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Management Systems Effect on Fertility Indicators of a Ferralsol with Vegetable Crops, as Determined by Different Statistical Tools

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ABSTRACT: The intensive nature of soil use in vegetable production areas has led to a marked decrease in soil quality. The objective of this study was to evaluate the effects of adoption of soil management systems on vegetable production with regards to the chemical properties of a Rhodic Ferralsol after five years and to evaluate the use of the Principal Component Analysis (PCA) statistical tool in discriminating the different treatments. The experiment was conducted under field conditions in central Brazil in a randomized block design with four replications and a 3 × 2 factorial arrangement (three soil management systems × two cover crops). The soil management systems used were NT (no-tillage), RT (reduced tillage), and CT (conventional tillage). The cover crops used were corn (*Zea mays*) alone and corn intercropped with the gray velvet bean (*Stizolobium niveum*). Reduced tillage showed the highest values of sum of bases, cation exchange capacity (T), and total organic carbon contents in the 0.00-0.05 m layer. In the same layer, RT and CT showed higher values of pH and K content. No-tillage and RT showed the highest P and Ca^{2+} contents and H+Al and T values. In the 0.05-0.10 m layer, RT had higher a pH value and Mg^{2+} contents. No-tillage and CT had higher potential acidity in this layer. The management systems (0.10-0.30 m) and the cover plants (all layers) had no effect on the properties analyzed. The use of PCA determined that the two principal components explained the following percentage of the data variance: 90.8 % (0.0-0.05 m), 79.8 % (0.05-0.10 m), and 83.1 % (0.10-0.30 m). Analysis of the eigenvectors and the grouping of treatments in PCA also showed that RT was most effective in improving soil fertility properties. Reduced tillage was most effective in increasing soil fertility after five years. The PCA is recommended as a useful tool and it allowed the identification of patterns not revealed by traditional tools.

Keywords: no-tillage system, reduced tillage system, conventional tillage system, principal component analysis.

INTRODUCTION

The intensive nature of soil use in areas of vegetable production has often led to a significant decrease in soil quality (Valarini et al., 2011). Improvement in soil quality in these areas should be achieved through the adoption of conservation systems. Assessment of the effects of such systems on chemical properties is an important part of evaluation of soil quality (Vezzani and Mielniczuk, 2009).

According to the 2015 Brazilian vegetable production statistics (Santos et al., 2015), the crop area of species belonging to this group in Brazil is 656,730 ha, with production estimated at 19.62 Mg, generating 2.4 million jobs and production value of R$ 53.4 billion after sale to the final consumer. Average yield is therefore about 30 Mg ha^{-1}, indicating the great yield potential of these species that require a large supply of agricultural inputs, especially water and nutrients. These numbers demonstrate the socio-economic importance of the sector. However, there has been little concern for adoption of soil management practices and conservation systems; this lack of concern compromises soil quality in vegetable production areas in Brazil (Valarini et al., 2011).

Agricultural production systems that have low soil disturbance, especially the no-tillage system, have proven effective in recovery of soil chemical quality in tropical and subtropical regions. The effects observed in these systems include nutritional enrichment (Santos et al., 2008) and improvement in the amount and quality of soil organic matter (SOM) (Conceição et al., 2013; Souza et al., 2014). For example, Santos et al. (2008) and Costa et al. (2009) found results that support that no-tillage and reduced tillage systems are able to increase P and Ca^{2+} contents. However, the vertical distribution of these chemical elements in the soil profile can be affected by the use of low disturbance systems (Schlindwein and Anghinoni, 2002). This is especially important for elements that have low mobility in soils, which are generally maintained on the surface, and it can be associated with processes and properties such as specific adsorption and the preference of cations with high ionic strength for adsorption sites.

Another aspect reported in several studies that aim to evaluate the effects of management systems on soil chemical properties is an increase in soil acidity brought about by the no-tillage system (Ciotta et al., 2002; Santos et al., 2008). Ciotta et al. (2002) attributed this increase in the acidity of the soils managed under a no-tillage system to the surface application of phosphate and N fertilizers, as well as to their great solubility, and the possibility of long periods without soil correction. The negative effects of soil acidity on crops can be minimized in the long term because of increases in SOM contents that are able to complex the Al^{3+}.

The effects of adoption of soil management systems are not immediate. Zhang et al. (2016) showed that the full capacity of NT for accumulating soil carbon is reached in about ten years after its adoption, especially when the soil was previously in agricultural use under conventional systems. The SOM is linked to many chemical processes in tropical soils, whose mineralogy is dominated by kaolinite, aluminum, and iron oxides (Fontes et al., 2001). Studies that aim to evaluate the effects of management systems on chemical properties should consider time since adoption in interpretation of results. It is possible that in short and medium term experiments, soil management systems that incorporate the plant residues of cover crops in the sub-surface layers, systems such as reduced tillage, exhibit higher potential for modifying soil chemical properties than no-tillage systems. Rapid degradation of these residues when incorporated supports this consideration (Carvalho et al., 2008), and this can accelerate the nutrient release and SOM accumulation (Lima et al., 2016).

However, most of the studies cited were conducted in field grain crop production areas, and few studies have been conducted in vegetable production areas. In the latter, particular aspects of production systems, such as the cultivation of short cycle commercial species, high soil disturbance, and the high fertilization rates normally used can change the nutrient and SOM dynamics (Lima et al., 2016). It is also possible that the high

fertilization rates used in vegetable production areas hinder evaluation of the effects of soil management and cover crops on soil chemical properties, especially when traditional statistical tools are used.

