particle size components in the Ferralsols profiles (scale at *left* side is representing the mean/median values; and at *right* side, the minimum/maximum values)

From the soil survey dataset, fifteen chosen Ferralsols had all horizons described, sampled, and the particle size analyzed; thus, the dataset (70 horizons) presented no missing data. Based on the selected dataset, soil depth functions were created and further analysis was performed. The descriptive values to the soil texture, of the seven profiles (30 horizons) of Haplic Ferralsols (Dystric) and eight profiles (40 horizons) of Haplic Ferralsols (Xanthic), are presented in Fig. 19.2. Observing the trends of minimum and maximum values, all Ferralsols have the same patterns and they show high clay content, followed by sand and silt (scale on the right side of Fig. 19.2).

In general, the Dystric Ferralsols showed less amplitude of values to all particle size components when compared with the Xanthic Ferralsols. Regarding the clay content, Ferralsols Xanthic and Dystric showed no difference among them; however, both soil types had higher values to the mean when compared with median parameter. Sand content had slightly smaller values compared to clay for all Ferralsols, and the same pattern was observed for both classes (FRxa and FRdy), with median higher than mean values. Silt was the fraction with less contribution in the particle size of Ferralsols, and the values were also similar among soil classes.

Summarizing, Fig. 19.2 shows that both Ferralsols classes are similar regarding the particle size components, although the mean and median values for sand and silt contents were slightly higher in the Haplic Ferralsols (Dystric)—FRdy. Further analysis, based on the vertical distribution of particle size in the soil profile through the soil depth functions, is needed to separate these classes quantitatively.

The visualization by standard sketches allows detecting similarities/dissimilarities among the soil profile collection, as observed in Fig. 19.3a, b. The P72 and P89 revealed a similar trend of particle size along the soil profiles in addition to the profiles P84 and P86, which also showed high content of clay and low values of sand. This kind of approach can be useful to support the

