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Soil microbial properties are improved by the adoption of soil management and conservation practices in no-tillage system

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ABSTRACT: No-tillage system (NTS) plays a prominent role in conservation agriculture, however, its benefits can be further improved by adopting complementary soil management and conservation practices, such as using autumnal cover crops, contour seeding, and terraces. This study aimed to evaluate how soil biological activity responds to soil management and conservation systems. The treatments consisted of three macroplots with an area of 11.000 m² each, as follows: a) Non-Terraced catchment (NTC), cultivated in NTS similar to most farmers of the region, in which the agricultural operations are carried out in the direction of the slope and without terraces used; b) Best Management Practices (BMPs) were adopted in NTS with additional autumnal cultivation of cover crops, and also the direction of machine traffic was transverse to the slope direction; and c) Terraced catchment (TC), cultivated in NTS was associated to mechanical practices to erosion control, using wide base terrace on level. Soil microbial properties sampled in the 0.00-0.10 m layer were evaluated during 2019, 2020, and 2021, all shortly after the summer crop harvest. Natural inoculum potential of arbuscular mycorrhizal fungi (AMF), respirometry, metabolic coefficient, acid phosphatase activity, and organic carbon and nitrogen in the microbial biomass were assessed. Averages of each microbiological properties were compared through the confidence intervals ($p<0.05$). The results showed a greater potential for AMF inoculum in BMPs and TC systems. The NTC showed the highest values of respirometry and metabolic quotient, releasing 31.7 and 27.3 % more CO_2 compared to BMPs and TC, respectively. The BMPs and TC were able to retain 13.8 and 16.5 % more carbon in the microbial biomass and 8.0 and 8.8 % more nitrogen in the biomass than NTC, respectively. Adopting soil management and conservation practices such as autumn cover crops, level seeding, and wide base terrace on level improved the soil microbial properties, with an increase in AMF inoculum potential, higher levels of acid phosphatase activity, and increment of carbon and nitrogen in microbial biomass.

Keywords: conservation agriculture, terracing, soil biology, best management practices.

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INTRODUCTION

No-tillage system has been adopted in an area of approximately 33 million hectares in Brazil (Fuentes-Llanillo et al., 2021). The use of this system is mainly linked to increasing crop yield (Calonego and Rosolem, 2010; Blanco-Canqui and Wortmann, 2020), reducing production costs (Dechen et al., 2015; Bertol et al., 2017), and achieving better soil and water conservation due to the non-turning and maintenance of crop residues on the soil surface (Bertol et al., 2017; Blanco-Canqui and Wortmann, 2020; Possamai et al., 2022).

Despite being revolutionary, no-tillage has been facing challenges regarding its sustainability, mainly due to poor management and lack of mechanical soil conservation practices. Many studies report a decrease in macroporosity and increase soil compaction (Tormena et al., 1998; Moraes et al., 2013; Keller et al., 2014), reduction in gas exchange and less water infiltration and redistribution in the soil (Canillas and Salokhe, 2002; Rienzi et al., 2016), lower plant root growth (Bergamin et al., 2010; Ribeiro et al., 2010; Bassegio et al., 2018), and, consequently, direct negative impacts on crop yield (Modolo et al., 2008; Kormanek et al., 2015; Grzesiak et al., 2016; Espessato et al., 2017; Bareta Junior et al., 2022).

Furthermore, intensive land-use has significantly increased CO_2 emissions (Kopittke et al., 2019), indicating negligence in soil use and management. On the other hand, aiming at conservation agriculture, three principles are sought: reduction of soil disturbance, maintenance of crop residues, and crop rotation (Pittelkow et al., 2014; Possamai et al., 2022). Furthermore, studies have shown that healthy soils contribute not only to the food and nutritional security of the population but also to mitigating climate change (Lal, 2016; Rojas et al., 2016). Adoption of soil conservationist practices in a no-tillage system (Possamai et al., 2022), such as crop rotation, mulch, and terracing, are alternatives to meet conservation agriculture principles, which contribute to increased yield and sustainability of agricultural systems (Nyirenda and Balaka, 2021; Shakoor et al., 2021).

In addition to the soil chemical and physical properties, it is necessary to evaluate the soil microbial properties to understand how adopting these practices affects the system quality. Microbial properties show high responsiveness to changes in the agricultural environment (Rocha Junior et al., 2014; Geraei et al., 2016; Marion et al., 2022); therefore, they can be good indicators of soil quality (Govaerts et al., 2007; Choudhary et al., 2018). In general, microbial soil properties are of great relevance in terms of sustainability, as they serve as an indirect tool to quantify the reduction in greenhouse gas (GHG) emissions (Gui et al., 2021), a crucial factor given that agriculture accounts for 11 % of anthropogenic GHG emissions (Arneth et al., 2019).

The main microbial properties used in the evaluation of soil quality are the natural inoculum potential of arbuscular mycorrhizal fungi (Gutjahr and Parniske, 2013; Gui et al., 2021; Kozjek et al., 2021), respirometry and metabolic coefficient (Pires et al., 2020), acid phosphatase activity (Zheng et al., 2021), and organic carbon (C) and nitrogen (N) in the microbial biomass (Jenkinson and Powlson, 1976; Anderson and Domsch, 1978; Vance et al., 1987; Pires et al., 2020). Conservationist systems with more plant residues on the soil surface have increased organic carbon and nitrogen in microbial biomass (Pires et al., 2020), reducing soil respirometry and mitigating CO_2 emissions into the atmosphere (Gui et al., 2021). The activity of acid phosphatase is influenced by fertilization management (Zheng et al., 2021), residue production, and crop rotation (Margenot et al., 2017).