The use of multivariate tools may allow a more comprehensive and integrated analysis of the data, increasing analytical capacity. Principal component analysis (PCA) is a multivariate statistical method that consists of rewriting the coordinates of samples in a system more convenient for analysis, thus allowing reduction in the number of variables evaluated and assessment of the importance of original variables, where those with greatest weight are more important from a statistical perspective (Santi et al., 2012). In PCA, each factor is a linear combination of the original variables, and when the two principal factors can cumulatively retain a sufficient amount of the total information contained in the set of variables, it is possible to arrange them as one point in a two-dimensional graph (Valladares et al., 2008). The PCA allows detection of anomalous samples, relationships among variables, and groups of samples with similar properties (Lyra et al., 2010). In soil science, PCA has been used in studies on chemical and physical properties that affect crop yield (Santi et al., 2012), on pedological relationships that aid soil classification (Gomes et al., 2004; Valladares et al., 2008), and on the effects of adoption of conservation practices on soil properties (Santos et al., 2008; Lima et al., 2015).

The working hypothesis was conservation systems maintain better fertility levels than the conventional production system after five years. The objective of this study was to evaluate the effects of the adoption of soil management systems on vegetable production with regards to the chemical properties of a Rhodic Ferralsol five years after adoption, and to evaluate the use of the PCA statistical tool in discriminating the different treatments.

MATERIALS AND METHODS

Environmental characterization of the area used to conduct the experiment

The experiment was conducted under the soil and climate conditions of the *Cerrado* (Brazilian tropical savanna) in an area in Gama, Distrito Federal, at the geographical coordinates of 15° 56' S and 48° 08' W and elevation of 997.6 m above sea level. The regional climate is classified as Aw according to the Köppen classification system (tropical savanna with rainfall concentrated in the summer). The average temperature during the experimental period was 22.92 °C and average annual rainfall was 1,516 mm.

The soil where the experiment was conducted is a Rhodic Ferralsol (WRB, 2014), which corresponds to a *Latossolo Vermelho Distrófico* (Santos et al., 2013) with silty clay texture (clay, silt, and sand contents of 507, 437, and 56 g kg^{-1}, respectively). The chemical properties of the 0.00-0.10 m layer prior to setting up the experiment were as follows: pH(H$_2$O) 5.8±0.1, P 75.8±17.3 mg dm^{-3}, K 253.8±7.5 mg dm^{-3}, Ca^{2+} 12.6±1.0 cmol$_c$ dm^{-3}, Mg^{2+} 3.7±0.1 cmol$_c$ dm^{-3}, Al^{3+} 0.1±0.1 cmol$_c$ dm^{-3}, H+Al 5.4±0.5 cmol$_c$ dm^{-3}, SB 16.9±1.0 cmol$_c$ dm^{-3}, t (effective CEC) 17.0±0.9 cmol$_c$ dm^{-3}, T (CEC at pH 7.0) 22.3±0.5 cmol$_c$ dm^{-3}, V 75.5±2.8 %, and TOC 17.3±0.7 g kg^{-1}. The values for the 0.00-0.30 m layer were: pH 5.3±0.1, P 19.1.8±3.2 mg dm^{-3}, K 95.3±6.0 mg dm^{-3}, Ca^{2+} 8.0±0.5 cmol$_c$ dm^{-3}, Mg^{2+} 3.6±0.1 cmol$_c$ dm^{-3}, Al^{3+} 0.2±0.1 cmol$_c$ dm^{-3}, H+Al 6.2±0.4 cmol$_c$ dm^{-3}, SB 11.8±0.5 cmol$_c$ dm^{-3}, t 12.0±0.4 cmol$_c$ dm^{-3}, T 18.1±0.5 cmol$_c$ dm^{-3}, V 65.5±2.5 %, and TOC 12.0±1.2 g kg^{-1}.

Experimental design and management systems adopted

The experiment was conducted from 2008 to 2012. The area, which originally had shrubby vegetation (*Campo sujo*), has been used in a conventional vegetable production system since the beginning of the 1980s. Data used in this study were collected at the end of the fifth crop cycle, conducted in 2012. Samples were obtained for the 0.00-0.05, 0.05-0.10, and 0.10-0.30 m soil depth layers.

A randomized block design was adopted with four replications, in a 3 × 2 factorial arrangement consisting of three management systems, no-tillage - NT, reduced tillage - RT, and conventional tillage - CT, and two cover crops, corn alone (*Zea mays*) – C and intercropping of corn and gray velvet bean (*Stizolobium niveum*) - CB. Each plot was 9 m wide and 12 m long, for an area of 108 m^2.

Management of the soil and cover crops, as well as the history of cultivation of the area, were previously described by Souza et al. (2014) and are summarized in the following paragraphs.

Under NT, soils were fertilized, limed, and tilled for planting. For RT, a single harrowing was used in tillage for subsurface incorporation (about 0.10 m deep) of the crop residue. In CT, one plowing and two harrowing passes were performed, incorporating the residues of plants used as cover crops (about 0.20 m deep).

The history of cultivation and fertilizer application is as follows: year 1 - cultivation of onions with fertilization at planting of 600 kg ha^{-1} of NPK 04-30-16 and 400 kg ha^{-1} of ammonium sulfate as topdressing; year 2 - cultivation of cabbage with fertilization at planting of 1,250 kg ha^{-1} of simple superphosphate + 250 kg ha^{-1} of ammonium sulfate and 400 kg ha^{-1} of ammonium sulfate as topdressing; year 3 - cultivation of broccoli with fertilization at planting of 1,000 kg ha^{-1} of simple superphosphate + 250 kg ha^{-1} of ammonium sulfate and 500 kg ha^{-1} of ammonium sulfate as topdressing; year 4 - cultivation of squash with fertilization at planting of 300 kg ha^{-1} of simple superphosphate and 150 kg ha^{-1} of ammonium sulfate; and year 5 - cultivation of cabbage with fertilization at planting of 1,000 kg ha^{-1} of simple superphosphate + 250 kg ha^{-1} of ammonium sulfate and 500 kg ha^{-1} of ammonium sulfate as topdressing. Soil acidity was corrected with dolomitic limestone to achieve 70 % base saturation when setting up the experiment.

