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Fertilization and tillage effects on soil properties and maize yield in a Southern Pampas Argiudoll

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ABSTRACT

Agricultural management practices, such as tillage and fertilization alter soil physical, chemical and biological properties over the medium term, which has a direct impact on the system's sustainability and crop performance. The aim of this work was to evaluate how fertilization with nitrogen (N), phosphorus (P), sulphur (S), micronutrients (Mi), liming (Li) and tillage systems affect soil properties in the medium term, and to measure the impact of these changes on maize (*Zea mays* L.) yield.

A seven-year experiment on a Typic Argiudoll in the Southern Pampas region of Argentina using seven fertilizations treatments (Control, N P, NS, PS, NPS, NPS + Mi, and NPS + Mi + Li) and two tillage systems – conventional tillage (CT) and no-till (NT) – was evaluated. Each sub-plot was analyzed to determine physical parameters – bulk density (BD) and aggregate stability (AS)-, biological parameters – total organic carbon (TOC), carbon in the particulate fraction (COP), anaerobically incubated nitrogen (AN), total nitrogen (TN) and nitrogen in the particulate fraction (PN) – and chemical parameters – nitrate, available phosphorus, sulphate and pH – at different depths. Also, maize yield was measured in the final year without fertilizer application, in order to evaluate the effects of soil changes on this crop.

Among the physical parameters, the only differences found were in BD between tillage systems in the 0–5 cm layer (1.28 g cm^{-3} in NT and 1.15 g cm^{-3} in CT). Biological parameters were unaffected by fertilization treatments. However, tillage systems modified many of them in the 0–5 cm layer: COT (17 Mg ha^{-1} in CT and 21 Mg ha^{-1} in NT), POC (2.4 Mg ha^{-1} in CT and 4.5 Mg ha^{-1} in NT), TN (1.4 Mg ha^{-1} in CT and 1.8 Mg ha^{-1} in NT), PN (0.3 Mg ha^{-1} in CT and 0.5 Mg ha^{-1} in NT) and AN (56 mg kg^{-1} in CT and 79 mg kg^{-1} in NT). These differences were not significant when the 5–20 cm depth was analyzed. Chemical properties such as pH (5.7 in treatments with N; 6.1 without N, and 6.4 with N and lime) and P Bray content were modified (35 mg kg^{-1} in treatments with P and 13 mg kg^{-1} without P). In both cases, there was interaction with the tillage system, with significant stratification under NT.

Maize yield was only affected by residual P; there were no other effects of medium-term fertilization or tillage systems.

1. Introduction

The Argentinean Southern Pampas region, due to its edaphic and climatic properties, is considered one of the areas with the highest agricultural potential in the world (Satorre and Slafer, 1999). However, the use of intensive crop production and traditional management practices has diminished the physical, chemical and biological properties of the soil (Echeverría and Ferrari, 1993). This degradation process is related, among other factors, to the use of aggressive tillage systems (Steinbach and Alvarez, 2005), while other management practices, such as no-till and fertilization, can counteract this negative trend in temperate regions (Alvarez, 2005).

Nitrogen (N) is the main nutrient limiting crop growth in the Southern Pampas (Echeverría and Sainz Rozas, 2006a,b). As a result, crops respond to N fertilization, mainly by increasing above-ground and root biomass production (Tognetti et al., 2006). This increase leads to more crop residue returned to soil (Studdert and Echeverría, 2000) which, in temperate agro-ecosystems, is considered the main factor controlling total soil organic carbon (TOC) dynamics (Stevenson and Cole, 1999). In a review of published information about Typic Argiudolls, Alvarez (2005) demonstrated that from 20 medium-term experiments (under 10 years) involving N fertilization, 10 showed an increase and six a decrease in TOC compared to unfertilized plots, while four were

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unaffected (Reeder et al., 1998; Varvel, 1994; Fabrizzi et al., 2003). These disparate results are a result of the differences in the balance between the amount of residues returned to soil and their decomposition rate (Khan et al., 2007), and depend on many factors such as the cumulative N applied, rotation, climate and soil texture (Alvarez, 2005). So, the effects of N fertilization on the soil cannot be generalized and must be evaluated in each particular condition.

