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# Soil Health Assessment in Brazilian Subtropical Oxisol Under Land Use and Long-term Tillage Systems

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**HIGHLIGHTS**

- The SMAF was used for the soil health assessment.
- The soil of the secondary forest was healthier than the agricultural areas.
- The VESS method is promising for monitoring soil health.

**Abstract:** Soil health has been used worldwide for soil monitoring in different soil use and management. The objective of the study was to evaluate, in a Subtropical Oxisol of the Campos Gerais region in Paraná state, if the Visual Evaluation of Soil structure (VESS) and Soil Management Assessment Framework (SMAF) approaches allow evaluate soil response to various land uses or soil tillage used in the region. The land use and tillage practices consist of conventional tillage, minimum tillage, no-tillage, and secondary forest. The SMAF was used as a tool to evaluate the soil health using five indicators: pH, phosphorus, potassium, bulk density, and soil organic carbon. The VESS was used to determine the soil structural quality. The secondary forest showed the best soil structure and tillage practices declined soil structure quality. Similarly, the soil health index was higher in secondary forest compared to tillage practices, and the tillage had little effect on soil health. The SMAF showed differences between land use and tillage practices. The VESS method could be used as a complementary tool for monitoring the soil health.

**Keywords:** Soil quality; Soil Management Assessment Framework; Visual Evaluation of Soil Structure; No-till; Minimum tillage.

## INTRODUCTION

The soil health assessment is an increasingly relevant concern for farmers and researchers worldwide, as it plays a key role in the sustainability and productivity of production systems [1]. Through this analysis, efficient management practices can be identified, which ensure a healthy environment for plant development

[2]. Different soil health assessment approaches have been used around the world [3] using quantitative methods, where the information obtained allows a more accurate interpretation of soil conditions and enables the identification of aspects that can be improved through appropriate management practices. These methods are quite common and widely recognized [4]. On the other hand, qualitative methods have a more subjective and perceptive approach, in other words, it provides a more contextualized and qualitative view, allowing to identify specific aspects that may be crucial for soil health. Although they are simpler, more accessible and do not require additional equipment costs, they are less accurate than quantitative methods and are subject to subjective influences [3,5].

In Brazil, soil health assessments have grown in recent decades [6] and it has been carried out by different methodologies. Recently, more robust quantitative methods, such as the Soil Management Assessment Framework (SMAF) have been tested in Brazil [5,7–10]. SMAF is a quantitative method that uses a range of soil physical, chemical, and biological indicators to provide a numerical assessment of soil health [4]. These indicators may include, for example, the amount of organic matter, nutrient concentration, water holding capacity, among others. The SMAF presents a very accurate and reliable approach, but its use requires specialized equipment and correct data handling.

The Visual Evaluation of Soil Structure (VESS) is a qualitative method based on the visual distinction of the structures present in different soil layers and it has been used in Brazil [5,11–14]. After the soil is sampled, visual scores of structure quality (Sq) are assigned to the layers, according to the aggregates size and appearance, visible porosity, root presence, appearance after handling and description of natural aggregates. The Sq are marks given in accordance with a reference chart. The VESS plays an important role in soil health assessment by providing a more holistic and general overview of soil conditions briefly [15].

In agricultural systems, soil management should be conducted to enhance soil health to increase production without degrading soils and the environment [16]. However, in conservation systems, such as no-till (NT), intense machinery traffic has caused soil compaction [17,18]. To redress this problem, soil tillage (minimum tillage) and/or mechanical intervention (conventional tillage) is used. Their effects depend on several factors [19]. Intensive tillage in conventional tillage favors erosion processes and $CO_2$ losses, which can be minimized with minimum tillage [20]. The objective of the study was to evaluate, in a Subtropical Oxisol of the Campos Gerais region of Paraná, if the VESS and SMAF approaches allow evaluate soil response to various land uses or soil tillage used in the region. The results obtained will provide a solid basis for assessing soil health, identifying areas that needed specific interventions.

## MATERIAL AND METHODS

### Experimental site

The experimental site used for this study belongs to the Paraná Rural Development Institute – Iapar-Emater, located in Ponta Grossa, State of Paraná, southern Brazil (25º 09’ 06,2” S, 50º 09’ 15,19” W, 862 m above sea level). The soil has a clay texture (726; 212 and 62 g kg$^{-1}$ of clay, silt, and sand, respectively), and is classified as Oxisol (Latossolo Vermelho Distroférrico, Brazilian classification; Rhodic Eutrudox, US Soil Taxonomy), formed from Ponta Grossa Formation, with the presence of the following minerals: gibbsite, kaolinite, halloysite, montmorillonite, hematite, rutile, anatase, goethite and quartz [21]. The climate of the region is Cfb (humid subtropical, without dry season) according to Koppen's classification [22].

