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No-tillage participatory quality index reflects the condition of soil management[1]

Índice de qualidade participativa do plantio direto reflete a condição do manejo do solo

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ABSTRACT - Conservation agriculture is fundamental for improving agricultural sustainability. However, the quality of soil management in conservation agriculture systems is highly variable. The goal of this study was to verify whether a no-tillage participatory quality index (PQI) is associated with the physical, chemical, and microbiological attributes of soil. Thus, we sought to validate its use as an indicator of soil management quality. A survey was conducted to assess the agricultural practices of farmers from the western mesoregion of the state of Paraná, Brazil to evaluate the PQI. The quality of soil management for annual crops was related to the PQI, as evidenced by its association with soil physical, chemical, and microbiological attributes. These results confirmed the usefulness of the PQI methodology as a tool for assessing the quality of soil management, demonstrating its sensitivity to short-term changes in management practices. Consequently, this may allow for the monitoring of management quality and inferences about the beneficial effects of the implemented practices.

Key words: Conservation agriculture. Oxisols. Soil degradation. Soil quality.

RESUMO - A agricultura conservacionista é fundamental para melhorar a sustentabilidade agrícola. No entanto, a qualidade do manejo do solo em sistemas de agricultura conservacionista é altamente variável. O objetivo deste estudo foi verificar se o índice de qualidade participativa do plantio direto (IQP) está associado aos atributos físicos, químicos e microbiológicos do solo. Dessa forma, buscou-se validar sua utilização como indicador da qualidade do manejo do solo. Foi realizado um levantamento para avaliar as práticas agrícolas utilizadas por agricultores da mesorregião oeste do estado do Paraná, Brasil, para a obtenção do IQP. A qualidade do manejo do solo para as lavouras anuais está relacionada ao IQP, conforme evidenciado por sua associação com atributos físicos, químicos e microbiológicos do solo. Os resultados confirmaram a utilidade da metodologia do IQP como ferramenta de avaliação da qualidade do manejo do solo, demonstrando sua sensibilidade às mudanças de curto prazo nas práticas de manejo. Consequentemente, isso pode permitir o monitoramento da qualidade do manejo e inferências sobre os efeitos benéficos das práticas implementadas.

Palavras-chave: Agricultura conservacionista. Degradação do solo. Qualidade do solo. Latossolos.

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INTRODUCTION

Conservation agriculture is fundamental for improving agricultural sustainability, especially in tropical and subtropical regions. It is based on three principles: i) minimum soil disturbance (such as no tillage), ii) permanent soil cover, and iii) diversified crop rotation (KASSAM *et al*., 2009). These conservation practices are directly related to the maintenance and/or improvement of the chemical, physical, and biological attributes of the soil, which enable proper functioning of the soil, making it capable of sustaining agricultural productivity.

The no-tillage practice has been adopted in Brazil since 1972, initially in the state of Paraná, to reduce soil loss caused by water erosion. However, the quality of soil management involving no-tillage in Brazil is highly variable, particularly because most farmers do not adopt the other two principles (CASÃO JÚNIOR *et al*., 2006).

The quality of soil management is a conceptual variable, and consequently, cannot be measured directly. The use of operational variables is necessary to distinguish between good and poor soil management. Operational variables based on farmer perceptions have been used to quantify conceptual variables for many purposes in many regions of the world (NEZOMBA *et al*., 2017; NUNES *et al*., 2020a; TESFAHUNEGN; TAMENE; VLEK, 2011). To measure the quality of soil management, a participatory quality index (PQI) was created based on farmers' responses regarding their agricultural practices.

The PQI aims to assess the quality and efficiency of the management of the production system, focusing on profitability and environmental conservation. It is comprised of a set of eight indicators: RI, rotation intensity; RD, rotation diversity; RP, rotation persistence; TF, soil tillage frequency; CT, correct terracing; SC, soil conservation evaluation; BC, balanced fertilization; and AT, no-tillage adoption time. These indicators are evaluated, and a macro-indicator called the PQI is generated.

Since its creation, attempts have been made to validate the PQI as an indicator of the quality of soil management (NUNES *et al*., 2020a). However, recently, Telles *et al*. (2020) suggested that some indicators of the PQI should be reviewed because they had a weak correlation with the final PQI index. These indicators were reviewed and altered by the Institute of Rural Development of Paraná (IDR-PR) and approved by the PQI Working Group, which is coordinated by the Brazilian Federation of No-tillage. The current methodology, which lacks validation, was applied for the first time in this study.

