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Sampling Layer for Soil Fertility Evaluation in Long-Term No-Tillage Systems

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ABSTRACT: In no-tillage (NT) systems, there is no plowed layer since the soil is not tilled. Thus, the soil layer for fertility evaluation can be defined as the one in which the fertility indices are affected by the surface application of lime and fertilizers and soil properties have the closest relationship with crop yields. The objective of this study was to determine the most appropriate soil layer under long-term NT for sampling for fertility evaluation in the South-Central region of Paraná, Brazil. A total of 99 field experiments of crop rotations were performed, including soybean, corn, barley, wheat, and white oat, all on Oxisols (Hapludox). Despite the surface application, lime and fertilizers increased base saturation (V) and available K to a depth of 0.20 m. The relationship with crop yields was high for V and low for available K for both soil layers (0.00-0.10 and 0.00-0.20 m); for P, however, the relationships with soybean and corn yields were strongest in the 0.00-0.20 m layer. Thus, considering the soil layer fertilized by the surface application of lime and potassium fertilizers and the highest relationship of soil P contents with the yield of the main crops of the crop rotation, the 0.00-0.20 m layer is the most appropriate for soil fertility evaluation under long-term no-tillage systems.

Keywords: diagnostic layer, liming, fertilization, soil sampling.

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INTRODUCTION

No-tillage (NT) is the current soil management system on more than 32 million hectares of agricultural land in Brazil, on about 70 % of the area with species of annual grain production (Derpsch et al., 2010). In the state of Paraná, the second largest national producer of corn (17.3 Mt yr^{-1}) and soybean (15.9 Mt yr^{-1}) (IBGE, 2013), NT covers approximately 90 % of the area cultivated with these crops, reaching nearly 100 % in the South-Central region (Fontoura et al., 2015). The widespread use of NT instead of conventional tillage (CT) by farmers is a result of the major technical, economic and environmental benefits of the conservation management system (Costa et al., 2003; Inoue, 2003; Nagaoka and Nomura, 2003; Conceição et al., 2005; Derpsch et al., 2010).

No-tillage promotes a number of changes in nutrient dynamics and distribution, as well as the properties related to acidity in the soil profile. While in the conventional system it is assumed that soil fertility in the 0.00-0.20 m layer is uniform, due to periodic soil tilling, in NT, nutrients and acidity indexes are gradually layered from the soil surface (Bayer and Mielniczuk, 1997; Schlindwein and Anghinoni, 2000; Ciotta et al., 2002; Costa et al., 2009), which is intensified over time in this conservation management system (Pauletti et al., 2005; Anghinoni, 2007). Under conventional tillage, the 0.00-0.20 m layer, i.e., the arable soil layer where fertility is influenced by the application of fertilizers and liming and periodically standardized by tillage, is widely adopted for evaluation of the fertility status, with a view to recommend fertilizers and liming in the different regions and States of Brazil (Raij et al., 1997; Ribeiro et al., 1999; CQFSRS/SC, 2004; Sousa and Lobato, 2004; Freire et al., 2013).

Changes in the chemical properties of soil under NT, in particular the nutrient and acidity stratification in the soil profile, may alter the extent of root exploration and the relative importance of each soil layer on the nutrient supply and crop development, requiring a change in the soil layer of sampling for fertility evaluation (Silveira and Stone, 2002; Anghinoni, 2007). However, few studies have evaluated the most appropriate layer for soil sampling in NT, which is the reason why the 0.00-0.20 m layer, originally used for this purpose under conventional tillage, is still being used for NT systems (Raij et al., 1997; Ribeiro et al., 1999; Sousa and Lobato, 2004; Freire et al., 2013). In contrast, in the states of RS and SC, the Committee of Chemistry and Soil Fertility chose to use the 0.00-0.10 m layer for sampling for the evaluation of soil fertility in this system (CQFSRS/SC, 2004). This decision was based on a number of initial studies developed in agricultural soils, mostly with less than 5 years under NT (Petrere et al., 1996; Schlindwein and Anghinoni, 2000; Rheinheimer et al., 2000) and on the commonly accepted assumption that the effects of fertilization and liming, applied on the soil surface, predominantly affects the topsoil (0.00-0.10 m) (Hoff et al., 2010). This decision proved correct, since subsequent studies have indicated a stronger correlation between crop yield and available P content in the 0.00-0.10 m than in the 0.00-0.20 m layer (Sá, 1999; Schlindwein and Gianello, 2008).