The cover crops were always planted in the rainy season, in November and December. Vegetable seeds or seedlings were always sown or transplanted in February and May. Corn was planted with between-row spacing of 0.80 m and five seeds per linear meter, using corrective phosphate fertilization with 100 kg ha^{-1} of P_2O_5 and the commercial hybrid Ag 1051 Agroceres®, generating a population of 55,000 plants ha^{-1}. Gray velvet bean was planted with a between-row spacing of 1.60 m and two seeds per linear meter, 30 days after planting the corn. Crop residue was shredded, followed by glyphosate application to stop regrowth, and one week before planting the vegetables, Paraquat was applied.

Soil sampling, determination of chemical attributes, and statistical analyses

Four small pits, measuring 0.8 m long × 0.8 m wide × 0.5 m deep, were dug in each experimental plot for soil sampling. In these pits, the 0.00-0.05, 0.05-0.10, and 0.10-0.30 m soil layers were sampled. Four simple samples, one from each small pit, formed a composite sample. After collection, the samples were placed in labeled plastic bags and then taken to the Soil Fertility laboratory where they were air dried and passed through a 2 mm mesh sieve to obtain air-dried fine earth.

The contents of available P, K, and Na; Ca^{2+}, Mg^{2+} and Al^{3+}, H+Al, and total organic carbon (TOC); and the pH values in H_2O were determined according to Donagema et al. (2011). Values of the sum of bases (SB), cation exchange capacity (t), cation exchange capacity at pH 7.0 (T), and base saturation (V) were calculated from the results of laboratory measurements, also according to Donagema et al. (2011).

The data obtained were checked for normal distribution and then subjected to analysis of variance (Anova). When significant, according to Anova, means were tested by the Scott Knott test at a significance level of 5 %. The relationships between variables were evaluated by determining the Pearson correlation coefficients at the same significance level.

Grouping of the treatments based on the properties of soil fertility was performed with the use of PCA for each depth evaluated. Both the eigenvalues and eigenvectors were

determined, and the treatments used were also grouped. To perform PCA, the treatments were grouped considering the soil management system and the cover crops used. For determination of patterns and interpretation of the results, the eigenvectors with moduli greater than or equal to 0.70 were considered.

RESULTS AND DISCUSSION

A detailed analysis of the results shows that the only effect on the fertility properties analyzed after five years resulted from the soil management systems (Table 1).

In general, soils collected in the three management systems showed high fertility, probably reflecting the high fertilization rates used. These high soil fertilization rates probably also led to results that did not allow for easy detection of the effects of management systems and cover crops on the properties analyzed. This leads to the hypothesis that the high fertilization rates used throughout the experiment, which are common in vegetable production areas, probably made it difficult to detect the effects of the soil management systems and cover crops, especially when each property is analyzed one at a time. However, multivariate statistical analysis tools allow the data to be evaluated interactively, increasing the possibility of detecting patterns that are not easily observed when traditional tools are used. According to the classification reported by Alvarez V. et al. (1999), the fertility properties analyzed can be rated as follows: concentrations of P, K, Ca^{2+}, Mg^{2+}, Al^{3+}, SB, t, and T can be classified as good or very good for all treatments and depths; potential acidity (H+Al) can be classified as high or very high in all treatments and depths; V can be classified as medium for all treatments and depths; pH values can be classified as low for all treatments and depths, except for RT at depths of 0.05-0.10 and 0.10-0.30 m, which can be considered good; TOC levels can be considered high or very high in the samples taken from the 0.00-0.05 and 0.05-0.10 m layers, and medium in the 0.10-0.30 m layer in all treatments.

Table 1. Fertility properties in a Rhodic Ferralsol with vegetable crops under conservation soil management systems and cover crops after five years of adoption of conservation soil management systems adoption

