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First validation of the method Visual Evaluation of Soil Structure in coal mining area using a long-term field revegetation experiment as testbed

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ABSTRACT

Topsoil compaction is a persistent problem in minesoils, jeopardizing the revegetation and ecological reclamation of the mined land. Evaluation of soil structural quality (Sq) through quantitative methods is usually labor-intensive and/or costly, especially if a large area has to be examined. Therefore, reconciling cost-effective and accurate diagnose of minesoil Sq is crucial. The Visual Evaluation of Soil Structure (VESS) is a spade-based method scoring the soil Sq from 1 (good) to 5 (poor), which has not yet been validated for minesoils, and this was exactly the aim of this study. We made use of our long-term field experiment where quantitative physical attributes differed between perennial grasses used for minesoil revegetation, creating a Sq range to be screened by VESS. The minesoil, located in Southern Brazil, was revegetated for 14.3 years with *Hemarthria altissima*, *Paspalum notatum*, *Cynodon dactylon*, and *Urochloa brizantha*. The Sq of the minesoil (0.00–0.10 and 0.10–0.20 m layer) was evaluated by VESS and tensile strength of aggregates (TS), soil macroaggregates and microaggregates (%), soil organic matter (SOM) content, bulk density (BD), macroporosity (MaP), microporosity, total porosity (TP), and soil penetration resistance (PR). Through significant correlations between VESS scores and TS, MaP, macroaggregates (%), microaggregates (%), TP, SOM and especially BD (r = 0.60) and PR (r = 0.56), we found VESS to be a suitable method for reliable assessment of minesoil Sq. VESS scores 2.0–3.1 confirmed improved Sq at 0.00–0.10 m compared to 0.10–0.20 m (2.7–3.5), and this was supported by the ordination of 0.00–0.10 m samples together with SOM, macroaggregates (%), MaP and TP by principal component analysis. Moreover, VESS confirmed improved Sq in *H. altissima* (2.7) compared to *C. dactylon* (3.6) at 0.10–0.20 m, likely due to gains in soil MaP, TP, macroaggregates (%) and SOM. In this pioneering study we validated VESS as a practical and science-grounded method to monitor the Sq of a clayey subtropical minesoil.

1. Introduction

Soil structural quality (Sq) plays a critical role in plant development and can be indirectly assessed through various low-cost but labor-intensive quantitative analyses. These analyses include measuring soil bulk density (BD), porosity, penetration resistance (PR), and the percentage distribution of micro- and macroaggregates, among other attributes (Mueller et al., 2013; Munkholm et al., 2013; Liu et al., 2021; Shaheb et al., 2021). In contrast, imaging-techniques such as microscopy and X-ray computed tomography provide direct insights into soil Sq. However, these approaches are not only labor-intensive but also costly (Weller et al., 2022), making them difficult to implement on a large-scale, especially in developing countries. As a result, visual methods for evaluating the Sq of soil have been developed to offer a more cost-effective yet accurate assessment of soil structure. These methods typically focus on evaluating aggregates' size and shape,

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resistance to rupture, and the presence of roots promoting soil decompaction or aggregation (Emmet-Booth et al., 2018).

The visual soil structure quality assessment is a spade-based method initially developed by Ball et al. (2007) based on the Peerlkamp test (Peerlkamp, 1959). This method was later adapted by Guimarães et al. (2011) to become simpler and more objective (reducing operator subjectivity) and renamed to Visual Evaluation of Soil Structure (VESS). VESS consists of a straightforward and reproducible examination of soil Sq within the 0.00–0.30 m layer (often equivalent to plough layer in arable lands) to assess the impact of agricultural practices. Unlike profile-based methods, VESS does not require advanced pedological knowledge, making it more accessible for practical use (Franco et al., 2019).

The VESS method assigns soil Sq scores ranging from 1 (good) to Sq 5 (poor) (Guimarães et al., 2013). Emmet-Booth et al. (2020) demonstrated that VESS scores progressively increased with traffic intensity and are correlated with progressive changes in soil BD, total porosity (TP), and PR. Accordingly, Tuchtenhagen et al. (2018) reported significant correlations between VESS scores and soil BD, porosity, and aggregate mean weight diameter (MWD) in hydromorphic soils. Likewise, Silva et al. (2022) found that VESS scores significantly correlated with soil BD and porosity in smallholder farms in the Brazilian Amazon.

The visual methods of soil Sq evaluation were first validated for soils from the Northern and later for soils from the Southern Hemisphere, more specifically in Scotland and Denmark (Ball et al., 2007), and in Brazil (Guimarães et al., 2011), respectively. Over the past decade, VESS has been widely adopted across diverse soil types, climatic regions, soil tillage and cultivation practices (Franco et al., 2019). Notably, most of VESS studies have been conducted in agricultural settings, with only a small percentage focusing on tropical (12 %) or subtropical (25 %) compared to temperate (63 %) climate locations, and on fine-textured (8 %) soils (Franco et al., 2019), where risk of soil compaction is elevated (Horn et al., 1995; Horn and Fleige, 2009). For instance, a meta-analysis by Franco et al. (2019) further revealed that fine-texture soils tend to exhibit higher Sq scores compared to medium- or coarse-textured soils.

To date, no data are available on the application of VESS to a particular group of soils highly prone to critical compaction—post-mining soils (Shrestha and Lal, 2011; Liu et al., 2017; Schmäck et al., 2022), also known as minesoils (Sencindiver and Ammons, 2000) or Technosols (WRB, 2015). The global mining area is currently estimated at 57,280 km^2, and it is predominantly located in developing countries (Maus et al., 2020), where VESS may be particularly useful. Minesoils generated after coal mining generally consist of two main layers: an overburden layer, composed of rock debris and eventually coal, and a topsoil layer, formed by a mixture of the original soil horizons (e.g., A, B, and C) (Stumpf et al., 2022).

Minesoils with fine-textured topsoil are especially susceptible to compaction because of the excessive and heavy machinery traffic typically involved in the topographical reconstitution of the mined area (Ahirwal and Maiti, 2016; Bohrer et al., 2017; Barboza et al., 2021; Kołodziej et al., 2024). Elevated minesoil compaction levels can persist for decades (Stutler et al., 2022), jeopardizing vegetation establishment and compromising the ecological reclamation of the land (Ruiz et al., 2020). The alleviation of minesoil compaction can be accelerated by root growth from plants well-adapted to such soil conditions and by soil organic matter (SOM) accumulation resulting from the successful vegetation growth (Vindušková and Frouz, 2013; Zhao et al., 2022; Miguel et al., 2023). According to Feng et al. (2019), the restoration of minesoil physical conditions may take 10–40 years, depending on the revegetation methods and plant species used.

In Brazil, mining areas cover approximately 1493 km^2 (Maus et al., 2020), with the Candiota Mine, located in the southernmost state of Rio Grande do Sul (RS), being the country's largest open-cast coal mine and coal reserve. In this region, coal mining has already impacted at least 766 ha of land (CRM, 2023). In the coming years, additional land may be affected as the Candiota Mine contains nearly 1.2 billion tons of coal accessible via surface mining (Pinto et al., 2020). This may be driven by the rising of global coal consumption, which has unprecedently increased since 2022 and may reach 8038 Mt in 2025, because of the growth of the industrial sector, population, and recent energetic crises (IEA, 2022).

Since 2003, we have been conducting a field experiment to revegetate the minesoil at Candiota Mine with various perennial grasses. Through a series of publications, we have documented the evolution of the Sq and SOM content of this minesoil as affected by the grass species (Leal et al., 2015a, 2015b; 2016; Pauletto et al., 2016; Stumpf et al., 2016; 2018a; 2018b; Barboza et al., 2021; Miguel et al., 2023). Nevertheless, VESS has not yet been applied in our experimental site. The reclamation of this mining area presents challenges due to machinery traffic on the fine-texture soil, resulting in soil BD and macroporosity (MaP) levels within the 0.00–0.20 m layer exceeding critical thresholds for plant development (Pauletto et al., 2016). Therefore, if validated to our minesoil, VESS may be a useful tool to accurately diagnose and monitor the recovery of Sq of these minesoils. This is of particular interest to cover the already large and still expanding area of minesoils in this region.