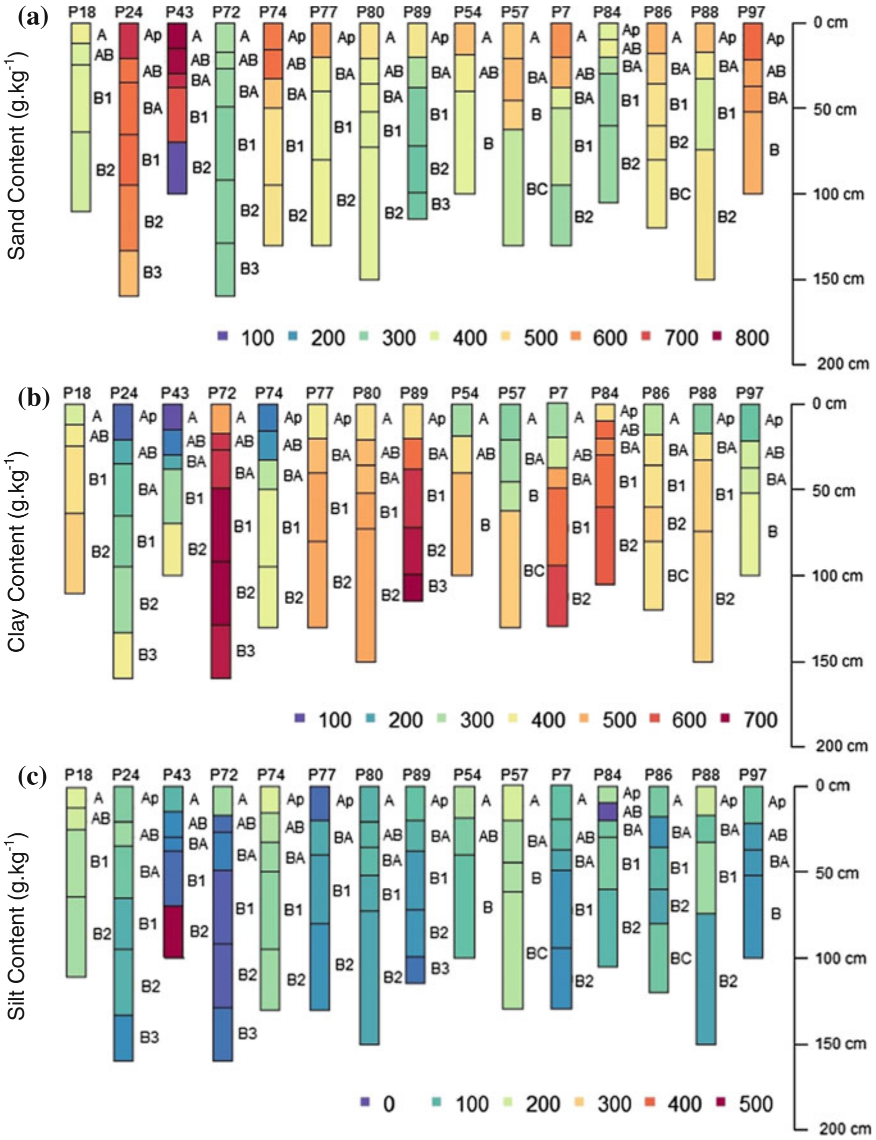

Fig. 19.3 Sand, clay, and silt distribution of Ferralsols profile collection

definition of lower taxonomic levels in soil classification (families and series), or even to define typical soil sequences based on relief, time, and parental material (toposequences, chronosequences, and lithosequences, respectively).

Sketches representing soil properties observed in the field are widely used and a very useful tool to soils scientists, particularly to report soil stratigraphy (horizons and transitions) and morphological features (Beaudette et al. 2013). However, those plots are not to scale and without standard legends and symbols; thus, they are subjective and not easily transmitted to other researchers and users in general. The distribution of sand, clay, and silt in the Ferralsols, according to horizon depth, is illustrated in Fig. 19.3. The sketches of profiles highlight the particle size components (sand, clay, and silt) in classes of 100 g kg^{-1} intervals (Fig. 19.3a–c). As expected, the deeper soils show more homogeneous texture composition along the profile (P24, P72, P74, P77, P80, P7, and P88), showing a sequence of overlaid B-horizons with smooth transitions. On the other hand, the shallowest profiles show remarkable differences between horizons, and when compared with the "modal" profile referred in soil classification systems, this pattern is related to the granite/gneiss parental material properties.

Looking at dissimilarities, an example is the profile P43, which is shallow compared to the other soils and shows the lowest values of sand content in contrast with the highest values of silt. Further investigation is needed, but a reasonable explanation is the local influence of parental material, which is corroborated by the thickness of soil profile. Regarding soil classification systems, this spline approach could be useful to set regional series or family of soils; or to propose new criteria to describe the soil series, which is a way improving the information associated with soil mapping units and their design.

19.3.2 Soil Depth Functions and Data Aggregation

Analysis of Profile Data (Components of Texture and Relation with Horizon Depth)

Corroborating the field observations and the characterization of the particle size in the soil horizons, sand and silt content in the Ferralsols tends to decrease with depth up to 100 cm (Fig. 19.4) which is within the control section used to define the diagnostic horizons. However, the clay content shows a distinct increase around 20 cm, which is usually the transition from the A to B-horizon. This trend was noticed particularly on the Haplic Ferralsols (Dystric), as observed in Fig. 19.4c. The Haplic Ferralsols (Dystric) have also a small contribution of profiles deeper than 150 cm depth to compound the estimative of a median profile at this depth, less than 14 % of the dataset. This can be related to the conditions of occurrence of these soils, particularly related to steep slopes in the mountainous areas of the watershed, inhibiting the formation of typical deep weathered B-horizons. Some of the Haplic Ferralsols (Dystric) showed a transitional BC horizon, in the sampled depth, similar to the one in the Haplic Cambisols (Dystric), but differing mainly in smaller content of easily weatherable minerals (biotite, montmorillonite, and feldspar).