This conservation management promotes, over the course of time, major changes in fertility indicators throughout the soil profile and on the proper nutrient cycling (Sá, 2004; Pauletti et al., 2005; Anghinoni, 2007; Caires et al., 2011). Consequently, the sub-surface layer (below 0.10 m) becomes more relevant, for both nutrient and water supply, which is particularly important in growing seasons with prolonged drought and crop failure and is very frequent in the subtropics of Brazil (Conab, 2015).

The hypothesis is that the 0.00-0.20 m layer is more suitable for the evaluation of soil fertility in long-term NT systems (>20 years). The objective was to determine the soil layer for sampling (0.00-0.10 or 0.00-0.20 m) which best represents the fertility status of soils in the South-Central region of Paraná, under long-term no-tillage.

MATERIALS AND METHODS

The study was developed in cooperation with the Department of Soils of the Universidade Federal do Rio Grande do Sul (UFRGS), Fundação Agrária de Pesquisa Agropecuária (FAPA), and Cooperativa Agrária Agroindustrial in the South-Central region of Paraná. A total of 99 experiments conducted between 2004 and 2014 in seven municipalities in the region (Guarapuava, Pinhão, Candói, Roncador, Goioxim, Reserva do Iguaçu and Campina do Simão) were analyzed to identify the most appropriate layer for sampling. These experiments, originally destined for liming and fertilization studies, consisted of surface applications of dolomitic limestone (five experiments) and of phosphorus (P) and potassium (K) (94 experiments). The soils of all experimental areas are classified as Humic Hapludox, corresponding to *Latossolo Bruno* according to Brazilian Classification System (Embrapa, 2006), and were cultivated under NT for 17 to 27 years. In this soil, the mean clay content was 600 g kg^{-1}, organic matter 54 g kg^{-1}, and $CEC_{pH\ 7.0}$ 15 $cmol_c$ dm^{-3}. The detailed characteristics of each experiment, including experimental duration, design, number of replicates, crops, and treatments, evaluated are listed in table 1.

In the experiments involving treatments with limestone or gypsum, only those with commercial limestone were taken into consideration. These experiments were performed from 2 to 10 years. The P and K calibration experiments were initiated in the winter of 2008, with the surface application of 0, 80, 160, 320, and 640 kg ha^{-1} P_2O_5 and K_2O in the main plots (9.6 × 10.0 m), establishing levels of these nutrients in the soil. After the following growing season (summer 2008/09), the plots were subdivided (4.8 × 10.0 m), maintaining one sub-plot without nutrient reapplication and another with reapplications (60 kg ha^{-1} P_2O_5 or K_2O) in each growing season, to reach fertility levels that would ensure maximum crop yields in each experiment. These experiments were conducted until April 2013.

Table 1. Characteristics of the experiments including location, duration, experimental design, number of replicates, crops and treatments

