Soil & Tillage Research 133 (2013) 32–39

Contents lists available at SciVerse ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Long-term effect of different soil management systems and winter crops on soil acidity and vertical distribution of nutrients in a Brazilian Oxisol

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ARTICLE INFO

Article history:
Received 31 October 2012
Received in revised form 18 May 2013
Accepted 23 May 2013

Keywords:
No-tillage
Conventional tillage
Winter cover crops
Nutrient availability
Subsurface soil fertility

ABSTRACT

"Strategies" to sustain crop productivity by reducing the fertilizer and lime demands must be developed. The use of plant species that use more efficiently the soil nutrients and tillage systems that provide nutrients accumulation in more labile forms are prerequisites for sustainable agroecosystems. This study aimed to evaluate the long period effect of cultivating different winter species under different soil management systems on vertical distribution of soil nutrients and the soil acidity distribution in soil profile. The experiment was established in 1986 with six winter treatments (blue lupine, hairy vetch, oat, radish, wheat and fallow) under conventional tillage (CT) and no-tillage (NT) in a very clayey Rhodic Hapludox in Southern Brazil. As a result of 19 years of no soil disturbance, soil chemical attributes related to soil acidity and the availability of P and K were more favorable to crops growth up to 10 cm in the soil under no-tillage than in the conventional tillage. On other hand, lime applications in low doses on the soil surface were not efficient in neutralizing the aluminum toxicity below 10 cm depth. It shows that repeated use of lime on the soil surface under NT system can be a viable alternative strategy only when soil acidity and aluminum toxicity in subsurface has been previously eliminated using the adequate amount of lime and incorporating it into the arable layer. Moreover, in the conventional tillage system P and K availability were higher below 10 cm depth compared to the no-tillage system. Even after 19 years of no soil disturbance in the NT system the available P content below 10 cm soil layer was lower than the optimal content of available P recommended to cash crops. The reduced surface K application over time was sufficient to gain adequate crop yields and to maintain the optimal content of soil available K in both soil management systems. The effects of soil management systems were predominant on the soil acidity attributes, and no effects of winter cover crops were observed on soil acidity attributes. Black oat and blue lupine were more efficient in P cycling, increasing the soil available P content especially in the surface soil under NT. The lower amount of biomass produced over time when no cover crops were used in the winter period resulted in lower P and K availability in the soil, showing the important role of growing winter species to maintain soil fertility.

1. Introduction

Most cultivated Oxisols in tropical and subtropical regions of the world have low soil organic carbon content and show nutrient depletion over time (Calegari and Alexander, 1998). In these cultivated soils, the inputs of organic and inorganic fertilizers affect plant growth and nutrient recycling through crop residues, affecting also soil organic carbon dynamics (Craswell and Lefroy, 2001). Therefore, patterns of organic carbon decline and nutrient depletion in Oxisols that have been under long term cultivation are of great concern for sustainable crop production on these soils.

In tropical and subtropical regions there is demand for increasing production which is usually achieved by expanding the cultivation area to the marginal lands (Greenland et al., 1997).

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0167-1987/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.still.2013.05.009

This is particularly critical especially where the average crop yields are declining in conventional production systems. To reverse it, the use of mineral fertilizers and lime can maintain the yields in areas with high production potential and increase the production on marginal areas. However, the growing demand for fertilizers and lime can make these practices economically nonviable over time (Craswell and Lefroy, 2001). Therefore, strategies to maintain or increase crop productivity, reducing the demand for fertilizers and lime must to be developed. Thus, the use of plant species more efficient in soil nutrients use and tillage systems that provide accumulation of nutrients in labile forms, are basic prerequisites to sustainable crop production systems.

The dynamics of essential nutrients and toxic elements are modified by the no-tillage (NT) system when compared to the conventional tillage (CT) system (Houx et al., 2011). Generally, fertilizers are applied on the soil surface layer, with the possibility to broadcast in the NT. In the NT system the soil is not disturbed and the nutrients retention capacity reaches slowly to saturation. It occurs because nutrients such as phosphorus, potassium, calcium, magnesium, all cation micronutrients and heavy metals, are strongly adsorbed to the soil colloids functional groups at the site of application in tropical and subtropical Oxisols. Moreover, in the NT system, crops residues are deposited on soil surface, maximizing the biocycling and bringing nutrients from the deeper to the upper soil layers. Therefore, several studies have shown that NT system builds up a nutrient availability gradient quickly, with higher concentration on the soil surface layers, mainly when the fertilizers applied are superior to the nutrients output from the system (Rheinheimer and Anghinoni, 2001, 2003). However, when nutrients deficiencies and aluminum toxicity have not been corrected before NT system implementation, it can promote root nutrients deficiency in the deeper soil layers and excess accumulation on the upper soil layers, which can be a limiting factor to the subsequent crop yields and also contribute to more nutrients losses by runoff (Panuelas et al., 2009).