Given the above considerations, we explored VESS for the first time as a practical and sensitive tool to directly assess the Sq of minesoils using our 14.3-year revegetated minesoil as testbed. The advantage of our experiment for this purpose relies on its experimental design, statistical control, long-term duration (for monitoring VESS scores evolution), and on the varying effects of perennial grasses on soil structure, which can be tentatively screened by VESS. Therefore, we aimed to 1) validate for the first time the use of VESS in minesoils through correlating the VESS scores to quantitative measures of soil Sq and to SOM content obtained at 0.00–0.10 and 0.10–0.20 m layer; and 2) test the sensitivity of VESS scores to the stratification of compacted soil layers and to the effects of grass species on the Sq of the minesoil. We hypothesized that VESS scores: i) significantly correlate with the quantitative physical attributes data as well as to SOM content; ii) effectively detect compacted layers in this minesoil as well as identify the grass(es) promoting remarkable improvement of soil structure.

2. Material and Methods

2.1. Experimental site location and design

The study was conducted in a coal mining area in Candiota City, RS State, Southern Brazil (Fig. 1). The climate is classified as subtropical humid (Cfa), the average annual air temperature is 17°C and average annual rainfall is 1400 mm (minimum average monthly rainfall of 60 mm), including cold winters and hot summers (Alvares et al., 2013).

The minesoil was constructed in early 2003. The topsoil, placed over the overburden of the minesoil, contains 465 g kg^{-1} clay (Ø: < 0.002 mm), 208 g kg^{-1} silt (Ø: 0.002–0.05 mm), 327 g kg^{-1} sand (Ø: 0.05–2 mm), 11.5 g kg^{-1} SOM, and consists mainly of the B horizon of the original soil (pre-mining), a Rhodic Lixisol (WRB, 2015), as detailed in Stumpf et al. (2016); (2018a) and illustrated in Leal et al. (2016).

The minesoil received dolomitic limestone equivalent to 10.4 Mg ha^{-1} and 900 kg ha^{-1} of a 5–20–20 fertilizer (45 kg N, 180 kg P_2O_5, and180 kg K_2O). Transit of massive machinery during the minesoil construction (trucks loaded with 20 Mg of soil and Caterpillar D8T model bulldozer with 38 Mg mass) resulted in severe compaction of the constructed minesoil (Stumpf et al., 2016). For this reason, the soil was chiseled with a bulldozer to 0.15 m depth by the occasion of minesoil construction finalization.

The experiment was installed on this minesoil in November/December 2003, in a randomized block design with four replications (plots of 20 m^2). The experimental treatments consisted of four perennial grasses: *Hemarthria altissima* (*H. altissima*), *Paspalum notatum* (*P. notatum*), *Cynodon dactylon* (*C. dactylon*), and *Urochloa brizantha*

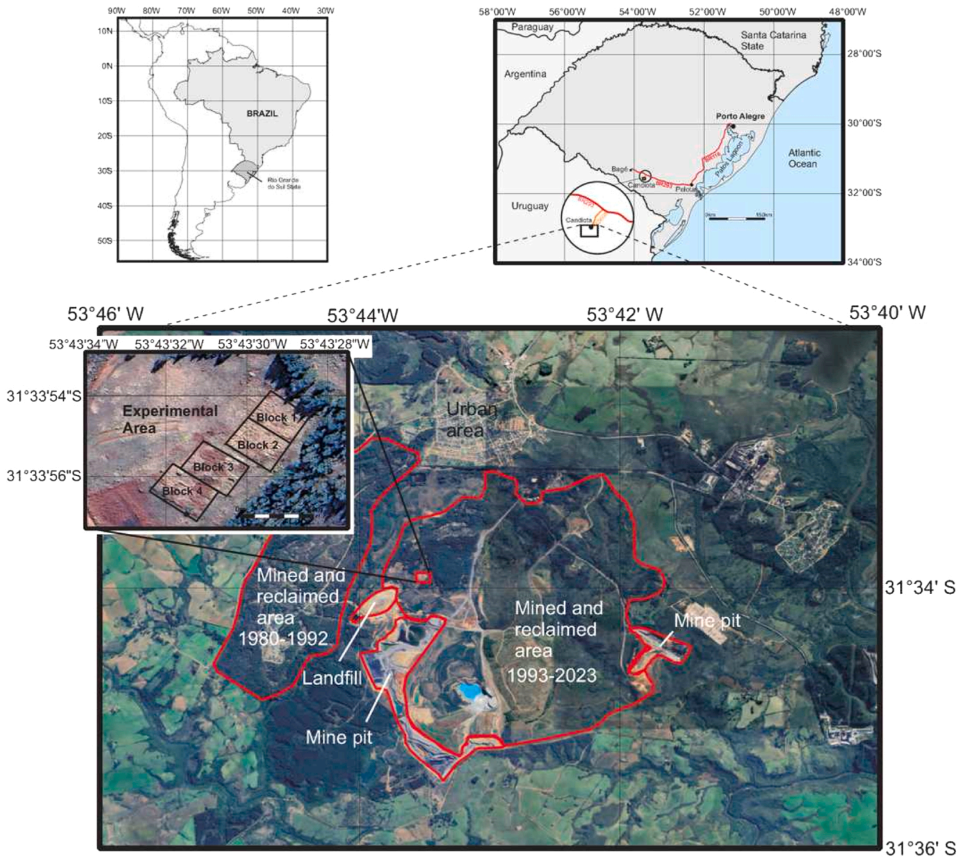

Fig. 1. Experiment design and location in Candiota city, RS State, Brazil.

(*U. brizantha*). Annually, all plots received 250 kg ha^{-1} of a 5–30–15 fertilizer (12.5 kg N, 75 kg P_2O_5, and 37.5 kg K_2O) and 250 kg ha^{-1} of ammonium sulfate.

2.2. Application of the VESS method

Elapsed 14.3 years of revegetation, one soil monolith (0.20 ×0.10–0.25 m depth) per experimental plot (totaling 4 soil monoliths per treatment) was sampled and Sq scores ranging from 1 to 5 were attributed to the layers of individual monoliths using the VESS reference chart of Guimarães et al. (2011). Briefly, VESS score Sq 1: *friable structural quality*, with aggregates readily crumbling (resulting in aggregates < 6 mm), and large aggregates composed of smaller ones held by roots. Soil is highly porous with roots throughout the soil. VESS score Sq 2: *intact structural quality*, in which aggregates are easy to break with one hand, and a mixture of porous aggregates, rounded, with 2 mm–7 cm, without clods. Most aggregates are porous, and roots are present throughout the soil. VESS score Sq 3: *firm structural quality*, with most aggregates breaking with one hand and a mixture of porous aggregates from 2 mm–10 cm (less than 30 % are <1 cm), with presence of some angular, non-porous aggregates (clods). Macropores and cracks are present, and aggregates exhibit internal pores and roots. VESS score Sq 4: *compact structural quality*, considerable effort required to break aggregates with one hand. Aggregates are mostly large (>10 cm), sub-angular and non-porous, horizontal/platy aggregates may also occur. Less than 30 % of aggregates are <7 cm, there are cracks and few macropores, and roots are clustered in macropores and around aggregates. VESS score Sq 5: *very compact structural quality*, aggregates are difficult to break up, mostly large >10 cm, very few <7 cm, angular, and exhibit no pores or cracks visible. There is very low porosity (macropores may be present) and anaerobic spots may occur. Roots are few, and if present, are restricted to cracks.