Considering that many aspects of soil management are included in the questionnaire, we hypothesized that the quality of soil management, as measured by the no-tillage PQI, relates to soil attributes, and consequently, to its quality. The goal of this study was to verify whether the no-tillage PQI was associated with soil physical, chemical, and microbiological attributes. Therefore, we sought to validate its use as an indicator of good soil management.

MATERIAL AND METHODS

Study area

The study area is located in the western mesoregion of the state of Paraná, Brazil (Figure 1). The geology consists of basaltic rocks from the Serra Geral Formation, and Latossolos and Nitossolos (SANTOS *et al*., 2018) are the predominant soil classes, which have a heavy clay texture and are mainly composed of kaolinite and iron oxides (MELO *et al*., 2019b). According to the Köppen-Geiger classification system, the climate is Cfa, humid subtropical, oceanic, without a dry season, and with hot summers (ALVARES *et al*., 2013).

A total of 27 farms in which soil management practices were adopted in the last three years were selected and the farmers were interviewed (according to the questionnaire in the supplementary material). The study was carried out only with those farmers who adopted no-tillage, since farmers with recent plowing in the soil would present good ephemeral structure of the soil. Among the selected producers, the average size of the property was greater than 10 bushels, with the main crops being soybeans and off-season corn. According to the Brazilian Federation of Zero Planting in Crop and Irrigation Residues (FEBRAPDP), based on the evaluation carried out on the PQI (Table 6), the selected farmers were classified as: very bad (0.00-1.99), bad (2.00-3.99), regular (4.00-5.99), good (6.00-7.99), and very good (8.00-10.00). The soil was sampled at three points on each property at a depth of 0–20 cm.