The cultivation of different plant species can also change the dynamics of nutrients in the soil, especially the P dynamics (Horst et al., 2001; Tiecher et al., 2012a,b). Plant strategies that increase the soil–root contact are particularly important in the uptake of P which has very low mobility in Oxisols. In this context, Vu et al. (2010) observed that wheat (*Triticum aestivum* L.) absorbed greater amount of soil available phosphorus due to its root system that explored large volumes of soil. Furthermore, Wang et al. (2008) reported that the acquisition of phosphate in low availability conditions was improved by the release of protons by wheat. Li et al. (2008) showed that common bean decreased the rhizosphere pH by 1.66 units reducing also the available P-resin to 43% of the no-plant control soil. Many factors contribute to this pH change, including the imbalance in cation–anion uptake, particularly affected by nitrogen sources, and increased efflux of protons as a result of P deficiency (Gahoonia and Nielsen, 2004). Besides this, the exudation of organic acids like citrate, malate, fumarate etc., can promote the P mobilization by ligand exchange and by occupying or dissolution of P adsorption sites (Bayon et al., 2006). Neumann and Römheld (1999) found that metabolic changes related to exudation of carboxylic acids and protons by plant roots are induced due to P deficiency which depend on multiple factors, i.e. patterns of cation uptake and ability of plants to accumulate carboxylic acids in root tissue. The acquisition of P of low lability due to exudation of organic acids has been observed in lupin (*Lupinus albus* L.) by several researchers (Bais, 2006; Bayon et al., 2006; Shane et al., 2008; Wang et al., 2008). Therefore, based on the above results, it can be expected that cultivating crops with different strategies to access soil nutrients over time may alter soil nutrients and acidity attributes, especially under NT system.

The objectives of this study include determining the long term effect of cultivation with different winter plant species under CT and NT system on: (i) vertical distribution of soil nutrient and (ii) the soil acidity distribution in soil profile to assess the sustainability of crop production.

2. Materials and methods

2.1. Site description

A long-term experiment was established in 1986 at the Agronomic Institute of Paraná (IAPAR) experimental station at Pato Branco, Southwestern Paraná State, Brazil (52° 41′ W, 26° 07′ S and 700 m altitude) (Fig. 1). The soil of the experimental site is a very clayey Rhodic Hapludox (Latossolo Vermelho Aluminoférrico – Brazilian Soil Classification System) and very acid. The A horizon (0–1 m) has 72% clay, 14% silt, and 14% sand. The mineralogical composition of A horizon is 68% silicate type 1:1 (kaolinite and halloysite), 13% silicate type 2:1 (vermiculite and/or montmorillonite), 14% iron oxides and 5% gibbsite, and the iron oxides composition is 51% hematite, 36% goethite and 13% maghemite (Costa, 1996). The area belongs to the sub-humid tropical zone or Köeppen's Cfb (climate without dry season, with rainy summer and the average hottest month lower than 22 °C). The annual rainfall (from 1979 to 2005) ranges from 1200 to 1500 mm. The monthly average temperature and monthly average precipitation of the experimental station in the period 1979–2005 are presented in Fig. 2.

2.2. History and layout of the experimental area

The experimental area was covered by subtropical forest until 1976, then it was cleared and cultivated with maize (*Zea mays* L.), soybean (*Glycine max* Merrill) and beans (*Phaseolus vulgaris* L.) for 10 years in a conventional system (1 disc plow + 2 disc harrowing). From 1976 to 1986, there were high soil losses by erosion, the crops residues were burned after each cultivation to facilitate soil management, and lime was applied several times at unknown rates. From the winter 1986, experimental treatments combining different soil tillage system and winter cover crop treatments were implanted in the experimental area in three blocks. Selected soil chemical attributes at the beginning of the experiment are presented in Table 1.

The winter treatment plots (12 m × 20 m) were randomized in each block. After that each block was subdivided in two strips and was laid out into two soil management systems (6 m × 20 m) within each winter treatments plot. Tillage treatments were conventional tillage (CT – one disc plow and two disc harrowing) and continuous no-tillage (NT). Several winter cover crop species were compared at various times throughout the 19-year period. The winter cover crops that were compared included: blue lupin (*Lupinus angustifolius* L.), hairy vetch (*Vicia villosa* Roth), black oat (*Avena strigosa* Schreb.), oilseed radish (*Raphanus sativus* L.), spring wheat (*T. aestivum* L.), and fallow. These winter cover crop treatments were applied to main plots in the years 1986–1990, 1992, 1994, 1999–2001 and 2005. During the winter seasons of 1991, 1995, 1996 and 1998, the entire experimental area was planted with black oat; in 1993 the soil remained fallow in winter; and, in 1997, 2002, 2003 and 2004 black oat + radish were planted in all main plots. The cover crops (lupine, hairy vetch, oats and radish) were controlled at the flowering stage by cutting with a roller knife. Herbicide was applied to the weedy fallow treatment to kill vegetation. Some years after cutting with roller knife, the plots were sprayed with herbicide when control treatment using roller-cutter was incomplete. Wheat was harvested for grain until 1995 (7 crops) and straw was left on top of the soil as mulch or