Besides the scores assigned for distinct layers identified according to the standard chart description, a weighted average of the scores was calculated for the 0.00–0.10 m and 0.10–0.20 m layers (Guimarães et al., 2011; 2013) to allow the correlation of the scores with quantitative attributes measured in these two layers. The soil layers receiving different scores were named (from soil surface down to 0.20 m depth) as top layer, second layer, third layer and fourth layer (only present in *C. dactylon* treatment), as similarly performed in Cherubin et al. (2017); (2019), Guimarães et al. (2017) and Mora-Mota et al. (2024).

2.3. Quantitative evaluation of soil structure and SOM content determination

On the same occasion of soil monoliths sampling for VESS evaluation, soil samples were collected for quantitative analyses of soil Sq and SOM, ultimately aiming for the validation of VESS use in this minesoil. In both layers (0.00–0.10 and 0.10–0.20 m), four soil blocks per treatment (one per plot) were collected to determine the tensile strength (TS) of aggregates, the distribution of water-stable aggregates in size classes, and the SOM content.

For TS analysis, a total of 640 aggregates (4 blocks × 4 treatments × 20 aggregates per plot × 2 layers), retained in metallic sieves of 19.0 and 12.5 mm of aperture were analyzed according to Imhoff et al. (2002). Each of the aggregates had its weight and effective diameter measured. The gravimetric moisture of soil aggregates ranged from 3.4 % to 12.1 % in the 0.00–0.10 m layer and from 4.8 % to 11.5 % in the 0.10–0.20 m layer. The indirect tension test was carried out using an electronic actuator, linear model MA933, at a constant speed of 4 mm s^{-1} until the aggregate failed. A data acquisition system recorded the electrical output. The TS was calculated according to Dexter and Kroesbergen (1985).

Three sub-samples (from the soil monoliths) of approximately 50 g of aggregates were submitted to wet-sieving with vertical oscillation for determination of water-stable aggregates distribution into size classes in the 0.00–0.10 and 0.10–0.20 m layers. The analysis was conducted according to Kemper and Rosenau (1986) adapted by Palmeira et al. (1999) (excludes sand from water-stable aggregates calculation) and the data was corrected to moisture content of samples. The intervals of aggregate classes were: 9.52–4.76 mm; 4.76–2.0 mm; 2.00–1.00 mm; 1.00–0.25 mm; 0.25–0.105 mm, and < 0.105 mm. For the present study, these aggregate classes were reduced to macroaggregates (>0.25 mm) or microaggregates (<0.25 mm) and expressed as mass percentage (Tisdall and Oades, 1982).

The Walkley-Black combustion method was employed to determine the soil organic carbon content, which was multiplied by 1.724 to be expressed as SOM content (Teixeira et al., 2017). This method was chosen because it is compatible to methods used in most routine laboratories processing soil samples from farmers in Brazil, and because it complies with the official manual of recommendation of fertilization and liming for the region where the experiment is embedded (CQFS, 2016).

A total of 128 undisturbed soil samples (4 blocks × 4 treatments × 4 sampling points per plot × 2 layers) were collected using stainless steel cylinders (0.05 m height and 0.047 m diameter) to determine soil BD and MaP. The soil BD was calculated by dividing the dry weight of soil contained in the cylinder by the volume of the cylinder. For soil MaP determination, the samples were saturated in water by capillarity for 24 h and placed on a tension table. After equilibration at 6 kPa tension (used to drain macropores with diameter >0.05 mm) the samples were weighed, and the weight difference between the saturated and the drained soil corresponded to MaP. After this drainage, the samples were dried at 105°C to constant weight and weighed. The weight difference between the sample equilibrated at 6 kPa and the dried sample corresponded to microporosity (MiP). The sum of MaP and MiP equals TP (Teixeira et al., 2017).

Soil PR was measured at 48 points across experimental plots (4 blocks × 4 treatments × 3 replicates per plot) using an impact penetrometer with a cone angle of 30°, and cone base diameter of 12.8 mm. These measurements were accompanied by determination of gravimetric soil water content, which was 142.3 and 142.1 g kg^{-1} at 0.00–0.10 and 0.10–0.20 m layer, respectively.

2.4. Data analysis

Analysis of variance (ANOVA) was performed to detect significant effect of treatments on the response variables. If this effect was significant, the means of treatments were compared by Tukey's test within soil layer. These significances were set to $p < 0.05$. Pearson correlations between VESS scores and quantitative soil physical attributes and SOM content were used to find correspondences between these methods of evaluation of Sq in minesoils. These correlation results are shown together with a reference line at VESS Sq 3.0 which has been used as a threshold for "suitable root growth" in different soils as for example in Cherubin et al., (2017); (2019), Castioni et al., (2018) and Mora-Mota et al. (2024). Principal component analysis (PCA) was performed to ordinate and illustrate shifts in the Sq of the minesoil at 0.00–0.10 and 0.10–0.20 m layer promoted by the treatments as revealed by VESS scores, soil physical attributes and SOM content as eigenvectors. The four quadrants (Q) of PCA plot were named Q1, Q2, Q3 and Q4 to facilitate the description of results and the discussion of the data. The MiP data did not correlate significantly with VESS Sq scores. Therefore, the MiP data is only displayed in Fig. S1, and it was excluded from PCA analysis. The supplemental materials display the loadings of PCA (Table S1) as well as the eigenvalues and data variance explanation (%) of the (nine) principal components (Table S2).

3. Results

3.1. VESS scores

In general, VESS Sq scores lower than 2.0 and higher than 4.0 were not observed in our study (Fig. 2), indicating that neither friable and highly porous nor very compact and low porosity Sq was verified in this minesoil after 14.3 years of revegetation, regardless of treatment. The VESS scores ranged from Sq 2.0 (*intact structural quality*) at 0.00–0.10 m layer (*H. altissima*) to Sq 3.8 (*firm-compact*) below 0.15 m depth in all treatments, except *H. altissima*, which exhibit Sq 3.0 at this depth (Fig. 2). Overall, these results reveal a remarkable improvement of soil Sq by *H. altissima* compared to the other treatments, with the existence of granular and subangular aggregates and roots distributed throughout the aggregate in this treatment.

The lowest Sq score found in *P. notatum* and *U. brizantha* treatment was Sq 2.5, observed at 0.00–0.08 and 0.00–0.07 m layer, respectively (Fig. 2). This score reflects the presence of granular and subangular aggregates penetrated by roots. Contrastingly, the *C. dactylon* treatment exhibited, within this same layer (at 0.00–0.05 m), Sq 3.0 (Fig. 2), which indicates the existence of granular and subangular aggregates (larger than those observed in Sq 2.0) and flattened roots. Both *H. altissima* and *U. brizantha* treatment also exhibited Sq 3.0, but at deeper layers, at 0.15–0.20 m and 0.07–0.14 m, respectively (Fig. 2). The highest Sq (3.8) was observed at 0.14–0.20 m layer in *P. notatum* and *U. brizantha* and at 0.16–0.20 m layer in *C. dactylon* (Fig. 2), including a mixture of granular, subangular, and angular aggregates ranging from small to large. Particularly, at these layers flattened roots were found in *C. dactylon* and *U. brizantha* treatments.

The weighted Sq scores (Fig. 3) for the 0.00–0.10 m layer did not differ statistically across treatments, but suggested good soil Sq in *H. altissima, P. notatum* and *U. brizantha* treatments (Sq scores between 2.0 and 2.6), and moderate Sq in *C. dactylon* (Sq score 3.1). Differently, at 0.10–0.20 m layer the Sq score of *H. altissima* (2.7) statistically differed from that of *C. dactylon* treatment (Sq 3.6), whereas the Sq score in *P. notatum* (3.4) and *U. brizantha* (3.5) did not differ statistically from any other treatment (Fig. 3).