Also, other soil properties are highly related to TOC content and can therefore also be modified by N fertilizers. These are properties such as bulk density (BD) (Jagadamma et al., 2008), aggregate stability (AS) (Blair et al., 2006) and N mineralization potential (Kolberg et al., 1999; Carpenter-Boggs et al., 2000). Some fertilizers like urea can also reduce soil pH (Liebig et al., 2002; Franzluebbers and Hons, 1996), a process that can be limited by the application of lime (Caires et al., 2005).

Phosphorus (P) is another limiting nutrient for crop production in the Southern Pampas region, where the P Bray level in the soil surface ranges from 10 mg kg^{-1} to 20 mg kg^{-1} (Sainz Rozas et al., 2011). However, the effect of this nutrient on soil properties has never been studied in this area, or in soils with similar characteristics. In an experiment in a semi-arid area with P Bray values similar to those found in the Southern Pampas (13.4 mg kg^{-1}), but with lower TOC (50 Mg ha^{-1} in 0–45 cm soil layer), Purakayastha et al. (2008) determined a 6.3% increase in the average annual root biomass yield generated by cumulative P fertilization. Although this caused an increase of 0.13 Mg ha^{-1} $year^{-1}$ in the estimated C return, the TOC content was not altered. In the same area, Rudrappa et al. (2006) found a slight increase in C fractions between N and N + P treatments. As soils with high C content have a low C storage capacity (Hassink and Whitmore, 1997), we would expect this response to be lower on a Typic Argiudoll.

Although N and P deficiencies are widespread in the area, crops began to respond to nutrients that were not limiting before, for example sulphur (S) (Pagani et al., 2009) and some micronutrients (Sainz Rosas et al., 2003), due to soil degradation. Therefore, fertilization with these nutrients may increase the amount of crop residues returned to soil. However, it was found that S fertilization did not affect TOC in soils with low C content (Mandal et al., 2007; Masto et al., 2007), and there are no reports of its effect on high TOC soils.

Tillage systems also contributed to soil quality reduction in the Southern Pampas (Steinbach and Alvarez, 2005). Among them, conventional tillage (CT) comprises the use of moldboard plowing, disking and field cultivation, and acts aggressively on the soil. However, in the early 1990s no-till (NT) management practices were introduced, and by 2009 this method was used on more than 75% of the Pampas planted area (AAPRESID, 2011). The introduction of NT management leads to changes in soil properties, such as TOC content (Puget and Lal, 2005), AS, BD (Alvarez and Steinbach, 2009), potentially mineralizable N (Fabrizzi et al., 2003), pH and nutrients stratification (Franzluebbers and Hons, 1996). These changes could interact with those produced by fertilization, altering their effect on the soil. For example, Fabrizzi et al. (2003) determined that changes in the TOC caused by N fertilization are more pronounced in the first layer of soil using NT methods.

As soil properties have a direct effect on crop growth and development, variations in yield can be used to detect changes in the edaphic environment. Maize is a crop commonly planted in the area, and it has been found to be sensitive to the changes caused by tillage (Domínguez et al., 2009) and N fertilization (Jagadamma et al., 2008).

Understanding the combined effect of tillage practices and fertilization on soil and crops can help to develop strategies to restore soil quality in the Southern Pampas. To achieve this, information obtained from medium-term experiments is essential, because it not only allows for a comparative assessment between two or more contrasting situations (Larson and Pierce, 1994), but it also provides knowledge about the direction and magnitude of change being generated by a management practice (Wienhold and Halvorson, 1999).

The objective of this study was to determine the medium-term effects of N, P, S, micronutrients and lime application under two different tillage systems (CT and NT) on the physical, chemical and biological properties of a Typic Argiudoll and the response of maize to these changes in the Southern Pampas.