Management system and cover crop	pH(H₂O)	P	K	Na	Ca²⁺	Mg²⁺	Al³⁺	H+Al	SB	t	T	V	TOC
		———— mg dm⁻³ ————			———————————— cmol$_c$ dm⁻³ ————————————							%	g kg⁻¹
						0.00-0.05 m							
NT	5.17 b	87.88 a	109.38 b	7.63[ns]	6.00 a	2.54[ns]	0.09[ns]	8.91 a	8.71 b	8.80 b	17.62 a	49.42[ns]	27.83 b
RT	5.48 a	95.60 a	135.75 a	8.00[ns]	6.93 a	3.01[ns]	0.04[ns]	7.59 b	10.32 a	10.36 a	17.91 a	57.31[ns]	31.29 a
CT	5.37 a	58.35b[ns]	124.13 a	8.25[ns]	5.38 b	2.15[ns]	0.06[ns]	7.58 b	7.88 b	7.93 b	15.45 b	50.80[ns]	23.84 c
Single	5.35[ns]	78.78[ns]	121.83[ns]	8.25[ns]	6.06[ns]	2.48[ns]	0.07[ns]	8.18[ns]	9.05[ns]	8.96[ns]	17.07[ns]	51.74[ns]	27.73[ns]
Intercropping	5.33[ns]	82.43[ns]	124.33[ns]	7.67[ns]	6.05[ns]	2.65[ns]	0.06[ns]	7.87[ns]	8.89[ns]	9.11[ns]	16.92[ns]	53.29[ns]	26.68[ns]
						0.05-0.10 m							
NT	5.36 b	83.99[ns]	91.38[ns]	8.00[ns]	5.51[ns]	1.51 b	0.09[ns]	8.39 a	7.29[ns]	7.38[ns]	15.68[ns]	46.36[ns]	23.64[ns]
RT	5.63 a	122.78[ns]	108.25[ns]	8.25[ns]	6.19[ns]	2.18 a	0.03[ns]	6.65 b	8.68[ns]	8.71[ns]	15.33[ns]	56.27[ns]	23.65[ns]
CT	5.39 b	61.51[ns]	101.25[ns]	8.00[ns]	5.21[ns]	1.63 b	0.06[ns]	7.70 a	7.13[ns]	7.19[ns]	14.83[ns]	47.93[ns]	24.00[ns]
Single	5.47[ns]	75.53[ns]	101.92[ns]	8.00[ns]	5.82[ns]	1.79[ns]	0.058[ns]	7.55[ns]	7.90[ns]	7.96[ns]	15.45[ns]	50.95[ns]	24.14[ns]
Intercropping	5.44[ns]	103.33[ns]	99.83[ns]	8.17[ns]	5.46[ns]	1.75[ns]	0.063[ns]	7.61[ns]	7.50[ns]	7.56[ns]	15.11[ns]	49.42[ns]	23.39[ns]
						0.10-0.30 m							
NT	5.41[ns]	58.19[ns]	85.75[ns]	8.75[ns]	5.43[ns]	1.76[ns]	0.13[ns]	7.60[ns]	7.44[ns]	7.57[ns]	15.04[ns]	48.92[ns]	21.02[ns]
RT	5.58[ns]	63.19[ns]	99.00[ns]	7.75[ns]	5.39[ns]	1.75[ns]	0.04[ns]	6.49[ns]	7.42[ns]	7.47[ns]	13.91[ns]	53.46[ns]	21.20[ns]
CT	5.38[ns]	44.25[ns]	91.38[ns]	8.13[ns]	4.39[ns]	1.71[ns]	0.08[ns]	7.20[ns]	6.37[ns]	6.45[ns]	13.57[ns]	46.99[ns]	20.65[ns]
Single	5.46[ns]	52.88[ns]	91.83[ns]	8.00[ns]	5.11[ns]	1.74[ns]	0.08[ns]	6.85[ns]	7.12[ns]	7.20[ns]	13.97[ns]	50.79[ns]	20.52[ns]
Intercropping	5.45[ns]	57.53[ns]	92.25[ns]	8.42[ns]	5.11[ns]	1.74[ns]	0.08[ns]	7.34[ns]	7.04[ns]	7.12[ns]	14.38[ns]	48.80[ns]	21.39[ns]

Means followed by the same letter are equal by the Scott-Knott test at the level of 5 %. NT: No-tillage; RT: Reduced tillage; CT: Conventional tillage. Single: NT/RT/CT with corn alone; Intercropping: NT/RT/CT intercropped with gray velvet bean. pH in water at a ratio of 1:2.5 v/v; P, K, and Na: extractor Mehlich-1; Ca^{2+} and Mg^{2+}: extractor KCl 1 mol L^{-1}; Al^{3+}: extractor KCl 1 mol L^{-1}; H+Al: extractor calcium acetate 0.5 mol L^{-1}; SB: sum of bases; t: effective cation exchange capacity (SB+Al^{3+}); T: cation exchange capacity at pH 7.0; V: bases saturation; TOC: total organic carbon determined by oxidation with $K_2Cr_2O_7$.

The effects of management systems on soil acidity components are ordered as follows. The RT and CT systems showed higher pH values in the 0.00-0.05 m layer. In the 0.05-0.10 m layer, RT showed higher pH than NT and CT. Furthermore, the highest potential acidity of the surface layer (0.00-0.05 m) was observed for NT. The NT system, together with the CT, also showed greater potential acidity than RT in the subsurface layer (0.05-0.10 m). No effects of the management systems were observed on the Al^{3+} content and base saturation (V).

As previously reported, soil acidity was corrected using dolomitic limestone when the experiment was set up in order to reach a V of 70 % and raise the contents of Ca^{2+} and Mg^{2+}. The high acidity of the soil may be linked to this long period during which soil acidity was not corrected. Ciotta et al. (2002) reported that in NT the application of fertilizer to the soil surface leads to higher acidity of the upper layers due to the dissolution of phosphate and N fertilizers. The authors also reported that acidification of the surface layers is strengthened when long periods go by without new lime application and when high fertilizer rates are applied, as occurred in the present study. Systems with soil tillage, such as RT and CT, dilute the acidity in the topsoil, reducing its impact on the surface. However, in NT the deleterious effects of soil acidity can be minimized in the long term by increased SOM levels because these organic compounds act in complexation of Al^{3+} (Vieira et al., 2013).

The pH values are the result of the ability of the systems to maintain higher V values. This is reinforced by the positive correlation between V and pH observed for the three depths evaluated (Table 2). The relationship between pH and V has been known for a long time, as shown in the study of Raij et al. (1968), and this is linked to the fact that increasing V values mean higher occupancy loads of the soil exchange complex by basic hydrolysis of cations, leading to an increase in the pH of the soil solution.

The RT and NT systems caused higher values of available P and Ca^{2+} and an increase in the value of CEC at pH 7.0 at the surface. Less mobile elements, such as P, in soils have greater horizontal and vertical variability in NT than CT due to the residual effect of fertilizers on the soil surface and in the plant row (Schlindwein and Anghinoni, 2002). An increase in surface P contents in soils in low-tillage systems (NT and RT) has been reported by other authors (Santos et al., 2008; Costa et al., 2009). The higher surface P contents in RT and NT are probably linked to the greater specific adsorption capacity of this element in soils rich in Fe and Al oxides, minerals commonly found in tropical and subtropical soils, retaining it in non-labile forms (Novais et al., 2007).

