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Soil Quality Evaluation Using the Soil Management Assessment Framework (SMAF) in Brazilian Oxisols with Contrasting Texture

Maurício Roberto Cherubin[(1)*], **Cássio Antônio Tormena**[(2)] **and Douglas L. Karlen**[(3)]

[(1)] Universidade de São Paulo, Centro de Energia Nuclear na Agricultura. Piracicaba, São Paulo, Brasil.
[(2)] Universidade Estadual de Maringá, Departamento de Agronomia, Maringá, Paraná, Brasil.
[(3)] United States Department of Agriculture/Agricultural Research Service, National Laboratory for Agriculture and the Environment, Ames, Iowa, United States of America.

*** Corresponding author:**
E-mail: cherubin@usp.br

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ABSTRACT: The Soil Management Assessment Framework (SMAF) was developed in the U.S.A. and has been used as a tool for assessing and quantifying changes in soil quality/health (SQ) induced by land uses and agricultural practices in that region and elsewhere throughout the world. An initial study using SMAF in Brazil was recently published, but additional research for a variety of soils and management systems is still needed. Our objective was to use data from five studies in southern Brazil to evaluate the potential of SMAF for assessing diverse land-use and management practices on SQ. The studies examined were: (i) horizontal and vertical distribution of soil properties in a long-term orange orchard; (ii) impacts of long-term land-use change from native vegetation to agricultural crops on soil properties; (iii) effects of short-term tillage on soil properties in a cassava production area; (iv) changes in soil properties due to mineral fertilizer and pig slurry application coupled with soil tillage practices; and (v) row and inter-row sowing effects on soil properties in a long-term no-tillage area. The soils were classified as Oxisols, with clay content ranging from 180 to 800 g kg^{-1}. Six SQ indicators [pH(H_2O), P, K, bulk density, organic C, and microbial biomass] were individually scored using SMAF curves and integrated into an overall Soil Quality Index (SQI) focusing on chemical, physical, and biological sectors. The SMAF was sensitive for detecting SQ changes induced by different land uses and management practices within this wide textural range of Brazilian Oxisols. The SMAF scoring curve algorithms properly transformed the indicator values expressed in different units into unitless scores ranging from 0-1, thus enabling the individual indicators to be combined into an overall index for evaluating land-use and management effects on soil functions. Soil sector scores (*i.e.*, chemical, physical, and biological) identify the principal soil limitations and can therefore be used to establish priorities for specific management actions. The SMAF can be used as a tool for assessing SQ in Brazilian soils, thus helping farmers, land managers, and politicians make better decisions regarding sustainable land-use and management practices.

Keywords: soil quality index, soil functions, soil indicators, soil use and management.

INTRODUCTION

Increasing demand for food, feed, fiber, and fuel has accelerated worldwide agricultural expansion (Foley et al., 2005) and consequently has increased pressure on natural resources, specifically the soil. The environmental impacts of agriculture include those caused by expansion (i.e., when croplands and pastures extend into new areas, replacing natural ecosystems) and those caused by intensification (i.e., when existing lands are managed to be more productive, often using irrigation, fertilizers, biocides, and heavy mechanization) (Foley et al., 2011). Assessing and monitoring changes in soil quality/health (SQ) induced by these land-use and management practices is, therefore, essential to help identify strategies with less environmental impact in order to achieve more sustainable agricultural systems (Cherubin et al., 2015).

Soil quality is the capacity of a specific soil resource to perform a variety of critical functions (Karlen et al., 1997). It is a complex functional concept that cannot be measured directly in the field or laboratory, but it can be inferred by soil properties and processes sensitive to land use and management, denominated soil quality indicators (Cardoso et al., 2013; Zornoza et al., 2015). Although many SQ assessment strategies have been tested (Andrews et al., 2002, 2004; Mukherjee and Lal, 2014; De Paul Obade and Lal, 2016), there is no comprehensive, universally agreed-upon strategy for evaluating either natural or anthropogenic ecosystems. Currently, however, one of the most promising approaches is the Soil Management Assessment Framework (SMAF) described by Andrews et al. (2004).

The SMAF was initially developed for North American soils (Andrews et al., 2004). The assessment protocol is based on three steps: (i) indicator selection (chemical, physical, and biological); (ii) indicator interpretation (non-linear scoring curves); and (iii) integration into an overall SQ index (SQI). The overall SMAF SQI is expressed as a fraction or percentage of full performance of soil functions such as crop productivity, nutrient cycling, or environmental protection (Andrews et al., 2004).

The current version of SMAF has scoring curves or interpretation algorithms for 13 indicators. Collectively, they reflect a variety of chemical properties [potential of hydrogen (pH), electrical conductivity (EC), sodium adsorption ratio (SAR), and extractable phosphorus (P) and potassium (K)]; physical properties [bulk density (BD), water stable aggregates (WSA), available water capacity (AWC), and water-filled pore space (WFPS)]; and biological properties [soil organic carbon (SOC), microbial biomass carbon (MBC), potentially mineralizable N (PMN), and β-glucosidase activity (BG)] (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2010). These scoring curves were developed and validated using datasets primarily from the U.S.A, Canada, and Mexico, although the WFPS curve also included data from China, and the BG curve included data from Brazil, Argentina, and Italy. Each scoring curve also accounts for site-specific factors (i.e., climate and/or inherent soil properties), analytical methodologies, and time of sampling, which can affect measured values and therefore the "score" associated with each indicator (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2010).

Since public release of SMAF in 2004, it has been broadly used in the U.S.A. for assessing SQ changes in natural ecosystems and agroecosystems on a variety of scales ranging from evaluations within experimental fields (plots) to regional evaluations (Andrews et al., 2004; Wienhold et al., 2006; Karlen et al., 2014). The SMAF has also been successfully used in several other countries around the world [e.g., South Africa (Swanepoel et al., 2015), Ethiopia (Gelaw et al., 2015), Nepal (Kalu et al., 2015)]. The first SMAF application to Brazilian tropical soils was conducted by Cherubin et al. (2016a), who verified that SMAF was effective for assessing SQ changes due to land-use change (LUC) for sugarcane expansion in the central-southern region. However, the effectiveness of SMAF in assessing other land uses and management practices under Brazilian tropical and subtropical soils remains unexplored.

We hypothesized that SQ changes induced by different land-use and management practices could be efficiently and effectively detected by the SMAF in Brazilian subtropical Oxisols. The objective of this study was to use datasets from five studies previously carried out in southern Brazil under Oxisols with contrasting textures to evaluate SQ changes induced by land-use and management practices using the SMAF.