3.2. Soil physical quantitative attributes and SOM content

The percentage of water-stable macroaggregates (Fig. 4a) and microaggregates (Fig. 4b) and the TS of aggregates (Fig. 4c) did not differ statistically across treatments, regardless of soil layer. Noteworthily, the macroaggregates (%) and microaggregates (%) remained relatively constant across 0.00–0.10 and 0.10–0.20 m layers (macroaggregates: 42.3–44 %, Fig. 4a; microaggregates: 56–57.7 %, Fig. 4b). In

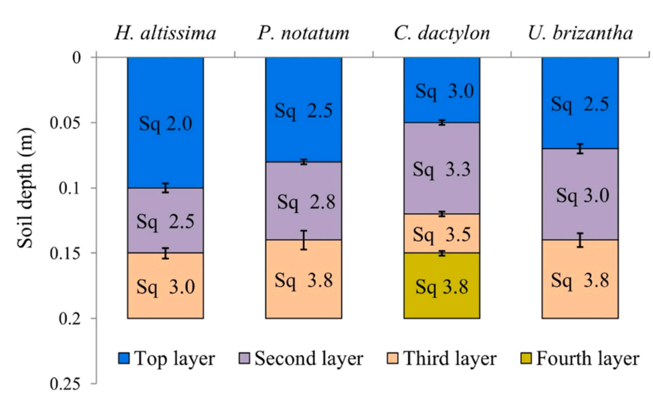

Fig. 2. Average (n = 4) depth of minesoil layers (top, second, third, and fourth-when present) distinguished by their VESS scores for soil structural quality (Sq) observed in the *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatment. Error bars refer to the standard deviation of the boundary between the layers.

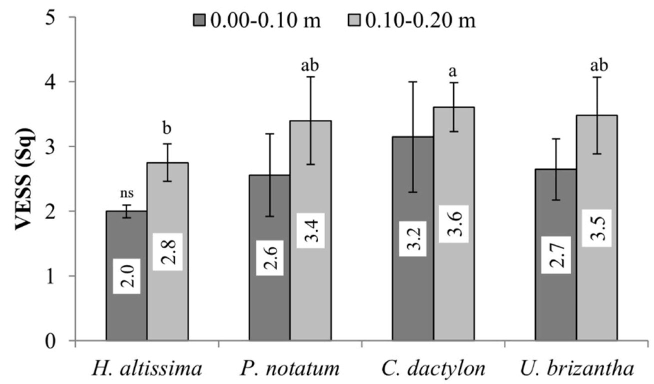

Fig. 3. Weighted VESS scores for soil structural quality (Sq) for the 0.00–0.10 and 0.10–0.20 m layer observed in the *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatment. Bars refer to average values (n = 4) and error bars to standard deviation. Different letters indicate statistically different averages (Tukey's test, p <0.05) within each layer. ns: not significant.

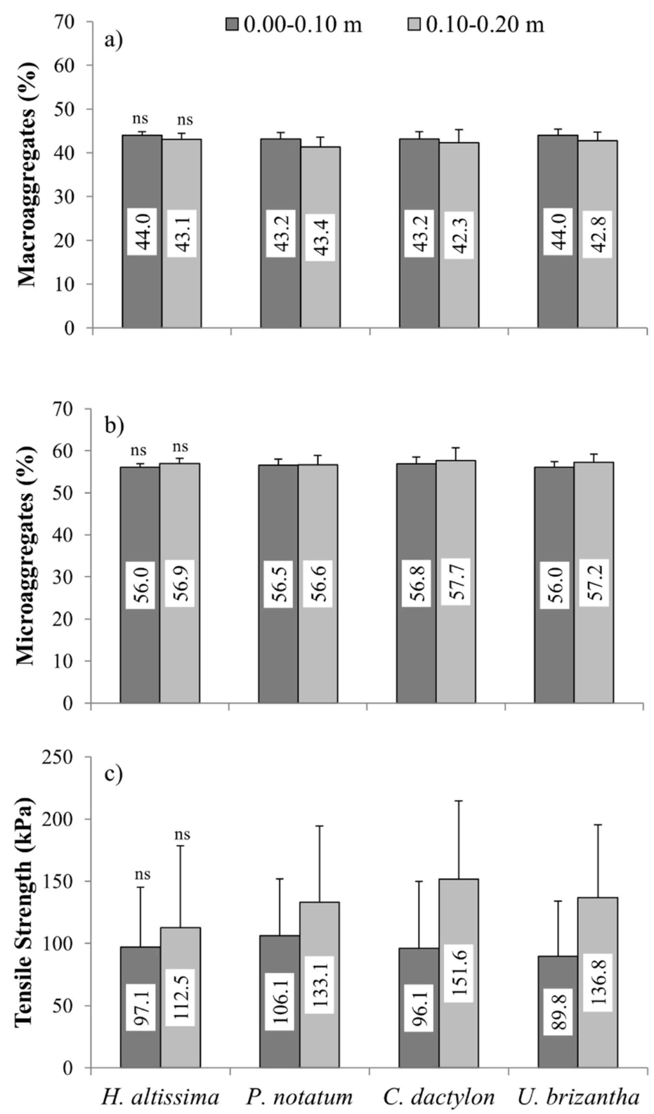

Fig. 4. Percentage of water-stable macroaggregates (a) and microaggregates (b), and tensile strength of aggregates (c) at 0.00–0.10 and 0.10–0.20 m layer observed in the *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatment. Bars refer to average values (n = 4) and error bars to standard deviation. ns: not significant.

contrast, the TS values tended to be lower at 0.00–0.10 m where it varied between 89.8 (*U. brizantha*) and 106.1 (*P. notatum*) kPa, and higher at 0.10–0.20 m where it varied between 112.5 (*H. altissima*) and 151.6 (*C. dactylon*) kPa (Fig. 4c). However, TS across treatments did not differ statistically within soil layers (Fig. 4c).

In the 0.00–0.10 m layer, the soil BD varied from 1.32 to 1.39 Mg m^{-3} (Fig. 5a), the MaP from 0.13 to 0.16 m^3 m^{-3} (Fig. 5b) and the TP from 0.48 to 0.52 m^3 m^{-3} (Fig. 5c), without statistical differences between treatments. Oppositely, in the 0.10–0.20 m layer, the soil BD in *C. dactylon* (1.54 Mg m^{-3}) was statistically higher compared to that in *H. altissima* (1.39 Mg m^{-3}), *P. notatum* (1.45 Mg m^{-3}), and *U. brizantha* (1.44 Mg m^{-3}), which did not differ statistically from each other (Fig. 5a). In this same layer, *U. brizantha* exhibited statistically higher MaP and TP (0.17 and 0.50 m^3 m^{-3}, respectively) compared to *C. dactylon* (0.10 and 0.42 m^3 m^{-3}, respectively), whereas the MaP and TP in *H. altissima* (0.13 and 0.48 m^3 m^{-3}, respectively) and *P. notatum* (0.13 and 0.46 m^3 m^{-3}, respectively) did not differ statistically from any other treatment (Fig. 5b, c).