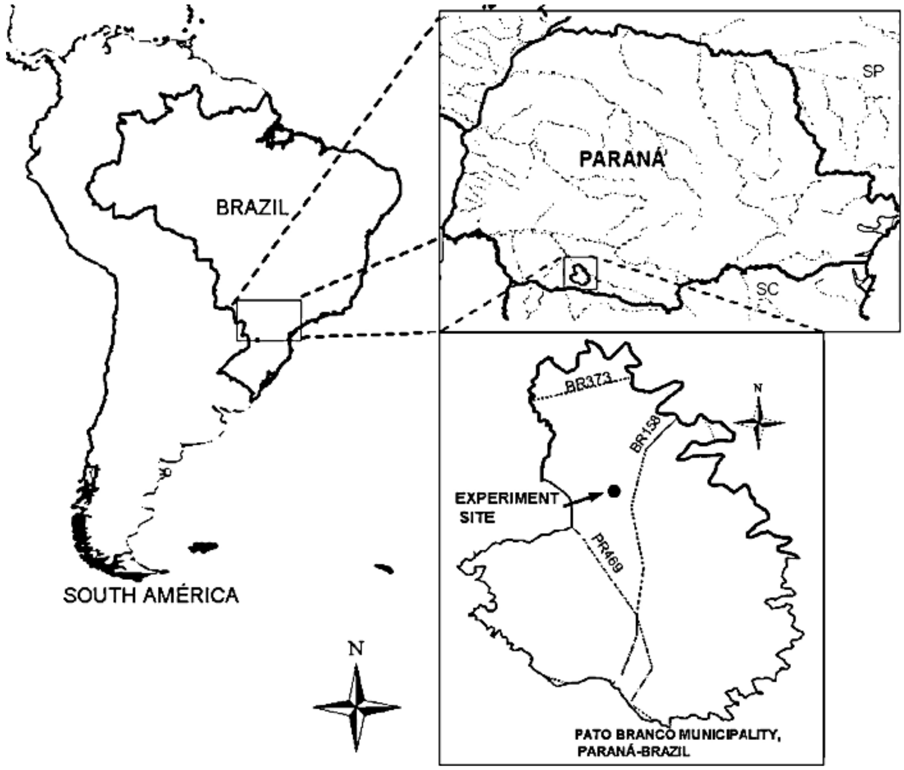

Fig. 1. Map of South America, Brazil, and Paraná State showing location of study site.

incorporated before planting the summer crop. Summer crops of maize and soybean were planted following the winter species. During the period of 1986–2005, maize was the summer crop for 8 years (1986–1988, 1992, 1994, 1996, 1999 and 2003) and soybean was the summer crop for 12 years (1989–1991, 1993, 1995, 1997, 1998, 2000–2005). The winter cover crops biomass yield, the summer crops residues and total above-ground dry biomass yield over 19 years under different winter treatments and soil managements systems are shown in Table 2.

Only the summer crops received fertilizer each year; the total amount of fertilizer applied during 19 years was 568 kg P ha^{-1}, 618 kg K ha^{-1}, and 501 kg N ha^{-1} using urea ($([NH]_2)_2CO$) as a nitrogen source. All the winter crops were sown without fertilizers. Full P, K and one-third of the N fertilizer were applied at planting time, while remaining two-thirds of the N was applied 45 days after planting. Lime was applied five times for a total of 9.5 Mg ha^{-1} (1.0, 2.0, 3.0, 1.5 and 2.0 Mg ha^{-1} of lime (dolomite) in all plots, in 1989, 1992, 1995, 1999 and 2001, respectively). For the NT system, lime was broadcasted on the soil surface and in the CT it was applied on the surface and then incorporated by plowing.

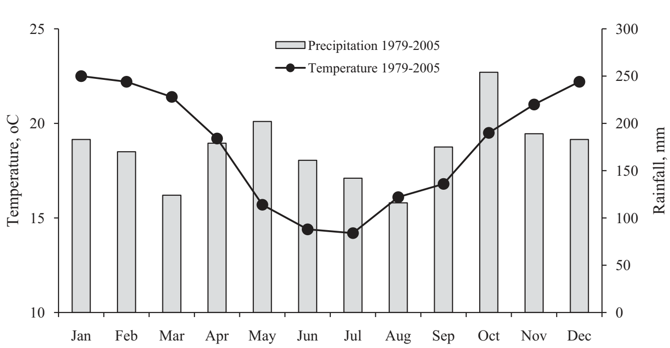

Fig. 2. Average temperature and precipitation in the experimental area in the period of 1979–2005.
Source: Meteorological Station of Experimental Station of IAPAR, Pato Branco, Paraná State.

2.3. Soil sampling and analyses

Bulk soil samples were collected in October 2005, before the winter species management with roller knife at the flowering stage, taking care to avoid addition of crop residues and live plant material to the soil sample. A trench was opened in each plot and two subsamples of soil taken at six depths: 0–5, 5–10, 10–20, 20–30, 30–40 and 40–60 cm. The soil sample from three trenches of the adjacent undisturbed forest that lies on the border of the experiment was also taken as control for comparison. All soil samples were air dried, sieved through 2 mm mesh and stored for further analysis.

Soil pH was determined in 0.01 M $CaCl_2$ suspension (1:2.5 soil:solution) after shaking for 20 min; exchangeable Al^{3+}, Ca^{2+}, and Mg^{2+} were extracted by 1.0 M KCl (soil:extractant 1:10) for 20 min shaking. Exchangeable Al^{3+} was determined by titration with standardized 0.015 M NaOH solution using bromothymol blue indicator and Ca and Mg by atomic absorption spectroscopy. Available P and K were extracted by Mehlich-1 (soil:extractant 1:10), and then K was measured by flame photometer and P was colorimetrically determined by Murphy and Riley (1962) method. The potential acidity ($H^+ + Al^{3+}$) was calculated using Eq. (1) proposed by Kaminski et al. (2001) and adopted by CQFS-RS/SC (2004):

$$H^+ + Al^{3+} = \frac{e^{10.665-1.148*\text{pH SMP}}}{10} \quad (1)$$

where the $H^+ + Al^{3+}$ is estimated by the pH balance of the soil with 1.78 M SMP solution (triethanolamine, paranitrofenol, K_2CrO_4, $Ca(CH_3COO)_2$ and $CaCl_2{\cdot}2H_2O$) buffered at pH 7.5 (Shoemaker et al., 1961). The cation exchange capacity at pH 7.0 ($CEC_{pH\ 7.0}$) was calculated as the sum of $H^+ + Al^{3+} + Ca^{2+} + Mg^{2+} + K^+$ (CQFS-RS/SC, 2004).