The hypothesis of this study was that conservationist soil management systems, which include crop rotation with cover crops, contour seeding, and terracing, are more effective in improving soil microbial properties. This study aimed to evaluate microbial properties in different conservation systems under no-tillage in the Center-South region of Paraná.

MATERIALS AND METHODS

Location and experimental design

The study was carried out in an experimental area located in the Entre Rios district, Guarapuava, Paraná, whose geographic coordinates are 25° 32’ 12” S and 51° 30’ 21” W and average slope of 0.047 m m^{-1}. The experiment was conducted in the field from January 2019 to December 2021 in a Xanthic Hapludox equivalent to *Latossolo Bruno distrófico* (Santos et al., 2018) with a very clayey texture. Soil chemical analysis and particle size composition are presented in table 1. According to the Köppen classification system, the local climate is Cfb, humid mesothermal (subtropical) climate, presenting no defined dry season, cool summers, and winters with severe and frequent frosts (Alvares et al., 2013). The average monthly precipitation of the experimental area from 2019 to 2021 and the historical climatic average are shown in figure 1.

Table 1. Soil chemical properties and particle size distribution in the 0.00-0.20 m layer at the experimental site

System	P (Mehlich^{-1})	SOC	pH($CaCl_2$)	Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	K^+	Clay	Silt	Sand
	mg dm^{-3}	g dm^{-3}		cmol$_c$ dm^{-3}					g kg^{-1}		
NTC	6.4	26.9	4.7	0.2	7.6	9.2	3.1	0.3	762	185	53
BMPs	6.7	27.2	4.6	0.3	7.6	10.5	4.0	0.3	769	175	56
TC	8.6	24.8	4.7	0.4	7.6	8.2	3.7	0.3	787	168	45

SOC: soil organic carbon; Clay: particles with diameters smaller than 0.002 mm; Silt: particles with diameters between 0.002 and 0.053 mm; Sand: particles with diameters between 0.053 and 2.0 mm.

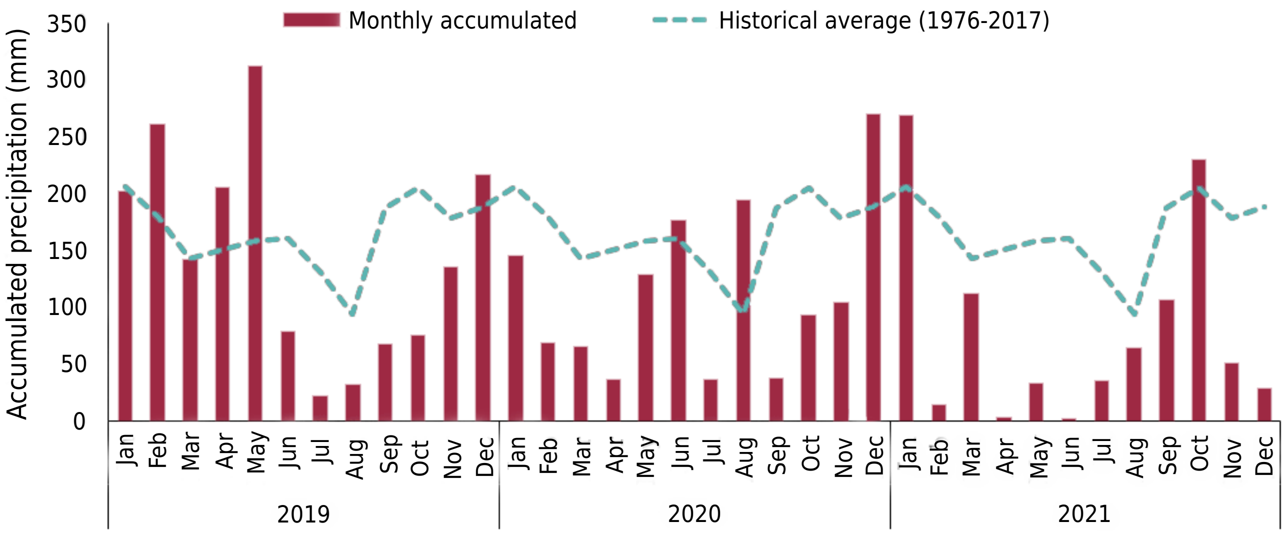

Figure 1. Monthly accumulated precipitation collected by a meteorological station at the experimental site and historical monthly precipitation (1976 to 2017). Entre Rios District, Guarapuava, Paraná.