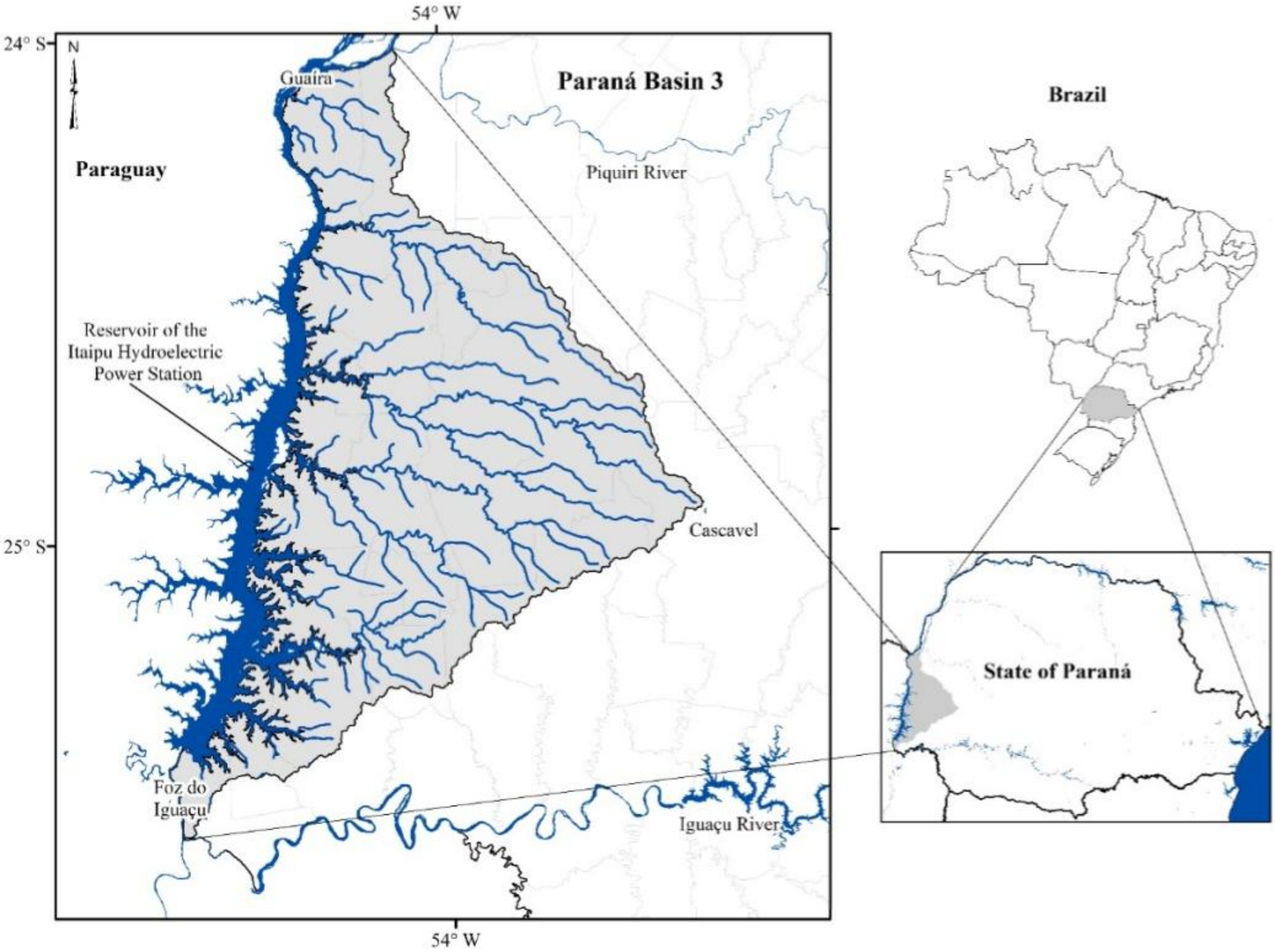
Soil sampling and analyses

Physical attributes

Soil density, field capacity, macroporosity, and microporosity were measured in stainless steel rings that were 5 cm each in diameter and height. The rings were collected from the center of the evaluated layer (0–20 cm) and protected against water loss until the analyses were performed. After saturation (24 h), the samples were placed on a tension table to determine their field capacity and macroporosity. After this period, the samples were oven-dried (105 °C) until a constant mass was obtained for the determination of microporosity and soil density.

Soil aggregates (≤ 19 mm) were collected and tested for stability in water. After drying under laboratory

Figure 1 - Location of the study area



conditions, the aggregates were wetted by capillarity for 10 min and sieved underwater (tap water) for 15 min at a rate of 40 vertical cycles per minute. Sieves with openings of 8, 4, 2, 1, 0.5, and 0.25 mm were used, and the mean weighted diameter (MWD), mean geometric diameter (MGD), and aggregate stability index (ASI) were calculated using the following formulas (1):

$$MWD(mm) = \frac{\sum_{i=1}^{n}(Diam_i \times Mass_i)}{Mass_{Sample}}$$

$$MGD(mm) = e^{\frac{\sum_{i=1}^{n}(Ln(Diam_i) \times Mass_i)}{Mass_{Sample}}} \quad (1)$$

$$ASI(\%) = \frac{100 \times Mass_{>0.25mm}}{Mass_{Sample}}$$

where, MWD is the mean weighted diameter, $Diam_i$ is the mean diameter of the size class i, $Mass_i$ is mass of aggregates within class i, $Mass_{Sample}$ is the total mass of the sample, MGD is the mean geometric diameter, ASI is the aggregate stability index, $Mass_{>0.25\ mm}$ is the mass of water-stable aggregates retained in the sieves with openings of 0.25 mm or larger.

Chemical attributes

Before chemical analyses, air-dried soil aggregates were crushed and passed through a 2 mm sieve. The pH was measured in a 0.01 mol L^{-1} $CaCl_2$ solution (soil: solution ratio of 1:2.5, mass:volume). Exchangeable potassium (K^+) and available phosphorous (P) were extracted with Mehlich-1 solution and quantified using flame photometry and spectrophotometry, respectively. Exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were extracted with a 1 mol L^{-1} KCl solution and quantified by titration with NaOH (Al^{3+}) and by atomic absorption spectrometry (Ca^{2+} and Mg^{2+}). The potential acidity ($H+Al^{3+}$) was estimated using potentiometry after equilibration with the SMP solution. The cation exchange capacity (CEC) was calculated as the sum of $H+Al^{3+}$, Ca^{2+}, Mg^{2+}, and K^+. These procedures have been described in Teixeira *et al*. (2017).

Biological attributes

Microbial biomass carbon (MBC) was determined using the fumigation-extraction method (VANCE;

BROOKES; JENKINSON, 1987). A conversion factor of Kc = 0.33 was used for the calculation (SPARLING; WEST, 1988). Arylsulfatase (EC 3.1.6.1), acid phosphatase (EC 3.1.3), and β-glucosidase (EC 3.2.1.21) activities, expressed in μg p-nitrophenol h^{-1} g^{-1}, were determined according to Tabatabai (1994).