Regarding soil depth and silt content relation, high silt values were observed in the 0–25 cm depths (Fig. 19.4). Haplic Ferralsols (Xanthic) also presented subtle increases in median silt values related to 70–100 cm depth, probably related to transition between horizons in the soils developed from colluvium deposits

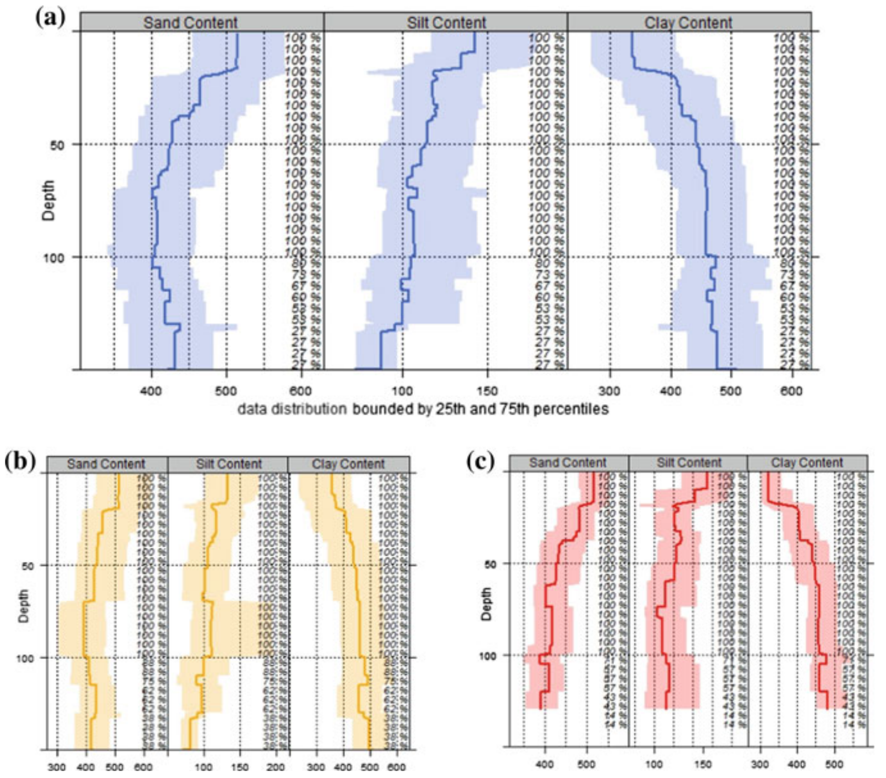

Fig. 19.4 Median distribution of sand, silt, and clay content along profile depth; **a** Ferralsols collection (15 Profiles); **b** Haplic Ferralsols (Xanthic); **c** Haplic Ferralsols (Dystric)

originated from the granite/gneiss materials. The variability in silt content, particularly below 80 cm depth, can also be correlated to parental material. The presence of BC horizons starting at this depth (80 cm) was observed in two soil profiles, both classified as Haplic Ferralsols (Dystric). The analysis of the graphs reveals how many profiles from the dataset were contributing to calculate the parameters, which give important information about the original dataset.

At the bottom of the soil profile (below 150 cm), the data contributing to the calculation were less than 27 % of the entire collection, which reduces the confidence of the estimative for the Haplic Ferralsols (Dystric). However, the soil information applied to orient land use and for taxonomic purposes is usually obtained to a depth of 1.5 m, where the subsurface diagnostic horizons express themselves in most soil classes (*solum*).

For comparative purposes, a harmonization of the dataset was performed based on the six predefined depth intervals suggest by the GlobalSoilMap project (Arrouays et al. 2014). According to Bishop et al. (1999), equal-area spline functions showed superiority over other soil depth functions (exponential, polynomials)