Experiment (Location[(1)]; years under NT)	Period	Des.[(2)]	Rep[(3)]	Crop[(4)]	Treatment
Liming experiment					
Liming-1 (G; >17 years)	2004-2014	RB-SP	3	WO, R, B, W, C, S	Main plots: control, normal lime, filler and divided filler (for V = 65 %); Sub-Plots: gypsum (0, 3, 6, and 9 Mg ha^{-1})
Liming-2 (G; >17 years)	2004-2014	RB-SP	4	WO, OC, R, B, W, C, S	Main plot: three crop rotations[(5)]; Sub-Plots: lime (0, 2, 4 and 8 Mg ha^{-1})
Liming-3 (P; >21 years)	2008-2012	RB	4	WO, B, S, C, W, R	Lime[(6)]: 0, 0.2, 2.3, 4.4, and 7.3 Mg ha^{-1}
Liming-4 (C; >21 years)	2008-2012	RB	4	WO, B, S, C, W, R	Lime[(6)]: 0, 0.8, 3.2, 5.6, and 8.7 Mg ha^{-1}
Liming-5 (C; >23 years)	2010-2012	RB	4	OC, R, B, S, C	Lime[(6)]: 0, 6.7, 9.0, 11.3, and 14.3 Mg ha^{-1}
Experiment with P					
Calibration (G, P, C; >21 years)	2008-2013	RB-SP	4	WO, W, S, R, C, B, OC	Main plots: P_2O_5 rates (0, 80, 160, 320, and 640 kg ha^{-1}); Sub-Plots: with and without reposition of P_2O_5 (60 kg ha^{-1}) in each growing season (60 kg ha^{-1})
Fertilization response (G, P, C; >25 years)	2011-2013	RB	3	W, B, S, C	P_2O_5 rates (0, 30, 60, 120, and 240 kg ha^{-1}) applied in the sowing row
Experiment with K					
Calibration (G, P, C; >21 years)	2008-2013	RB-SP	4	WO, W, S, R, C, B, OC	Main plots: K_2O rates (0, 80, 160, 320, and 640 kg ha^{-1}); Sub-Plots: with and without reapplication of K_2O (60 kg ha^{-1}) in each growing season
Fertilization response (G, P, C; >25 years)	2011-2013	RB	3	W, B, S, C	K_2O rates (0, 30, 60, 120, and 240 kg ha^{-1}) applied in the sowing row

[(1)] Locations: G - Guarapuava, P - Pinhão, C - Candói. [(2)] Design: RB: randomized blocks, RB-SP: randomized blocks with split-plots. [(3)] Rep: number of replicates. [(4)] Crops: WO - white oat, OC - white oat used as soil cover, W - wheat, B - barley, S - soybean, C - corn, R - radish. [(5)] Crop rotations: (a) OC/S, R/C, OC/S, R/S; (b) R/S, OC/C, R/S, OC/S and, (c) B/S, WO/C, W/S, B/S. [(6)] Lime rates to raise V to 50, 65, 80, and 100 %.

The fertilization response experiments were designed to assess the grain yield of the species in response to applications of increasing P and K rates in the sowing line, which was related to the nutrient availability in these two soil layers (0.00-0.10 and 0.00-0.20 m) found prior to fertilization. Thus, each experiment was conducted at one location for only one growing season (winters of 2011 and 2012 and summers of 2011/12 and 2012/13). Except for soybean, which was not fertilized with N, the fertilization and liming management was according to the directions adopted in PR for the evaluated crops, as stated by Raij et al. (1997), CQFSRS/SC (2004) and Embrapa (2008; 2009).

Soil sampling and chemical analysis

Soil samples were collected from the 0.00-0.10 and 0.00-0.20 m layers with a cutting shovel, according to the method of sampling crosswise to the sowing line, in a width corresponding to the spacing of the last crop, with the line located in the middle of the sampled width (CQFSRS/SC, 2004). In the liming experiments, sampling was carried out annually between the growing seasons (after harvesting the summer and prior to sowing of the winter crop). In turn, in the calibration and fertilization response experiments, samples were taken every six months immediately prior to fertilization and seeding of the crop under study.

In the liming experiments, base saturation values (V) were calculated from the ratio of the exchangeable bases (Ca, Mg and K) and cation exchange capacity at pH 7.0 ($\text{CEC}_{\text{pH 7.0}}$). In the experiments involving P and K application, the available levels of these nutrients in the soil were quantified by Mehlich-1 extractor. All analyses were performed by established methods described by Tedesco et al. (1995).

Evaluation of crop yields

The grain yield was evaluated in all crops and experiments after mechanical harvesting (combine harvester) of the plots, corresponding to an area of 20-30 m^2 in the experiments of liming and P and K calibration, and 3-7 m^2 in the fertilization response experiments. Grain yield was expressed for a moisture content of 13 %.