The treatments consisted of three macroplots with an area of 1.10 ha (Figure 2), characterized as follows:

a) Non-Terraced Catchment (NTC): applying the soil management and cultivation process carried out by most regional producers. This management consists of a no-tillage system without mechanical erosion control (downhill planting). The most common rotation system in the region was used: grain crops in a no-tillage system with the main rotation consisting of ¾ soybean and ¼ corn, in addition to the cultivation of winter cereals. The sequence of crops established in NTC was black oat (*Avena strigosa*) + forage turnip (*Raphanus sativa*) / corn (*Zea mays*) / barley (*Hordeum vulgare*) / soybean (*Glycine max*) / wheat (*Triticum aestivum*) / soybean / barley / soybean.

b) Best Management Practices (BMPs): employing a set of soil management and conservation practices mainly aimed at improving the soil physical conditions under a no-tillage system. Crop rotation with autumnal cover crops is performed for permanent soil coverage, mainly after the summer crop and the beginning of winter cereal sowing. Furthermore, level seeding and spraying related to agricultural practices were carried out. The sequence of crop rotation was black oat + forage turnip / corn / forage turnip (ACC) / barley / soybean / forage turnip (ACC) / wheat / soybean / mix with black oat + rye (*Secale cereale*) + vetch (*Vicia sativa*) + chickling vetch (*Lathyrus hirsutus*) (ACC) / barley / soybeans, where ACC represents autumnal cover crops grown between the summer and the winter crops.

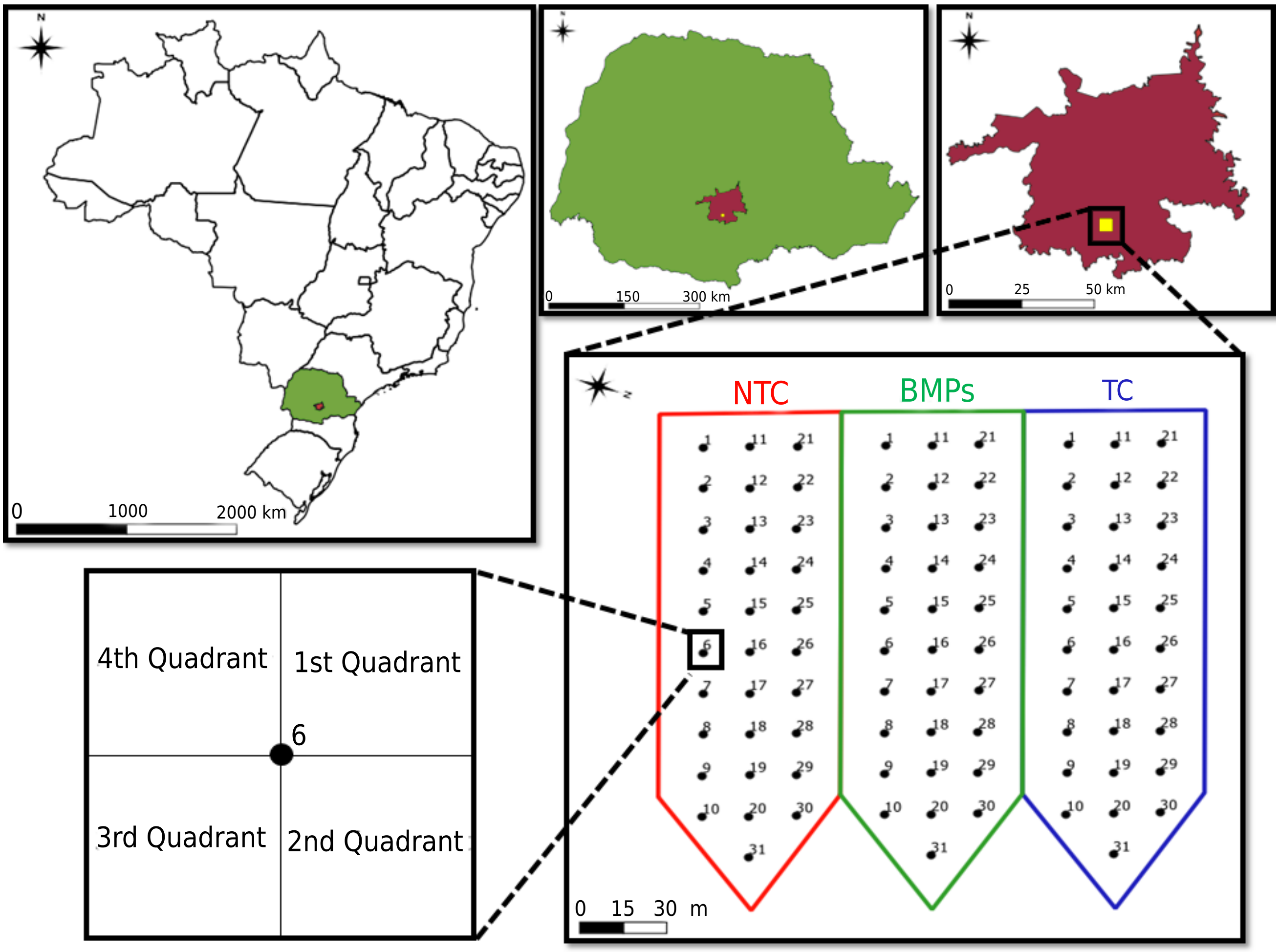

Figure 2. Location, organization, and sample grid of the experimental area. Entre Rios District, Guarapuava, Paraná, Brazil.

c) Terraced Catchment (TC): adopting the same system as NTC but associated with mechanical practices of erosion control (with terraces and level cultivation). Terrace spacing was defined using the Terrace for Windows program, adapting from the method proposed by Lombardi Neto et al. (1994), and determining the infiltration velocity with a pressure infiltrometer with concentric rings.

In all treatments, a regular sampling grid was defined with 16.5 m between points, generating 31 georeferenced sampling points in each soil management system (Figure 2). The points were georeferenced (GPS/RTK), allowing the return to the same position with centimeter precision over time. Sample collections were carried out in quadrants to avoid collections at the same site. Therefore, in the first year, samples were collected in the first quadrant (April 12, 2019), in the second year in the second quadrant, (April 17, 2020) and, in the third year, in the third quadrant (April 11, 2021).