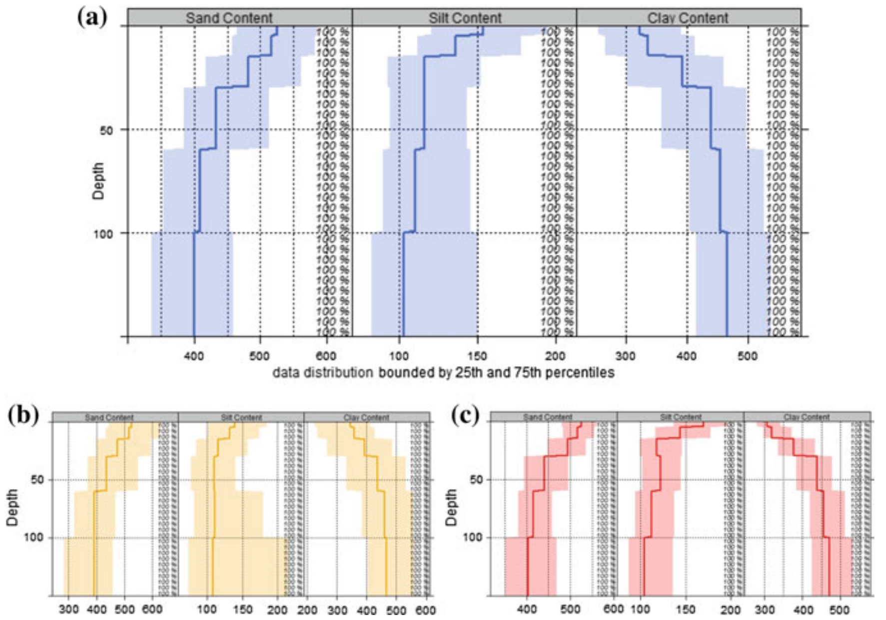

Fig. 19.5 Distribution of sand, silt, and clay content according spline depth function fitted to predefined depth; **a** Ferralsols collection; **b** Haplic Ferralsols (Xanthic); **c** Haplic Ferralsols (Dystric)

to predict the soil properties pH, clay content, water content. Thus, the spline function was applied to harmonize the data in six layers (Fig. 19.5).

The spline functions reveal the same trend for the components, in both soil classes, with values of sand and silt decreasing with depth, while the clay content increases (Fig. 19.5). Observing the Haplic Ferralsols (Dystric), there is a remarkable difference in texture component (mainly, sand, and clay content) below 30 cm depth, when compared to Haplic Ferralsols (Xanthic) in which the changes in soil properties are smoother along the soil profile.

Most-Likely Diagnostic Horizons Probability as a Function of Particle Size Data

The most-likely horizons based of the frequency of particle size data from Ferralsols profile collection are presented in Fig. 19.6. The six columns on the left of Fig. 19.6 represent individual probability per horizon, identified with a black line representing the most-likely (i.e., modal) horizon, and the red line corresponds to the horizon probability fitted to the dataset, considering the contributing factor to each depth. On the right side of Fig. 19.6, the horizons are represented by assorted colors and plotted in a single column.

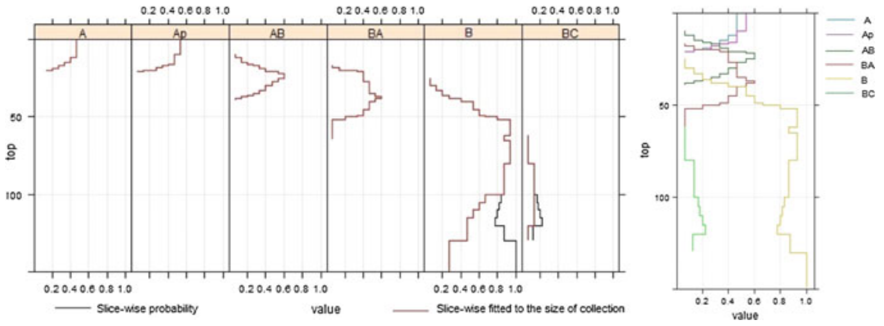

Fig. 19.6 Probability of most-likely horizon depths by slicewise aggregation technique

The A and Ap horizons have similar thickness pattern, both up to 10 cm depth. However, Ap horizons have a tendency of being shallowest, mostly due to erosion favoured by the slope (degree and form) and land use observed in the area. Below 10 cm, the occurrence of transitional horizons (AB, BA) was observed, with peaks of occurrence around 20 cm for AB and 40 cm for BA, not necessarily occurring together in the profile. In the field, the transitional horizons were mostly separated based on color, structure, and biological activity, related to the organic material deposition in the topsoil layer. In general, the transitional horizons (AB, BA) occurred at the 20–30 cm depth.

According to the slicewise aggregation (Fig. 19.6), the Ferralsols diagnostic B-horizon was observed from 25 to 150 cm and below, in deep soil profiles with a sequence of B-horizons, always with the main diagnostic B-horizon in the 50–100 cm layer. Simultaneously, in this layer, transition BC horizons were found in two profiles: their presence is not common in Ferralsols and may imply a different response for soil management and hydrology, indicating a layer of impediment, such as shallow altered bedrock.