The NT system also showed higher Ca^{2+} contents in the 0.00-0.05 m layer compared to CT in a *Latossolo Vermelho Distrófico típico* under different soil management and crop rotation systems. Souza et al. (2012) found that NT promoted an increase in Ca^{2+} contents in the 0.00-0.10 m layer in a Distroferric Red Ferralsol under different management systems, with and without application of gypsum. Surface accumulation of Ca^{2+} may be associated with the surface application of lime and the higher ionic strength of this cation in solution, as well as preferential adsorption of divalent cations compared to monovalent cations (Freire et al., 2003; Wiethölter, 2007).

In the 0.00-0.05 m layer, the NT system showed a lower content of K than RT and CT. Like CT, NT showed lower SB and t than RT did. The lower content of K is probably associated with the fact that NT adsorption sites are mainly saturated by Ca^{2+}, due to surface liming and the preferential adsorption of divalent cations, as mentioned, and that can result in greater leaching of K. The higher concentrations of K, as well as SB values, in RT may also be related to incorporation of crop residues to the depth of about 0.10 m, accelerating their decomposition. The higher Mg^{2+} content in the 0.05-0.10 m layer observed in RT may also be related to this fact. Carvalho et al. (2008) found that the decomposition of cover crop plant residues is accelerated when they are incorporated into the subsurface layers, possible accelerating nutrient release.

Table 2. Pearson correlation coefficients determined for the relationships among the soil fertility properties determined in a Rhodic Ferralsol with vegetable crops under conservation soil management systems and cover crops after five years

	pH(H₂O)	P	K	Na	Ca²⁺	Mg²⁺	Al³⁺	H+Al	SB	t	T	V	TOC
					0.00-0.05 m								
pH(H₂O)	1.00	0.00	**0.98****	0.41*	0.53*	0.36	**-0.95****	**-0.88****	0.50*	0.49*	-0.09	**0.83****	0.49
P		1.00	0.12	-0.28	**0.84****	**0.76****	-0.01	0.29	**0.82****	**0.83****	**0.93****	0.47	**0.80**
K			1.00	0.27	**0.61****	0.49*	**-0.97****	**-0.86****	**0.60****	**0.59****	0.01	**0.89****	0.55
Na				1.00	-0.06	-0.45*	-0.31	-0.23	**-0.19**	-0.20	-0.32	-0.05	-0.04
Ca²⁺					1.00	**0.88****	-0.47*	-0.20	**0.98****	**0.98****	**0.78****	**0.84****	**0.97**
Mg²⁺						1.00	-0.33	-0.12	**0.95****	**0.95****	**0.79****	**0.76****	**0.89**
Al³⁺							1.00	**0.92****	-0.45	-0.44*	0.16	**-0.82****	-0.37
H+Al								1.00	-0.20	-0.18	0.44*	-0.68**	-0.11
SB									1.00	**0.99****	**0.79****	**0.85****	**0.97**
t										1.00	**0.80****	**0.84****	**0.97**
T											1.00	0.35	**0.82**
V												1.00	**0.77**
TOC													1.00
					0.05-0.10 m								
pH(H₂O)	1.00	0.68**	**0.79****	0.34	**0.75****	**0.92****	**-0.88****	**-0.94****	**0.88****	**0.86****	-0.04	**0.96****	-0.07
P		1.00	0.31	0.67**	0.40*	**0.71****	-0.39	-0.50*	0.55*	0.55*	0.10	0.56*	-0.68
K			1.00	0.31	**0.60****	**0.81****	**-0.84****	**-0.91****	**0.74****	**0.73****	-0.21	**0.87****	0.11
Na				1.00	0.24	0.65**	0.02	-0.19	0.43*	0.44*	0.36	0.31	-0.37
Ca²⁺					1.00	**0.74****	-0.53*	-0.63**	**0.96****	**0.96****	0.51*	**0.85****	0.07
Mg²⁺						1.00	-0.69**	**-0.83****	**0.90****	**0.90****	0.15	**0.91****	-0.69
Al³⁺							1.00	**0.97****	-0.64**	-0.62**	0.44*	**-0.86****	-0.05
H+Al								1.00	**-0.76****	**-0.75****	0.30	**-0.94****	0.02
SB									1.00	**0.99****	0.39	**0.94****	0.01
t										1.00	0.41*	**0.93****	0.01
T											1.00	0.05	0.04
V												1.00	0.00
TOC													1.00
					0.10-0.30 m								
pH(H₂O)	1.00	0.67**	**0.82****	-0.62**	0.51*	-0.11	**-0.74****	-0.79**	0.49*	0.44*	-0.22	**0.90****	0.12
P		1.00	0.29	0.00	**0.88****	-0.05	-0.19	-0.18	**0.84****	**0.80****	0.49*	0.66**	0.67
K			1.00	**-0.84****	0.00	-0.17	**-0.99****	**-0.86****	0.00	-0.06	-0.65**	0.66**	0.07
Na				1.00	0.11	0.21	**0.89****	**0.96****	0.12	0.17	**0.80****	-0.63**	0.26
Ca²⁺					1.00	0.22	0.09	-0.11	**0.99****	**0.99****	0.66**	0.68**	0.45
Mg²⁺						1.00	0.19	0.10	0.36	0.37	0.34	0.13	0.10
Al³⁺							1.00	**0.86****	0.10	0.16	**0.72****	-0.60**	-0.05
H+Al								1.00	-0.11	-0.05	0.67**	**-0.80****	0.25
SB									1.00	**0.99****	0.67**	0.68**	0.45
t										1.00	**0.71****	0.64**	0.44
T											1.00	-0.09	0.52
V												1.00	0.11
TOC													1.00

Numbers in bold refer to correlation coefficients with moduli greater than 0.70; * and **: significant at 5 and 1 %, respectively. t: CEC, T: CEC at pH 7.0, SB: sum of bases, V: bases saturation, and TOC: total organic carbon.