Table 1
Selected soil chemical characteristics in the soil before the beginning of the experiment in 1986, affected by 10 years of cultivation under conventional tillage.

Soil depth (cm)	TOC[a] (%)	Soil pH	Exchangeable by 1.0 M KCl ($cmol_c\,kg^{-1}$)			H + Al ($cmol_c\,kg^{-1}$)	$CEC_{pH\ 7.0}$ ($cmol_c\,kg^{-1}$)	m[b] (%)	V[c] (%)	Available by Mehlich I	
			Al	Ca	Mg					P ($mg\,kg^{-1}$)	K ($cmol_c\,kg^{-1}$)
0–10	2.54	4.7	0.12	3.7	2.1	5.7	11.9	1.9	52	3.8	0.43
10–20	2.43	4.7	0.16	3.4	2.0	5.9	11.5	2.8	49	2.2	0.31
20–40	2.22	4.7	0.27	2.8	1.7	6.2	10.9	5.5	43	1.7	0.23

[a] Total organic carbon.
[b] Aluminum saturation = Al/(Al + Ca + Mg + K) × 100.
[c] Base saturation = (Ca + Mg + K)/(H + Al + Ca + Mg + K) × 100.

2.4. Statistical analyses

For the analysis of variance (ANOVA) of the data, the following model was used:

$$Y_{ijkl} = \mu + B_i + W_j + \text{error } a(i,j) + M_k + \text{error } b(i,k) + WM_{jk} + \text{error } c(i,j,k) + D_l + \text{error } d(i,l) + WD_{jl} + \text{error } e(i,j,l) + MD_{kl} + \text{error } f(i,k,l) + WMD_{jkl} + \text{error } g(i,j,k,l)$$

where μ is the overall experimental average; B is the blocks (i = 1, 2, 3); W is the winter treatment (j = 1, 2, 3, 4, 5, 6); M is the soil management system (k = 1, 2); D is the depth (l = 1, 2, 3, 4, 5, 6) and 'error' represents the experimental error. The winter treatments were considered as a between-subject and the soil management systems and the soil layers were considered within-subjects. When treatment effects were significant at 5% probability of error by F test, the differences between means of soil management systems were compared by the Least Significant Differences (LSD) test. Furthermore, in each soil layer, we compared the data from reference soil under forest (n = 3) with the cultivated soil under NT (n = 18) and the cultivated soil under CT (n = 18) using the Mann–Whitney U test (non-parametric test).

3. Results and discussion

3.1. Differences between cultivated and forest soil

The natural forest presents typical characteristics of a highly weathered soil that occurs in subtropical regions. The soil pH in the soil layer of 0–60 cm was 4, and Al saturation increased from 53% to 89% in the soil layers of 0–5 and 40–60 cm, respectively (Table 3). The indigenous plants that occur in these high weathered soils are genetically and/or environmentally adapted to the soil acidity conditions provoked by Al. According to Vitorello et al. (2005), some plant mechanisms to survive under these adverse soil conditions are: (i) low plant growth synchronized to the low nutrients availability; (ii) increase of soil pH in the rizosphere soil; (iii) Al uptake and its subsequent complexation into the plants tissues; (iv) Al and Fe complexation by organic acids released by roots; (v) high P affinity; and (vi) micorryza associations. Additionally, the nutrients biocycling and the capability of organic compounds accumulated on the forest surface soil in complex toxic Al are also natural strategies that allow native plants to grow. The deforestation followed by burning of the native forest, contributes to obtain reasonable crop yields in the first 2–3 years. After that, nutrients depletion occurs and the crop cultivation that is not adapted to this environmental leads to lower crop yields. In Southern Brazil, this soil chemical depletion was responsible by the first farmer's migratory cycle that occurred before soil physical degradation (Mielniczuck et al., 2000).

When compared to the forest soil, the cultivated soil (mean of two soil management in the soil layer of 0–60 cm) showed on average 0.8 units of pH increase and lowered the exchangeable Al content 12 times (Table 3). This change in soil acidity below cultivated surface layer occurred mainly because of continuous liming with continuous ploughing and disc harrowing operations from 1976 to 1986 before each crop growth season (Table 3). Thus, even under NT system modifications were observed in soil acidity attributes in the deeper soil layers (below 10 cm) as a result of the early tillage and lime application.

The P availability in highly weathered soils under the forest soil is very low when the P demands by commercial crops are taken into account (Fig. 3a). However, the proportion of organic P in the surface soil of subtropical forests can be more than 50% of the soil total P (Rheinheimer and Anghinoni, 2003; Tiecher et al., 2012a), and the remaining P is comprised of forms adsorbed to inorganic colloids with high bond energy and low bioavailability (Rheinheimer and Anghinoni, 2001). Therefore, in the forest soil, P availability depends largely on mineralization of organic P forms (Vincent et al., 2010).