We hypothesized that: (1) medium-term N fertilization alters soil properties, and its effects depend on tillage systems; (2) medium-term fertilization with P, S and micronutrients, and liming do not affect soil properties; (3) maize crop is capable of detecting changes in soil properties caused by tillage and fertilization.

2. Materials and methods

2.1. Site description

The experiment was initiated in 2001 in Balcarce, Argentina (37°45′ S, 58°18′ W; 870 mm mean annual rainfall; 13.8 °C mean temperature) on a Typic Argiudoll which had been farmed for more than 50 years using CT. This soil has a superficial loamy texture (23% clay, 36% silt, 41% sand), 5.8 pH (1:2 soil/water), 32 g kg^{-1} C content, 29 mg kg^{-1} P Bray and 654 mg K^{+} kg^{-1}.

The experiment was designed using a randomized complete block with a split-plot arrangement. The tillage systems used in the main plot were CT (plowing or disking to incorporate the residues into the soil) and NT (chemical weed control and seeding directly into the standing residue); and fertilizers were applied on the split-plot (5 m × 25 m size). Treatments were replicated three times. Seven different fertilization treatments were evaluated: unfertilized (Control), fertilized with N and P (NP), N and S (NS), P and S (PS), N, P and S (NPS), N, P, S and the micronutrients Cu, B and Zn (NPS + Mi), and N, P, S, micronutrients and lime (NPS + Mi + L). The nutrients applied were chosen either because they are commonly deficient in this area – N and P (Melgar, 2005) – or because they are now emerging as limiting factors for grain production due to the depletion of soil organic matter – S (Pagani et al., 2009), Cu, B and Z (Ratto de Miguez and Fatta, 1990). Fertilizer rates were established in order to obtain the maximum yield in each crop in the sequence (Table 1).

The rotation cycle used was the conventional one for the area: maize, soybean (*Glycine max* (L.) *Merr*) and wheat (*Triticum aestivum* L.)/soybean double crop. Maize and soybean were sown in October and November respectively, and both were harvested during April–May. Wheat was planted in June–July and harvested

Table 1
Doses of nutrients (kg ha^{-1}) and fertilizers applied (and lime) in each crop in the sequence.

Nutrient	Dose (kg ha^{-1})			Fertilizer
	Maize	Soybean	Wheat	
N	150	–	120	Urea
P	30	30	30	Triple superphosphate
S	15	15	15	$CaSO_4$
Zn	0.4	1	1	$ZnSO_4$
Cu	–	1	1	$CuSO_4$
B	–	1	–	$Na_2B_4O_7{\cdot}10H_2O$
Lime	600	600	600	$CaMg(CO_3)_2$

at the end of December or early January. Double-cropped soybean was sown immediately after the wheat harvest and was harvested during May. The crop sequence during the first rotation cycle was maize (2001), soybean (2002) and wheat/soybean (2003); the second rotation cycle was wheat/soybean (2004), maize (2005) and soybean (2006), and the third comprised wheat/soybean (2007) and maize (2008). The experiment was irrigated, but only when soil moisture was below the physiological threshold for each crop, thereby compromising its survival. This practice was carried out in 2001, 2002 and 2005 with less than 50 mm of water, and in 2008 with 310 mm spread across the crop cycle, due to the extremely dry conditions.

2.2. Soil sampling and laboratory methods

Composite soil samples were collected in October 2008 from each split-plot, shortly before maize was sown, at different depths: 0–5, 5–20, 20–40 and 40–60 cm. Samples were dried at 30 °C and ground to pass through a 2 mm sieve. Recognizable crop residues on the 2 mm sieve were removed.

Soil BD was measured in two separate layers: 0–5 cm and 5–20 cm using the volumetric cylinder technique (Blake and Hartge, 1986). Sharpened stainless steel core samplers of 5 cm diameter were used to randomly extract four undisturbed soil samples in each plot. Cores were then dried at 100 °C and weighed. BD was calculated as the quotient between the weight of each core and its volume.