Soil microbial properties

Soil collections were carried out during three consecutive years at the layer of 0.00-0.10 m, comprising an annual collection in each macroplot immediately after the harvest of summer crops. In each system, 31 soil samples were collected, totaling 93 samples per year. After collection, the samples were kept in Styrofoam boxes, cooled during transport to the laboratory and preserved in a cold chamber at 4 °C until the time of microbial evaluations. Then, a portion of 50 g of soil from each sample was dried in an oven at 105 °C until constant weight to determine the moisture content.

Evaluating the natural inoculum potential of arbuscular mycorrhizal fungi (AMF) in the soil

Natural inoculum potential of AMF in the soil was established by spore counting. The soil spores were extracted using the wet sieving technique (Colozzi Filho and Balota, 1994). Spores were counted in a checkered Petri dish using a stereoscopic microscope with a magnification of up to 40 times. The results were expressed as the number of AMF spores for each 50 g of soil.

Respirometry and metabolic coefficient (qCO_2)

Microbial respiration was determined from the release of C-CO_2 in non-fumigated samples after seven days of incubation by adapting the fumigation-incubation method (Jenkinson and Powlson, 1976). The results were expressed in μg C-CO_2 g^{-1}. Finally, the metabolic coefficient (qCO_2) was calculated by the ratio between the amount of CO_2 released per hour and the sample microbial biomass (Anderson and Domsch, 1978).

Acid phosphatase activity assessment

Acid phosphatase activity was determined according to Tabatabai (1994). The reaction mixture consisted of 1.0 g of soil, 1.0 mL of *p*-nitrophenyl phosphate substrate, 4.0 mL of buffer (pH 5.5), and 0.25 mL of toluene, which were incubated for 1 h at 37 °C. Then, 1.0 mL of $CaCl_2$ (0.5 mol L^{-1}) and 4 mL of NaOH (0.5 mol L^{-1}) were added, followed by filtration on filter paper (Whatman No. 1). The released *p*-nitrophenol was quantified in a spectrophotometer at 400 nm, which represents a unit of enzymatic activity. The results were expressed in mg *p*-nitrophenol g^{-1} soil h^{-1}.

Evaluation of carbon and nitrogen in microbial biomass

The determination of microbial biomass N and C was carried out to evaluate the microbial activity using the fumigation-extraction method (Vance et al., 1987). Two 20-g aliquots of soil were weighed and placed in a beaker. One of these samples was fumigated at 25 °C for 24 h with chloroform to release the soil microbial biomass. The other, non-fumigated, was subjected to the same process, replacing chloroform with distilled water. After 24 h of fumigation, extraction with K_2SO_4 0.5 mol L^{-1} was performed, followed by filtration. The microbial biomass C was determined by oxidation with potassium dichromate ($K_2Cr_2O_7$) in the presence of concentrated sulfuric acid (H_2SO_4). The microbial biomass N was determined following the method proposed by Bremner (1965), which includes digestion of the extracted samples with concentrated sulfuric acid and a catalyst consisting of potassium sulfate and cupric sulfate (10:1) and subsequent colorimetric determination of the NH_4^+ ion by the salicylate method (Kemper and Rosenau, 1986). The readings were performed in a spectrophotometer at 697 nm. The results of microbial biomass C and N were expressed in μg of C or μg of N per g of dry soil (μg g^{-1}).

Statistical analyses

Data were subjected to normality verification (Shapiro-Wilk and Lilliefors). Then, the variables were subjected to analysis of variance (ANOVA). The means were compared with a confidence interval ($p<0.05$). In addition, a principal component analysis was performed to identify which variables had the greatest influence on each treatment.

A principal component analysis (PCA) with soil microbial attribute data from 2019 to 2021 was performed to establish the components that represent the maximum possible data variability. As the evaluated variables have different measurement units, the correlation matrix (normalized var-covar) method was used, disregarding the groups. Next, the eigenvalues and variance percentages accounted for by the components were calculated, determining the number of principal components (eigenvalues greater than 1.0 and/or broken stick). After defining the number of principal components of the analysis, the data were plotted in biplot graphs on the scale of eigenvalues.

RESULTS

Soil microbial properties

Number of AMF spores did not differ between the soil management systems in 2019. However, in 2020, the BMPs system (78 spores 50 g^{-1} of soil) was superior to NTC (60 spores 50 g^{-1} of soil) and similar to TC (70 spores 50 g^{-1} of soil) (Figure 3). In 2021, a greater number of AMF spores was observed for all systems compared to 2020; however, the BMPs (97 spores 50 g^{-1} soil) and TC (94 spores 50 g^{-1} soil) systems were superior to NTC (74 spores 50 g^{-1} of soil).

Concerning respirometry, no difference was observed between the soil management systems in 2019. However, in 2020, the highest respirometry was verified for NTC (7.71 μg C-CO_2 g^{-1}) and the lowest for BMPs (5.99 μg C-CO_2 g^{-1}), as shown in figure 4a. In 2021, the same behavior as the previous year was detected.