MATERIALS AND METHODS

Study sites

Data for this evaluation of the SMAF was obtained from five previous studies carried out in southern Brazil under a wide range of soil texture conditions and land-use and management practices. A brief description of each is given below:

1. an on-farm study carried out in Alto Paraná, PR (Lat. 23° 05' S, Long. 52° 26' W), climate type Cfa (humid subtropical) on an Oxisol [*Latossolo Vermelho Distrófico típico,* Santos et al., 2013) with 180 g kg^{-1} clay content (sandy loam). Soil sampling was carried out in a 7-yr-old orange orchard that had trees spaced at 7 × 3.5 m. Undisturbed and disturbed soil samples for the 0.00-0.20 and 0.20-0.40 m layers were collected at 24 points selected within the row (in-row), under the projection of the tree canopy, and between the row (inter-row) positions. This two-depth by three-position by 24-site sampling scheme provided 144 samples for soil physical and chemical analyses, including SOC. Additional information about the original study is available in Fidalski et al. (2007a);

2. an on-farm study carried out in Maringá, PR (Lat. 23° 21' S, Long. 52° 03' W), which included an undisturbed native vegetation area (seasonal semi-deciduous forest, Atlantic Forest biome) and an adjacent long-term agricultural area (approx. 20 years). The agricultural area had been managed under conventional tillage (plowing and disking), alternating with minimum tillage (chiseling), and primarily cropped with corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sorghum (*Sorghum bicolor* L.), oat (*Avena sativa* L.), and cassava (*Manihot esculenta*). The soil was classified as an Oxisol (*Latossolo Vermelho Distrófico típico,* Santos et al., 2013) with 230 g kg^{-1} clay (sandy clay loam), and the climate type is Cfa. For each land use, 24 sampling points were selected at random. Undisturbed and disturbed soil samples were collected at each point from the 0.00-0.20 m layer. More information about these areas is available in Araújo et al. (2004);

3. an experiment located in Araruna, PR (Lat. 23° 54' S, Long. 52° 30' W), which has climate type Cfb (mesothermal) and a soil classified as an Oxisol (*Latossolo Vermelho Distrófico típico*, Santos et al., 2013) with 310 g kg^{-1} clay content (sandy clay loam). This experiment tested the effects of conventional tillage (moldboard plowing and disking), minimum tillage (chiseling plus disking), and no-tillage systems on soil properties under cassava production. Soil samplings were carried out once during the year of setting up the experiment. The experimental design was randomized blocks with eight replications. Undisturbed and disturbed soil samples were collected from the 0.00-0.15 and 0.15-0.30-m layers within each block. Additional information about this experiment can be found in Tormena et al. (2004) and Cavalieri et al. (2006);

4. an experiment located in Taquaruçu do Sul, RS (Lat. 27° 28' S, Long. 53° 26' W) with climate type Cfa and a soil classified as an Oxisol (*Latossolo Vermelho Aluminoférrico típico*, Santos et al., 2013) with 450 g kg^{-1} clay content (clay). It included two fertilization strategies [pig slurry (80 m^{-3} ha^{-1}) and mineral fertilizer (NPK)] with three tillage practices (no-tillage, minimum tillage, and chisel plowing). The experimental design was randomized blocks, with four replications. Tillage was performed once a year before winter cropping, and pig slurry was applied twice a year, before summer and winter cropping. Mineral fertilizer (NPK) applications were made to summer crops, following the recommendations

of CQFSRS/SC (2004). The cropping system included two years of succession with corn and black oat (*Avena strigosa* Schreb) and one year with soybean and wheat (*Triticum aestivum* L.). Pinto et al. (2014) and Cherubin et al. (2015) provided a detailed description of soil and pig slurry properties and management practices. Soil sampling was carried out three years after setting up the experiment. Undisturbed and disturbed soil samples were collected within each block from the 0.00-0.10 m layer. In addition, a native vegetation area (seasonal semi-deciduous forest, Atlantic Forest biome) located close to the experiment was sampled as a reference for soil quality; and

5. an on-farm study carried out in Maringá, PR (Lat. 23° 30' S, Long. 51° 59' W) with climate type Cfa and a soil classified as an Oxisol (*Latossolo Vermelho Distrófico típico*, Santos et al., 2013) with 800 g kg^{-1} clay content (clay). The study was carried out within a long-term (35 year) no-tillage agricultural area, primarily cropped with soybean (first season) and corn (second season). A transect of approximately 72 m was established perpendicular to the corn rows, along which 80 sampling positions were selected: 40 in-row and 40 inter-row positions. Seeding was performed using a seeder/fertilizer with front cutting discs and parabolic tines at a cutting angle of 20°, rod thickness of about 30 mm, and penetration depth from 0.10 to 0.12 m. Undisturbed and disturbed soil samples were collected within each sampling position from the 0.00-0.10 and 0.10-0.20 m layers, just after corn harvest. Further details about soil management and the experimental design are available in Moreira et al. (2016).

Laboratorial analyses

Disturbed soil samples were analyzed for: pH in water, P, K, and soil organic carbon (SOC) according to methods described by Claessen (1997). In addition, but only for experiment IV, microbial biomass carbon (MBC) was determined as described by Reis Junior and Mendes (2007). Undisturbed soil samples were used to determine bulk density (BD), which was calculated by dividing the dry matter of soil by cylinder volume (100 cm^{-3}), as described by Claessen (1997).

Soil quality assessment

The SMAF was used to evaluate land-use and management effects on SQ. Five soil indicators [pH(H_2O), P, K, BD, and SOC] were used for experiments I, II, III, and V, and six [pH(H_2O), P, K, BD, SOC, and MBC] for experiment IV. This approach was consistent with the general SMAF guidelines, which recommend using a minimum of five indicators, provided at least one each represents soil chemical, physical, and biological properties and processes (Karlen et al., 2008).

The first three (pH, P, and K) are chemical indicators, which are broadly used to investigate soil acidity and nutrient availability and to guide soil fertility management. Bulk density is closely associated with several key soil physical properties and processes, such as soil aeration, water dynamic, and mechanical resistance to root growth. Soil organic carbon and MBC were used as biological indicators. Soil organic carbon plays a crucial role in multiple soil processes, including nutrient cycling and storage, structuring of soil, and providing a food source for edaphic organisms. Microbial biomass carbon is the primary indicator of microbiological activity of the soils. The importance of each indicator for soil functionality is consistently reported in the literature (Andrews et al., 2004; Cardoso et al., 2013; Zornoza et al., 2015). Furthermore, these indicators are consistent with those recommended by Doran and Parkin (1994), who stated that selected SQ indicators should correlate well with ecosystem processes, integrate soil properties and processes, be accessible to many users and sensitive to management and climate, and, whenever possible, be components of existing databases.