The slicewise probabilities organized by major horizon types can enhance the quantitative characterization of site patterns, such as topsoil thickness or presence of compact layers, bedrock contact, among other important terrain characteristics (Beaudette et al. 2013). For example, soil depth functions aggregated by horizon may help in establishing limiting values and standard deviation of collected data, assisting to create mean/median taxonomic sections; and allowing comparison with modal profiles, as described in the soil taxonomic systems (Pereira et al. 1984). Furthermore, this technique can be useful to compare soil data among profiles classified in different taxonomic systems.

The estimated horizon midpoint depth from Ferralsols profiles, as well the midpoint to clay, sand, and silt content related to the genetic horizons is presented in Fig. 19.7.

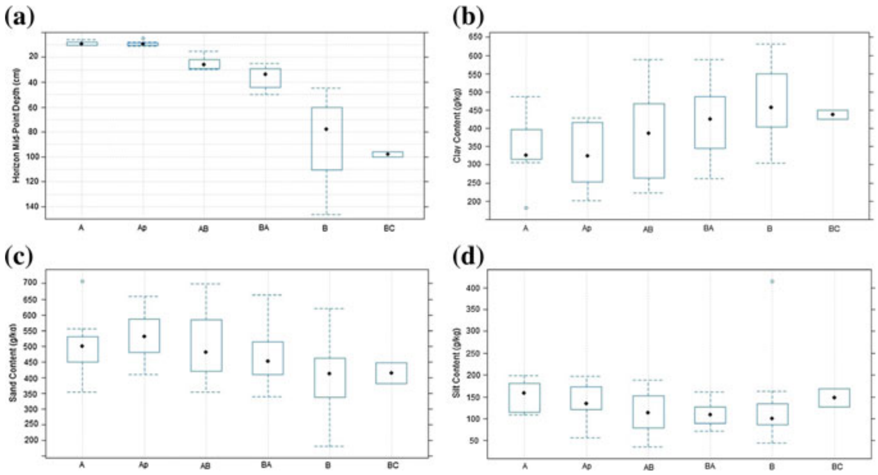

Fig. 19.7 Midpoint: **a** depth of horizons; **b** clay content; **c** sand content; **d** silt content

The boxplot graph for the horizons midpoint depth shows small differences for A and Ap horizons, since they occupy the same position in the profile (Fig. 19.7a). The transitional AB and BA horizons presented the midpoint depth closer to 25 and 30 cm, respectively, ranging between 15 and 45 cm. The generalized depth considering the consistence of data (frequency) is highlighted by the boxplot graph on 25–75th percentiles. The diagnostic B-horizons have the greatest range, mostly because the Ferralsols show a sequence on sub B-horizons (B1, B2, B3). All the estimative related to the BC horizon had contribution from two profiles of the entire dataset (less than 14 %), which means that BC is not commonly observed before the 200 cm depth.

Regarding the clay, sand, and silt contents, the distribution of the midpoints along the soil profile showed the same trends of median depth function (Fig. 19.4), where clay content slightly increases with the depth, in contrast to sand and silt. However, the boxplot graph (Fig. 19.7) better represents the range of values beyond the frequency of data. According to Fig. 19.7c, d, sand and silt content decreased with depth, although the variability of sand in the diagnostic horizons (A and B) was greatest. Generally, the AB horizon showed greater particle size variability, when compared with other horizons, even the BA, which by definition is similar to the B-horizon regarding to morphological properties.

Based on the analysis and observations from field survey, the most-likely horizon depth can be generalized as the following: A (0–15 cm), AB (15–30 cm), BA (30–45 cm), B (45–150 cm), and BC (85–200 cm). The superposition of B and BC horizons will be addressed by aggregation soil data with different depth intervals. Nevertheless, the lower probability of BC horizon occurrence has to be considerate based on the frequency of data from the collection.