After forest clearing, the amount of P added during the first 10 years of cropping (from 1976 to 1986) was not enough to reach the critical level of P availability, that is 6.0 $mg\,kg^{-1}$ according to the CQFS-RS/SC (2004) (Fig. 3a). Large doses of phosphate fertilizers are needed in order to increase soil P availability in soils with high adsorption capacity such as the Oxisols in this study. Note that these Oxisols have high clay content, are dominantly 1:1 clay minerals and have Fe oxides (Rheinheimer et al., 2003). This is confirmed by our results from CT system, where after 19 years, the P availability still below the optimum levels for crop production and close to the content of available P in the forest soil.

Table 2
Total above-ground dry biomass yield over 19 years in different winter treatments and soil management systems.

Winter treatments	Above-ground dry biomass yield ($Mg\,ha^{-1}$)							
	Winter cover crops[a]		Summer crops residues[b]		Total		Annual mean	
	NT	CT	NT	CT	NT	CT	NT	CT
Fallow[c]	34.0	23.7	80.5	79.8	114.5	103.6	6.0	5.5
Wheat	63.2	58.8	77.5	74.6	140.8	133.4	7.4	7.0
Vetch	68.1	58.9	83.6	78.6	151.8	137.4	8.0	7.2
Radish	71.3	58.0	85.4	84.5	156.7	142.4	8.2	7.5
Lupin	69.6	60.9	82.8	78.1	152.4	139.0	8.0	7.3
Oat	83.1	73.5	82.2	81.4	165.3	154.9	8.7	8.2

CT, conventional tillage; NT, no-tillage.
[a] Values are the sum of biomass yield of the winter cover crop used as treatments in 1986–1990, 1992, 1994, 1999–2001 and 2005; plus black oat biomass yield in 1991, 1995, 1996 and 1998; plus black oat + radish biomass yield in 1997, 2002–2004.
[b] Values are the sum of crops residues produced by maize cultivated in 1986–1988, 1992, 1994, 1996, 1999 and 2003) and by soybean cultivated in 1989–1991, 1993, 1995, 1997, 1998, 2000–2002 and 2004.
[c] The fallow biomass yield consisted of weed biomass.

Table 3
Soil pH, exchangeable aluminum, calcium and magnesium content, aluminum and base saturation, potential acidity (H + Al) and cation exchange capacity at pH 7.0 ($CEC_{pH\ 7.0}$), in the forest soil and in the cultivated soil affected by soil management after 19 years.

Soil depth (cm)	Soil management system		Forest soil‡	P-value[a]		Soil management system		Forest soil‡	P-value[a]	
	NT	CT		NT	CT	NT	CT		NT	CT
	Soil pH†					Exchangeable Al ($cmol_c\ kg^{-1}$)†				
0–5	5.5 aA	4.8 bA	4.1	0.008	0.007	0.01 bD	0.12 aC	2.40	0.002	0.008
5–10	5.0 aB	4.8 bAB	4.0	0.008	0.008	0.15 aC	0.15 aBC	2.83	0.008	0.008
10–20	4.7 bC	4.8 aA	3.9	0.007	0.008	0.31 aB	0.15 bBC	2.95	0.008	0.008
20–30	4.5 bD	4.8 aAB	4.0	0.007	0.008	0.39 aA	0.16 bBC	2.74	0.008	0.008
30–40	4.5 bD	4.7 aB	4.0	0.007	0.008	0.41 aA	0.23 bA	2.51	0.008	0.008
40–60	4.6 bC	4.7 aB	4.1	0.007	0.008	0.29 aB	0.20 bAB	2.22	0.008	0.008
	Exchangeable Ca ($cmol_c\ kg^{-1}$)†					Exchangeable Mg ($cmol_c\ kg^{-1}$)†				
0–5	7.0 aA	3.8 bA	1.3	0.008	0.008	3.4 aA	2.3 bA	0.8	0.008	0.008
5–10	4.5 aB	3.9 bA	0.7	0.008	0.008	2.6 aB	2.2 bA	0.6	0.008	0.008
10–20	2.9 bC	3.8 aA	0.4	0.008	0.008	2.0 bC	2.2 aA	0.4	0.008	0.008
20–30	1.9 bD	3.0 aB	0.3	0.008	0.008	1.6 bD	2.0 aB	0.3	0.008	0.008
30–40	1.5 bE	2.0 aC	0.2	0.008	0.008	1.4 bE	1.6 aC	0.2	0.008	0.008
40–60	1.4 bE	1.6 aD	0.1	0.008	0.008	1.3 bE	1.5 aC	0.1	0.008	0.008
	Al saturation (%)†					Base saturation (%)†				
0–5	0.1 bE	2.2 aC	53.2	0.002	0.008	66 aA	46 bA	13	0.008	0.008
5–10	2.5 aD	2.7 aC	68.2	0.008	0.008	51 aB	45 bA	9	0.008	0.008
10–20	6.4 aC	2.9 bC	77.0	0.008	0.008	38 bC	45 aA	6	0.008	0.008
20–30	10.1 aB	4.1 bB	81.5	0.008	0.008	31 bD	41 aB	5	0.008	0.008
30–40	12.4 aA	6.8 bA	84.4	0.008	0.008	28 bE	34 aC	4	0.008	0.008
40–60	9.5 aB	6.1 bA	89.2	0.008	0.008	28 bE	32 aC	2	0.008	0.008
	H + Al ($cmol_c\ kg^{-1}$)†					$CEC_{pH\ 7.0}$ ($cmol_c\ kg^{-1}$)†				
0–5	5.5 bC	7.5 aA	15.3	0.008	0.008	16.4 aA	14.0 bAB	17.5	0.175	0.008
5–10	7.3 bB	7.7 aA	14.3	0.008	0.008	14.7 aB	14.1 bA	15.6	0.248	0.145
10–20	8.3 aA	7.5 bA	13.9	0.008	0.008	13.5 aC	13.7 aB	14.8	0.119	0.079
20–30	8.2 aA	7.1 bB	13.1	0.007	0.008	11.8 aD	12.2 aC	13.7	0.039	0.079
30–40	7.9 aA	7.0 bB	12.0	0.008	0.008	11.0 aE	10.7 aD	12.4	0.079	0.008
40–60	7.3 aB	6.8 bB	11.7	0.008	0.008	10.1 aF	10.1 aE	12.0	0.039	0.014