Soil indicators were scored by transforming measured values into 0-1 values using algorithms on an Excel® spreadsheet. The scoring curves that were developed for each potential indicator were based on soil taxonomy, texture, typical temperature and rainfall regimes for the sampling area, mineralogy, slope, season when samples were collected, dominant crop, and selected analytical methods for P analysis, as previously published (Andrews et al., 2004; Wienhold et al., 2009). The organic matter class factor (based on soil classification and used for scoring SOC and MBC) was 4 (low OM) for all study sites. The texture class factor (used for scoring BD, SOC, and MBC) was 1 (sandy loam) for experiment I, 2 (sandy loam and sandy clay loam) for experiment II and III, and 4 (clay) for experiments IV and V. The climate factor (used for scoring SOC and MBC) was 1 (≥170 degree days and ≥550 mm of mean annual precipitation) for all experiments. The seasonal factor, affecting MBC scores, was 4 (sampling in the fall - April) for experiment IV. The mineralogy class factors, used for scoring BD, were 3 (clay 1:1 and Fe and Al oxides), and the slope and weathering class factors, used for scoring P, were 2 (2-5 % slope) and 2 (high weathering), respectively, for all experiments. The method used to measure extractable P was Mehlich-1 (class 1). New crop factors, which affected P and pH scores, needed to be added to the SMAF spreadsheet to include Brazilian natural vegetation (seasonal semi-deciduous forest - Atlantic Forest Biome), corn, orange trees, and cassava. Phosphorus and pH thresholds for each "new crop" were set up using regional recommendations for these crops (Iapar, 2003; CQFSRS/SC, 2004).

In addition to individual indicator scores, an overall SQI was calculated by adding up the scores and dividing by the number of indicators. The overall SQI was also subdivided into chemical (pH, P, and K), physical (BD), and biological (SOC and MBC) components, as well as their relative contribution to the overall SQI. This approach helps identify the management areas of greatest concern (i.e., lowest index scores) so that land managers can be given better guidance on how to most effectively restore or improve SQ at that specific location (Karlen et al., 2014).

Data analyses

An analysis of variance (Anova) was computed using PROC GLM to test the influence of land-use and management practices within each site on individual SMAF scores and the overall SQI values. If the Anova F statistic was significant ($p<0.05$), means were compared using Tukey's test ($p<0.05$). For experiment VI, the mean value for each treatment was compared with the reference (native vegetation) value using Dunnett's test ($p<0.1$). All statistical procedures were completed using the Statistical Analysis System - SAS 9.3 (SAS Inc, Cary, USA) software.

RESULTS AND DISCUSSION

Experiment I – Horizontal and vertical distribution of soil properties in a long-term orange orchard

Management practices performed in the orange orchard, including mechanized operations for fertilization, weed, pest, and disease control, and harvesting operations, induced vertical and horizontal spatial variability within soil properties, as previously reported by Fidalski et al. (2007a). Higher acidity beneath the rows is due to N fertilizer, as well as increased root activity and plant uptake of basic cations. Overall, pH scores ranged from 0.54 to 0.81 in-row and from 0.72 to 0.82 in the inter-row and beneath the canopy projection positions (Table 1). Regardless of soil depth, increased P and K scores (P scores ranged from 0.73-0.99, and the K score was 0.50) were found in the in-row position (Table 1). These greater nutrient levels are likely due to fertilizer applications concentrated in the in-row position and higher nutrient cycling from crop residues under orange plants. Lower K scores can be attributed to high demands by citrus plants and high K leaching that was verified in the sandy loam soil. Cherubin et al. (2016a) also verified lower scores for K than P or pH in weathered soil from the *Cerrado* (Brazilian tropical savanna).

Intense machinery-based farming operations increased BD and consequently decreased SMAF-BD scores within the 0.00-0.20 m layer under the canopy projection and within the inter-row (Table 1) positions, agreeing with Fidalski et al. (2007b, 2010), who reported higher

Table 1. Mean values and SMAF scores of soil quality indicators for the 0.00-0.20 and 0.20-0.40 m layers in the in-row, canopy projection, and inter-row positions within an orange orchard

Soil sampling position	$pH(H_2O)$	P	K	BD	SOC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}
		Mean values (0.00-0.20 m)			
In-row	5.46	72.58	67.88	1.64	0.73
Canopy projection	6.68	5.01	24.75	1.70	0.71
Inter-row	6.77	2.79	23.33	1.76	0.80
		Mean values (0.20-0.40 m)			
Row	4.92	11.29	67.71	1.63	0.57
Canopy projection	5.98	1.95	11.33	1.62	0.51
Inter-row	5.99	3.16	11.67	1.62	0.56
		SMAF scores (0.00-0.20 m)			
Row	0.81 a‡	0.99 a	0.50 a	0.52 a	0.74 ab
Canopy projection	0.74 a	0.40 b	0.22 b	0.36 c	0.72 b
Inter-row	0.72 a	0.18 c	0.21 b	0.44 b	0.82 a
		SMAF scores (0.20-0.40 m)			
Row	0.54 b‡	0.73 a	0.50 a	0.56 a	0.51 a
Canopy projection	0.79 a	0.10 b	0.11 b	0.57 a	0.41 a
Inter-row	0.82 a	0.18 b	0.11 b	0.57 a	0.50 a

$pH(H_2O)$: pH in water, 1:2.5 v/v; P and K: extracted by Mehlich-1; BD: bulk density, SOC: soil organic carbon. ‡Mean scores in the column within each depth followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

BD values under the inter-row position in orange orchards. Compaction is a very common soil physical problem in Brazilian citrus orchards due to intense traffic of agricultural machinery for management practices, which occur about 15 times each year (Tersi and Rosa, 1995).

Greater SOC contents were found in the surface layer in the row (0.74 g kg^{-1}) and within the inter-row (0.82 g kg^{-1}) areas compared to the canopy projection (0.72 g kg^{-1}) area. Spontaneous vegetation management (mowing and herbicide use) within the orchard inter-row kept residues on the soil surface, thus increasing C inputs (including C roots) and improving SOC scores within the 0.00-0.20 m layer (Table 1). Lower SOC scores within the canopy projection areas were the result of low C inputs due to low biomass productivity in response to poor soil physical condition induced by intensive machinery traffic and soil compaction.

The SMAF was sensitive for detecting SQ changes between the row and inter-row sampling positions and between soil layers within the orange orchard (Figures 1a and 1b). The SMAF scores calculated for each sampling position indicated that SQ decreased from the surface to subsurface layer and from the row to inter-row zone (inter-row and canopy projection area). Several factors contribute to improving SQ in the in-row position, such as the absence of machinery traffic and localized inputs of lime and fertilizer.

The highest overall SMAF SQI score was found within the in-row sampling position, indicating that this soil was functioning at 71 and 57 % of potential capacity for the 0.00-0.20 and 0.20-0.40 m layers, respectively (Figure 1b). The reduced soil physical and chemical quality in the canopy projection and inter-row positions diminishes the volume of soil exploited by roots, thus limiting water and nutrient uptake (Souza et al., 2008) and increasing the likelihood of yield loss (Homma et al., 2012), even under short periods of drought. Soil compaction is a major obstacle in orange orchards because it damages soil physical quality (Fidalski et al., 2010) and thus reduces root growth and fruit yield (Medeiros et al., 2013) and orchard longevity. Fidalski et al. (2007b) suggested that better soil physical quality could be achieved in orchards by increasing soil organic matter and reducing BD with cover crops within the orchard inter-rows. Based on SMAF scores, better soil management practices are needed to balance soil physical, chemical, and biological properties. Therefore, our results suggest that using SMAF to assess SQ within orange orchards could help farmers and their consultants make better decisions regarding sustainable management practices.