The land use and tillage practices consist of (i) conventional tillage (CT) - a plow tillage followed by two narrow disking after summer and winter harvest; (ii) minimum tillage (MT) - comprising of one chisel plow and one narrow disking after summer and winter harvest; (iii) no-tillage (NT) - no soil disturbance and (iv) secondary forest (SF). In 1981 the experiment began, initially by conducting two tillage systems: NT and CT. In 1989, the area of CT was divided to perform the MT in the same place of study. Currently, the areas of each preparation system are 10000 m$^2$ for NT; 5000 m$^2$ for MT and 5000 m$^2$ for CT.

The cultures cultivated from the beginning of the experimental period were: (i) succession of soybean (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) during the spring-summer; (ii) succession of black oat (*Avena strigosa* Schreb), wheat (*Triticum aestivum* L.), common vetch (*Vicia sativa* L.) and intercropping of black oat and common vetch during the autumn-winter. Previous of the soil sampling (from 2012 to 2017) the following crops were cultivated: (i) soybean during the spring-summer of 2012–2013, 2014–2015, and 2016–2017 and maize during the spring-summer of 2013–2014 and 2015–2016; (ii) intercropping of black oat + common vetch in 2013 during the autumn-winter and black oat from 2014 to 2017 during the autumn-winter. The same crops were cultivated on all soil tillage systems.

## Soil sampling and analysis

Soil sampling was conducted in the winter of 2017. The samples were collected in a regular grid with twenty-five samples in each land use and tillage practices, in the depth of 0-0.10 m and 0.10-0.20 m, and then forwarded to laboratory analysis. For biological and chemical analyses, disturbed samples were collected at each point and layer. For physical analyses, undisturbed samples were collected using 100 $cm^3$ volume rings at all points and layers.

Soil bulk density (BD) was calculated by dividing dry soil mass (oven-dried for 24 h at 105 °C) by ring volume, according to the method described by [23]. For the phosphorus (P) and potassium (K) analyses, disturbed samples were oven dried under forced air circulation at 40 °C to constant weight and then passed through a 2mm diameter sieve. After extraction using the Mehlich$^{-1}$ method, exchangeable K was determined by flame photometry, and the available P was measured using a spectrophotometer, according to the method described by [24] and [25]. The soil organic carbon (SOC) content was determined by Walkley-Black method. For pH measurement, a glass electrode was used upon stirring and standing of soil mixed to distilled water.

## Soil health assessment

The SMAF was used as a tool to evaluate the land use and tillage practices effects on soil health. The SMAF assessment is based on three steps: i) selecting a minimum dataset; ii) interpreting measured indicators; iii) integrating indicators into an overall index. In Step I, we selected the indicators that are most used in Brazil and in the world [6,26] and responds to multiple soil functions and ecosystem services, including: plant production, nutrient cycling, C sequestration, regulating water entry and mitigating wind and water erosion [27]. These indicators include pH, P, and K, which represent soil chemical health, mainly soil acidity, as well as P and K, which are crucial for crop production in tropical soils. Additionally, we considered BD as an indicator of soil structure to represent physical health. Finally, SOC was an indicator of soil biological functions.

In step II, the values measured for the soil indicators, originally expressed in different units, were transformed into scores ranging from 0 to 1, using the algorithms (scoring curves) presented in the SMAF spreadsheet. The standardization process of the soil indicators into scores was tailored to account for variations dependent on the type of soil, soil texture, mineralogy, climate, slope, crop type, and analytical method used [4,28]. The organic matter class had a factor of 4; the texture class had a factor of 5; the climate class had a factor of 1 (≥170-degree day and ≥550mm mean annual rainfall); the mineralogy class had a factor of 3 (1:1 clay and Fe and Al oxides); the slope class had a factor of 3 in CT, MT and SF (7.5% slope) and a factor of 4 in NT (10% slope) and the weathering class had a factor of 2. The Mehlich$^{-1}$ method (class 1) was used to measure extractable P. The interpretation of the limits (critical level) of the pH, P and K values followed the recommendations for soils and culture of the Parana state, according to [29]. Optimal pH values of 6 were added for areas with annual crops, which is considered a high value in the interpretation of pH according to [29] and 5 for SF. For P in SF, an optimal P value of 6 mg $dm^{-3}$ and a maximum of 12 mg $dm^{-3}$ was used. Soil under native or secondary forest generally have low pH values and low levels of available nutrients [30–32]