In the 0.00–0.10 m layer, the soil PR ranged from 1.90 to 2.60 MPa across treatments, without statistical differences (Fig. 6a). In the 0.10–0.20 m layer, the PR in *H. altissima* (3.66 MPa) was statistically

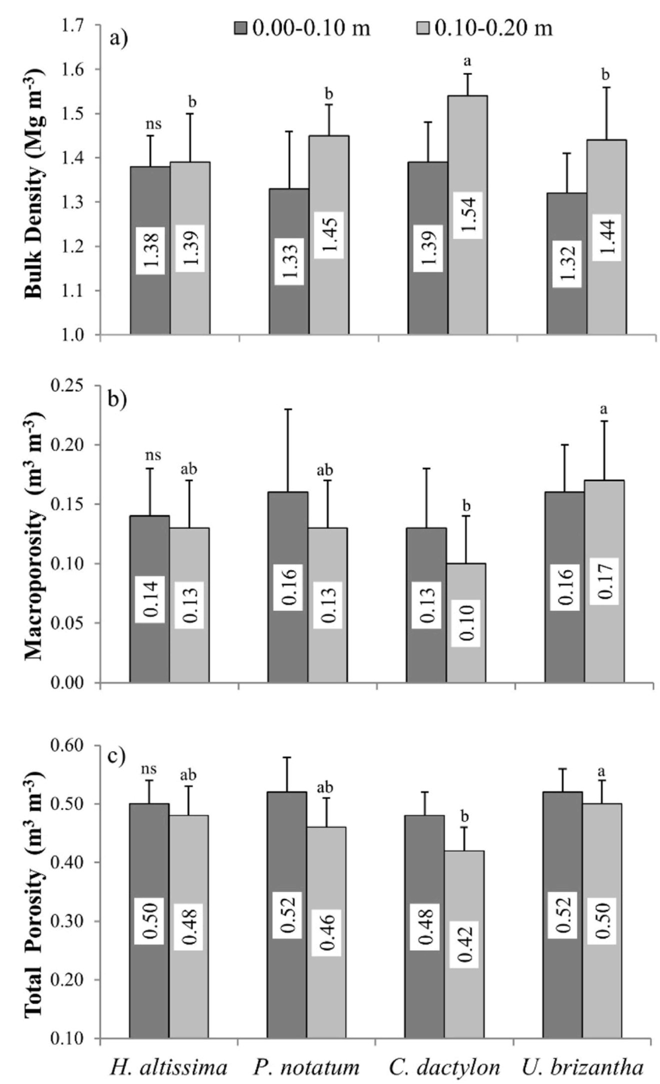

Fig. 5. Soil bulk density (a), macroporosity (b), and total porosity (c) at 0.00–0.10 and 0.10–0.20 m layer observed in the *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatment. Bars refer to average values (n = 4) and error bars to standard deviation. Different letters indicate statistically different averages (Tukey's test, p <0.05) within each layer. ns: not significant.

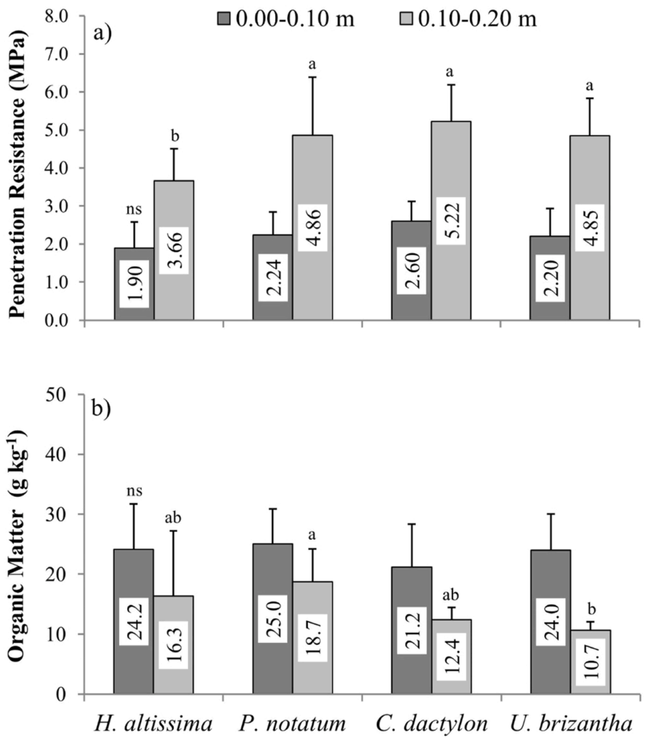

Fig. 6. Soil penetration resistance (a) and organic matter content (b) at 0.00–0.10 and 0.10–0.20 m layer observed in the *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatment. Bars refer to average values (n = 4) and error bars to standard deviation. Different letters indicate statistically different averages (Tukey's test, $p < 0.05$) within each layer. ns: not significant.

lower compared to all other treatments, where PR varied from 4.85 (*U. brizantha*) to 5.22 MPa (*C. dactylon*) without statistical differences (Fig. 6a).

The SOM content in the 0.00–0.10 m layer ranged from 21.2 to 25.0 g kg^{-1} across treatments, without statistical significances (Fig. 6b). However, in the 0.10–0.20 m layer the SOM content was significantly lower in *U. brizantha* (10.6 g k^{-1}) than in *P. notatum* treatment (18.7 g kg^{-1}), whereas in *H. altissima* and *C. dactylon* the SOM content (16.3 and 12.4 g kg^{-1}, respectively) did not differ statistically from any other treatment (Fig. 6b).

The effects of the different treatments on the physical attributes and SOM content of this minesoil have been discussed in our previous publications as aforementioned. In the present study, we avoid redundant discussions and specifically use these data to examine their correlation with VESS scores for the first time.

3.3. Correlation and PCA analysis of VESS scores and minesoil attributes

The Sq scores positively and significantly correlated with TS of aggregates (r = 0.47, Fig. 7a), soil BD (r = 0.60, Fig. 7b), PR (r = 0.56, Fig. 7e) and microaggregates (%) (r = 0.39, Fig. 7g). The Sq scores between 2.0 and 3.0 (indicative of suitable conditions for root growth) included most TS values between 60 and 120 kPa (Fig. 7a), BD values between 1.18 and 1.50 Mg m^{-3} (Fig. 7b), PR values lower than 3 MPa (Fig. 7e), and microaggregates values <57 % (Fig. 7g). On the other hand, Sq scores >3.5 (indicative of restrictive conditions for root growth) occurred along with most TS values between 100 and 200 kPa (Fig. 7a), BD values between 1.30 and 1.57 Mg m^{-3} (Fig. 7b), and PR values >4 MPa (Fig. 7e). For microaggregates (%), the Sq scores >3.5 occurred along with values <59 %, as similarly observed for Sq scores 2 and 3 (Fig. 7g).

The Sq scores negatively and significantly correlated with soil MaP (r = –0.36, Fig. 7c), TP (r = –0.50, Fig. 7d), SOM content (r = –0.37, Fig. 7f), and macroaggregates (%) (r = –0.39, Fig. 7h). Here, the Sq scores between 2.0 and 3.0 generally occurred along with MaP and TP values between 0.07–0.24 (Fig. 7c) and 0.41–0.55 m^3 m^{-3} (Fig. 7d), respectively, SOM contents >15 g kg^{-1} (Fig. 7f), and macroaggregate values >43 % (Fig. 7h). On the other hand, Sq scores >3.5 occurred along with MaP and TP values between 0.05–0.18 (Fig. 7c) and 0.45–0.50 m^3 m^{-3} (Fig. 7d), respectively, SOM content between 10 and 15 g kg^{-1} (Fig. 7f), and macroaggregate values ranging from 38.2 % to 45.2 % (Fig. 7h).

Soil MiP was the only attribute in the present study that did not exhibit a statistically significant correlation ($p < 0.05$) with VESS Sq scores. Significant correlation between these attributes occurred only at p = 0.09 (r = –0.31, Fig. S1). Therefore, the MiP data is not further discussed.