No-tillage PQI

The no-tillage PQI was obtained by applying a questionnaire that considered the crop and soil management practices adopted by the farmer in the last three years. Initially, the PQI indicators were calculated based on the farmers' responses. These indicators were: i) rotation intensity (RI); ii) rotation diversity (RD); iii) rotation persistence (RP); iv) soil tillage frequency (TF); v) correct terracing (CT); vi) soil conservation evaluation (SC); vii) balanced fertilization (BF); and viii) no-tillage option time (AT). The PQI indicators were calculated using the following formula:

$$RI = \frac{N^0_{covered}}{36} \times PF \quad (2)$$

where, RI: rotation intensity. $N°_{Covered}$: number of months (within a 36-months period) that the soil remains covered. PF: ponderation factor (1.5 for RI), Equation (2).

$$RD = \frac{N^0_{Species}}{4} \times PF \quad (3)$$

where, RD: rotation diversity. $N°_{Species}$: number of different species (within a 36-months period) used in the crop rotation. PF: ponderation factor (1.5 for RD), Equation (3).

Table 1 - Grading of the RP indicator

N° of grasses	Grade
6	1.00
5	0.75
3 or 4	0.50
2	0.25
0 or 1	0.00
Maximum value	1.00

$$RP = RP_{Grade} \times PF \quad (4)$$

where, RP: rotation persistence. RP_{Grade}: grade based on the number of grasses in the crop rotation within a 36-months period (grasses used for haying or silaging are not considered), Equation (4); this grading is presented in Table 1. PF: ponderation factor (1.5 for RP).

Grasses used for haying or silaging are not considered

$$TF = TF_{Grade} \times PF \quad (5)$$

where, TF: tillage frequency. TF_{Grade}: grade based on the tillage frequency (within a 36-months period), equation (5); this grading is presented in Table 2 and depends on whether the farmers till the whole area, just the area's borders, or in the terrace channel. PF: ponderation factor (2.0 for TF).

$$CT = CT_{Grade} \times PF \quad (6)$$

CT: correct terracing. CT_{Grade}: grade based on the number of times the terraces have overflowed in the last five years, equation (6); this grading is presented in Table 3. PF: ponderation factor (1.0 for CT).

$$SC = \left(OL_{Grade} + SC_{Grade} + SE_{Grade}\right) \times PF \quad (7)$$

SC: soil conservation evaluation. OL_{Grade}: grade based on the operations performed at level. SC_{Grade}: grade based on the observations of soil compaction. SE_{Grade}: grade based on the observation of soil erosion, equation (7); these grades are presented in Table 4. PF: ponderation factor (1.0 for SC).

$$BF = \left(Li_{Grade} + MF_{Grade} + OF_{Grade}\right) \times PF \quad (8)$$

BF: balanced fertilization. Li_{Grade}: grade based on the use of liming. MF_{Grade}: grade based on the use of mineral fertilizers. OF_{Grade}: grade based on the use of organic fertilizers (when available in the region), equation (8); these gradings are presented in Table 5. PF: ponderation factor (1.0 for BF).

Table 2 - Grading of the TF indicator

Tillage frequency (years)	Area tilled		
	Whole area	Area's borders only	Terrace channel only
	Grade		
12 or more	1.00	1.00	1.00
9 to 11	0.75	0.95	1.00
6 to 8	0.50	0.90	1.00
3 to 5	0.25	0.85	1.00
0 to 2	0.00	0.80	1.00
Maximum value		1.00	

$$AT = \begin{cases} 0{,}5, \cdots ifTime_{N0-lillage} \geq 25 \\ \dfrac{Times_{N0-tillage}}{25} \times PF, ifTime_{N0-tillage} < 25 \end{cases} \quad (9)$$

AT: adoption time. $Time_{No\text{-}tillage}$: time of no-tillage adoption (years); if $Time_{No\text{-}tillage} > 25$, AT= 1. PF: ponderation factor (0.5 for AT), Equation (9).

$$PQI = RI + RD + RP + TF + CT + SC + BF + AT \quad (10)$$

PQI: participatory quality index. RI: rotation intensity. RD: rotation diversity. RP: rotation persistence. TF: soil tillage frequency. CT: correct terracing. SC: soil conservation evaluation. BF: balanced fertilization. AT: no-tillage adoption time, Equation (10).