For the combined yield analysis of the different growing seasons, crops and locations, the results were expressed as relative grain yield (RY), which was based on the yield of the control treatment (no lime in liming treatments; no P in P experiments and no K in K experiments) compared to the maximum yield of the crops (RY = 100) in the respective seasons and locations, calculated by equation 1, as described in detail by Vieira (2014) and Vieira et al. (2015).

$$\text{RY (\%)} = (\text{Yield control/maximum yield}) \times 100$$

Results analysis and interpretation

The suitability of the two layers (0.00-0.10 or 0.00-0.20 m) studied for the evaluation of soil fertility in the experiments was analyzed based on two criteria: (i) analysis of variance, to verify whether the base saturation and levels of available P and K differed between the soil layers, by the LSD test ($p<0.05$); and (ii) the significance or not of the correlation between crop yields with these soil fertility properties between the layers studied. Due to the non-linearity of these relationships (Vieira et al., 2015), the curves were linearized by logarithmic transformation of the V values and available P and K in the soil, to determine the linear correlation coefficients (Pearson) between the relative crop yields and the logarithm of the V values and available P and K in the 0.00-0.10 and 0.00-0.20 m layers.

RESULTS AND DISCUSSION

Soil fertility properties after surface application of lime and fertilizers

Base saturation increased in the 0.00-0.10 m layer after only one year of surface liming in all experiments (Table 2). This effect lasted until the 10th year in the two longest-running experiments. In the mean, base saturation increased from 49.6 to 69.6 %. Although there was an increase of this attribute in the 0.00-0.20 m layer, this increase occurred gradually and varied between the five experimental areas, although it occurred in the first year in one area. In this area, the V value increased from 10 to 38 %; in the others, the effect of surface liming in the 0.10-0.20 m layer occurred from the second year (one area) and third year (two areas). On average for all evaluations, base saturation in the 0.10-0.20 m layer increased from 45.4 to 56.1 %. This represents an increase of 24 % which, compared to the 0.00-0.10 m layer, was similar to the results after longer periods of liming (Table 2).

Table 2. Base saturation in two layers from one to 10 years after surface liming in no-till Humic Hapludox soils from the South-Central region of Paraná

Liming experiment	**Years after liming**	**Soil layer**				**T test (LSD)(2) p<0.05**	
		0.00-0.10 m		**0.10-0.20 m**			
		Without	**With(1)**	**Without**	**With**	**0.00-0.10 m**	**0.10-0.20 m**
Guarapuava (1)	1	50	65	53	60	*	ns
	2	46	66	45	60	*	*
	3	53	71	54	60	*	*
	4	60	78	54	65	*	*
	5	55	72	50	62	*	*
	6	48	76	45	60	*	*
	7	43	72	45	68	*	*
	8	45	77	46	64	*	*
	9	37	67	40	59	*	*
	10	38	64	41	52	*	ns
Guarapuava (2)	1	57	63	54	54	*	ns
	2	56	63	48	51	*	ns
	3	49	64	42	48	*	*
	4	-	-	-	-	-	-
	5	62	75	53	63	*	*
	6	60	72	52	60	*	*
	7	59	71	58	61	*	ns
	8	53	69	51	59	*	*
	9	48	65	46	57	*	*
	10	48	66	43	56	*	*
Pinhão (3)	1	59	75	53	54	*	ns
	2	60	69	54	56	*	ns
	3	58	77	55	67	*	*
	4	47	65	47	57	*	*
Candói (4)	1	60	74	45	49	*	ns
	2	57	71	45	55	*	ns
	3	59	67	45	52	*	ns
	4	43	65	37	43	*	ns
Candói (5)	1	19	65	10	38	*	*
	2	9	75	6	38	*	*

(1) Rate corresponding to the amount of lime to raise soil base saturation to 65 % in the 0.00-0.20 m layer. (2) *: significant difference ($p<0.05$) between base saturation of treatments with and without liming; ns: not significant.

The increase in V values in both layers (0.00-0.10 and 0.00-0.20 m), in the mean of the years, was proportional to the limestone rates (Experiment 5). In this experiment, the increase in this attribute was five-fold, whereas in the other experiments, it ranged from 24 to 37 % in the 0.00-0.10 m and from 12 to 20 % in the 0.10-0.20 m layer (Table 2). Consequently, it was confirmed that the depth effect of surface lime application on soil acidity indicators is related to the time period after liming and that improvements in acidity indicators occurred after 12 months in the 0.00-0.10 m layer and after 24 to 30 months in the 0.10-0.20 m layer in Oxisols under long-term NT, as similarly stated by Caires et al. (2005). These results showing an increase in V values in the 0.10-0.20 m layer reinforced the results of the two longer-duration experiments, with increases of up to 13 % in the first year and 48 % after 10 year of liming (Table 2). Importantly, the effects of liming on the deeper soil layers under long-term NT were not restricted to the upper 0.20 m of soil, since a decrease in soil acidity was observed to a depth of 0.60 m after only 3 year of liming in Oxisols under NT for more than 20 year under NT (Caires et al., 2008; Fontoura et al., 2012). The physical movement of limestone particles through soil biopores may provide an explanation for the amelioration of soil acidity in the 0.00-0.20 m layer, as confirmed by Amaral et al. (2004), in a Haplumbrept under NT.