Experiment II - Impacts of long-term LUC from native vegetation to agriculture on soil properties

Long-term LUC from native vegetation to agriculture led to significant changes in soil indicators and, consequently in SQ (Table 2 and Figure 2). Conversion from native vegetation to agricultural crops significantly decreased SOC scores from 0.96 (10.64 kg ha^{-1}) to 0.60 (6.35 kg ha^{-1}). Losses in SOC due to LUC are primarily induced by removal and burning of native vegetation and exposure and respiration of SOM due to tillage, soil erosion, and runoff (Guo and Gifford, 2002; Don et al., 2011). Furthermore, even if the productivity of new agricultural land is as high as that of forest, less biomass accumulates as litter because most of it is harvested and subsequently consumed or lost through respiration (Guo and Gifford, 2002). Reduction in SOC associated with excessive tillage and machinery traffic caused soil to become more vulnerable to physical degradation (Cherubin et al., 2016b).

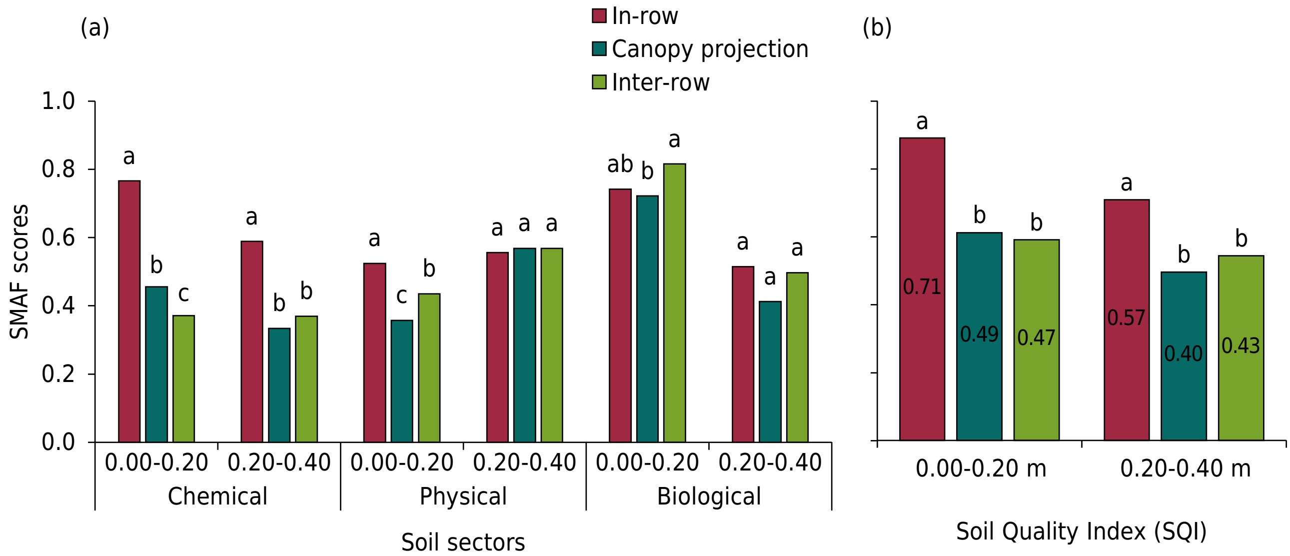

Figure 1. Soil sectors (chemical, physical, and biological) (a) and overall Soil Quality Index (SQI) (b) for the 0.00-0.20 and 0.20-0.40 m layers in the row, canopy projection and inter-row within an orange orchard. Mean scores within each depth and sector or SQI followed by the same letter do not differ among themselves according to Tukey's test (p<0.05).

Table 2. Mean values and SMAF scores of soil quality indicators for the 0.00-0.20 m layer in a native vegetation and long-term agriculture area

Land use	$pH(H_2O)$	P	K	BD	SOC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}
			Mean values		
Native vegetation	5.64	4.74	69.08	1.47	10.64
Agriculture	6.78	34.43	55.83	1.70	6.35
			SMAF scores		
Native vegetation	0.82 a‡	0.84 b	0.51 a	0.88 a	0.96 a
Agriculture	0.73 b	1.00 a	0.43 b	0.44 b	0.60 b

$pH(H_2O)$: pH in water, 1:2.5 v/v; P and K: extracted by Mehlich-1; BD: bulk density, SOC: soil organic carbon. ‡Mean scores in the column within each depth followed by the same letter do not differ among themselves according to Tukey's test (p<0.05).

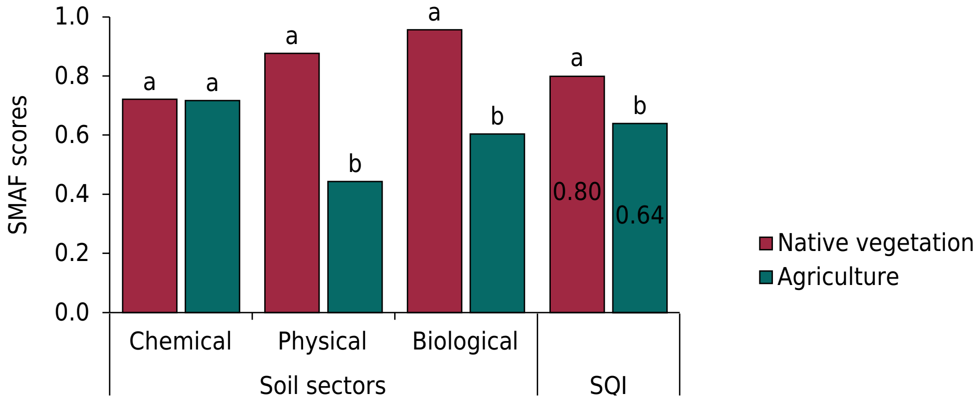

Figure 2. Soil sectors (chemical, physical, and biological) (a) and overall Soil Quality Index (SQI) (B) for the 0.00-0.20 m layer in a native vegetation and long-term cropped area (agriculture). Mean scores within each sector or SQI followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

After more than 20 years of agricultural land use, BD increased an average of 15 %, but even more revealing was that this decreased BD scores from 0.88 (native vegetation) to 0.44 (agriculture), suggesting a substantial restriction in conditions ideal for plant growth. These SMAF scores are consistent with least limiting water range (LLWR) results found within these areas (Araújo et al., 2004). Those authors verified accentuated reduction in LLWR when native vegetation was converted to an agricultural area, and a BD of about 1.85 Mg m^{-3} resulted in LLWR = 0.