Each PQI indicator contributes differently to the PQI. The amplitudes and classifications of the values of each PQI indicator are presented in Table 6.

Statistical procedures

Principal component analysis (PCA) was performed based on the correlation matrix of the data using R software. The number of plotted components was defined by the Kaiser criterion, in which those with a variance higher than one were used.

Table 3 - Grading of the CT indicator

Times that terraces overflowed in the last five years	Grade
0 or 1	1.00
2 or 3	0.50
3 or more	0.00
Maximum value	1.00

Table 4 - Grading of the SC indicator

Component	Class	Grade
Operations in level	Seeding and spraying	0.250
	Seeding only	0.175
	Spraying only	0.075
	None	0.000
Soil compaction	None	0.500
	Area's borders	0.250
	Whole area	0.000
Soil erosion	No	0.250
	Yes	0.000
Maximum value		1.000

Table 5 - Grading of the BF indicator

Parameter	Criteria	Organic amendment availability	
		Available	Not available
		Grade	
Liming	Application based on soil analysis	0.25	0.50
	Application not based on soil analysis	0.00	0.00
	Not applied	0.00	0.00
Mineral fertilization	Application based on soil analysis	0.25	0.50
	Application not based on soil analysis	0.00	0.00
	Not applied	0.00	0.00
Organic fertilization	Waste characterization performed and application based on nutrients content	0.50	Not applicable
	Application based on the amount (without considering the nutrients content)	0.25	Not applicable
	Not applied	0.00	Not applicable
Maximum value		1.00	1.00

Table 6 - Amplitude and classification of PQI indicators

Indicator	Classification				
	Very bad	Bad	Regular	Good	Very good
RI	0.000	0.375	0.750	1.125	1.500
RD	0.000	0.375	0.750	1.125	1.500
RP	0.000	0.375	0.750	1.125	1.500
TF	0.000	0.500	1.000	1.500	2.000
CT	0.000		0.500		1.000
SC	0.000	0.250	0.500	0.750	1.000
BF	0.000	0.250	0.500	0.750	1.000
AT	0.000	0.010 – 0.125	0.126 – 0.250	0.251 – 0.375	0.376 – 0.500
PQI	0.00 – 1.99	2.00 – 3.99	4.00 – 5.99	6.00 – 7.99	8.00 – 10.00

RI: rotation intensity. RD: rotation diversity. RP: rotation persistence. TF: soil tillage frequency. CT: correct terracing. SC: soil conservation evaluation. BF: balanced fertilization. AT: no-tillage adoption time. PQI: participatory quality index

RESULTS AND DISCUSSION

All the variables were within the expected ranges (Table 7). The coefficient of variation of most variables was relatively high, suggesting a considerable variation in soil management quality, particularly considering that these soils are pedogenetically similar and the same management was used (annual crops under no-tillage).

No-tillage is used over more than 33 million hectares in Brazil (IBGE, 2017). However, most farmers do not meet all the requirements for conservation agriculture (TELLES *et al*., 2019). This suggests that within no-tillage farmers, the quality of soil management and, consequently, soil quality is highly variable. In the present study, despite all soils being managed under no-tillage and presenting similar parent materials and climatic conditions, most soil attributes varied considerably (Table 7).

Most variables with marginal variability were physical, but this pattern was expected. Particle density was highly influenced by soil mineralogy and organic matter content. As all soils were pedogenetically similar and only the surface layer (0–20 cm) was analyzed, a marginal variability was expected. These soils commonly contain kaolinite as the main mineral in the clay fraction. However, these soils also contain a considerable proportion of Al and Fe oxides, which tends to increase particle density. Contrasting this, organic matter reduces particle density. Soil density, ASI, microporosity, and total porosity were naturally less variable in these soils (MELO *et al.*, 2018). This was mainly because of the high clay content and the layer (0–10 cm) from which the samples were collected. The pH also showed marginal variability, probably because all the farmers used lime to reduce acidity. Most areas had adequate pH for crop development. However, a few areas presented a pH (in $CaCl_2$ solution) lower than 5.0, where Al^{3+} is expected to be present at higher concentrations in the soil solution.

Not all classes of PQI indicators (very bad, bad, regular, good, and very good) were obtained in this study. This was probably a reflection of factors such as: i) the study region, which has several technologies in areas of soybean/ maize production, and ii) the studied farmers, who included only those adopting no-tillage for at least three years.