Samples to determine AS were delicately taken using a shovel from the whole arable layer (0–20 cm), when soil water content was close to field capacity. Aggregates in the sample were manually fragmented along their planes of weakness to pass a 8 mm sieve, exerting the least possible force, and then dried at 30 °C. Dry samples were sieved through a nest of sieves (4.80, 3.36, and 2.00 mm opening sieves), and a proportion of each dry fraction obtained was wetted and sieved under water through a set of six stacking sieves (4.80, 3.36, 2.00, 0.84, 0.50, and 0.30 mm opening sieves) for 30 min. The change in mean weight diameter (MWD) was calculated as the difference between soil samples sieved in dry or wet conditions (De Boodt et al., 1961). Values of MWD range from 0 to 1, and higher values represent less AS.

Some chemical soil properties were determined at all depths, such as nitrate concentration, using steam microdistillation (Keeney and Nelson, 1982), and sulphate concentration, using the turbidimetric method (Johnson, 1987). Other properties were only measured in the 0–5 and 5–20 cm layers. These were: available P (Bray and Kurtz, 1945) and soil pH (1:2.5 w/w soil-to-water ratio). A soil P balance was determined using historical information from the experiment, where P income was the amount of the nutrient applied as fertilizer each year, and P export in grains was calculated as the product between crop yield and grain P concentration (Walinga et al., 1995). To simplify the analysis of this balance, treatments were grouped as follows: Control, N (NS), P (PS) and NP (NP, NPS, NPS + Mi and NPS + Mi + Li).

For biochemical properties, total organic carbon (TOC), using wet combustion with maintenance of the oxidation reaction temperature (120 °C) for 90 min (Schlichting et al., 1995), and total nitrogen (TN) using dry combustion and N thermo-conductivity detection (LECO, 2010) were determined. Also, soil samples were dispersed with sodium hexametaphosphate (2 N), sieved through a 53 μm and then dried to obtain the mineral-associated fraction of organic matter (Cambardella and Elliott, 1992), where C and N were determined. Particulate organic C (POC) and particulate N (PN) were estimated by subtracting the mineral-associated fraction C and N values from the TOC and TN values respectively. In addition to these properties, potentially mineralizable nitrogen was estimated by the amount of NH_4^+-N recovered from soil samples incubated under anaerobic conditions for seven days at 40 °C (AN) (Waring and Bremner, 1964).

2.3. C input estimation

Every year, grain yield was determined by manually harvesting a 10.5 m^2 surface in each plot at crop maturity. Above-ground crop residues were returned to the soil, something which is a common practice in the area. The amount of C returned to the soil as aboveground biomass, was estimated using yield records for each crop in the rotation, assuming harvest indexes of 0.45 for maize, 0.37 for soybean (Andrade, 1995) and 0.4 for wheat (Studdert and Echeverría, 2000), and a C content of 42% (Sánchez et al., 1996). Root C contribution and root exudates C were calculated according to the ratio of root: aerial biomass proposed by Buyanovsky and Wagner (1997): 0.35 for maize, 0.48 for wheat and 0.38 for soybean. The proportion of the total contribution of root C and root exudates C located in the 0–20 cm depth was considered to be 0.91 for maize, 0.90 for wheat and 0.84 for soybean (Buyanovsky and Wagner, 1986).

2.4. Maize yield determination in 2008–2009 season.

In the last year of the experiment (the 2008–2009 season) no fertilizer was applied to the plots in order to see if the residual effects of fertilization on the soil were evident in the crop. To that end, DK882R maize hybrid was seeded in 70 cm rows at 80,000 seed ha^{-1} on 17 October 2008. Weed control was carried out using herbicide (Glifosate) before sowing. After crop harvest in March 2009, yield was determined and corrected to 14% moisture.

2.5. Statistical analysis

Analysis of variance was performed using SAS PROC MIXED procedure (SAS Institute, 1985) to detect differences among tillage systems and fertilization treatments for all the studied soil parameters, at each respective depth. When a parameter was studied over time, this variable was individually analyzed, year by year, using the same statistical procedure. Effects were considered statistically significant at $p < 0.05$. The Tukey–Kramer test was used to compare treatments means. Other statistical analyzes, as regression analysis, were also performed.