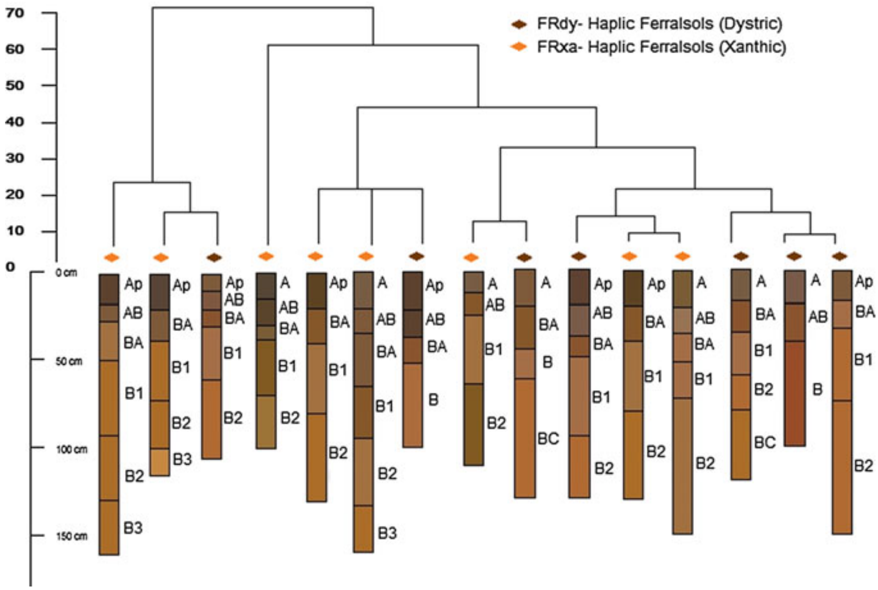

Fig. 19.8 Similarity among the fifteen Ferralsols from Guapi-Macacu watershed, Rio de Janeiro

Representative Soil Profile (Similarity and Variability of Soil Texture Parameters)

The comparison of the taxonomic classes can be based on similarity analysis between soil profiles through divisive hierarchical clustering, assuming that a soil order represents a large collection of profiles that can be split into smaller groups (Kaufman and Rousseeuw 2005; Beaudette et al. 2013). In this sense, dendrograms and sketches were created to compare the soil profiles supporting analysis of similarities and differences between the two Ferralsols taxonomic classes (Fig. 19.8). The horizontal axis (*X*) of Fig. 19.8 organizes the pairwise dissimilarities based on clay, sand, and silt contents, while the vertical (*Y*) represents the depths of horizons according to field soil horizon description. The upper scale on the left side corresponds to numerical dissimilarity based on sand, silt, and clay content.

The Haplic Ferralsols (Xanthic)—FRxa usually show deeper profiles than the Haplic Ferralsols (Dystric)—FRdy, in the data collection from the Guapi-Macacu watershed. In addition, FRxa showed a sequence of B-horizons, extending beyond 150 cm depth, with small variability of the particle size parameters. In contrast, FRdy presented shallowest profiles, in some cases, with BC horizon showing signs of the altered granite/gneiss parental material.

Analysis of similarity among profiles can contribute to quantitative comparison between soils and landscape conditions. In that way, it may be a useful tool to individualize taxonomic subgroups and review the outline and composition of soil mapping units; always supported by additional analyses due to the scale and regional characteristics of landscape. Quantitative methods based on soil profile characteristics (morphometrics), combined with terrain analysis could also improve the designation of criteria for family and series in taxonomic systems, such as in the Brazilian Soil Classification System, where these taxonomic levels are still undeveloped. Furthermore, this approach makes easier to include legacy data through the taxonomic correspondence to representative profiles, even with data from different classification systems.

The particle size parameters of "modal" Ferralsols in the Guapi-Macacu watershed, with values of mean, median, and harmonized (spline function) data, aggregated at predefined depths and as most-likely inferred horizon depths are presented in Table 19.1.

The Ferralsols topsoil layer can be generalized to the 30 cm depth, corresponding to the first three layers of harmonized dataset with GlobalSoilMap project (six predefined depths), and first two most-likely inferred horizon (corresponding to A/Ap horizons plus the transitional AB). Consequently, the subsurface horizon is placed from 30 to 150 cm depth, where the characteristics reflecting pedogenesis are more intensively expressed. In this sense, texture components as described by layers B1, B2, B3, and B4 (45–150 cm depth) are representing the modal B-horizon used as a diagnostic criterion to soil classification.