Despite this limitation, several associations with soil attributes were observed. All groups of soil attributes (physical, chemical, and microbiological) were related to PQI indicators. Consequently, the PQI methodology can be considered adequate for measuring soil management quality. Although the overall PQI was associated with many of the evaluated soil attributes, some associations were more evident with the PQI indicators that constituted the overall index. This suggests that all PQI indicators, as well as the overall index, should be considered when measuring the quality of soil management.

In these heavy clay soils, lower soil density and microporosity, and higher macroporosity and total porosity indicate soil structural improvement (TAVARES FILHO *et al*., 2014) because most of their porosity is composed of micropores (MELO *et al*., 2018). As expected, total porosity and macroporosity were inversely related to soil density and microporosity. However, these attributes were weakly related to the PQI indicators (Figure 2). This was unexpected because the soil structure is supposed to improve by improving the conservation practices as measured by the PQI indicators. For example, increasing the time the area remains with living plants improves the soil structure, mainly because of root growth (ADETUNJI *et al*., 2020).

Table 7 - Descriptive statistics of the studied variables

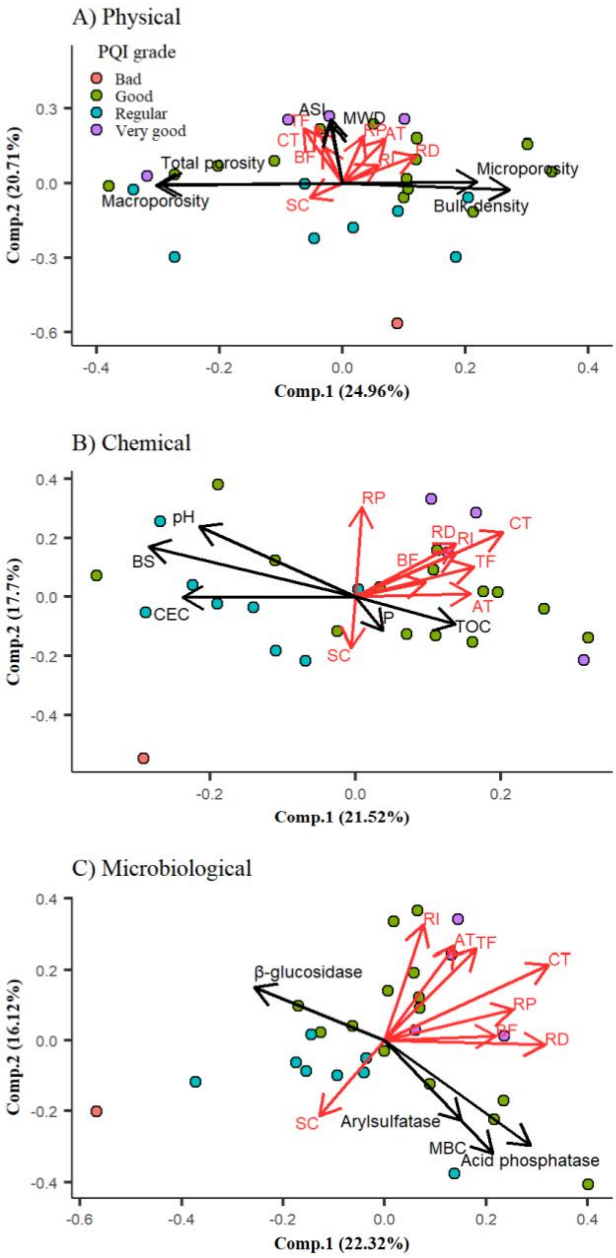
Variable		Unit	Minimum	Mean	Maximum	CV (%)
PQI indicator	RI		0.75	0.17	1.50	25.66
	RD		0.75	0.98	1.50	26.69
	RP		0.38	0.77	1.13	21.42
	TF		0.00	0.12	2.00	72.73
	CT		0.00	0.87	1.00	30.21
	SC		0.25	0.78	1.00	28.89
	BF		0.25	0.63	1.00	37.11
	AT		0.12	0.41	0.50	27.73
	PQI		3.97	6.70	8.89	18.52
Physical	Particle density	g cm^{-3}	2.76	2.91	3.03	2.47
	Soil density	g cm^{-3}	1.03	1.24	1.37	8.21
	MWD	Mm	4.41	6.41	8.60	19.31
	GWD	Mm	1.69	3.32	5.42	31.06
	ASI	%	86.65	93.51	97.05	3.07
	Macroporosity	m^3 m^{-3}	0.10	0.18	0.26	23.69
	Microporosity	m^3 m^{-3}	0.35	0.40	0.43	4.66
	Total porosity	m^3 m^{-3}	0.52	0.58	0.64	5.21
	Field capacity	%	29.09	32.53	39.89	8.75
Chemical	TOC	g kg^{-1}	13.36	18.94	23.27	14.37
	pH	-log[mol dm^{-3}]	4.47	5.07	5.57	5.82
	CEC	$cmol_c$ dm^{-3}	13.27	16.20	19.56	11.92
	Al^{3+}	$cmol_c$ dm^{-3}	0.00	0.07	0.52	171.67
	Base saturation	%	46.56	63.73	76.94	12.12
	Phosphorous	mg dm^{-3}	6.77	26.38	102.77	85.44
Biological	Arylsulphatase	mg pn h^{-1} kg^{-1}	0.39	1.41	2.67	46.69
	CMB	mg kg^{-1}	75.09	180.61	467.65	58.27
	β-glucosidase	mg pn h^{-1} kg^{-1}	16.23	39.46	80.32	47.64
	Acid phosp.	mg pn h^{-1} kg^{-1}	213.56	338.72	665.94	31.34