Principal component 1 (PC1) and principal component 2 (PC2) of PCA explained 50.2 and 17.7 % of the variation in the data set, respectively (Fig. 8). Notably, samples collected from the 0.00–0.10 m layer were ordinated to the negative portion of PC1 (in Q1 and Q4) alongside the eigenvectors for TP, MaP, macroaggregates (%) and SOM (Fig. 8). In contrast, samples from the 0.10–0.20 m layer were ordinated to the positive portion of PC1 (in Q2 and Q3) associated with the eigenvectors for VESS, PR, TS, BD and microaggregates (%) (Fig. 8). The VESS eigenvector was ordinated to the positive portion of PC2 axis (in Q2), closely associated to the eigenvectors for microaggregates (%), PR and TS pointing mainly to *U. brizantha* samples (0.10–0.20 m). The BD eigenvector was ordinated alone to the negative portion of PC2 axis in Q3, yet closely associated to VESS eigenvector in Q2, pointing mainly to *C. dactylon* and *P. notatum* samples collected from the 0.10–0.20 m layer (Fig. 8). Notably, *H. altissima* was the only treatment lacking samples from either the 0.00–0.10 or the 0.10–0.20 m layer ordinated together with VESS eigenvector in Q2 (Fig. 8). Moreover, all four *H. altissima* replicates from the 0.0–0.10 m layer clustered together with the eigenvectors for macroaggregates (%) and SOM within Q4 of the PCA biplot, opposite to VESS, PR, TS and microaggregates (%) eigenvectors (Q2, Fig. 8). Soil samples (0.00–0.10 m) from *U. brizantha* and *P. notatum* treatment were ordinated similarly to those of *H. altissima* (0.00–0.10 m) along the PC1 axis. However, they exhibited a stronger positive association with the TP and MaP eigenvectors (Fig. 8). This distinction is evidenced by the scattering of the four replicates of *U. brizantha* and *P. notatum* along PC2 axis, with two replicates located in Q1 and two in Q4, while all *H. altissima* replicates (0.00–0.10 m) were concentrated solely in Q4 because of their stronger positive association to SOM and macroaggregates (%) (Fig. 8).

4. Discussion

4.1. Sensitivity of weighted Sq scores (0.00–0.10 and 0.10–0.20 m) against compaction

Overall, in the 0.00–0.10 m layer the weighted Sq scores ranged from 2.0 to 3.2 (Fig. 3), which indicate good Sq (Ball et al., 2017). This is likely due to 14.3 years of continuous grass cultivation, coupled with the concentration of the roots of the perennial grasses in this layer, as illustrated in Stumpf et al. (2018b). In fact, these authors found higher root density, volume and length in the 0.00–0.10 m than in the 0.10–0.20 m layer after 8.6 years of revegetation in this same experimental field. Nevertheless, the predominantly good Sq observed at 0.00–0.10 m layer was still accompanied by TS of aggregates (100–120 kPa) and soil PR (2–3 MPa) levels potentially restrictive to the growth of grass roots (Causarano, 1993; Calonego et al., 2017; Pott et al., 2019). In our study site, compression-formed aggregates (Fig. 9) originated at topographic reconstitution of the mined area are known to increase soil compaction. Such compacted soil layers tend to be disrupted by root action with increasing years of recultivation, originating small but cohesive aggregates, primarily at 0.00–0.10 m, in response to roots' concentration (Stumpf et al., 2016; 2018b). The presence of cohesive

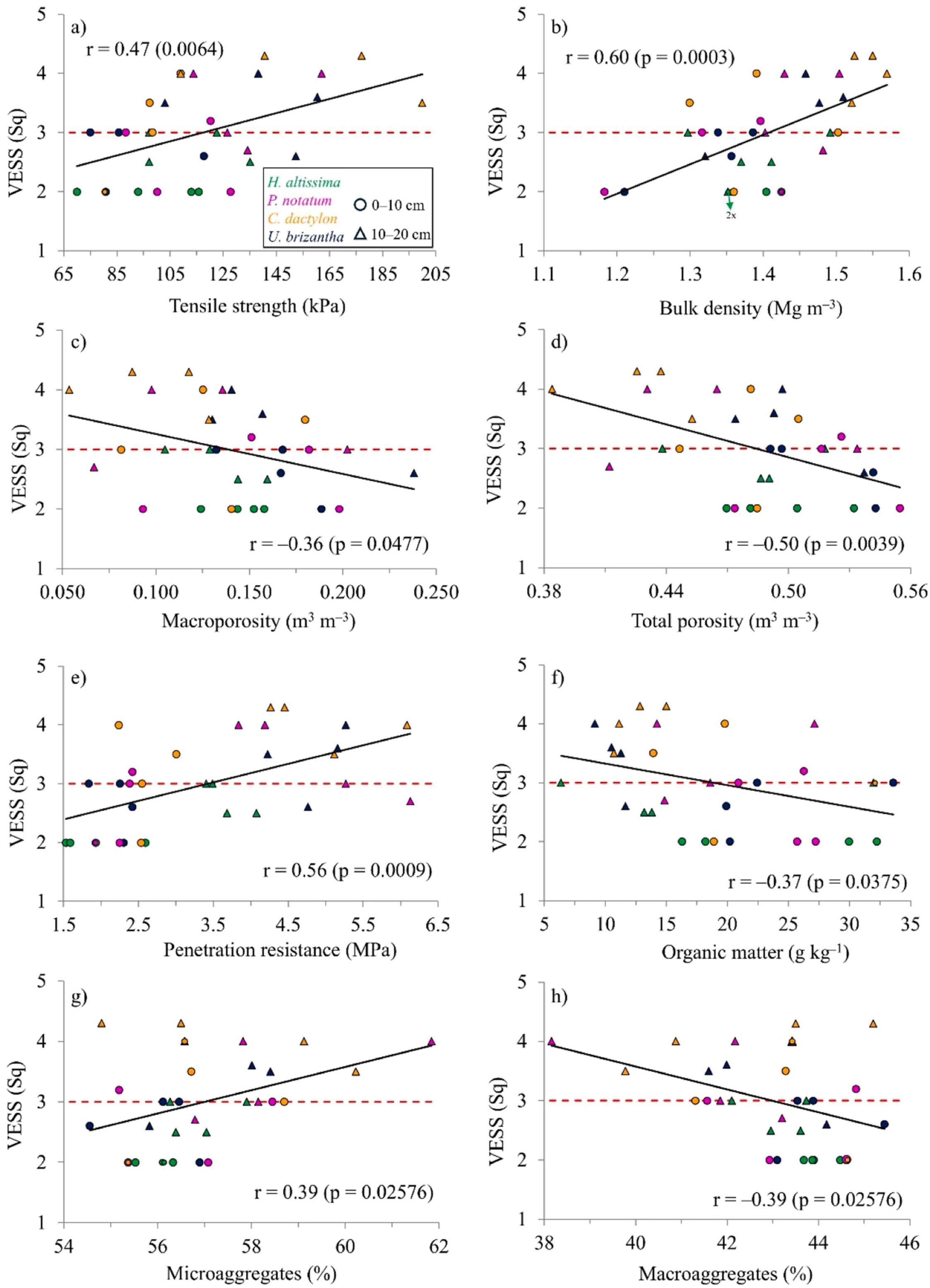

Fig. 7. Pearson's correlation coefficients (r) and significance of correlations (p value) between VESS structural quality scores (VESS Sq) and soil aggregates' tensile strength (a), soil bulk density (b), macroporosity (c), total porosity (d), penetration resistance (e), organic matter content (f), percentage of microaggregates (g) and percentage of macroaggregates (h) at 0.00–0.20 m layer (n = 32). The red dashed line at VESS Sq 3 indicates moderate structural quality with possible restrictions for plant development (Cherubin et al., 2017).

aggregates in the 0.00–0.10 m layer converges with the absence of Sq scores 1.0 (*friable structural quality*) and with the occurrence of only one treatment (*H. altissima*) with Sq score 2.0 (*intact structural quality*) within this layer (Fig. 2).