The soil properties values from the deepest layer in both aggregation procedures (150–200 cm) are representing less than half of dataset collection. Thus, the occurrence of a transitional horizon BC is considered, as well as, the probability of a sequence of B-horizons. Particular conditions of parental material exposure and landscape forms observed on the field survey were the main factors defining soil thickness.

The clay content in the topsoil layer (0–30 cm depth or A/Ap plus AB horizon) varies between 32 and 40 %, while sand values range from 49 to 53 % (less than 50 g kg^{-1} variation). The combination of soil particle size components shows dominance of clay loam texture in the Ferralsols topsoil layer. The transitional AB and BA horizons (15–45 cm depth) showed, in general, a slight increase in clay (around 3% more clay), with relative values ranging from 38 to 43 %. At the same time, sand values ranged from 49 (AB) to 42 % (BA), showing more variability in the transitional layers (around 7 %).

The diagnostic B-horizons had clay values clay from 43 to 47 % in the subsurface (45–150 cm). When a large sequence of B-horizons was observed, the clay values reached up to 50 % in the deepest horizons (below 1.5 m depth). Sand content, in general, showed slightly decreasing values with depth, varying from 40 to 55 % in the subsurface layers (Ferralsols diagnostic horizons).

The silt content varied from 15 to 20 % in the topsoil, and from 10 to 13 % in the subsurface, showing a linear trend with depth. Below the sequence of B-horizons, the probability of the occurrence of a transitional BC horizon (around 1 m depth), related to a slight increase of silt content, has to be considered, but it is usually restricted to a particular soil-landscape condition. However, the silt content had low contribution to soil texture when compared with other particle sizes. The

Table 19.1 Values of mean, median, and harmonized (spline function) data, aggregated at predefined depths and as most-likely inferred horizon depths

Modal profile texture values—GlobalSoilMap project predefined depths

*	Sand content (g/kg)				Clay content (g/kg)				Silt content (g/kg)			
	Mean	Median	Spline	Range	Mean	Median	Spline	Range	Mean	Median	Spline	Range
1	519.5	510.0	527.5	510.0–527.5	335.7	325.0	320.1	320.1–335.7	144.7	138.0	152.4	138.0–152.4
2	519.6	510.0	522.3	510.0–522.3	340.1	325.0	337.8	325.0–340.1	140.3	134.5	139.9	134.5–140.3
3	490.7	487.0	492.7	487.0–492.7	387.6	408.0	385.8	385.8–408.0	121.7	120.0	121.4	120.0–121.7
4	449.6	421.0	451.3	421.0–451.3	434.5	428.0	433.7	428.0–434.5	155.9	113.0	115.0	113.0–115.9
5	410.0	413.0	408.8	408.8–413.0	465.8	450.0	466.0	450.0–466.0	124.2	105.0	125.1	105.0–125.1
6[a]	419.1	413.0	387.9	387.9–419.1	480.4	450.0	478.7	450.0–480.4	100.5	98.0	133.4	98.0–133.4

Modal profile texture values—most-likely horizon depth

**	Sand content (g/kg)				Clay content (g/kg)				Silt content (g/kg)			
	Mean	Median	Spline	Range	Mean	Median	Spline	Range	Mean	Median	Spline	Range
A	519.6	510.0	524.0	510.0–524.0	338.6	325.0	331.9	325.0–338.6	141.8	138.0	144.1	138.0–144.1
AB	490.7	487.0	492.7	487.0–492.7	387.6	408.0	385.8	385.8–408.0	121.7	120.0	121.4	120.0–121.7
BA	458.0	431.0	451.3	431.0–458.0	423.6	428.0	433.7	423.6–433.7	118.4	114.0	115.0	114.0–118.4
B1	441.3	415.0	451.3	415.0–451.3	445.4	445.0	433.7	433.7–445.4	113.3	112.0	115.0	112.0–115.0
B2	414.6	411.0	408.8	408.8–414.6	464.2	450.0	466.0	450.0–466.0	121.2	102.0	125.1	102.0–121.2
B3	402.4	413.0	408.8	402.4–413.0	468.4	450.0	466.0	450.0–468.4	129.2	105.0	125.1	105.0–129.2
B4[b]	419.0	413.0	387.9	387.9–419.0	479.0	450.0	478.7	450.0–479.0	102.0	98.0	133.4	98.0–133.4
B5[c]	421.5	421.5	387.9	387.9–421.5	506.5	506.5	478.7	478.7–506.5	72.0	72.0	133.4	72.0–133.4