With regard to the values of available P in the soil, as expected, the effect of surface fertilization was more pronounced in the 0.00-0.10 m layer, as shown by the higher and significant ($p<0.05$) coefficients of determination (R^2) of linear regression (Table 3). However, a slight increase in this content in the 0.10-0.20 m layer in the experiments of Guarapuava and Candói in the first year is worth mentioning. Although some increases in available nutrient concentrations may occur over time in this layer, they are not expected to be relevant, since the soils within this study area (Humic Hapludox) have a high nutrient retention capacity, by forming inner sphere complexes, determined by high Al and Fe oxide contents (Inda Junior et al., 2007).

Therefore, the absence of soil tillage favors P accumulation in the soil surface layer, even in the first years of NT, especially by broadcast fertilization (Eltz et al., 1989; Bayer and Mielniczuk, 1997; Schlindwein and Anghinoni, 2000). However, in long-term NT experiments (>15 years), in Oxisols of Paraná (Eltz et al., 1989; Ciotta et al., 2002; Pauletti et al., 2005), as well as in an Ultisol of Rio Grande do Sul (Costa et al., 2010) an increase in the available P content below a depth of 0.10 m was observed. Indeed, it seems that there is no vertical movement of the nutrient, since the explanation would be the fertilizer application at the bottom of the planting furrow with direct drilling. According to some authors (Dick, 1983; Rheinheimer and Anghinoni, 2003; Costa et al., 2010), there seems to be an increase in the form of P derived from the decomposition of crop residues left on the surface and from roots that have their growth increased in the area of phosphate fertilization (Anghinoni and Barber, 1980).

Table 3. Relationship between applied P_2O_5 rates and increase of available P in two soil layers of Humic Hapludox soils at different times after application in long-term no-tillage experiments

Experiment	**Years**(1)	**Soil layer**				**Δ P available**(2)	
		0.00-0.10 m		**0.10-0.20 m**		**0.00-0.10 m**	**0.10-0.20 m**
		Equation	**r^2**	**Equation**	**r^2**		
						mg dm^{-3}	
P Guarapuava	1	$\hat{y} = 20.36 + 0.0693^{**}$ x	0.99^{**}	$\hat{y} = 4.96 + 0.0077^{**}$ x	0.92^{**}	21.2	2.6
P Guarapuava	5	$\hat{y} = 12.18 + 0.0312^{**}$ x	0.94^{**}	$\hat{y} = 3.58 + 0.0020$ x	0.63^{ns}	5.6	1.5
P Pinhão	1	$\hat{y} = 7.88 + 0.0108^{**}$ x	0.97^{**}	$\hat{y} = 3.56 + 0.0012$ x	0.17^{ns}	3.3	0.3
P Pinhão	5	$\hat{y} = 7.28 + 0.0074$ x	0.73^{ns}	$\hat{y} = 4.74 + 0.0007$ x	0.18^{ns}	4.5	0.2
P Candói	1	$\hat{y} = 4.71 + 0.0201^{**}$ x	0.96^{**}	$\hat{y} = 2.48 + 0.0010^{*}$ x	0.82^{*}	6.6	0.5
P Candói	5	$\hat{y} = 4.69 + 0.0047^{**}$ x	0.97^{**}	$\hat{y} = 2.61 + 0.0004$ x	0.32^{ns}	1.0	0.0

(1) Years after application of P rates; (2) Δ available P (Mehlich-1) = difference between P content in the soil after application of 320 kg ha^{-1} P_2O_5, and P content in soil without P application. * and **: significant at 5 and 1 %, respectively; ^{ns}: not significant.