RI: rotation intensity. RD: rotation diversity. RP: rotation persistence. TF: soil tillage frequency. CT: correct terracing. SC: soil conservation evaluation. BF: balanced fertilization. AT: no-tillage adoption time. PQI: participatory quality index. MWD: mean weighted diameter. MGD: mean geometric diameter. ASI: aggregate stability index. Al^{3+}: exchangeable aluminum. TOC: total organic carbon. Phosphorous: available phosphorous. CEC: cation exchange capacity. CMB: carbon of the microbial biomass. Acid phosp.: acid phosphatase

The aggregation indices (MWD, GWD, and ASI) were positively associated with most PQI indicators (except AC) and the PQI index. This suggests that the methodology accurately measured improvements in soil structural stability but not structural quality. The stability of aggregates in these soils responds intensely to organic matter increments because of their high clay content, which also has a significant metallic sesquioxide content (MELO *et al*., 2018, 2019a). This explains why these attributes are related to many of the PQI indicators that reflect organic matter dynamics (RP, TF, CT, SC, BF, and AT).

The soil attributes used in this study are associated with important soil processes, and can be considered adequate for validating the PQI methodology. MWD, GMD, and ASI are indicators of aggregate stability and consequently reflect their persistence against disrupting agents and hydration (BARBOSA *et al*., 2015; MELO *et al*., 2019a, 2019b). Soil density, porosity (macroporosity, microporosity, and total porosity), and field capacity reflect the quality of soil structure, with implications for water and gas dynamics (CENTENO *et al*., 2020). Total organic carbon (TOC) is a central indicator of soil quality and is associated with several processes (LEHMAN *et al*., 2015). pH, CEC, base saturation, and phosphorous are indicators of nutrient availability, and Al^{3+} is associated with plant toxicity.

Figure 2 - Biplots of principal component analysis showing the relationship between soil physical (A), chemical (B) and microbiological (C) attributes (in black) with PQI indicators (in red)



The PQI and indicators were positively correlated with TOC, suggesting that these indicators were associated with higher organic matter input in the system. Rotation diversity, tillage frequency, correct terracing, and balanced fertilization are factors of soil management that are related to the TOC content in the soil. As an important indicator of soil quality, the strong association between PQI indicators and TOC is essential for its use as an indicator of soil management quality. Studies on these heavy clay soils have shown a high potential for organic matter increment by soil management practices such as manure application (MELO *et al*., 2019c) and adoption of no-tillage (TAVARES FILHO *et al*., 2014).

The remaining soil chemical attributes (cation exchange capacity, available phosphorous, base saturation, pH, and exchangeable aluminum) were not good indicators of soil quality in the present study because they were within adequate ranges for crops (Table 7) according to the high fertilization and liming rates suggested in the liming and fertilization recommendation manual for the state of Paraná (PAULETTI; MOTTA, 2019). This was expected because the farmers from the study region use several technologies, with a high input of chemical fertilizers and lime. Consequently, soil chemical attributes, such as nutrient concentration and pH, were not capable of reflecting the quality of soil management, because most of them were associated with conservation practices (see the calculations of PQI indicators in the supplementary material). Additionally, these soils are weathered from basalt, which is reflected in their natural slight acidity and high base availability.