*Aggregate data as GlobalSoilMap project depth. 1: 0–5 cm, 2: 5–15 cm, 3: 15–30 cm, 4: 30–60 cm, 5: 60–100 cm, 6: 100–200 cm. **Aggregate data as probability intervals (most-likely inferred horizon). A: 0–15 cm, AB: 15–30 cm, BA: 30–45 cm, B1: 45–60 cm, B2: 60–85 cm, B3: 85–100 cm, B4: 100–150 cm, B5: 150–200 cm. Contributing fraction to mean and median functions corresponding to: [a]0.4333; [b]0.4933; [c]0.1333. Other layers = 1.0

combination of sand, clay, and silt showed a trend of clay texture related to the subsurface layer of Ferralsols in Guapi-Macacu watershed.

The type of horizon transition (contrast and thickness) is key information for taxonomic purposes, highlighting gradients between morphological and physical properties, contributing to characterize diagnostic horizons and modal profiles. As observed on Table 19.1 and Fig. 19.7 (midpoints depth analysis), the Ferralsols transitional horizons were omitted, or misinterpreted, when the aggregation procedure is based on the six predefined depths as suggested by the GlobalSoilMap project, instead when the data are aggregated by most-likely horizon depth. The results show that the slicewise method can be used to balance the variability of soil horizons by depth considering the natural distribution of soil properties along the profile.

The predefined depths as proposed by the global consortium are useful to support decisions regarding land use and management. However, for soil taxonomic purposes, a different approach may be needed to represent the diagnostic horizons criteria, considering variability of soil properties with depth. As example, the transitional horizons of the Ferralsols showed no necessary correspondence with the predefined depths (GlobalSoilMap project), justifying a different approach, such as aggregation based on most-likely horizons probability.

The slicewise aggregation allowed to study different "representative depth functions" to characterize sand, silt, and clay content of the Ferralsols profiles. This approach contributed to transpose the concept of modal soil profile into an assemblage of representative depth functions, as suggested by Beaudette et al. (2013).

In this sense, soil depth models to represent the variability of properties with depth is a promising tool to taxonomic purposes and to support land usage decisions, improving the products obtained from soil surveys and reaching a greater number of users.

19.4 Conclusions

The process of examining data using the slicewise aggregation method and equal-area spline function was useful for comparing soil properties and taxonomic classification. The mid-depth horizon and soil properties depth function analysis showed the most-likely horizons of Ferralsols in the Guapi-Macacu watershed corresponding to: A (0, 15 cm), AB (15–30 cm), BA (30–45 cm), B (45–150 cm), and BC (85–200 cm). In general, the Haplic Ferralsols (Xanthic) showed deeper soil profiles and with more clay in subsurface horizons, compared with the Haplic Ferralsols (Dystric).

The Ferralsols topsoil layer presents commonly clay loam texture, and the subsurface is clayey. The modal profile showed representative values varying between 32 and 50 % of clay, 40 and 55 % of sand, and 10 and 20 % of silt.

The application of depth functions to evaluate the particle size variability of Ferralsols in Guapi-Macacu watershed showed that the slicewise aggregation technique can elucidate the distribution of continuous properties and to support definition of representative functions and their relationship with diagnostic horizons.

Haplic Ferralsols (Xanthic) and Haplic Ferralsols (Dystric) have a wide occurrence in the watershed, and they diverge mostly by landscape and parental material resulting in morphological and morphometric differences in color, texture, and thickness. The visualization by sketches and pairwise dissimilarity of the fifteen soil profiles showed a potential application of the procedure for soil taxonomy and mapping.

The evaluation of particle size variation and content as criteria of Ferralsols diagnostic horizons helps to build quantitative parameters to improve the Brazilian Soil Classification System and other taxonomic systems as well.

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