Finally, in step III, individual indicator scores were integrated into a weighted soil health index (SHI) by Equation 1:

$$SHI = \sum_{i=1}^{n} Si\, Wi$$

where: Si is the indicator score and Wi is the indicator weight, and *n* the number of indicators integrated in the index. SHIs were calculated individually for each soil layer (0.0–0.10 and 0.10–0.20 m) and an average SHI for the entire layer (layer 0–0.20 m). The contribution of each component (chemical, physical and biological) to the overall SHI was calculated to identify the management practices that will improve soil health.

For the Visual Evaluation of Soil Structure (VESS), the methodology proposed by [33] and [34] was followed. With the aid of a straight shovel, mini trenches measuring 20 cm wide and 22-25 cm long were opened for the extraction of semi-deformed slices (blocks). The evaluation was based on the appearance, resistance, and characteristics of the soil aggregates, being defined by five visual scores (Sq): Sq = 1 (best structural quality) to Sq = 5 (poor structural quality).

## Statistical analysis

Statistical differences between indicators, scores and indices were established by the nonparametric Kruskal–Walli's test, followed by the Dunn's test for multiple comparisons with a significance level of α= 5%. Principal Component Analysis (PCA) was performed to understand the relationships of each component of the SHI (chemical, physical, and biological), the SHI scores (for the layer 0–0.20 m) and VESS scores. All data analyses were conducted in statistical software RStudio version 4.0.4 [35], using the R package "dunn.test" [36] "Hmisc" [37] and "Factoextra" [38].

# RESULTS

## Soil Physical, Chemical and Biological Indicators

The conversion from SF to different tillage practices resulted in a significant increase in BD, in the 0-0.10 m and 0.10-0.20 m soil layer (Table 1). The BD in NT, MT and CT was similar. Similar behavior was observed for the SMAF scores, with mean values of 0.988, 0.980, 0.984 and 0.994, respectively in the 0-0.10 m soil layer and 0.985, 0.974 and 0.961, respectively for the 0.10-0.20 m soil layer. Despite this, the scores for BD were high in the different land use and tillage practices.

In the 0-0.10 m soil layer, pH ($H_2O$) did not show significant differences between SF (4.90) and MT (4.83), but there was a significant reduction in NT (4.60) and CT (4.68). NT and CT had the lowest scores compared to MT, with mean scores of 0.38, 0.42 and 0.51, respectively. In this case, the highest scores were observed in SF (0.99) differing significantly from the other treatments. In the 0.10-0.20 m soil layer, the pH of CT (4.79) did not differ statistically from NT (4.72) and MT (4.88), but NT presented lower pH values when compared to MT. The SMAF scores for pH were higher for FS (0.97) in relation to the tillage practices. NT presented lower score (0.44) than MT (0.53), while there were no significant differences between CT (0.48) with NT and MT.

The highest P contents and SMAF scores were observed in NT (19.45 mg dm$^{-3}$ and 0.99, respectively), differing significantly from the other treatments. SF presented the lowest P contents and SMAF scores, with averages of 4.86 mg dm$^{-3}$ and 0.78, respectively. In the 0.10-0.20 m soil layer, P contents and SMAF scores were highest in MT (9.09 mg dm$^{-3}$ and 0.91, respectively), while NT (5.33 mg dm$^{-3}$ and 0.80, respectively) and CT (5.53 mg dm$^{-3}$, 5.53 and 0.80, respectively) were statistically equal. In SF the results for P were lower compared to NT, CT, and MT. In agricultural areas there is a reduction in K contents when compared to SF, which resulted in lower SMAF scores for NT, CT, and MT, in the 0-0.10 m soil layer. However, there were no significant effects for K in the 0.10-0.20 m soil layer.