Microbial biomass carbon in 2019 was higher in TC (129.02 μg C g^{-1}) than in NTC (120.61 μg g^{-1}). In 2020, the difference between NTC and the other systems was even more pronounced (Figure 4b). In 2021, the microbial biomass C of all systems was higher than that in the two previous years; NTC and TC did not differ from each other, and BMPs had the highest value for this variable, corresponding to 152.10 μg C g^{-1}. Metabolic quotient did not differ between the systems in 2019 (Figure 4c), but in 2020 and 2021, the NTC system had the highest metabolic quotient, with qCO_2 mean values of 0.07 and 0.06, respectively.

Microbial biomass N was statistically higher in the BMPs (4.34 μg g^{-1}) and TCs (4.37 μg g^{-1}) systems in 2020 and did not differ among the systems in 2019 (Figure 5). The BMPs and TC had an increase in microbial biomass N from 2019 to 2020. In 2021, there was a significant increase in the microbial biomass N in the NTC system compared to previous years, equaling the TC system, which had no significant increase in relation to 2020. The values obtained for BMPs were higher than the other systems and in relation to previous years, corresponding to 4.62 μg g^{-1}.

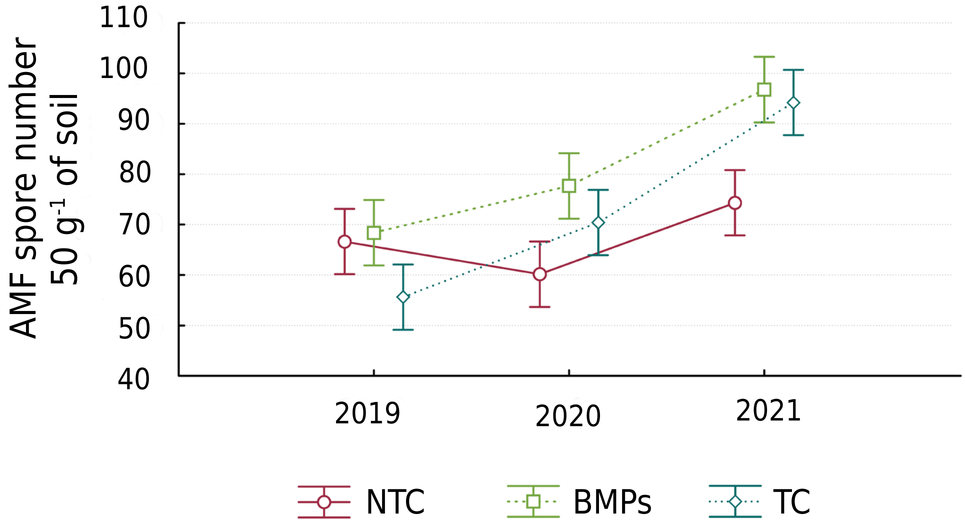

Figure 3. Arbuscular mycorrhizal fungi spore number in different conservation management systems in 2019, 2020, and 2021. Vertical lines represent the least significant difference by the confidence interval ($p<0.05$).

Acid phosphatase activity showed no difference between management systems in the first experimental year (Figure 6). In 2020, NTC presented the lowest average values of enzymatic activity (316.59 mg *p*-nitrophenol g^{-1} soil h^{-1}), while BMPs and TC had the highest values, 364.63 and 364.77 mg *p*-nitrophenol g^{-1} soil h^{-1}, respectively. In 2021, similar to 2020, NTC showed the lowest acid phosphatase activity value (344.13 mg *p*-nitrophenol g^{-1} soil h^{-1}), while BMPs (376.52 mg *p*-nitrophenol g^{-1} soil h^{-1}) and TC (394.32 mg *p*-nitrophenol g^{-1} soil h^{-1}) had the highest activities.

Principal component analysis (PCA)

Principal component analysis indicated that principal component 1 explained 46.34 %, while principal component 2 explained 25.58 % of the data variability, adding up to 71.92 % (Figure 7). Within principal component 1, the soil respirometry and metabolic quotient variables had negative loadings of -0.59 and -0.78, respectively. The other variables showed a positive loading, with 0.62 for AMF spore number, 0.69 for acid phosphatase, 0.71 for microbial biomass carbon, and 0.67 for microbial biomass nitrogen. Regarding principal component 2, respirometry and metabolic quotient presented the highest loads, 0.79 and 0.61, respectively. Thus, the NTC system presented the highest respirometry and metabolic quotient values over the three years evaluated. Additionally, TC and BMPs showed the highest values of microbial biomass N and C, AMF spore number, and acid phosphatase activity.

DISCUSSION

The first year of evaluating the soil microbial properties was shortly after the withdrawal of corn in mid-April 2019. At this time, as mentioned earlier, the different management systems had yet to be completely installed, which explains the equality in the response of the microbial activity among the soil management systems. Among the evaluated properties, only the microbial biomass C showed a difference in the first year of evaluation, which was lower in NTC than in TC, even TC showing slightly lower SOC content (Table 1).

In 2020, the soil microbial properties showed a response depending on the management system for all the evaluated biological properties, indicating that they are good indicators to predict the differences among soil management systems, as highlighted by other authors (Rocha Junior et al., 2014; Geraei et al., 2016; Kozjek et al., 2021; Marion et al., 2022).