In contrast, regular lime and fertilizer applications increased pH and available P within the agricultural area. Available P had the greatest improvement, reaching the maximum score (1.0). However, since the SMAF scoring curve for pH has a mid-point optima shape – Gaussian function (i.e., maximum score = 1 is when pH was 6, decreasing when pH is lower or higher than this optimum value), agricultural soils had lower pH scores than native vegetation sites even though the pH measurements were higher. Nevertheless, agricultural land use has a trend to acidify soils (Souza et al., 2007); therefore, pH scores will likely improve over time. Low K scores were found for both native and agricultural land uses (0.51 and 0.43, respectively).

Both native vegetation and agricultural soils had similar chemical functioning at 72 % of projected capacity, even though variations were found among indicator responses. In contrast, our findings indicated significant soil physical and biological degradation under agriculture. Overall, SMAF SQI scores suggest that native soil was functioning at 80 % of its capacity, while long-term agricultural soil was functioning at only 64 % of its potential.

Based on SMAF scores, management strategies to recovery SQ under agriculture areas should primarily be directed toward increasing soil C and alleviating soil compaction.

Experiment III – Effects of short-term soil tillage systems on soil properties in a cassava cultivation area

Tillage systems have a key role in agricultural management plans but cause distinctive changes in soil physical, chemical, and biological properties. Our results showed that tillage led to significant changes in SQ indicators for both the 0.00-0.15 and 0.15-0.30 m layers (Table 3); a more favorable soil chemical and biological environment was observed under no-tillage and minimum tillage than under conventional tillage within the 0.00-0.15 m layer, as was also reported by Castro et al. (2009). However, the absence of tillage in a no-tillage system induced nutrient stratification within the surface layer, especially for P, which is a relatively immobile element within the soil. Therefore, while SMAF P scores were close to 1 within the 0.00-0.15 m layer, they decreased to nearly 0 within the 0.15-0.30 m layer.

Table 3. Mean values and SMAF scores of soil quality indicators for the 0.00-0.15 and 0.15-0.30 m layers in an area of cassava production under different tillage systems

Tillage system	pH(H_2O)	P	K	BD	SOC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}
			Mean values 0.00-0.15 m		
No-tillage	5.20	9.89	128.27	1.63	9.09
Minimum tillage	5.20	10.43	125.51	1.53	9.20
Conventional tillage	4.90	6.56	108.18	1.47	6.93
			Mean values 0.15-0.30 m		
No-tillage	4.84	1.00	88.46	1.64	4.74
Minimum tillage	4.90	3.50	101.17	1.58	5.67
Conventional tillage	4.79	1.75	108.50	1.55	6.31
			SMAF scores 0.00-0.15 m		
No-tillage	0.95 a‡	0.98 a	0.74 a	0.37 c	0.71 a
Minimum tillage	0.92 ab	0.98 a	0.74 a	0.52 b	0.73 a
Conventional tillage	0.83 b	0.93 b	0.69 a	0.65 a	0.48 b
			SMAF scores 0.15-0.30 m		
No-tillage	0.77 a	0.06 b	0.60 a	0.37 b	0.25 a
Minimum tillage	0.82 a	0.38 a	0.64 a	0.44 ab	0.33 a
Conventional tillage	0.77 a	0.27 ab	0.69 a	0.49 a	0.39 a

pH(H_2O): pH in water, 1:2.5 v/v; P and K: extracted by Mehlich-1; BD: bulk density, SOC: soil organic carbon. [‡]Mean scores in the column within each depth followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

A significant depletion of SOC (approx. 25 %) was observed under conventional tillage compared to no-tillage or minimum tillage for the 0.00-0.15 m layer. This resulted in reduction of SOC scores from 0.71 (no-tillage) and 0.73 (minimum tillage) to 0.48 (conventional tillage). Potential C sequestration under less intensive tillage systems was reported by Sá et al. (2014) and is broadly discussed in the literature (Lal, 2015). Soil organic carbon is considered a key property of SQ because it influences the dynamics of soil biota and plays a key role in several physical and chemical functions within the soil (Sá et al., 2013).

In contrast, conventional tillage improved soil physical quality (*i.e.*, lower BD) (Table 3). Higher BD values under no-tillage and minimum tillage were also verified by Tormena et al. (2004). These results were consistently shown by SMAF BD scores, which decreased significantly from 0.65 for conventional tillage to 0.52 for minimum tillage to 0.37 for no-tillage within the 0.00-0.15 m layer (Table 3). This same trend was observed for the 0.15-0.30 m layer, decreasing from 0.49 to 0.44 to 0.37, respectively. Our findings obtained by SMAF scores are consistent with those found by Cavalieri et al. (2006) in the same experiment. Those authors demonstrated that LLWR followed the same sequence: conventional tillage > minimum tillage > no-tillage, and suggested that decreasing tillage intensity negatively impacted soil physical quality.

Soil quality assessment for tillage practices requires tools that provide easy and straightforward SQ status information. The SMAF scores detected changes in SQ among tillage systems (Figures 3a e 3b). The physical sector was more sensitive for capturing tillage effects on SQ than the chemical or biological sectors.

The scores of SMAF components, as well as the overall SQI, indicated that SQ decreased from the surface to subsurface layers. The highest SMAF SQI scores within the 0.00-0.15 m layer suggests the soils under no-, minimum- and conventional tillage were functioning similarity at 75, 78 and 72 % of their potential capacity. Within the 0.15-0.30 m zone, the worst soil chemical, physical, and biological conditions were found under no-tillage,