**Table 1.** Mean values and scores (SMAF) of the indicators in land use and tillage practices: No-till (NT), Minimum tillage (MT), Conventional tillage (CT) and Secondary Forest (SF) in the 0-0.10 m and 0.10-0.20 m soil layer.

| Indicator | | NT | MT | CT | SF | *p-value*[1] |
|---|---|---|---|---|---|---|
| | | | **0.00-0.10 m** | | | |
| **BD** | g cm$^{-3}$ | 1.02 a | 1.02 a | 1.01 a | 0.86 b | 2.9E-10 |
| | Score | 0.988 a | 0.980 a | 0.984 a | 0.994 b | 2.0E-10 |
| **pH ($H_2O$)** | - | 4.60 b | 4.83 a | 4.68 b | 4.90 a | 2.1E-09 |
| | Score | 0.38 c | 0.51 b | 0.42 c | 0.99 a | 1.1E-15 |
| **P** | mg dm$^{-3}$ | 19.45 a | 13.07 b | 8.07 c | 4.86 d | 6.4E-12 |
| | Score | 0.99 a | 0.93 b | 0.93 b | 0.78 c | 9.5E-10 |
| **K** | mg dm$^{-3}$ | 125.90 b | 127.94 b | 114.95 b | 154.37 a | 6.03E-4 |
| | Score | 0.87 b | 0.88 b | 0.84 b | 0.94 a | 6.03E-4 |
| **SOC** | g dm$^{-3}$ | 30.07 b | 28.83 b | 29.08 b | 35.63 a | 5.5E-10 |
| | Score | 0.9999 b | 0.9996 b | 0.9997 b | 1.00 a | 5.5E-10 |
| | | | **0.10-0.20 m** | | | |
| **BD** | g cm$^{-3}$ | 1.04 a | 1.07 a | 1.05 a | 0.92 b | 2.7E-08 |
| | Score | 0.985 b | 0.974 b | 0.961 b | 0.991 a | 3.0E-08 |

Cont. Table 1

| | | | | | | |
|---|---|---|---|---|---|---|
| **pH ($H_2O$)** | **-** | **4.72 b** | **4.88 a** | **4.79 ab** | **4.57 c** | **2.2E-09** |
| | Score | 0.44 c | 0.53 b | 0.48 bc | 0.97 a | 1.7E-13 |
| **P** | mg dm$^{-3}$ | 5.33 b | 9.09 a | 5.53 b | 3.64 c | 6.3E-08 |
| | Score | 0.80 b | 0.91 a | 0.80 b | 0.69 c | 1.1E-06 |
| **K** | mg dm$^{-3}$ | 68.50 ns | 70.22 | 75.23 | 78.20 | 0.3081 |
| | Score | 0.65 ns | 0.66 | 0.69 | 0.71 | 0.3081 |
| | g dm$^{-3}$ | 30.36 a | 23.12 c | 24.40 bc | 26.46 ab | 1.9E-05 |
| | Score | 0.99922 a | 0.99672 c | 0.99748 bc | 0.99840 ab | 1.9E-05 |

The values mean followed by the same letter do not differ statistically from each other by the Dunn's test (α=0.05). BD: Soil bulk density. P: phosphorus. K: potassium. SOC: soil organic carbon. [1]Significant at 5% by the Kruskal-Walli's test.

For SOC, in the 0-0.10 m soil layer, there was a reduction in SF for tillage practices, in the proportion of 10.71, 10.27, 10.36 % for NT, MT and CT, respectively. The mean score of SMAF for SF received a value of 1.00 and of the tillage practices, values of 0.99. In the 0.10-0.20 m soil layer, SOC was higher in NT (30.36 g dm$^{-3}$), not differing statistically from SF (26.46 g dm$^{-3}$). There were no significant differences between CT (24.40 g dm$^{-3}$) and MT (23.12 g dm$^{-3}$) and SF, but MT presented lower values than NT. The SMAF score was higher for NT in relation to the other treatments, but all presented values of 0.99.

## Overall Soil Health Index and components (chemical, physical and biological)

Overall SHI and SHI components (chemical, physical, and biological) for each soil layer are shown in Figure 1 and Figure 2. Soil health was higher in SF for the two layers evaluated and lower in CT when compared to MT (Figure 1 and 2). In the 0-0.10 m soil layer, no differences were found between NT with MT e CT (Figure 1). In the 0.10-0.20 m soil layer, there was a lower SHI in CT and NT (Figure 2).