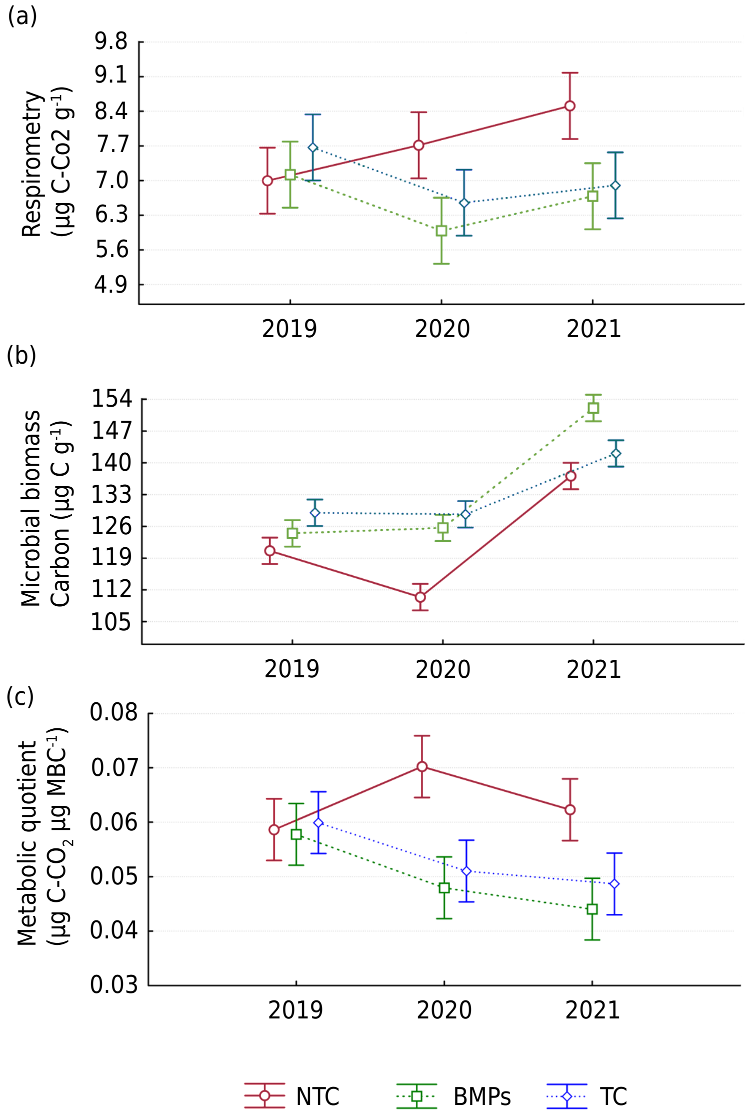

Figure 4. Soil respirometry (a), microbial biomass carbon (b) and metabolic quotient (c) in soils subjected to different conservation management systems in 2019, 2020, and 2021. The vertical lines represent the least significant difference by the confidence interval ($p<0.05$).

Regarding the inoculum potential of arbuscular mycorrhizal fungi (AMF), a greater number of AMF was observed in the BMPs and TC systems. These fungi establish symbiosis with various crops, and in exchange for photosynthetic carbon, they provide mineral nutrients such as phosphorus and nitrogen to plants (Gutjahr and Parniske, 2013; Zhang et al., 2021). In addition to helping in the absorption of nutrients (Van Der Heijden et al., 1998) and plant growth (Cofré et al., 2020; Naseer et al., 2022), AMF can help plants cope with water stress (Augé, 2001).

Plants have different degrees of AMF dependence and, therefore, can change the density of AMF spores in the soil. Plant species may or may not be mycotrophic, with legumes and grasses better performing the role of AMF multipliers, in opposition to species such as crucifers, which are inefficient as host plants (non-mycotrophic), aspects that interfere with AMF colonization and sporulation (Gomide et al., 2009). The cultivation of plants with a high degree of mycorrhizal dependence can increase the population of AMF in the soil and benefits subsequent crops (Miranda et al., 2001). Soybeans, beans, corn, and black oats favor the mycotrophic effect, which constituted the crop rotation system used in all treatments. The cultivation of forage turnip was also used for all treatments (2019), which has low or no mycorrhizal dependence and can reduce the propagation of

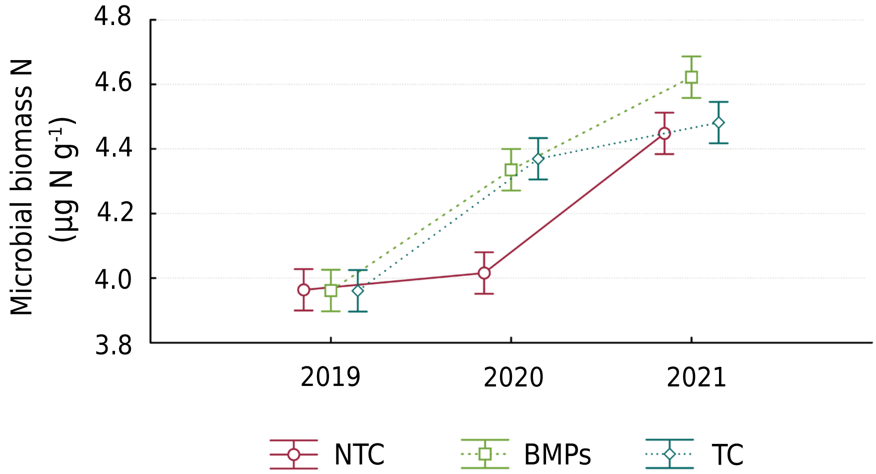

Figure 5. Microbial biomass N in soils subjected to different conservation management systems in 2019, 2020, and 2021. The vertical lines represent the minimum significant difference by the confidence interval ($p<0.05$).