For soil available K, the levels in the layers 0.00-0.10 and 0.10-0.20 m increased in the first year in all three experiments, demonstrating a quick movement of K applied to the surface of the soil profile. After 5 year of K application, the increase of this nutrient in the 0.10-0.20 m layer was linear in both experiments, while at only one location (Pinhão) was the effect only observed in the 0.00-0.10 m layer, which may be related to the sequence of intense K fertilization in the past, resulting in very high (4.5 %) K saturation in the CEC.

There was a greater increase in available K (Table 4) than in available P (Table 3) when comparing the 0.00-0.20 m with the 0.00-0.10 m layer, as expected. This is due to the rapid release from crop residues after plant senescence (Giacomini et al., 2003) and the greater mobility of K in the soil profile.

Relationship between soil properties and crop yields

The relationship between soil properties in the 0.00-0.10 and 0.00-0.20 m layers, and the relative crop yield (RY) were evaluated to identify which soil layer is most correlated with nutrient supply and plant development. In the liming experiments, correlation coefficients between RY of the crops (soybean, corn, wheat, barley, and oat) (n = 473) and base saturation were significant ($p<0.01$), but similar between the layers studied (0.50 in 0.00-0.10 m and 0.51 in 0.00-0.20 m) (Table 5). Similar relationships between grain yield, water pH and base saturation were also reported by Nolla and Anghinoni (2006) in the layers 0.00-0.10 and 0.00-0.15 m and by Nicolodi et al. (2008) for the layers 0.00-0.10 and 0.00-0.20 m. These results indicate that any of the studied layers can be used for acidity diagnosis of lime recommendation in soils under long-term NT.

In view of the different relationships between grain yield and the contents of available P and K in the soil of the crops (Lantmann et al., 1996; Vieira et al., 2013), the species were grouped into winter cereals (oat, wheat and barley) and summer crops (soybean and corn).

Table 4. Relationship between K_2O rates applied and increase in available K in two soil layers of Humic Hapludox soils at different times after application in long-term no-tillage experiments

Experiment	Years[1]	Soil layer				Δ K available[2]	
		0.00-0.10 m		0.10-0.20 m		0.00-0.10 m	0.10-0.20 m
		Equation	r^2	Equation	r^2		
						$cmol_c\ dm^{-3}$	
K Guarapuava	1	$\hat{y} = 0.64 + 0.0012^{*} x$	0.87^{*}	$\hat{y} = 0.26 + 0.0007^{*} x$	0.92^{*}	0.54	0.16
K Guarapuava	5	$\hat{y} = 0.37 + 0.0004^{**} x$	0.99^{**}	$\hat{y} = 0.14 + 0.0002^{*} x$	0.89^{*}	0.13	0.07
K Pinhão	1	$\hat{y} = 0.85 + 0.0009^{**} x$	0.93^{**}	$\hat{y} = 0.50 + 0.0008^{**} x$	0.98^{**}	0.42	0.28
K Pinhão	5	$\hat{y} = 0.70 + 0.0002 x$	0.52^{ns}	$\hat{y} = 0.43 + 0.0002 x$	0.77^{ns}	0.09	0.00
K Candói	1	$\hat{y} = 0.32 + 0.0009^{*} x$	0.90^{*}	$\hat{y} = 0.13 + 0.0006^{*} x$	0.91^{*}	0.35	0.26
K Candói	5	$\hat{y} = 0.29 + 0.0007^{*} x$	0.76^{*}	$\hat{y} = 0.12 + 0.0003^{**} x$	0.94^{**}	0.42	0.14

(1) Years after application of K rates; (2) Δ K available (Mehlich-1) = difference between K content in the soil after application of 320 kg ha^{-1} K_2O, and K content in soil without K application. * and **: significant at 5 and 1 %, respectively; ns: not significant.