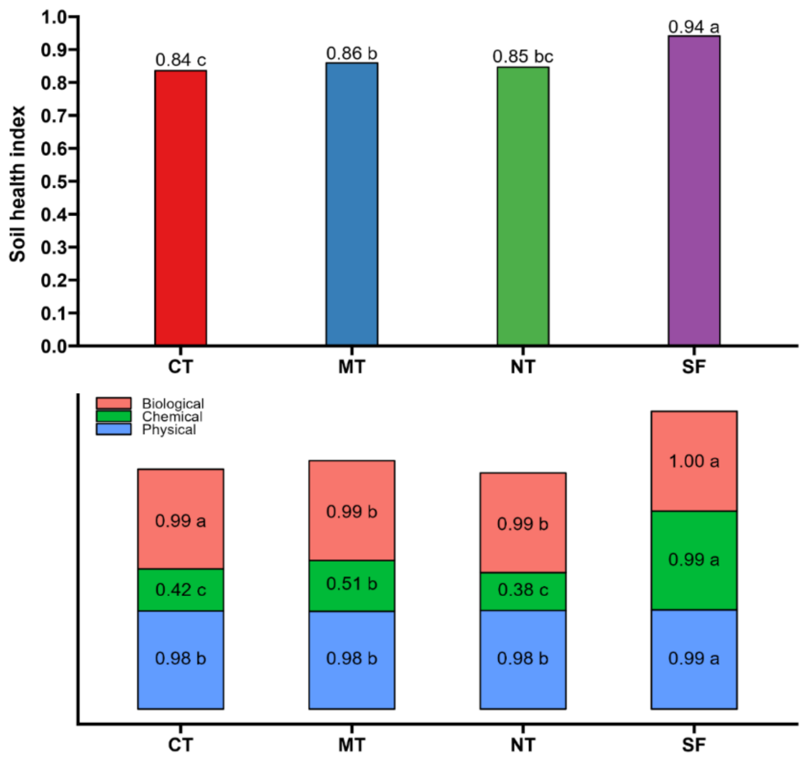


**Figure 1.** Soil health index and weighted contribution of the chemical, physical and biological components for layers 0.0-0.10 m, under No-till (NT), Minimum tillage (MT), Conventional tillage (CT) and Secondary Forest (SF). * The values mean followed by the same letter do not differ statistically from each other by the Dunn's test (α=0.05).

The SMAF was useful to assess which components (chemical, physical or biological) require priority management. The chemical component had the greatest effect on SHI. Long-term land use with agriculture led to chemical impoverishment of the soil. The SHI computed for each depth (0-0.10 and 0.10- 0.20 m) indicated that soil health decreased with depth.

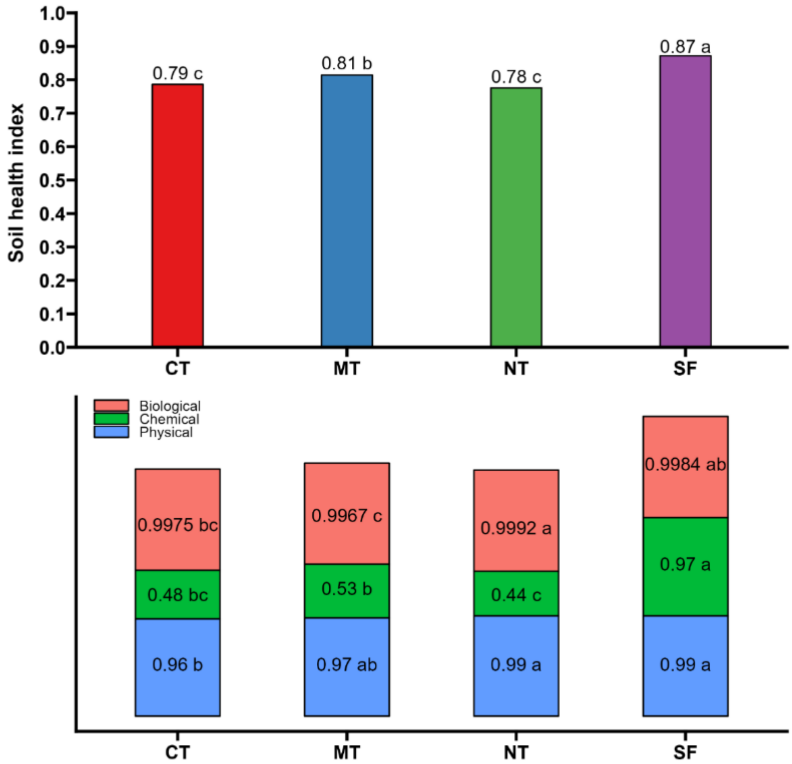


**Figure 2.** Soil health index and weighted contribution of the chemical, physical and biological components for layers 0.10-0.20 m, under No-till (NT), Minimum tillage (MT), Conventional tillage (CT) and Secondary Forest (SF). * The values mean followed by the same letter do not differ statistically from each other by the Dunn's test (α=0.05).