The VESS scores revealed similar Sq across treatments in the 0.00–0.10 m. Here it is important to emphasize that it is justified not by the insufficient sensitivity of VESS against Sq levels. Instead, this agrees with the absence of statistical differences across treatments for the

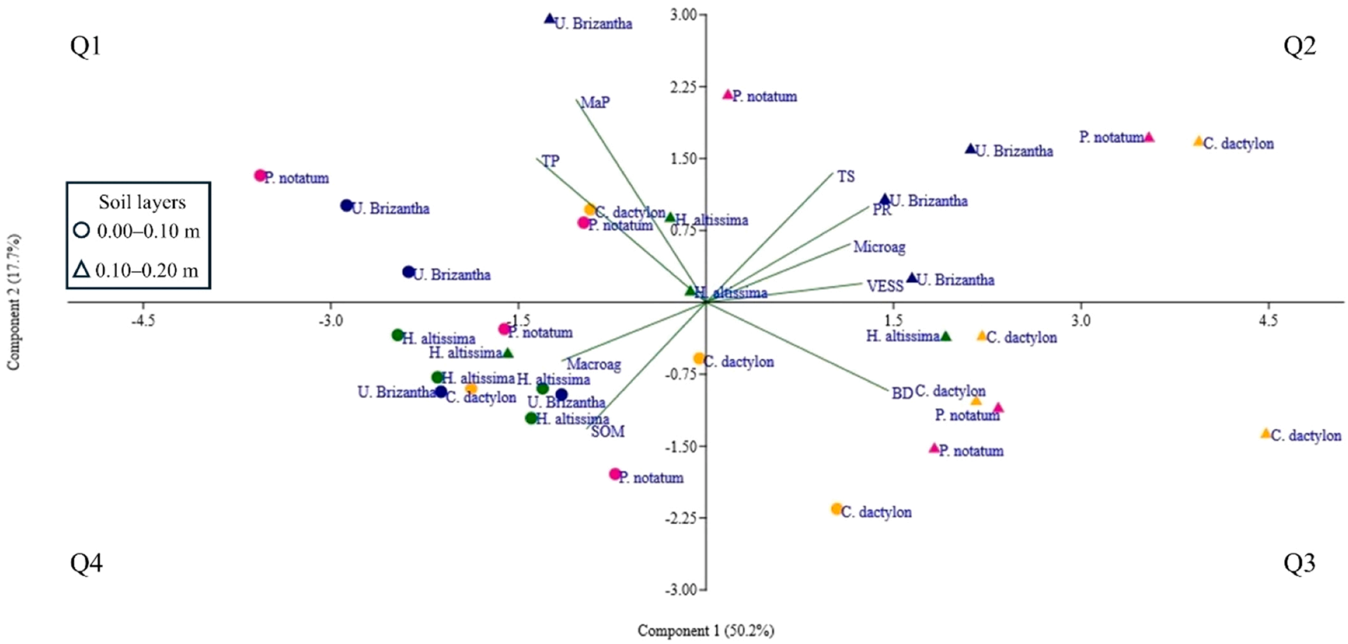

Fig. 8. Principal component analysis biplot with eigenvectors pointing towards increasing values of VESS scores (VESS), bulk density (BD), macroporosity (MaP), total porosity (TP), penetration resistance (PR), tensile strength of aggregates (TS), soil organic matter content (SOM), and percentage of macroaggregates (Macroag) and microaggregates (Microag) for soil samples collected at 0.00–0.10 m (circle symbols) and 0.10–0.20 m layer (triangle symbols) in *H. altissima*, *P. notatum*, *C. dactylon* and *U. brizantha* treatments.

Fig. 9. Soil slices collected whit a spade within 0.00–0.20 m layer exhibiting aggregates typically formed by compression (a) and VESS scores between 2 and 3 (b).

quantitative soil attributes in this layer (Figs. 4–6). The consistency of these results is reflected by the significant correlation of VESS scores with diverse soil attributes (Fig. 7).

The weighted Sq scores in the 0.10–0.20 m layer (2.7–3.6, Fig. 3) reflect the higher TS of aggregates (Fig. 4c), soil BD (Fig. 5a), and PR (Fig. 6a), and the lower MaP (Fig. 5b), TP (Fig. 5c) and SOM content (Fig. 6b) compared to the 0.00–0.10 m layer. Overall, these Sq scores indicate inadequate Sq for roots below 0.10 m, even after 14.3 years of revegetation, especially in *C. dactylon* treatment. For instance, Bohrer et al. (2017) found limited root growth of grasses and legumes close to the surface of a minesoil even after 40 years of reclamation due to elevated soil PR (5.5 MPa). In our study, similar PR values were observed in the 0.10–0.20 m layer, mainly in *C. dactylon* (5.22 MPa) (Fig. 6a), which is coherent with the highest Sq score exhibited by this treatment in this soil layer (Fig. 3). In addition to restricted root development below 0.10 m, the clear stratification of minesoil layers due to compaction (Fig. 3) may have also resulted from soil chiseling restricted to 0.15 m depth at experiment installation. Likely, chiseling favored compaction alleviation (and thus root growth) mainly within 0.00–0.10 m and less within 0.10–0.20 m layer. These findings are coherent with Sq scores up to 3.8 occurring alongside TS values between 100–200 kPa below 0.10 m depth (Fig. 7a).

The sensitivity of Sq scores to the different levels of soil compaction observed at 0.00–0.10 and 0.10–0.20 m layer in the studied minesoil was clearly demonstrated by the clustering of soil samples belonging to different layers at opposite sides of PC1 axis (Fig. 8), which explained the majority of data variance. Such sensitivity of Sq scores to compaction layering in our subtropical fine-textured minesoil is consistent with that reported for fine-textured tropical soils under cropping and cattle production (Moncada et al., 2014), sugarcane and pasture (Cherubin et al., 2017), as well as with that reported for temperate fine-textured soils under agriculture (Guimarães et al., 2011; 2013). The convergence of our findings with these studies may endorse the validation of VESS as a tool to accurately assess the Sq of fine-textured minesoils.

Interestingly, the significant correlation of Sq scores with micro-aggregates (%) and macroaggregates (%) (Fig. 7g, h) suggests that the aggregation process in this minesoil has undergone its first steps, conceptualized in Stumpf et al. (2018a). First, the cohesive aggregates formed by compression at initial soil reclamation stages are gradually broken down by roots within the first 15 years of revegetation (close to soil sampling for the present study), and thereafter reaggregation starts induced by roots (Stumpf et al., 2016; 2018a). This mechanism may explain the balanced distribution of macroaggregates (Fig. 4a) and microaggregates (Fig. 4b) percentage in this minesoil at this reclamation stage. Likewise, Castioni et al. (2018) reported significant correlation (r = –0.68) between VESS scores and MWD of aggregates in clayey non-mined soils under sugarcane plantation. Indeed, the meta-analysis of Olivares et al. (2023) surveyed different studies reporting significant correlation of VESS scores with aggregation attributes in non-mined soils with contrasting texture and use. Together these findings suggest that from this stage of minesoil reclamation onwards the aggregation hierarchy in our minesoil likely mimics that observed in non-mined soils, and that such aggregation development is detected by VESS. Based on this same aggregation concept, here we hypothesize that, at early reclamation stages of the minesoil, the Sq scores may not correlate significantly with micro- and macroaggregates (%), because of the disaggregation-reaggregation processes undergoing at initial minesoil revegetation, which may appear inconsistent with the enhancement of other soil attributes. This hypothesis may be tested in future studies using minesoils newly formed adjacent to our experimental site. Conversely, Mora-Motta et al. (2024) found that MWD of aggregates was the only attribute (among BD, PR, TP, SOM, and other chemical attributes) insignificantly correlated with VESS Sq scores in tropical pasture and forest sites across soils with varying texture. Although unexplained by the authors, this could be assigned to a limited aggregation in the sandy soil under forest, despite the improvement of diverse soil attributes exerted by the forest over the pasture vegetation, which accompanied the VESS scores more sensitively than MWD. Combined with our findings, this suggests that other physical attributes rather than aggregate size ranges may relate more straightforwardly to VESS scores in soils with restricted (coarse-textured soils) or incipient (minesoils) aggregation. However, this needs further verification.