CT, conventional tillage; NT, no-tillage.
† Values for each soil management system within each depth are the overall mean of six winter treatments ($n = 18$); means followed by the same letter in the row, comparing soil management system for each depth, and means followed by same capital letter in the column, comparing depth within each soil management system are not significantly different at $P < 0.05$ by LSD test.
‡ Values for each depth in the forest soil are the mean of three samples ($n = 3$).
[a] Probability of difference between the forest soil and the cultivated soil under NT or CT by Mann–Whitney *U* test.

In the forest soil, the available K content decreased from 0.18 to 0.05 $cmol_c\ kg^{-1}$ in the soil layers of 0–5 and 40–60 cm, respectively (Fig. 3b). Indeed, the natural K availability in basaltic soils with high clay contents is relatively high in the soil surface and follows the distribution of negative charges in the soil profile. In the cultivated soil, the K availability after 19 years of cropping and fertilizer-K addition was higher than in the forest soil and also higher than the K availability in the soil at the beginning of the experiment (Fig. 3b), showing that the amount of K applied over time was higher than the amount of K exported (crop grains and water erosion).

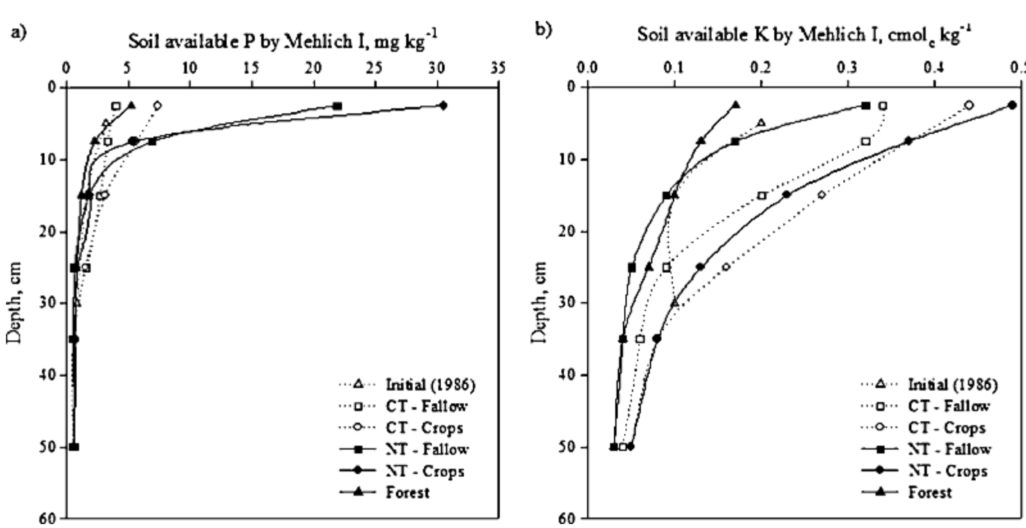

Fig. 3. Soil phosphorus and potassium availability after 19 years cultivation with no-tillage and conventional tillage with fallow and crops in relation to initial soil condition and forest soil.

Table 4
Significance of the effects of experimental factors and their interactions on soil acidity attributes and on phosphorus and potassium availability as resulting from analysis of variance (ANOVA).

Variable	Winter treatment (*W*)	Soil management system (*M*)	Depth (*D*)	$W \times M$	$D \times W$	$D \times M$	$D \times W \times M$
Soil pH	NS	NS	***	NS	NS	***	NS
Exchangeable aluminum	NS	NS	***	NS	NS	***	NS
Exchangeable calcium	NS	NS	***	NS	NS	***	NS
Exchangeable magnesium	NS	NS	***	NS	NS	***	NS
Potential acidity	NS	NS	***	NS	NS	***	NS
$CEC_{pH\ 7.0}$	NS	NS	***	NS	NS	****	NS
Base saturation	NS	NS	***	NS	NS	***	NS
Aluminum saturation	NS	NS	***	NS	NS	***	NS
Available potassium	NS	NS	****	**	NS	***	*
Available phosphorus	***	*	***	*	***	***	***

NS, not significant.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.

3.2. Effect of tillage system and winter treatments on soil acidity attributes

The soil pH, exchangeable Al, Ca and Mg content, Al and base saturation, potential acidity and $CEC_{pH\ 7.0}$, were not affected by winter treatments, but showed significant interaction between soil management and soil depth (Table 4). This shows that the effects of soil management systems are preponderant on the soil acidity attributes compared to the cultivation of different cover crops. In fact, the effects of cultivation of different plants on soil acidity attributes are most frequently determined at rhizosphere level (Li et al., 2008). As we did not evaluate the rhizosphere soil, but the bulk soil, it is possible that the winter cover crops effect on soil acidity attributes may have been diluted.