## Overall Soil Health Index *vs*. Visual Evaluation of Soil Structure Scores

The different tillage practices declined soil structure quality, assessed by VESS scores (Table 2). The SF area showed the best soil structure (VESS score = 1.03), with aggregates highly porous and roots throughout the soil, which readily crumbled with fingers. In different tillage practices the VESS scores were 1.46 in NT, 1.53 in MT and 1.60 in CT, with a mixture of prous agregates and less porous hard to break aggregates (clods). Statistical similarity was found at these sites and they differed from SF. Overall SQI integrating 0.00–0.20m (Table 2), showed that NT (0.81), MT (0.84) and CT (0.81) degrade soil health compared to SF (0.91). However, MT is promoting improvements in soil health compared to NT and CT, which was not verified by VESS.

**Table 2.** VESS scores and overall soil health index (SHI) in the 0-0.20 m soil layer in land use and tillage practices: No-till (NT), Minimum tillage (MT), Conventional tillage (CT) and Secondary Forest (SF).

| | VESS | SHI |
|---|---|---|
| NT | 1,46 a | 0,81 c |
| MT | 1,53 a | 0,84 b |
| CT | 1,60 a | 0,81 c |
| SF | 1,03 b | 0,91 a |
| *p-value*[1] | 8,0E-11 | 1,01e-12 |

The values mean followed by the same letter do not differ statistically from each other by the Dunn's test (α=0.05). [1]Significant at 5% by the Kruskal-Walli’s test.

The relationship of SHI, land use and tillage practices, and VESS scores investigated by PCA analysis is in Figure 3. The first two components explain 73.4% of the data variance. If the SHI was higher, the lower were the scores obtained by the VESS method, which demonstrates better soil structural quality.