Interpretation of the Pearson correlation coefficients suggests that TOC contents positively influenced other fertility properties, such as available P, exchangeable Ca^{2+} and Mg^{2+}, SB, CEC, CEC at pH 7.0, and V in the 0.00-0.05 m layer. The increase in TOC contents can lead to greater availability of P in tropical soils (Souza et al., 2006). The organic matter in the soil and its fractions is responsible for generating much of the negative electrical charges in tropical soils, thus affecting the CEC and related properties (Dobbs et al., 2008). No correlation was observed between TOC contents and other fertility properties in the two other depths sampled. It is probable that in the 0.05-0.10 and 0.10-0.30 m layers, the lack of a strong correlation between the TOC contents and the fertility properties is linked to reduced influence of the management systems.

The PCA was used to group similar treatments and to obtain a more comprehensive analysis of the data. The fertility properties discussed above were used for this purpose. Lyra et al. (2010) commented that through PCA, it is possible to detect anomalous samples, relationships between variables, and groups of samples with similar properties. The table 3 shows the eigenvalues for each of the depths evaluated. The table 4 shows the eigenvectors for the first two principal components, which allows visualization of the correlation of each component variable.

The first two principal components explained over 70 % of the variance in the data in the three layers studied. However, the cumulative percentage of variance explained by the first two principal components was greater on the surface than in the subsurface: 90.7 % in the 0.00-0.05 m layer, 79.8 % in the 0.05-0.10 m layer, and 83.1 % in the 0.10-0.30 m layer. It is possible that this decrease in the explanatory potential of PCA regarding variation in the data with depth is linked to the fact that the properties analyzed are affected by soil management systems and/or cover crops (DeMaria et al., 1999; Ciotta et al., 2002; Schlindwein and Anghinoni, 2002; Santos et al., 2008; Costa et al., 2009; Souza et al., 2012; Vieira et al., 2013), and this effect is more intense in the upper layer of the soil profile. Typically, in deeper layers, the effects of management and/or cover crop systems are smaller, and it is possible that pedogenetic properties are of greater intensity, for example, the texture and mineralogy of the soil, leading to less explanatory power through chemical properties sensitive to changes in land use and occupation.

The eigenvectors are values that represent the weight of each property in each principal component and range from -1 to +1 (Santi et al., 2012). Although authors such as Coelho (2003) and Santi et al. (2012) recommend classification of eigenvectors with moduli higher than 0.50 as highly significant, in the present study it was observed that the use of values lower than 0.70 complicated interpretation of the results, since many properties had eigenvector values between 0.50 and 0.69 for the first two principal components. Therefore, properties that had eigenvectors with values greater than or equal to 0.70 were classified as highly significant.

The percentage of variance explained by the first principal component when analyzing the data for the 0.00-0.05 m layer was 60.7 %, while the second principal component explained 30.0 % of the variance. The eigenvectors determined showed that the first principal component strongly correlated with the following soil properties: available P and K, Ca^{2+} and Mg^{2+}, t, SOM, SB, and V. All values were negative, and the SB had the score closest to -1 (-0.98). The second principal component strongly correlated with pH, Al^{3+}, H+Al, and T. For this component, the score of the pH was positive, while those of the Al^{3+}, H+Al, and T were negative. The H+Al was the property with the greatest influence on the second principal component, with a score of -0.88.

Table 3. Eigenvalues and percentage of variance explained by the first two principal components related to fertility properties at the depths of 0.00-0.05, 0.05-0.10, and 0.10-0.30 m in a Rhodic Ferralsol with vegetable crops under different soil management systems and cover crops

Principal component	Eigenvalue	% of total variance	Cumulative eigenvalue	% of cumulative variance
		0.00-0.05 m		
1	7.9	60.7	7.9	60.7
2	3.9	30.0	11.8	90.8
		0.05-0.10 m		
1	8.2	62.9	8.2	62.9
2	2.2	16.9	10.4	79.8
		0.10-0.30 m		
1	5.7	43.8	5.7	43.8
2	5.1	39.3	10.8	83.1

Table 4. Correlations between the properties evaluated and the first two principal components calculated for the data referring to the 0.00-0.05, 0.05-0.10, and 0.10-0.30 m layers in a Rhodic Ferralsol with vegetable crops under different soil management systems and cover crops

Property	Principal component 1	Principal component 2
0.00-0.05 m		
pH(H$_2$O)	-0.67	**0.73**
P	**-0.71**	-0.63
K	**-0.75**	0.64
Na	0.08	0.53
Ca^{2+}	**-0.97**	-0.18
Mg^{2+}	**-0.90**	-0.32
Al^{3+}	0.63	**-0.75**
H+Al	0.39	**-0.88**
SB	**-0.98**	-0.21
t	**-0.97**	-0.23
T	-0.65	**-0.74**
V	**-0.93**	0.30
SOM	**-0.94**	-0.21
0.05-0.10 m		
pH(H$_2$O)	**0.97**	0.12
P	0.65	-0.45
K	**0.85**	0.34
Na	0.45	-0.67
Ca^{2+}	**0.84**	-0.18
Mg^{2+}	**0.96**	-0.14
Al^{3+}	**-0.81**	-0.55
H+Al	**-0.91**	-0.38
SB	**0.95**	-0.16
t	**0.94**	-0.18
T	0.10	**-0.79**
V	**0.99**	0.12
SOM	-0.08	0.47
0.010-0.30 m		
pH(H$_2$O)	**-0.96**	-0.08
P	**-0.71**	0.60
K	**-0.79**	-0.54
Na	0.67	0.69
Ca^{2+}	-0.60	**0.77**
Mg^{2+}	-0.00	0.38
Al^{3+}	**0.73**	0.62
H+Al	**0.81**	0.53
SB	-0.60	**0.78**
t	-0.54	**0.82**
T	0.16	**0.99**
V	**-0.97**	0.08
SOM	-0.24	0.55

Numbers in bold refer to correlation coefficients with moduli greater than 0.70. t: CEC, T: CEC at pH 7.0, SB: sum of bases, V: bases saturation, and SOM: soil organic matter.