3. Results and discussion

3.1. Biochemical properties

Medium-term fertilization with N, P, S and Mi, and liming did not alter biochemical properties or interact with tillage systems at any depth. However, tillage systems affected all the studied biochemical properties: TOC, POC, TN, PN and AN in the 0–5 cm layer, where NT had higher values relative to CT (Table 2). This trend was described by other authors (Puget and Lal, 2005; Domínguez et al., 2009), and it is explained by a stratification phenomenon, where NT has a higher accumulation of TOC and other related properties in the surface layer, but a lower one in the 5–20 cm layer relative to CT (Murage et al., 2007). Even so, in this study, no difference was detected in the 5–20 cm layer for any of the biochemical parameters (Table 3).

After eight years of experiment, cumulative C input generated by crop residues was not affected by lime or fertilization with S and Mi, while N caused an average increase of 9.7 Mg ha^{-1} relative to Control, and NPS an increase of 3.9 Mg ha^{-1} relative to NS (Table 4). Nevertheless, TOC and POC were not modified by fertilization treatments (Tables 2 and 3).

Table 2
Effect of medium term fertilization and tillage systems on soil properties (0–5 cm). Main effects, interaction and analysis of variance (ANOVA).

Tlillage	Fertilization	BD	TOC	POC	TN	PN	AN	pH	P-Bray
CT	Control	1.18	17.2	3.13	1.48	0.34	48.9	6.00 b	23.3 b
	NP	1.14	17.3	3.20	1.50	0.40	60.4	5.77 cd	57.0 a
	NS	1.14	17.6	2.52	1.49	0.27	58.3	5.80 cd	17.4 b
	PS	1.13	15.3	1.40	1.33	0.22	48.9	5.90 bc	59.5 a
	NPS	1.17	16.8	2.17	1.49	0.35	52.3	5.87 d	52.5 a
	NPS + Mi	1.15	16.2	2.13	1.42	0.29	59.2	5.73 d	54.4 a
	NPS + Mi + Li	1.13	16.9	2.10	1.40	0.27	63.6	6.10 a	49.9 a
NT	Control	1.28	19.9	3.99	1.54	0.36	70.7	6.20 b	24.5 c
	NP	1.27	20.8	4.64	1.65	0.47	73.5	5.77 c	86.9 b
	NS	1.28	21.3	4.66	1.64	0.44	78.3	5.70 c	20.4 c
	PS	1.28	20.2	4.52	1.52	0.43	79.4	6.10 b	103.1 ab
	NPS	1.27	20.1	4.41	1.55	0.43	85.2	5.73 c	104.3 ab
	NPS + Mi	1.25	21.3	4.53	1.67	0.47	80.3	5.70 c	96.0 b
	NPS + Mi + Li	1.30	20.9	5.08	1.67	0.55	85.3	6.60 a	117.7 a
	CT	1.15 b	16.8 b	2.38 b	1.44 b	0.31 b	55.9 b	5.88	44.9
	NT	1.28 a	20.6 a	4.55 a	1.61 a	0.45 a	79.0 a	5.97	79.0
	Control	1.23	18.5	3.56	1.51	0.35	59.8	6.10	23.9
	NP	1.21	19.1	3.92	1.57	0.43	67.0	5.77	72.0
	NS	1.21	19.5	3.59	1.57	0.36	68.3	5.75	18.9
	PS	1.21	17.8	2.96	1.43	0.32	64.1	6.00	81.3
	NPS	1.22	18.4	3.29	1.52	0.39	68.8	5.80	78.4
	NPS + Mi	1.20	18.8	3.33	1.55	0.38	69.7	5.72	75.2
	NPS + Mi + Li	1.22	18.9	3.59	1.54	0.41	74.4	6.35	83.8
	ANOVA								
	Tillage	*	*	*	*	*	*	*	*
	Fertilization	ns	ns	ns	ns	ns	ns	*	*
	T × F	ns	ns	ns	ns	ns	ns	*	*
	VC %	2.9	5.9	31.2	6.9	26.1	12.2	1.6	34.8