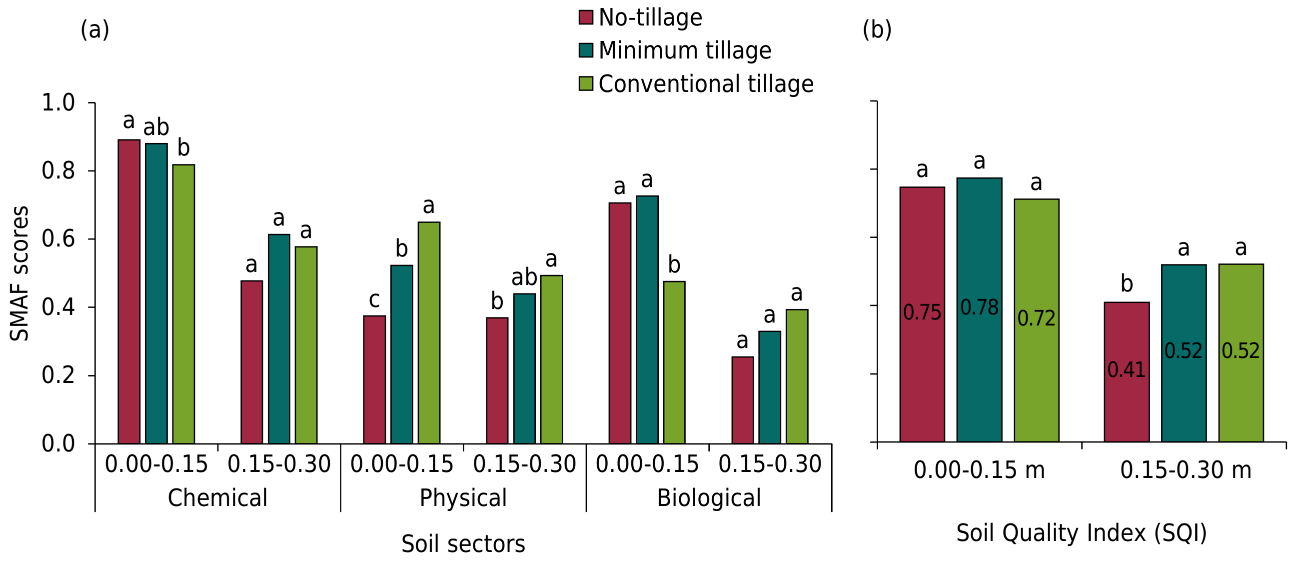

Figure 3. Soil sectors (chemical, physical, and biological) (a) and overall Soil Quality Index (SQI) (b) for the 0.00-0.15 and 0.15-0.30 m layers in a cassava production area under different tillage systems. Mean scores within each depth and sector or SQI followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

and indicated that the soil was functioning at 41 % of its potential capacity. Meanwhile, soils under conventional and minimum tillage were functioning at 52 % (Figure 3b). The SQ assessments using the SMAF were consistent with the cassava yields reported by Pequeno et al. (2007). They averaged 36.0, 25.6, and 21.1 Mg ha^{-1} for conventional, minimum, and no-tillage practices, respectively.

For this study, our results suggest that soil management practices should be prioritized to reduce the vertical chemical gradient and soil compaction under reduced tillage systems, and to strive for maintaining or even increasing SOC under conventional tillage.

Experiment IV – Soil property changes due to mineral fertilizer and pig slurry application coupled with soil tillage systems

The interaction between fertilizer management and soil tillage was non-significant for all the SQ indicators measured. The impact of each individual factor on indicator scores is shown in table 4, while the integration for each sector and the overall SQI are shown in figure 4. The use of organic fertilizer (swine manure, 80 m^3 ha^{-1}) improved several SQ indicators compared to application of mineral fertilizer. Significant increases in pH, K, SOC, and MBC, as well as a trend toward increasing available P were found after applying pig slurry for three years. Near-surface soil chemical and biological improvements due to pig slurry applications are also supported in the literature (Balota et al., 2012; Lourenzi et al., 2013). Pig slurry has a high concentration of nutrients (N-P-K) that are readily available to plants and microorganisms. Soil nutrient levels are increased directly by slurry inputs and through nutrient cycling by microbial biomass.

Bulk density had lower scores for both organic (0.33) and mineral fertilizer (0.41) treatments, suggesting that physical restrictions limited plant growth at these sites. In addition, the sector scores showed that management strategies focused on improving soil physical functions needed to be given the highest priority.

The overall SMAF SQI score suggests that soil fertilized with pig slurry was functioning at 84 % of its potential capacity, while soil under mineral fertilization was functioning at 77 %. The SQ improvements promoted by pig slurry application, coupled with the large supply of this material in the region studied, suggest that pig slurry should be used not only as an alternative nutrient source for crop production in this region, but also as an

Table 4. Mean values and SMAF scores of soil quality indicators for the 0.00-0.10 m layer under fertilization management and tillage systems and under native vegetation

Management practice	pH(H_2O)	P	K	BD	SOC	MBC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}	mg kg^{-1}
				Mean values		
Fertilization management						
Swine manure	5.40	9.32	238.89	1.47	14.85	1007.65
Mineral fertilizer	5.29	7.12	153.89	1.42	12.88	512.47
Tillage system						
No-tillage	5.29	6.91	161.67	1.45	12.66	651.06
Minimum tillage	5.36	7.74	209.17	1.47	15.61	953.43
Chisel plow	5.40	10.01	218.33	1.41	13.32	675.70
Native vegetation	5.82	9.09	96.67	0.92	24.87	480.54
				SMAF scores		
Fertilization management						
Swine manure	0.83 a‡*	0.97 a	0.99 a*	0.33 a*	0.93 a	1.00 a
Mineral fertilizer	0.77 b*	0.88 a	0.92 b*	0.41 a*	0.84 b*	0.82 b*
Tillage system						
No-tillage	0.77 b*	0.95 a	0.94 a*	0.36 a*	0.85 a*	0.77 b*
Minimum tillage	0.81 ab*	0.85 a	0.97 a*	0.33 a*	0.92 a	1.00 a
Chisel plow	0.83 a*	0.97 a	0.97 a*	0.42 a*	0.89 a	0.97 ab
Native vegetation	0.97	0.97	0.75	0.99	1.00	1.00

pH(H_2O): pH in water, 1:2.5 v/v; P and K: extracted by Mehlich-1; BD: bulk density, SOC: soil organic carbon. ‡Mean scores in the column within each factor followed by the same letter do not differ among themselves according to Tukey's test ($p<0.1$). Mean scores followed by * (asterisk) statistically differ from native vegetation according to Dunnett's test ($p<0.1$).