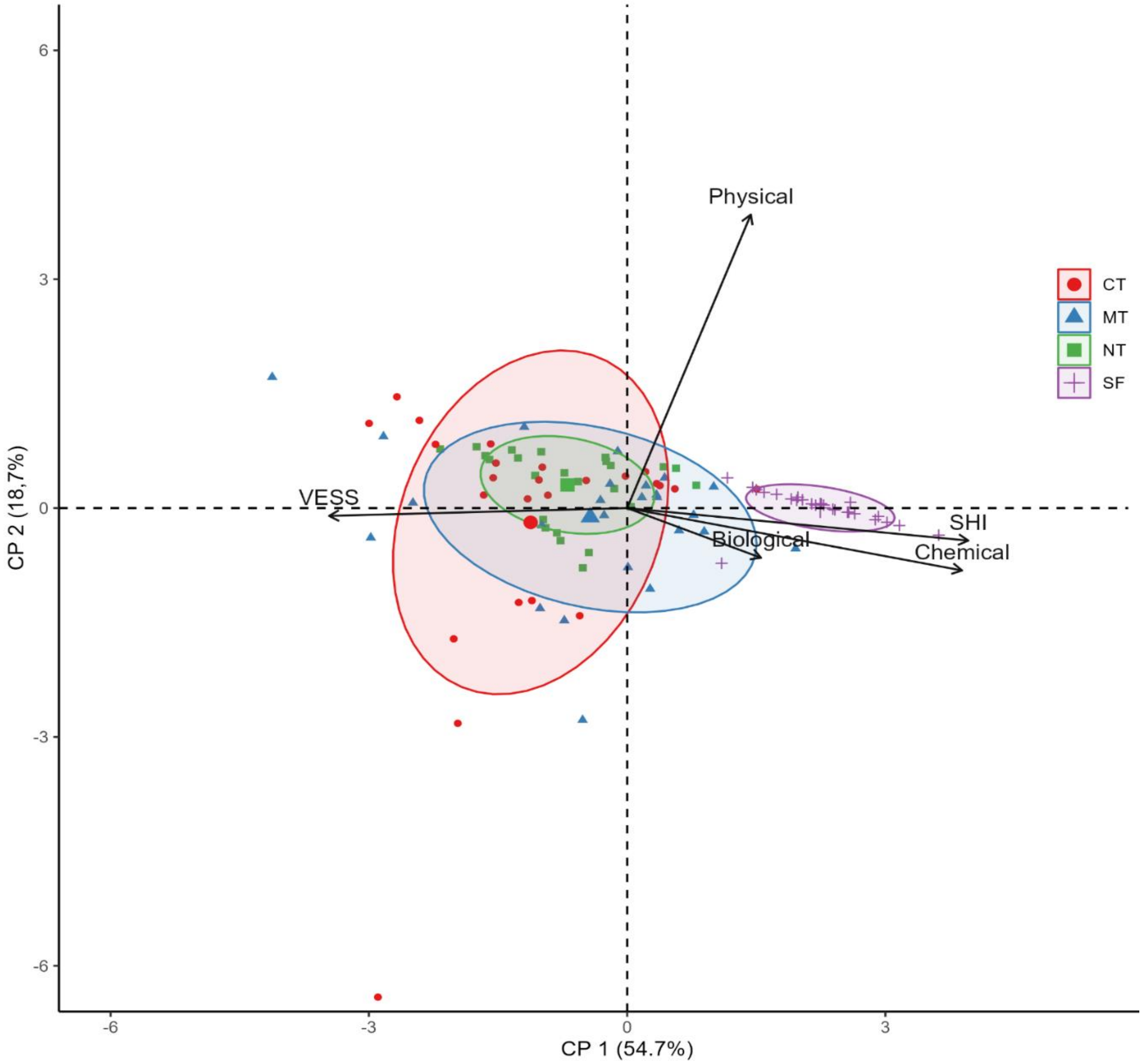


**Figure 3.** Principal component analysis (PCA) of the 0-0.20 m depth in no-till (NT), minimum tillage (MT), conventional tillage (CT) and secondary Forest (SF).

The Figure 3 shows that the data were grouped into two clusters, with SF being separated from tillage practices, influenced by its higher SHI.

## DISCUSSION

### *Soil Health indicators response to land use and soil tillage*

In relation to the physical component of soil health, all tillage practices and SF showed optimum BD measured values [39] and SMAF-scores [4] at both soil layers. Besides lower BD measured values in SF at the 0-0.10 m and 0.10-0.20 m soil layers, the NT, MT, and CT practices did not show a critical BD for root development [40] which was established in BD SMAF-scores (i.e., values from 0.96 to 0.99). The main reasons for those optimum values are associated with crop rotation and cover crops in the trial field. The root development of diversified crops created a functional porous system that improved the soil’s physical stability and support. It increases the soil’s resistance to compaction over time. In addition, we highlight that the adoption of CT and MT practices did not improve soil structure compared to NT practice after 36 years of cultivation. Therefore, no-tillage associated with cover crops and diversified crop rotations in the long term is an advisable strategy to improve soil physical properties and soil conservation [41] as well as maintain soil physical health under different tillage practices.

Conversely, the SF showed the best soil chemical health related to tillage practices. The indicators contributing to this difference were pH at the 0-0.10 m soil layer and pH and K at the 0.10-0.20 m soil layer. Measured values and SMAF scores of those indicators were lower in NT, MT, and CT practices. Soil pH is the soil indicator to guide and support agricultural practices on soil acidity management and chemical fertility. In this way, standard lime application practices have been developed to increase soil pH and maintain it near 6.0 which is the optimum pH value for crop growth and yield [42]. However, a double recommended lime rate has been suggested for increasing soil pH and base saturation as well as reducing aluminum toxicity instead of the traditional standard lime rate [43]. It can explain the lower pH measured values and SMAF scores in NT, MT, and CT tillage practices over the years.

In addition, not only the standard lime rate but also the standard potassium recommended is underestimated. Modern soybean genotypes are more demanding in macronutrients than older varieties. They require greater amounts of macronutrients such as potassium for refilling their greater removal by seeds [44]. Therefore, these authors recommended a review of the standard values for macronutrient removal by soybean seed from Brazilian fertilization recommendation systems. In addition, a study carried out by [45] showed a yield gap in soybean cultivation due to insufficient chemical fertility in the soil profile in southern Brazil.

Besides high P-measured values (i.e., above critical limits) and SMAF scores in all tillage practices at the 0-0.10 m soil layer, the MT practice increased P-content at the 0.10-0.20 m soil layer. The phosphorus is immobile in the soil profile [46]. Therefore, tillage practices such as MT can incorporate immobile nutrients in deep soil layers reducing P stratification [19]. However, the P SMAF-score was above 0.80 in NT practice at the 0.10-0.20 m soil layer. This value shows non-poor chemical soil health in the NT practice related to MT and CT practices. This finding is according to [47]. These authors measured P-content in deep soil layers under different tillage practices. They found no difference between no-tillage and conventional tillage regarding P-content at the 0.10-0.20 m soil layer. Therefore, after initial incorporation of lime and phosphorus at the no-tillage establishment, additional tillage is not necessary to ensure soil fertility in terms of phosphorus at deep soil layers [47].