BD, bulk density ($Mg\,m^{-3}$); TOC, total organic carbon ($Mg\,ha^{-1}$); POC, particulate organic carbon ($Mg\,ha^{-1}$); TN, total nitrogen ($Mg\,ha^{-1}$); PN, particulate nitrogen ($Mg\,ha^{-1}$); AN, anaerobically incubated nitrogen ($mg\,N\,kg^{-1}$); P-Bray, available P ($mg\,kg^{-1}$); VC%, variation coefficient.
* Significant difference ($p < 0.05$).

Table 3
Effect of medium term fertilization and tillage systems on soil properties (5–20 cm). Main effects, interaction and analysis of variance (ANOVA).

Tillage	Fertilization	BD	TOC	POC	TN	PN	AN	pH	P-Bray
CT	Control	1.27	50.6	3.10	4.38	0.68	51.2	6.13	12.2
	NP	1.28	51.9	3.63	4.50	0.49	45.1	5.97	24.3
	NS	1.28	54.6	4.89	4.76	1.01	51.7	6.03	10.2
	PS	1.31	47.5	3.21	4.06	0.32	48.1	6.03	25.7
	NPS	1.27	50.7	2.38	4.33	0.83	45.6	6.03	34.0
	NPS + Mi	1.33	48.2	2.95	4.21	0.58	46.3	6.00	19.4
	NPS + Mi + Li	1.29	35.5	2.70	3.98	0.67	51.4	6.20	17.5
NT	Control	1.31	50.7	2.72	4.64	0.92	45.9	6.03	10.5
	NP	1.32	51.1	4.04	4.54	0.64	42.4	5.80	15.3
	NS	1.30	50.4	3.19	4.59	0.88	46.8	5.93	9.5
	PS	1.28	49.9	2.96	4.35	0.67	41.1	6.00	18.1
	NPS	1.31	48.9	4.18	4.32	0.74	41.1	5.93	17.6
	NPS + Mi	1.26	52.0	5.14	4.50	0.77	45.0	6.03	16.8
	NPS + Mi + Li	1.29	51.0	3.96	4.38	0.71	43.2	6.10	19.4
	CT	1.29	48.4	3.26	4.32	0.65	48.5	6.06	20.48
	NT	1.30	50.6	3.74	4.47	0.76	43.6	5.98	15.32
	Control	1.29	50.7	2.91	4.51	0.80	48.6	6.08 ab	11.3 b
	NP	1.30	51.5	3.83	4.52	0.56	43.7	5.88 b	19.8 a
	NS	1.29	52.5	4.04	4.67	0.94	49.3	5.98 b	9.9 b
	PS	1.30	48.7	3.09	4.21	0.50	44.6	6.02 b	21.9 a
	NPS	1.29	49.8	3.28	4.32	0.79	43.4	5.98 b	25.8 a
	NPS + Mi	1.30	50.1	4.04	4.35	0.68	45.7	6.02 b	18.1 a
	NPS + Mi + Li	1.29	43.3	3.33	4.18	0.69	47.3	6.15 a	18.5 a
	ANOVA								
	Tillage	ns	ns	ns	ns	ns	ns	ns	ns
	Fertilization	ns	ns	ns	ns	ns	ns	*	*
	T × F	ns	ns	ns	ns	ns	ns	ns	ns
	VC %	2.9	13.4	52.5	7.1	49.1	12.7	2.0	28.3

BD, bulk density ($Mg\,m^{-3}$); TOC, total organic carbon ($Mg\,ha^{-1}$); POC, particulate organic carbon ($Mg\,ha^{-1}$); TN, total nitrogen ($Mg\,ha^{-1}$); PN, particulate nitrogen ($Mg\,ha^{-1}$); AN, anaerobically incubated nitrogen ($mg\,N\,kg^{-1}$); P-Bray, available P ($mg\,kg^{-1}$); VC%, variation coefficient.
* Significant difference ($p < 0.05$).