4.2. *Persistent minesoil compaction revealed by VESS and PCA*

VESS successfully detected a persistent compaction at 0.10–0.20 m and moreover indicated where this compaction was less (*H. altissima*) or more critical (*C. dactylon*) (Figs. 2, 3). The critical compaction at 0.10–0.20 m in *C. dactylon* treatment was confirmed by the positioning of its four replicates across Q2 and Q3 of PCA together with VESS scores, BD, TS, PR, and microaggregates (%) eigenvectors (Fig. 8). On the other hand, the outstanding alleviation of compaction in *H. altissima* treatment was confirmed by the shift of these samples towards the opposite side of the PCA (Q1 and Q4), mainly due to enhancement of MaP, TP, SOM and macroaggregates (%) (Fig. 8). Particularly, the samples with the lowest Sq scores, mainly *H. altissima* (0.00–0.10 m layer), were grouped together with SOM and macroaggregates (%) within Q2 of PCA (Fig. 8). Gains in soil porosity are known to favor root growth and thereby SOM content building along the soil profile (Sharma and Kumar, 2023).

Even though the weighted VESS scores (0.00–0.10 and 0.10–0.20 m) of *U. brizantha* and *P. notatum* did not differ from the other treatments (Fig. 3), their Sq scores resembled more that of *C. dactylon* than that of *H. altissima* treatment. This is supported by the ordination of *H. altissima* samples mainly across Q1 and Q4 of PCA, whereas samples of other treatments, especially samples from the 0.10–0.20 m layer, remain more closely associated to eigenvectors indicative of higher compaction in Q2 and Q3 of PCA (Fig. 8). Furthermore, the ordination of soil samples exhibiting intermediate Sq scores within or towards Q1 of PCA suggests that gains in MaP and TP precede gains in SOM and macroaggregates (%) as well as the improvement of minesoil Sq detectable by VESS.

The ordination of VESS and SOM at opposite quadrants of PCA (Fig. 8) informed the importance of increasing the SOM content of the minesoil as a key strategy to achieve lower VESS scores. This is particularly relevant for minesoils under reclamation, where mechanization for compaction alleviation, as commonly performed in agricultural soils, is undesired because it disrupts and delays the process of reclamation and recovery of minesoil functions (Rashmi et al., 2024). The highest SOM content observed in the 0.00–0.10 m compared to the 0.10–0.20 m layer (Fig. 6b) probably results from litter deposition and root concentration close to soil surface, and from impeditive root growth conditions below 0.10 m depth, as confirmed by Sq scores between 2.5 and 3.8 (Fig. 3). This stratification of SOM along the soil profile was captured by VESS scores as inferred from the significant correlation between these attributes (Fig. 7f). Nevertheless, the SOM content in both layers is still classified as "low ($\leq$25 g kg^{-1})" for southern Brazilian soils (CQFS, 2016), despite 14.3 years of revegetation. Thus, measures to simultaneously enhance SOM and Sq of this minesoil may be required.

4.3. *Validation, considerations and perspectives of VESS use in minesoils*

The VESS scores well integrated the soil Sq expressed by a series of quantitative attributes. The significant correlation coefficients ($|r|$ = 0.36–0.60) between Sq scores, physical attributes and SOM content found in our minesoil (Fig. 7) are comparable to that used to validate the use of VESS in soils under agriculture, forest and pasture ($|r|$ = 0.11–0.72) (Guimarães et al., 2013; 2017; Cherubin et al., 2017; Mora-Mota et al., 2024). Among these significant correlations, the highest coefficients were observed for BD (r = 0.60) and PR (r = 0.56), and the lowest coefficient was observed for MaP (r = –0.36) (Fig. 7). These data are well-aligned to the meta-analysis conducted by Olivares et al. (2023) including diverse soil attributes evaluated across different soil types, land uses and geographical locations (n = 120). The authors also found that the strongest correlation of VESS scores was with BD and PR (r = 0.58 and 0.72, respectively), and that the weakest correlation was with MaP (r = 0.11). Hence, VESS seems to be a reliable predictor of the minesoils Sq, particularly with respect to BD and PR levels. This is strategically relevant, as these attributes are major impediments to root growth in our minesoil (Stumpf et al., 2018b). The possibility of diagnosing this problematic compaction using VESS facilitates timely interventions to improve soil conditions and root development.

The VESS method has been shown to correlate well with its variations, including SubVESS (specifically developed for VESS of compacted subsoil), DSVESS (Double Spade VESS method to evaluate 0.00–0.40 m topsoil profile walls) and CoreVESS (VESS of small cores typically used for soil physical laboratory analysis) across different soil textures (Lin et al., 2022a, 2022b) as well as with GrassVESS (developed for VESS of pasture soils) (Emmet-Booth et al., 2018) and soil quality (Cherubin et al., 2016) and health indexes (Willoughby et al., 2023; Becker et al., 2024). Based on that and on the consistence of our VESS data with literature it is plausible to consider the VESS scores obtained here as a holistic and reliable translation of the current reclamation stage of the minesoil as affected by the different grasses. Future studies should assess the validity of VESS and explore its potential adaptation into a "MineVESS" method to capture early disaggregation-reaggregation processes taking place at initial reclamation stages of the minesoil (Stumpf et al., 2018a). Additionally, sequential studies correlating the VESS scores with quality indexes obtained from the minesoils may strengthen the role of VESS to diagnose the overall improvement of minesoil by the grasses.

5. Conclusions

This pioneering study was performed within the frame of a long-term field experiment to validate VESS as a method to assess the Sq of a minesoil revegetated with perennial grasses.

Through significant correlations of VESS Sq scores with TS of aggregates, soil MaP, TP, macroaggregates (%), microaggregates (%), SOM content and especially BD ($r = 0.60$, $p = 0.0003$) and PR ($r = 0.56$, $p = 0.0009$), and through the alignment of our data with literature, we validated VESS as a suitable, semi-quantitative, and science-grounded method to reliably monitor the Sq of a clayey subtropical minesoil (0.00–0.20 m). This was in accordance with our first objective and hypothesis.

The VESS Sq scores converged with multiple soil attributes as demonstrated by PCA and revealed improved Sq at 0.00–0.10 m compared to 0.10–0.20 m, probably resulting from root-assisted disruption of compressive aggregates mainly at the upper layer. The Sq scores did not distinguish the treatments at 0.00–0.10 m, just as the traditional quantitative attributes. Below 0.10 m, higher VESS scores were in line with more critical BD and MaP values, which may limit root growth and Sq improvement. Moreover, at 0.10–0.20 m the VESS scores sensitively confirmed improved Sq in *H. altissima* compared to *C. dactylon*. Confirming such sensitivity of Sq scores to grasses used for revegetation and to minesoil layers exhibiting different compaction levels met our second objective hypothesis.

Our findings suggest prioritizing *H. altissima* over the other grasses for reclamation of the studied minesoil. Furthermore, increasing the Sq of these minesoils through increasing their SOM content is a prioritary strategy, because mechanization to alleviate minesoil compaction is detrimental to its reclamation process. Finally, future studies should explore the validity and eventually required adaptations of VESS for its reliable application in earlier stages of minesoil reclamation. Thus, the Sq of the minesoil can be easily, cheaply and immediately assessed and monitored by VESS from the beginning of minesoil reclamation, allowing timely measures to accelerate the reclamation of minesoils.

CRediT authorship contribution statement

Marilia Alves Brito Pinto: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Thais Palumbo Silva:** Investigation, Formal analysis, Data curation. **Lizete Stumpf:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Stephan Domingues Nachtigall:** Methodology, Investigation, Formal analysis, Data curation. **Mateus Fonseca Rodrigues:** Investigation, Formal analysis, Data curation. **Pablo Miguel:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Luiz Fernando Spinelli Pinto:** Writing – original draft, Supervision, Methodology, Conceptualization. **Rachel Muylaert Locks Guimarães:** Supervision, Methodology, Conceptualization. **Otavio dos Anjos Leal:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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