AMF in the soil (Miranda and Miranda, 2001). These, in turn, may also have contributed to the increase in the number of AMF inoculum in BMPs that used autumn cover crops. In addition, when using different cover crops, a mixture of cover plants is provided that will serve as hosts for the fungi, influencing the number of propagules, the inoculum potential, and the diversity of AMFs (Alguacil, 2008).

Acid phosphatase followed a similar pattern as AMF in 2021, indicating that the greater activity of this enzyme was related to more AMF since a greater density of AMF spores was also verified in BMPs and TC. Thus, adopting conservationist soil management favored microbial activity in the soil over time, which was already observed in previous analyses in the first year of monitoring. Acid phosphatase is influenced by fertilization management (Zheng et al., 2021), however, in our study, which presented similar mean levels of phosphorus at the beginning of the research (Table 1), the values of acid phosphatase increased in the second and third years of the experiment, indicating influence of soil management and conservation practices, such as using cover crops and terracing. Additionally, recent studies indicate that enzymes produced by microorganisms play an important role in soil quality, such as decomposing pesticide molecules commonly used in agriculture (Wołejko et al., 2020). Furthermore, these enzymes hydrolyze phosphorus

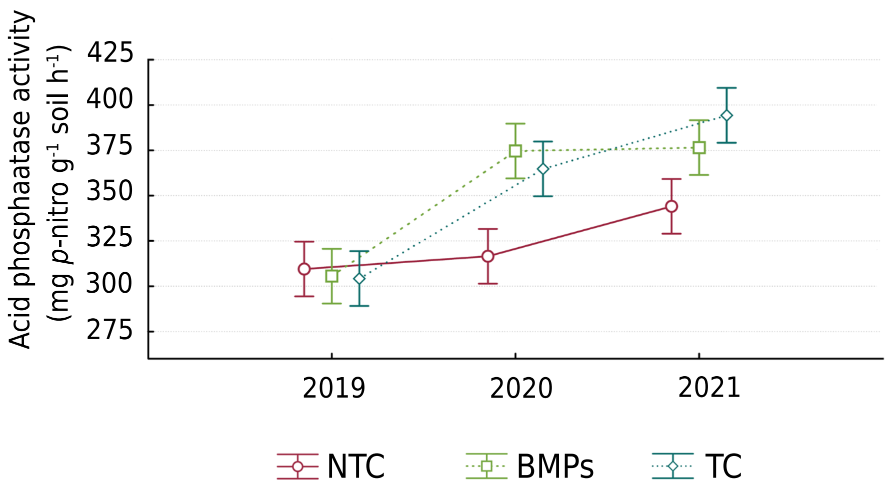

Figure 6. Soil acid phosphatase activity under different conservation management systems in 2019, 2020, and 2021. Vertical lines represent the least significant difference by confidence interval ($p<0.05$).

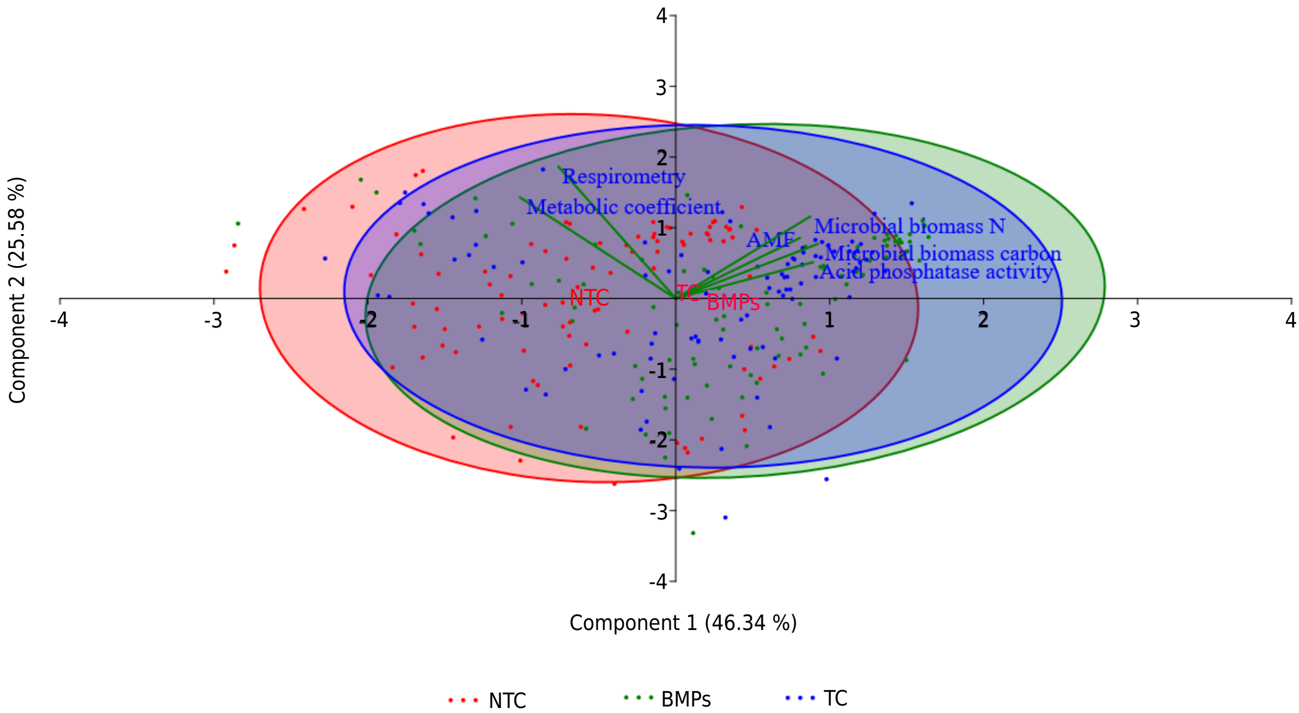

Figure 7. Principal component analysis in different management systems. * Ellipses represent 95 % of the data. Entre Rios District, Guarapuava, Paraná.