Moreover, no-tillage improves not only soil chemical health but also soil biological health. In general, the soil carbon sequestration potential of no-tillage is higher related to other tillage practices [48]. It reduces the soil structure disturbance protecting soil carbon against microbial decomposition. Therefore, it was observed higher measured values of SOC in the SF at the 0-0.10 m and 0.10-0.20 m soil layer and in the NT practice at the 0.10-0.20 m soil layer. However, there was no difference in SMAF scores among tillage practices and SF as well as the scores were about 0.99 in all treatments. It occurred because values of SOC > 20 g $kg^{-1}$ reach the maximum value of soil biological quality in clayey soils [4]. In the same way, the results of some studies such as [49] and [45,50] showed a good relationship between maximum crop yield and SOC at a content of 20 g $kg^{-1}$. Nevertheless, if we consider the potential of no-tillage associated with cover crops for sequestering carbon in clayey soils, the values of SOC can reach more than 62 g $kg^{-1}$ in the Cfb climate region [50], i.e., Campos Gerais region.

### *Soil Health response to soil tillage in Campos Gerais region*

In general, the soil health index was 9% higher in the SF compared to tillage practices (i.e., CT, MT, and NT) after 36 years of agricultural cultivation. In the SF, the soil was functioning above 87% of its potential capacity. Previous studies such as [7] found that soil under native vegetation (e.g., Atlantic Forest) performed at 88% of its potential capacity in a Clay Ferralsol in the same region. In addition, native vegetation is a baseline regarding soil health studies [5] as well a soil health index > 0.70 are frequently found in Brazilian clayey soils [7–9] due to its inherent (e.g., basic soil forming factors and processes) soil health [10]. In addition, the results are according to [51] who found soil health index above 0.70 in different tillage practices (i.e., no-tillage and conventional tillage) and above 0.85 in native forest in Southern Brazil. They also found no difference between no-tillage and conventional tillage in soil health index after 17 years of soybean cultivation.

In both soil layers, the reduction of 9% in soil health index comes about due to the chemical component of soil health in all tillage practices, mainly pH and K. In that case, an adjustment in lime and fertilizer application can contribute to improving soil health under different tillage practices. In addition, along with diversified cover crops, the inclusion of organic residues such as cattle manure and organic compost can contribute positively to the maintenance of soil pH and improvements of macronutrient availability [52] in all tillage practices.

Furthermore, we highlight that soil in all tillage practices and SF was functioning close to the maximum potential of physical and biological capacity. The main factor that contributed to it is the presence of diversified cash (e.g., wheat, soybean, and corn) and cover crops (oat and vetch) in the trial field. They can improve soil structure and soil organic carbon. For example, diversified crops are a source of particulate organic matter which can persist over long periods and can be a direct precursor to mineral-associated organic matter [53]. This process along with climate and soil characteristics can explain the similar soil health among NT, MT, and CT despite soil tillage.

### *Land uses influences the soil structural quality*

Visual soil structure analysis methods have good sensitivity in distinguishing management practices [54], and are particularly used to detect compacted layers in the soil. The increase in scores (Table 2) found in agricultural areas (NT – 1.46; CT – 1.60 and MT – 1.53) in relation to secondary forest (1.03) is related to changes in soil structure, provided by intense traffic of machinery, which reduce soil pores and increase compaction [19]. Another fact is linked to the reduction of organic matter, the main agent in the formation of stable aggregates [55,56]. However, the non-distinction of management by VESS is related to the resilience of clayey soils, which are naturally less prone to reduction in structural quality than coarse-textured and sandy soils [56–58].

The VESS method is sensitive enough to distinguish different tillage practices, mainly contrasting uses such as agriculture and SF. The method was found to be reliable for identifying the structural quality of tropical and subtropical soils under different management and cultivation practices [59] Overall, the information on the scores per layer allows checking the difference in structure and presence of compressed layers compared to the overall score [14,60]. The relationship of SHI and VESS scores investigated by PCA analysis suggests that VESS method could be used as a complementary tool for monitoring the soil health or could be further included how indicator into the SMAF or in other soil health assessment tool. It corroborates data reported by [5], who concluded that VESS scores that has shown potential for monitoring of soil health.

## CONCLUSION

Through the SMAF tool, it was possible to detect that the that soil health was higher in secondary forest than in tillage practices. Similarly, VESS scores showed better soil structural quality in secondary forest. Thus, both approaches are efficient to assess the impact of land use and tillage practices on soil quality.

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