In comparison to the CT, the soil layers up to 10 cm under NT showed increase in soil pH, exchangeable Ca and Mg content, base saturation and $CEC_{pH\ 7.0}$ whereas the potential acidity and Al saturation were decreased (Table 3). The exchangeable Al was lower in the NT system only in the soil layer of 0–5 cm, and in the soil layer of 5–10 cm it was equal between the soil management systems. However, in the soil layer of 10–60 cm, the soil pH, exchangeable Ca and Mg content, and base saturation were lower under NT when compared to soil under CT. On the other hand, exchangeable Al, potential acidity and Al saturation were higher in the soil layer of 10–60 cm under NT system when compared to the CT system.

After adopting the NT system, the total amount of lime applied on the soil surface was 9.5 Mg ha^{-1} over a 19 years period. As a consequence of this, there were lower active soil acidity and Al saturation, and higher exchangeable Ca and Mg content and base saturation (Table 3) in the soil layer of 0–10 cm under NT when compared to the soil under CT. These results were similar to the findings of Hargrove et al. (1982) and Edwards et al. (1992). Additionally, the nutrient recycling by crops under NT may contribute to the accumulation of Ca and Mg in the soil surface and the formation of availability gradient. However, the exchangeable Al was effectively neutralized in the 20–60 cm depth only in the CT system (Al saturation lower than 10% – CQFS-RS/SC, 2004) (Table 3), due to the effect of slow migration of lime particles or their products to the deeper soil layers over time.

According to Rheinheimer et al. (2000a), high soil pH values result in decreased lime solubility. Thus, in the NT system the neutralization reaction of lime was limited to the upper layer, delaying the effect on subsurface layers and it is in accordance with the results of other researchers (Rheinheimer et al., 2000a, 2003; Kaminski et al., 2005; Caires et al., 1999; Kitur et al., 1994; Karlen et al., 1991; Ismail et al., 1994). To neutralize the acidity in subsurface layers the fine lime particles or the dissociation products must be moved down the soil profile (Rheinheimer et al., 2000a). Some factors that can contribute to lime migration in undisturbed soil profiles are: soil channels from crop roots continuous to the soil surface, water infiltration that can bring some lime particles into biopores (crop roots and fauna) and, earthworms and other soil organisms. However, in our experiment, the CT system was favorable to water infiltration and probably was the system where there was higher migration of small lime particles to the deeper soil layers (Calegari, 2006). Therefore, it is evident that lime application at lower rates to the soil surface is not efficient in neutralizing the aluminum toxicity in subsurface soil layers (below 10 cm depth) (Table 3). Consequently, repeated use of lime on the soil surface under NT system can be a viable alternative only when soil acidity and Al toxicity in subsurface has been previously corrected using the recommended site specific lime amount and incorporating it into the arable layer.

3.3. Effect of tillage system and winter treatments on soil phosphorus and potassium availability

The available P content showed significant interaction among soil management systems, winter treatments and depth. The maximum difference in available P content among the winter treatments were observed in the soil surface (0–5 cm) under NT system, where the highest average available P was obtained in the succession of cultures involving black oat (45.8 mg kg^{-1}), followed by lupin (31.7 mg kg^{-1}), radish (27.6 mg kg^{-1}), and vetch (26.7 mg kg^{-1}), and finally by wheat (20.8 mg kg^{-1}) and fallow (21.9 mg kg^{-1}) (Table 5). The available P in the 0–5 cm depth under CT system, the 5–10 cm and 10–20 cm depths in both soil management systems followed the same trends as the surface soil under NT system. However, the differences between the winter treatments were small. Bellow 20 cm depth, soil available P was smaller than 1.5 mg kg^{-1}, showing no difference among winter treatments. The P uptake by plants from deeper layers accumulate on the surface after the decomposition of their residues (Rheinheimer and Anghinoni, 2001), promoting the higher difference in available P among the winter treatments in the soil layer of 0–5 cm under NT. However, in the CT the plowing distributed the organic waste in-depth, with the consequent reactions of P with the soil after mineralization, decreasing the differences in the content of soil available P among the winter treatments.

Since there was no difference in yield and consequently in the amount of nutrients exported by corn and soybean grown during the 19 years of trial period, the lowest level of soil available P in the fallow treatment was due to the 12 years when no crop was grown during winter. This resulted in a lower amount of biomass

Table 5
Soil available phosphorus affected by soil management systems and winter treatments after 19 years.

Soil depth (cm)	Soil management system	Soil available phosphorus (mg kg^{-1}) Winter treatments[a]					
		Fallow	Wheat	Vetch	Radish	Lupin	Oat
0–5	No-tillage	21.9 dA	20.8 dA	26.7 cA	27.6 cA	31.7 bA	45.8 aA
	Conventional	4.0 dB	5.8 cB	6.4 cB	6.3 cB	8.8 bB	9.6 aB
5–10	No-tillage	6.9 bA	3.1 eB	5.0 cdB	4.7 dB	5.5 cB	8.8 aA
	Conventional	3.2 dB	3.6 dA	6.2 bA	5.2 cA	7.1 aA	6.1 bB
10–20	No-tillage	1.8 bcB	1.4 bcB	1.2 cB	1.7 bcB	2.9 aB	2.0 bB
	Conventional	2.7 bcA	3.4 abA	2.2 cA	2.8 bcA	3.9 aA	3.1 bA