Table 5. Correlation between relative grain yield and fertility attributes of soil layers under long-term no-tillage management

Crop	Base saturation		Available P		Available K	
	0.00-0.10 m	0.00-0.20 m	0.00-0.10 m	0.00-0.20 m	0.00-0.10 m	0.00-0.20 m
Crop rotation	0.50^{**}	0.51^{**}	0.58^{**}	0.66^{**}	0.18^{*}	0.19^{*}
Soybean and corn	-	-	0.58^{**}	0.69^{**}	0.04	0.04
Wheat, barley and oat	-	-	0.66^{**}	0.68^{**}	0.30^{*}	0.32^{*}

* and **: significant at 5 and 1 %, respectively.

Correlations between the concentration of available K and winter crop yield and the system as a whole (crop rotation) were low and similar for the two layers assessed, although significant ($p<0.05$) (Table 5). For summer crops, the correlations were very low and not significant. This is probably due to the low response of these crops to the addition of K, since its availability in the soil was high due to the high content in the soil (0.14-0.87 $cmol_c\ dm^{-3}$) and its rapid movement in the soil profile after surface application (Table 4).

In the evaluation of relationships between soybean and corn yield with available P, the correlation coefficients, although both significant ($p<0.01$), were higher for the 0.00-0.20 m ($r = 0.69$) than the 0.00-0.10 m layer ($r = 0.58$) (Table 5). The correlation coefficients between the yields of winter crops (wheat, barley and oat) and available P were significant ($p<0.01$) and similar: 0.68 in the 0.00-0.20 m and 0.66 in the 0.00-0.10 m layer. However, for the crop rotation system (winter + summer), although the significance was the same ($p<0.01$), the coefficients were higher for the 0.00-0.20 m layer (0.66 in 0.00-0.20 m and 0.58 in the 0.00-0.10 m layer).

The summer crops, representing the main income source of the producers in the South-Central region of Paraná in a rotation system of the crops under study, must be emphasized in the discussion of the results. Thus, the better correlation with P content in the 0.00-0.20 m than in the 0.00-0.10 m layer indicates the importance of including the sub-surface layer (0.10-0.20 m) in the evaluation of the availability of P in soils under long-term NT. This disagrees with the highest correlations between available P content in the topsoil and the crop yields observed by Sá (1999) and Schlindwein and Gianelo (2008), probably for the shorter period under NT of the areas studied by these authors in comparison with the present study (17-27 year).

Due to the higher nutrient concentrations in the surface layer of NT soil, particularly of P, it has been suggested that samples for the evaluation of soil fertility in some regions of Brazil should be collected from the 0.00-0.05 and 0.05-0.10 m (Ribeiro et al., 1999) or the 0.00-0.10 m layer (CQFSRS/SC, 2004), rather than the 0.00-0.20 m, as this layer is usually indicated for systems with mechanical tillage and soil stirring.

The long-term cultivation of soils under no-tillage (Table 1) is an important aspect that reinforces the results of this study. Thus, and according to Sá (1999; 2004), during the first years of this system, the soil undergoes re-aggregation and structuring, during which the beneficial effects such as accumulation of organic matter, increased CEC and increase in inorganic and organic forms of labile P are not yet detectable. These characteristics, combined with surface applications of fertilizers and liming, result in nutrient accumulation in the topsoil in the initial years, justifying a higher correlation of the indicators in the 0.00-0.10 m layer with crop yields, as reported in various studies (Petrere et al., 1996; Sá, 1999; Schlindwein and Anghinoni, 2000; Schlindwein and Gianello, 2008), and justifying the indication of this layer for soil sampling in the initial stages of system structuring (<10 year). However, with increasing the time of soil under NT, the effects of surface application are not limited to the surface soil layer (0.00-0.10 m), but also occur in the sub-surface layer (0.10-0.20 m), which strongly recommends sampling of the 0.00-0.20 m layer for evaluation the soil fertility in long-term no-tillage systems.

CONCLUSIONS

Lime and fertilizer application on surface of long-term no-tilled soils increased base saturation and available K to a depth of 0.20 m.

The relationship with crop yields was high for base saturation and low for available K for the two soil layers (0.00-0.10 and 0.00-0.20 m); for P, however, the relationships with soybean and corn yields were strongest in the 0.00-0.20 m layer.

Considering the criteria of the fertilized layer (base saturation and available K) and the relationship with crop yields (available P), 0.00-0.20 m is the most appropriate soil layer for soil fertility evaluation in long-term no-tilled soils.

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