The soil pH was measured in $CaCl_2$ (0.01 mol dm^{-3}) solution. The observed values reveal that the acidity of these soils is adequately neutralized in most cases. The CEC of these soils is relatively high for intensely weathered soils but is a reflection of their high clay content and capacity to protect organic matter; consequently, it is within the expected range. Available phosphorus values indicate excess fertilization in several cases. According to the state's fertilization manual (PAULETTI; MOTTA, 2019), values higher than 60 mg dm^{-3} of available phosphorus can lead to problems in terms of environmental degradation and nutritional deficiency of other elements to plants. Some areas analyzed in the present study presented values higher than this threshold. This reinforces the need for a better evaluation of farmers' fertilization criteria, which is most likely not based on adequate parameters. The principal component analysis showed a correlation between the microbiological attributes that were indicative of soil quality and PQI indicators. The first two components explained 38.44% of the total variability in the data (Figure 2).

MBC, acid phosphatase, and arylsulfatase were positively correlated with the PQI indicators, suggesting an increase in soil carbon and protein content, promoting a greater source of energy and nutrients for microbial communities (WEIL *et al*., 2003). These correlations separated the observations classified as good and very good in the PCA (Figure 2). This suggests that the PQI methodology can accurately measure improvements in soil microbiological quality, whereas biomass and microbial activity, as measured by MBC, β-glucosidase, arylsulfatase, and acid phosphatase, are useful for assessing short-term changes in soil quality (BONGIORNO *et al*., 2019; NUNES *et al*., 2020b; VAN ES; KARLEN, 2019; WANDER *et al*., 2019).

Microbial activity responds quickly to the increased addition of organic matter and proteins by living plants as it is a source of energy and nutrients for microbial communities. Another point is the positive effect of the time of adoption of the no-tillage system on microbiological indicators of soil quality, which are frequently reported and have been associated with a greater retention of crop residues on the soil surface (NUNES *et al*., 2018; VEUM *et al*., 2015; VEUM; LORENZ; KREMER, 2019). This explains why these attributes are related to most PQI indicators that reflect the dynamics of organic matter (RI, RD, RP, TF, CT, BF, and AT).

The SC indicator was not associated with these microbiological variables, considering that this indicator reflects adequate soil management and conservation practices. Such a pattern was unexpected given the sensitivity of microbiological attributes to soil changes (BONGIORNO *et al*., 2019; VAN ES; KARLEN, 2019). According to the PCA results, β-glucosidase enzyme activity showed a low association with IQP indicators (Figure 2). However, the inverse association with BF indicator reflects the validation of this indicator through β-glucosidase activity. Several studies have shown that chemical fertilization reduces the enzymatic activity of β-glucosidase (ADETUNJI *et al*., 2017; ČUHEL; MALÝ; KRÁLOVEC, 2019; MULIDZI; WOOLDRIDGE, 2016).

Most soybean farmers in Brazil assess the soil nutrient status through soil analysis. However, they rarely measure soil physical or biological status, except for soil particle distribution (clay, silt, and sand content). Considering this scenario, the PQI, an easy-to-measure approach, can help fill this gap and allow farmers to self-assess the quality of soil management (NUNES *et al*., 2020a). Additionally, the PQI can be used as a tool for the evaluation of payment of ecosystem services as it considers conservation agriculture-related practices.

Finally, these results confirmed the usefulness of the PQI methodology as a tool for assessing the quality of soil management under annual crops, demonstrating their sensitivity to short-term changes in management practices. This will allow for the monitoring of management quality and inferences about the benefits of implemented practices. Despite this, not all major attributes of soil quality (such as compaction and nutrient availability) could be explained by PQI, suggesting that changes must be made in the index to include practices related to their improvement.

CONCLUSION

The quality of soil management under annual crops can be assessed using the no-tillage participatory quality index (PQI), as evidenced by its association with soil physical, chemical, and microbiological attributes. This method has been shown to be sensitive to short-term changes in soil management practices. Consequently, it may allow for the monitoring of management quality and inferences about the beneficial effects of the implemented practices. Practices that are more closely related to soil compaction and nutrient availability must be included to improve the capacity of the PQI to reflect the quality of soil management.

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