[a] LSD for depth = 0.67 mg kg^{-1}.

production (Table 2) and consequently a lower amount of P cycled biologically. However, in the succession of cultures involving wheat, the lower content of available P probably was due to the P exported by seven wheat harvests between 1986 and 1995. In the succession of cultures involving black oat the amount of dry matter produced during the period of 1986–2005 was approximately 15 Mg ha^{-1} higher than in the other winter treatments (Table 2). Thus, these residues probably cycled a larger amount of P, resulting in the higher content of soil available P, especially under NT system. Lupine is well known for excreting large amounts of organic acids such as citrate, malate and fumarate, even under relatively high P availability (Bayon et al., 2006), which promotes the mobilization of P by ligand exchange and/or by dissolving and occupying the adsorption sites. Du to this higher excretion of organic acid, lupine possible accessed some soil P forms that are inaccessible to the other winter species. Thus, the lupine might cycle also large amounts of P, which may have increased the concentration of soil available P.

For very clayey soils (clay content higher than 60%) the recommendations of the CQFS-RS/SC (2004) in Southern Brazil, is that the optimum content of P available by Mehlich-I is between 6.0 and 12.0 mg kg^{-1}. Below this range there is a high probability of crop response to P addition whereas the soil P levels higher than 24 mg kg^{-1} should be avoided to prevent P losses by runoff and aquatic environment disturbance. In this way, the available P in the surface soil layer under NT reached critical environmental level, especially in the treatments involving oat and lupine. On the other hand, the content of available P in the soil layer of 0–5 cm under CT system was within the recommendation level, although the soil available P in the treatments involving fallow and wheat are below the critical level (Table 5).

In the surface soil layer (0–5 cm), the average amount of available P was 29.1 and 6.8 mg kg^{-1} in the NT and CT systems, respectively (Table 5). The higher amount of available P in the soil surface under NT compared to the soil under CT is a result of surface nutrient application and no soil disturbance in NT system, which avoids the exposure of new P adsorption labile sites (Tiecher et al., 2012b). Thus, in the NT system, the phosphate applied quickly saturates the inorganic soil adsorption sites (Rheinheimer et al., 2000b). Nevertheless, the nutrient availability was enhanced only in the surface soil layer 0–5 cm. In the 10–20 cm depth, the available P content was higher in CT than in NT in all winter treatments. The soil layers below 10 cm depth in both soil managements (NT and CT) are below the critical level established by the CQFS-RS/SC (2004). Even the soil layer of 5–10 cm is P deficient in many treatments (Table 5). This shows the difficulty to promote correction of P deficiency in subsurface layers after practicing the NT system, and that this deficiency should be corrected before starting the NT system.

Similar to P, the available K content showed significant interaction among soil management systems, winter treatments and depth. There was no difference in soil available K among the winter cover crops. Nevertheless, compared to the treatments with cultivation of plants in the winter period, the fallow treatment showed lower content of available K in both soil management systems (Fig. 3b). It was also due to the 12 years in which there was no crop grown in winter period, which resulted in a lower amount of biomass produced (Table 2) resulting in a reduced K biocycling. Thus, these results demonstrate the important role of cultivation of winter species over time to maintain the levels of soil available K.

Unlike P, the enhancement of K availability in weathered soils is easily achieved, because this nutrient remains stored in soil cation exchange sites (Bortoluzzi et al., 2005). Generally, K adsorption in these soils is sufficiently strong to avoid the leaching process and sufficiently weak to supply the nutrient to the soil solution. According to the recommendation of the CQFS-RS/SC (2004) in Southern Brazil, the optimum content of available K by Mehlich-I is between 0.15 and 0.31 $cmol_c$ kg^{-1}, and below this range there is a high probability of crop response to K addition. Thus, in both soil management systems (NT and CT) the available K levels in the soil layer of 0–10 cm are adequate to obtain reasonable crop yields in all winter treatments (Fig. 3b), showing that the applied doses (≈40 kg K_2O ha^{-1} for each cash crop) was adequate to maintain high crop grain yields and enhance the K levels, as suggested by Brunetto et al. (2005) in the recommendation system of fertilizing in the states of Rio Grande do Sul and Santa Catarina.

4. Conclusions

As a result of 19 years of no soil disturbance, soil chemical attributes related to soil acidity and the availability of P and K were more favorable to crops growth up to 10 cm in the soil under NT than in the CT. On the other hand, lime applications in low doses on the soil surface were not efficient in neutralizing the aluminum toxicity below 10 cm depth, showing that repeated use of lime on the soil surface under NT system can be a viable alternative strategy only when soil acidity and aluminum toxicity in subsurface have been previously eliminated, using the adequate amount of lime and incorporating it into the arable layer. Moreover, in the CT system P and K availability were higher below 10 cm depth compared to the NT system. Even after 19 years of no soil disturbance in the NT system the available P content below 10 cm soil layer was lower than the optimal content of available P recommended for cash crops. The reduced surface K application over time was sufficient to gain adequate crop yields and to maintain the optimal content of soil available K in both soil management systems.

The effects of soil management systems were predominant on the soil acidity attributes, and no effects of winter cover crops were observed on soil acidity attributes. Black oat and blue lupine were more efficient in P cycling, increasing the soil available P content especially in the surface soil under NT. The lower amount of biomass produced over time when no cover crops were used in the winter period resulted in lower P and K availability in the soil, showing the important role of growing winter species to maintain soil fertility.

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