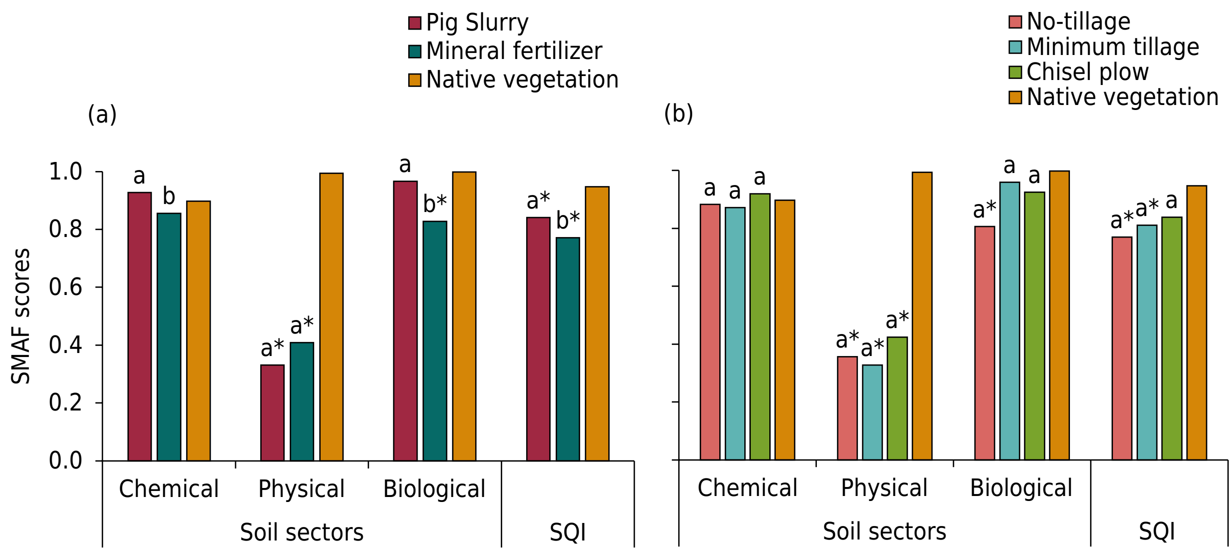

Figure 4. Soil sectors (chemical, physical, and biological) and overall Soil Quality Index (SQI) for the 0.00-0.10 m layer under pig slurry and mineral fertilizer treatments (a) and no-tillage, minimum tillage, and chisel plow treatments (b). All treatments were compared with native vegetation. Mean scores within each sector and SQI followed by the same letter do not differ among themselves according to Tukey's test ($p<0.1$). Mean scores followed by * statistically differ from native vegetation according to Dunnett's test ($p<0.1$).

amendment for enhanced soil health. It should be noted that agricultural use of pig slurry must follow the rules established by local environmental laws.

Short-term tillage treatments had minimal impact on individual SQ indicators and, consequently, did not change the overall SQI. However, no-tillage, which is broadly considered as a conservation practice due to the multiple ecosystem services it influences (Lal, 2015), improved SQ compared to tilled treatments in this study. Some indicators, such as pH and MBC, had lower scores under no-tillage (pH = 0.79; MBC = 0.77) than under minimum tillage (pH = 0.81; MBC = 1.0) or chisel plowing (pH = 0.83; MBC = 0.97). However, the tilled systems were not able to alleviate soil compaction as expected, so the SMAF analysis showed they had poor physical quality and were generally functioning at between 33 and 42 % of their capacity. This may be due to the period of time (one year) between tillage and soil sampling. Short-term effects of tillage are consistently reported in the literature (Reichert et al., 2009; Moraes et al., 2016).

Overall SQI suggests soils were functioning at 77, 81, and 84 % of their potential capacity under no-tillage, minimum tillage, and chisel plowing, respectively. The SMAF-SQI scores also showed a close relationship with corn yield, which as reported by Pinto et al. (2014) for this same area, averaged 5.95, 6.80, and 6.90 Mg ha^{-1} for no-tillage, minimum tillage, and chisel plowing, respectively.

Regardless of the management practices being used, agricultural land use resulted in significant SQ degradation compared to native vegetation (Table 4), which had soil functioning at 95 % of its potential capacity (Figure 4). Soil beneath undistributed native vegetation is in dynamic equilibrium, in which chemical, physical, and biological properties act in cooperation, enabling soil to perform its functions properly (Cherubin et al., 2016a). In addition to indicating soil degradation under agricultural uses, scores under native vegetation were useful for validating the SMAF curves for this soil. Individual indicator scores were close to 1.0 (0.97-1.00), except for K (0.75). Most likely, the lower SMAF score for K under native vegetation is associated with the K algorithm, which was developed based on a corn yield response to soil-test K (Wienhold et al., 2009). Therefore, futures studies are needed to adjust and validate SMAF algorithms using datasets from different crops and ecosystem conditions.

Experiment V - The effects of sowing on row and inter-row soil properties in a long-term no-tillage area

There were no significant changes in chemical properties between row and inter-row sampling positions for the 0.00-0.10 and 0.10-0.20 m layers (Table 5). Although fertilizer was distributed in the row position, successive changes between row and inter-row

Table 5. Mean values and SMAF scores of soil quality indicators for the 0.00-0.10 and 0.10-0.20 m layers in the row and inter-row position under a long-term no-tillage area

Soil sampling position	pH(H_2O)	P	K	BD	SOC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}
		Mean values (0.00-0.10 m)			
In-row	5.42	60.89	60.73	1.07	19.89
Inter-row	5.50	58.68	53.94	1.21	21.48
		Mean values (0.10-0.20 m)			
In-row	5.58	11.87	32.84	1.31	13.60
Inter-row	5.78	10.09	34.75	1.32	15.12
		SMAF scores (0.00-0.10 m)			
In-row	0.80 a[‡]	0.98 a	0.56 a	0.94 a	0.97 a
Inter-row	0.84 a	1.00 a	0.53 a	0.76 b	0.99 a
		SMAF scores (0.10-0.20 m)			
In-row	0.85 a	0.84 a	0.36 a	0.56 a	0.85 b
Inter-row	0.92 a	0.75 a	0.38 a	0.53 a	0.92 a

pH(H_2O): pH in water, 1:2.5 v/v; P and K: extracted by Mehlich-1; BD: bulk density, SOC: soil organic carbon. [‡]Mean scores in the column within each depth followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

positions over time promoted horizontal homogenization of soil chemical properties over the total area. The SMAF pH and P scores were >0.80 and 0.75, respectively. In general, K concentration was the major chemical limitation found in both soil sampling positions, with average scores of 0.56 (in-row) and 0.53 (inter-row). Low available K levels are likely associated with the soil type, because Oxisols are naturally characterized by low K concentrations and high leaching potential. In addition, this area had a history of gypsum application, which can promote leaching of K to deeper layers.

No-tillage is classified as conservation management because of the absence of tillage and the maintenance of crop residues on the soil surface. However, the furrow opening for seeding is a mechanical soil disturbance that can modify the soil physical environment in NT crop rows (Moreira et al., 2016). Decreased BD values were found in-row (1.07 Mg m^{-3}) compared to inter-row (1.21 Mg m^{-3}) for the 0.00-0.10 m depth. The SMAF BD scores indicated this soil was physically functioning at 94 % of its potential capacity within the rows and at 76 % in the inter-row positions, which is consistent with other no-tillage studies (Tormena et al., 2008; Betioli Júnior et al., 2012; Blum et al., 2014). Tormena et al. (2008), using the S index assessment, observed decreased soil physical quality in the inter-row compared to the row position in a clay soil under no-tillage. Blum et al. (2014) verified that soil physical quality was higher within the row than in inter-row positions due to lower bulk density and higher total porosity, hydraulic conductivity, air permeability, and macroporosity.