In the 0.05-0.10 m layer, the first principal component explained 62.9 % and the second, 16.9 %. The first principal component has a strong correlation with pH, K, Ca^{2+} and Mg^{2+}, SB, t, Al^{3+}, H+Al, and V. The pH, K, Ca^{2+} and Mg^{2+}, SB, t, and V had positive scores, whereas the Al^{3+} and H+Al had negative scores. The V had the highest score (0.99). The second principal component had strong correlations with the T, and its score was negative (-0.79).

In PCA referring to the 0.05-0.10 m layer, there was, additionally, a low correlation between the first two principal components and the SOM levels, demonstrating the low capacity of these components in explaining the behavior of this property. Factor analysis shows that the SOM content is strongly correlated with only the third major component (-0.76),

also indicating the low capacity of the first two components to explain the behavior of this property at the depth evaluated. It is also noteworthy that in most cases only the first two principal components in PCA are used; they are considered sufficient to explain the data and facilitate interpretation since they generate a two-dimensional graph (Gomes et al., 2004). Lima et al. (2016) analyzed data from this same experiment and found low capacity of the main operations at this depth, such as incorporation of crop residues and cover crops, to positively influence the increase in SOM contents, perhaps due to the priming effect caused by the intense supply of particulate organic carbon, fertilizers, and corrective agents, especially in systems with soil tillage.

The first principal component explained 43.8 % of the data variance in the 0.10-0.30 m layer, while the second principal component explained 39.3 %. The first principal component correlated strongly with the pH, P and K, and Al^{3+}, H+Al, and V. The eigenvectors exhibited positive scores for the Al^{3+} and H+Al and negative scores for pH, P and K, and V. The largest factor loading was observed for the V (-0.97). The second principal component, in turn, showed strong positive correlation with the Ca^{2+}, SB, t, and T. The highest score was assigned to E (0.98).

The Na did not show strong correlations with the first two principal components in the three layers analyzed, which is probably related to the low potential of tillage and cover crops to influence it. In fact, several studies (DeMaria et al., 1999; Ciotta et al., 2002; Schlindwein and Anghinoni, 2002; Santos et al., 2008; Costa et al., 2009; Souza et al., 2012; Vieira et al., 2013) reported no change in Na levels according to the use of soil management systems and cover crops.

Grouping of the soil management systems and the cover crops provided by PCA can be found in figure 1. Better grouping of similar management systems in the 0.00-0.05 and 0.10-0.30 m layers can be inferred from joint analysis of the results. In the 0.05-0.10 m layer, it is clear that the effect of RT was more intense than the effects of CT and NT. This fact is probably associated with the subsurface incorporation of cover crop plant residues and fertilizers by the harrowing. Lima et al. (2016) evaluated the influence of management systems and cover crops used in this experiment on SOM particle size fractions and they reported the influence of this process on increasing particulate organic C, thus reinforcing the influence of RT on the 0.05-0.10 m layer.

In the 0.00-0.05 m layer, a clear segregation was observed between treatments with similar soil management systems (Figure 1a). The position of the NT with corn alone and the intercropped NT treatments in the fourth quadrant, below the intersection of the two axes, largely reflects the higher acidity of the treatments without soil disturbance. The position of the RT with corn alone and the intercropped RT treatments to the left of the intersection between the axes reflects the higher fertility of soils subjected to reduced soil tillage. Furthermore, in relation to RT, the position of the intercropped RT in the second quadrant and the RT with corn alone in the third quadrant reflects the higher basicity of the treatment using corn intercropped with velvet bean as a cover crop when incorporating the crop residues, a fact not observed by parametric analysis and for other management systems when using PCA. The position of the CT with corn alone and intercropped CT treatments indicates that they had fertility properties similar to treatments that used NT as the soil management system, where the most striking difference was soil acidity, which was lower in the former than in the latter.