esters and anhydrides, having great importance in the mineralization of soil organic phosphorus (Shang et al., 2020; Zhang et al., 2020; Wang et al., 2022).

Respirometry was significantly higher in NTC, which indicates greater metabolic activity of microorganisms, in which the CO_2 flux is related to catabolic process intensity. When evaluating the behavior of the soil management systems, it appears that BMPs and TC had their respirometry levels reduced over time, while NTC presented the highest levels in 2019, which did not differ significantly from the levels obtained in 2020. It should be noted that high values of basal respiration indicate undesirable conditions in the soil and lower quality of the system, as they may reflect, in the long term, excessive losses of organic carbon to the atmosphere, that is, degradation of the system.

Biomass carbon is the most active part of soil organic matter and is composed of several microorganisms. This fact is reflected in the carbon and nitrogen stocks of the microbial biomass, which was significantly higher in BMPs and TC, evidencing the potential of these systems in fixing these elements in the soil and avoiding the loss of N to the atmosphere. On average, BMPs and TC retained 13.8 and 16.5 % more C in the microbial biomass than the NTC system.

The NTC had the highest metabolic quotient, with an average of 31.7 and 27.3 % more CO_2 being released than the BMPs and TC systems, respectively, showing greater efficiency in using the microbial substrate by both conservation systems. These results indicate that soil conservation practices in the BMPs and TC management systems are good alternatives to retaining CO_2 in the soil. Soil microbial respiration directly affects atmospheric CO_2 concentrations (Hashimoto et al., 2015). Therefore, soil management and conservation practices directly influence the soil physical and biological quality (Marion et al., 2022) and, consequently, influence CO_2 emissions. Therefore, priority must be given to adopting practices that reduce the degradation of organic matter and the loss of C from the soil to mitigate climate change.

Microbial biomass N did not show differences in soil management systems at time zero (2019). However, in the subsequent analyses, the averages presented by the BMPs and

TC systems were statistically higher than those displayed by NTC, with BMPs and TC retaining 8.0 and 8.8 % more N in the biomass than NTC. Therefore, it can be suggested that using autumnal cover crops and the construction of terraces stimulated the microbial population. In this case, the greater access to carbon and nitrogen by the microorganisms may have favored the incorporation of a greater amount of these elements in their biomass. Terracing, as well as other soil and water conservation practices, is designed to increase the agricultural potential of areas (Tarolli et al., 2014; Wei et al., 2016; Ackermann et al., 2019). Therefore, using terraces aims at greater water retention in the soil and reduced erosion processes. In turn, soil microbial properties depend on soil water availability (Wall and Heiskanen, 2003; Geisseler et al., 2011).

Soil management and conservation practices such as using cover crops, level seeding, and terracing are promising alternatives for improving the system and increasing carbon and nitrogen fixation in the soil. In this study, it was found that the highest rates of respirometry and metabolic quotient are associated with the NTC system of the rural producer. Although the NTC system meets some premises of direct planting, it can still be optimized by applying management practices and soil conservation strategies adopted in the other conservationist systems proposed in this study.

CONCLUSION

Adopting soil conservation practices such as cover crops, level seeding, and terracing improves soil microbial properties, with an increase in the inoculum potential of arbuscular mycorrhizal fungi, higher levels of acid phosphatase activity, and elevation of microbial biomass C and N. Higher values of respirometry and metabolic quotient observed in the NTC system reflect a greater stress condition of the microbial biomass, which results in a decrease in net gains in soil organic carbon content.

Soil conservation systems are essential in mitigating climate-related threats, as they are key players in retaining carbon and nitrogen in the soil, elements that make up the main greenhouse gases. In this sense, associating the basic principles of the no-tillage system with complementary practices of soil management and conservation, such as the use of cover crops, level seeding, and terracing, contributes significantly to the sustainability of crops under no-tillage.

AUTHOR CONTRIBUTIONS

Conceptualization: Adriana Knob (equal), Cristiano Andre Pott (equal), Jhonatan Spliethoff (equal), Leandro Rampim (equal) and Marcelo Marques Lopes Müller (equal).

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Project administration: Adriana Knob (equal), Cristiano Andre Pott (equal), Jhonatan Spliethoff (equal), Leandro Rampim (equal) and Marcelo Marques Lopes Müller (equal).

Resources: Adriana Knob (equal), Cristiano Andre Pott (equal), Jhonatan Spliethoff (equal), Leandro Rampim (equal) and Marcelo Marques Lopes Müller (equal).

Software: Adriana Knob (equal), Cristiano Andre Pott (equal), Jhonatan Spliethoff (equal), Leandro Rampim (equal) and Marcelo Marques Lopes Müller (equal).

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