The SMAF BD scores were consistent with results previously reported by Betioli Júnior et al. (2012) for this same area. Those authors observed the degree of soil compactness to be 69 and 77 % (i.e., values below the critical limit suitable for plant growth) within in-row and inter-row positions at the 0.00-0.10 m depth. They also found critical bulk density (i.e., LLWR = 0) above 1.32 Mg m^{-3}. Moreira et al. (2016) also verified a reduction in plant available water content from 17.2 (in-row) to 15.9 m^3 m^{-3} (inter-row position) for the 0.00-0.10 m layer. However, this positive effect of mechanical disturbance caused by furrow opening was restricted to the surface layer (0.00-0.10 m). Within the 0.10-0.20 m layer, BD increases were verified for both in-row (1.31 Mg m^{-3}) and inter-row (1.32 Mg m^{-3}) positions, and there were few significant differences between them. Consequently, the soil physical functioning decreased from on 56 to 53 % of its potential for the in-row and inter-row positions, respectively. Moreira et al. (2016) also reported a decrease, but no statistical difference, in plant available water content (average of 12.7 m^3 m^{-3}) between in-row and inter-row positions for the 0.10-0.20 m layer.

These results indicated the need for management practices that alleviate soil compaction below the 0.10 m depth in order to enable plant roots to exploit deeper soil layers for water and nutrients. Recently, Nunes et al. (2015) demonstrated that deeper furrow opening action (0.17 m) was an efficient strategy for alleviating subsurface soil compaction under long-term no-tillage, mitigating its deleterious impacts on corn growth. Another strategy is to intercrop deep-rooted cover crops [*e.g.*, brachiaria (*Brachiaria spp.*) and radish (*Raphanus sativus*)] into corn or to establish them throughout the total area after corn or soybean harvest. This is a biological strategy that can alleviate deeper soil compaction and provide other soil benefits.

High SOC contents were verified regardless of sampling position. Therefore, SMAF SOC scores suggested the soil was functioning close to its biological potential capacity - 97 and 99 % for the 0.00-0.10 m layer, or 85 and 92 % for the 0.10-0.20 m layer. Higher clay content (800 g kg^{-1}) is probably the primary controlling factor for C stabilization and protection through formation of organic-mineral complexes. In addition, C sequestration under a long-term no-tillage system is often noted in the literature (Lal, 2015).

Overall, the in-row and inter-row positions had statistically similar soil quality (Figure 5). The SMAF SQI scores suggest that the soil was functioning at 85 and 82 % of its potential capacity for in-row and inter-row positions within the 0.00-0.10 m layer, and at 70 and 69 %

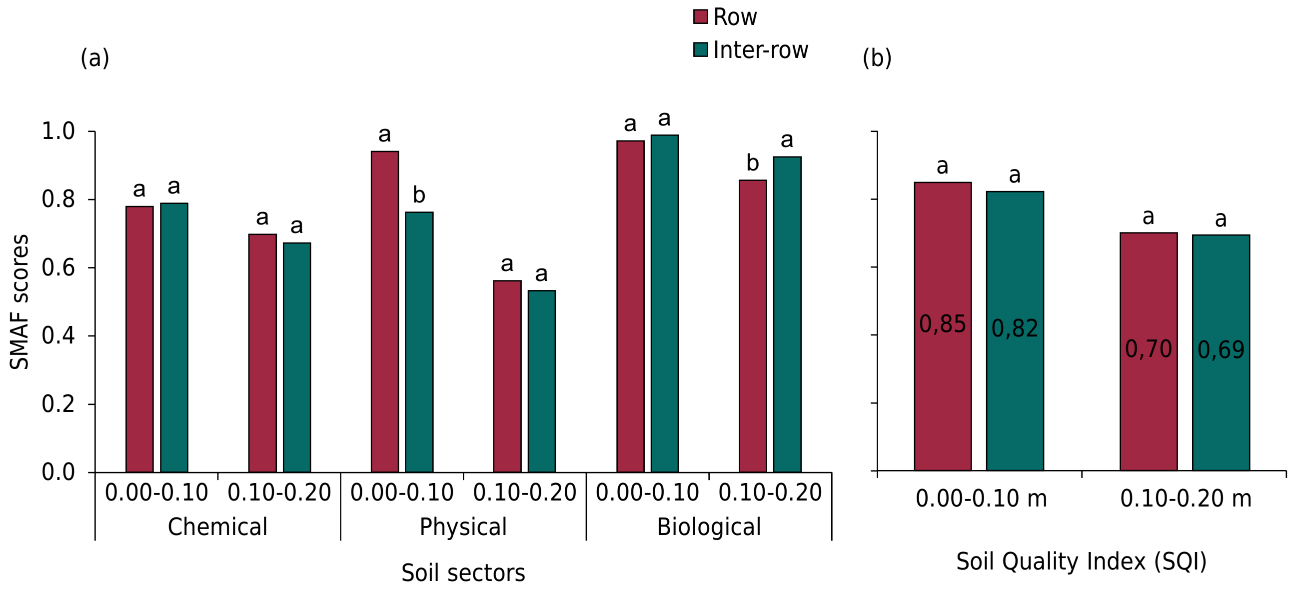

Figure 5. Soil sectors (chemical, physical, and biological) (a) and overall Soil Quality Index (SQI) (b) for the 0.00-0.10 and 0.10-0.20 m layers in the in-row and inter-row positions under a long-term no-tillage area. [‡]Mean scores within each depth and sector or SQI followed by the same letter do not differ among themselves according to Tukey's test ($p<0.05$).

for in-row and inter-row positions for the 0.10-0.20 m layer, respectively. The high SQ assessed through SMAF scoring curves is consistent with high crop yields obtained from these soils in years without water deficits (Cardoso et al., 2006). Therefore, our findings suggest that SMAF scores properly assessed SQ in this clay soil under long-term no-tillage.

CONCLUSIONS

The SMAF was sensitive for detecting SQ changes induced by land uses and management practices in Brazilian Oxisols with contrasting texture. Long-term conventional management of orange orchards leads to horizontal and vertical changes in SQ, with significant losses in soil function in the canopy projection and inter-row positions. Land-use change from native vegetation to agriculture depletes SQ, driven by reductions in physical and biological indicators. The short-term no-tillage system decreases subsurface SQ for cassava cultivation compared to tilled systems.

Organic fertilization with pig slurry at 80 m^3 ha^{-1} improves soil chemical and biological indicators and, consequently, overall SQ compared to use of mineral fertilizer.

Although long-term no-tillage management induces more physical conditions that limit plant growth within the inter-row sowing position, overall SQ was similar to the in-row sowing position.

The algorithms of SMAF scoring curves properly transformed indicator values expressed in different units into unitless scores ranging from 0-1, facilitating individual interpretation of land-use and management practice effects on soil properties. The overall SMAF SQI scores summarize individual soil indicator scores into a comprehensible number that helps evaluate the overall soil functioning. Individual sector scores (chemical, physical, and biological) enable identification of the principal soil limitations and where to prioritize management actions. Therefore, SMAF could be a useful tool for assessing SQ in Brazilian soils and helping farmers or land managers make the best decisions regarding sustainable use and management practices for their land.

Future studies are encouraged for testing and improving the sensitivity of SMAF algorithms for detecting management-induced SQ changes under different soils, crops, and climates, thus expanding its potential for use in Brazil.

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