A different pattern related to the management systems was observed for the result of PCA in the 0.05-0.10 m layer (Figure 1b). In this level, it is possible to identify a clear segregation between the treatments that used RT as the soil management system. Reduced tillage with corn alone and intercropped RT had clearly higher fertility in this layer, providing higher levels of most of the nutrients evaluated, as well as the attributes derived from the nutrients and lower acidity than the treatments that used NT and CT. As previously discussed, it is possible that these results were strongly influenced by
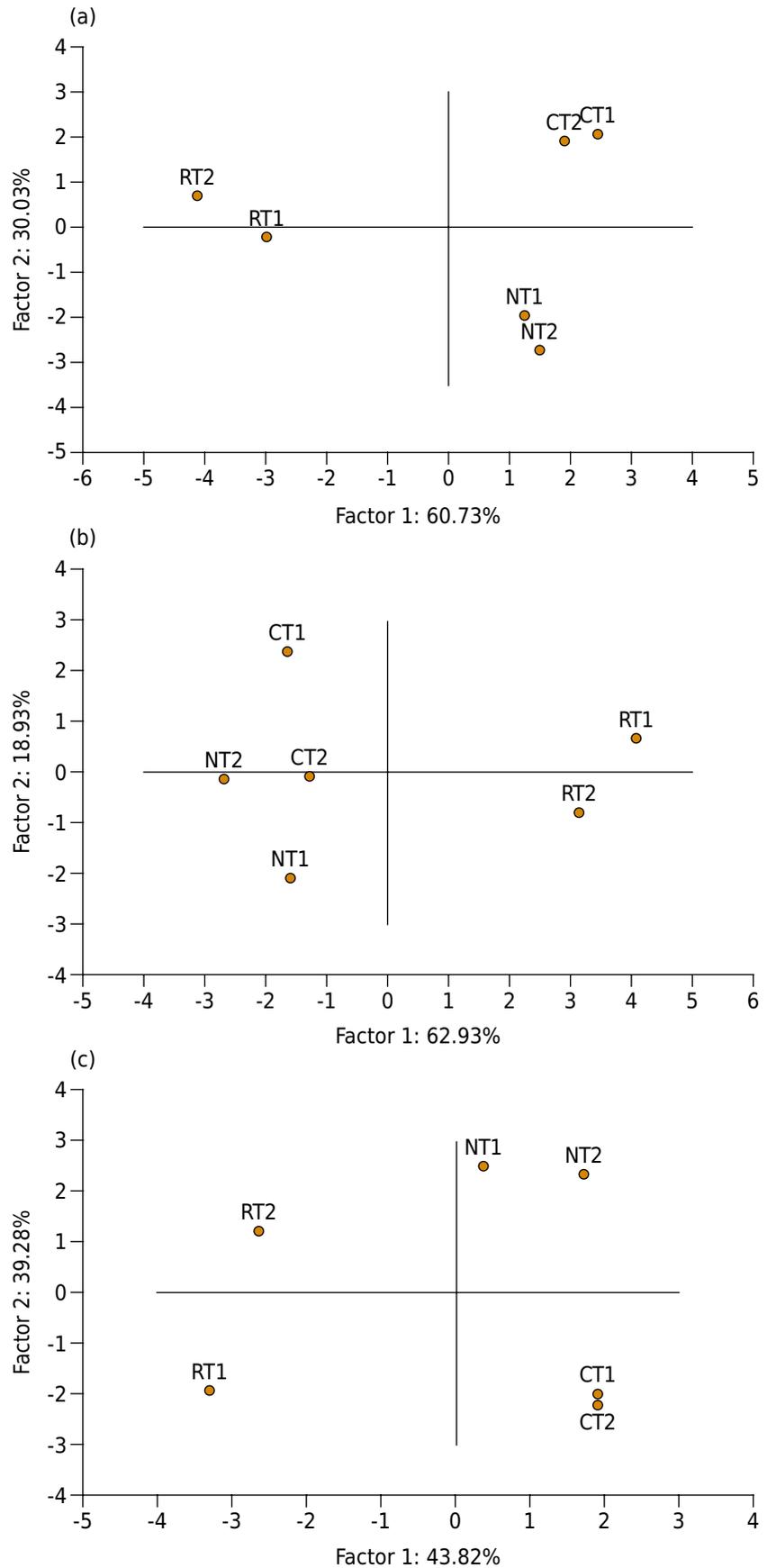
Figure 1. Grouping of the management systems and cover crops indicated by Principal Component Analysis based on the fertility properties of a Rhodic Ferralsol after 5 years of adoption of conservation soil management systems adoption in the 0.00-0.05 m layer (a), in the 0.05-0.10 m layer (b), and in the 0.10-0.30 m layer (c). NT1, RT1, and CT1: no-tillage, reduced tillage, and conventional tillage, respectively, with corn alone; NT2, RT2, and CT2: no-tillage, reduced tillage, and conventional tillage, respectively, with corn intercropped with gray velvet bean.

subsurface incorporation of cover crop residues, fertilizers, and corrective agents. Alcântara et al. (2000) found that the incorporation of cover crop plant residues accelerates their decomposition. This may accelerate the release of nutrients and allow higher soil fertility to be maintained in short and/or medium term experiments. Results in Bayer et al. (2001) and Zhang et al. (2016) under different soil and climate conditions suggest that NT reaches its full capacity to improve qualitative aspects of the soil at around ten years after its implementation. It should be noted that intercropping corn and velvet bean in RT can reduce the effects of soil acidity. Moreover, NT and CT showed similar soil properties when subjected to intercropping, whereas PCA suggests that NT with corn alone provides a higher E value than the intercropped CT and NT treatments and the CT with corn alone treatment.

Better distribution of the treatments in accordance with the management systems could also be observed in PCA in the 0.10-0.30 m layer. Therefore, although the greatest effects of the management systems on chemical properties of the soil are normally observed in the surface layers when classical statistics are used, as previously discussed, PCA was able to distinguish similar treatments in the 0.10-0.30 m layer, suggesting that this method is more robust in detection of differences between treatments at greater depths. Again, RT was the management system that had the highest soil fertility, with a good distinction between RT with corn alone and intercropped RT, which maintained higher levels of Ca^{2+}, SB, t, and T, properties that were strongly correlated with the second principal component. The NT and CT systems, in turn, showed higher acidity than the RT system. Principal component analysis also indicated greater fertility of NT than CT at this depth.

CONCLUSIONS

The RT system showed the highest soil fertility among the systems evaluated, probably due to accelerated decomposition of cover crop plant residues, as well as the subsurface incorporation of fertilizers and lime.

The most significant effects of the management systems were found in the 0.00-0.05 m layer.

The NT system had the greatest effect on soil acidity components, especially in the 0.00-0.05 m layer.

Principal component analysis allowed patterns to be detected that were not observed by the Anova and the Scott-Knott test, especially in the 0.05-0.10 m and 0.10-0.30 m layers, demonstrating the robustness of this method and the possibility of its use for data analysis in soil science.

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