Table 4
C input (Mg ha^{-1}) in different medium term fertilization treatments.

	C input (Mg ha^{-1})
Control	44.9 c
NP	55.0 a
NS	51.1 b
PS	46.3 c
NPS	54.6 a
NPS + Mi	55.8 a
NPS + Mi + Li	54.7 a

The high frequency of soybean in the crop rotation may be a cause of the lack of response to N because as this crop does not need to be fertilized with this nutrient, the cumulative dose applied is reduced. However, this hypothesis can be rejected because other authors in the area found no response using either crop rotation with a low frequency of soybean (Fabrizzi et al., 2003) or without it (Domínguez et al., 2009).

Local results show that N fertilization can enhance TOC content in degraded soils, but not in non-degraded ones (Fabrizzi et al., 2003), because soils close to TOC saturation have a low storage capacity (Hassink and Whitmore, 1997). However, initial TOC concentration in this essay (32 g kg^{-1}) was far from the one observed in pristine soils from the area (45 g kg^{-1}) (Sainz Rozas et al., 2011). So, the soil could still have the potential to increase its C content. On the other hand, the additional C input generated by N fertilization (ΔC = 9 Mg ha^{-1} among the average of N fertilized plots and Control) is minimal compared to the TOC content at the beginning of the experiment (78 Mg ha^{-1}). Even if the stabilization efficiency of this additional C input had been 100%, TOC concentration would only increase by 3.76 g kg^{-1}. Therefore, it is reasonable to state that the lack of response of this property to N fertilization is caused by a dilution of the C supplied by residues into the soil's larger pool, rather than a saturation of its storage capacity. Using the same reasoning, if there was no response to N, it is logical to find no response to those treatments that caused a lower enhancement in C input (P) or that did not affect it (S, Mi and Li).

The increase in C and N fractions in NT relative to CT in the 0–5 cm layer (Table 2) was 19% for TOC, 48% for POC, 10% for TN and 32% for PN. The C:N ratio averaged 11.3 $\pm$ 0.8 and 12.8 $\pm$ 0.8 for the total and mineral-associated organic fraction respectively for all depths. These C:N ratios agree with those reported by Domínguez et al. (2009) and Fabrizzi et al. (2003). In contrast, the values observed in the particulate fraction where lower than expected: 6.2 $\pm$ 2.1 at 0–5 cm and 5.3 $\pm$ 2.6 at the 5–20 cm layer. As this fraction is more dynamic than the others, it should have a higher C:N ratio. This incongruence may be explained by the high variability caused by the experimental method used for this fraction separation.

The improvement in the AN level in the 0–5 cm layer under NT (Table 2) could be caused by a higher TN content resulting from the conservation of active or passive fractions of the organic matter (Franzluebbers et al., 1994), or by a reduction in the C:N ratio that accelerates N turnover (Paustian et al., 1992). Since the C:N ratio did not change, and TN and PN content were higher in NT, the improvement in N mineralization potential can be explained by the first process. Also, a significant positive relationship between N fractions and AN was determined. The higher coefficient was obtained when PN was used as a regressor (R^2 = 0.68). In contrast, values were lower when TN or N associated with the mineral fraction was used (R^2 = 0.51 and R^2 = 0.08 respectively). This trend was expected since the particulate fraction is more dynamic and has a higher mineralization rate, and therefore is more relevant to soil fertility (Cambardella and Elliott, 1992). Some authors described a similar coefficient between AN and PN (R^2 = 0.67) (Sharifi et al., 2007) while others, using a wider range of conditions, obtained a higher one (Fabrizzi et al., 2003).

3.2. Physical properties

Due to the lack of disturbance, BD was significantly higher in NT over CT (1.28 $\pm$ 0.06 and 1.15 $\pm$ 0.05 Mg m^{-3} respectively) in the 0–5 cm layer (Table 2). These results agree with the findings of other authors in the same zone (Fabrizzi et al., 2005; Aparicio and Costa, 2007). However, this trend was not observed in the 5–20 cm layer (Table 3), indicating that the effect of the mechanical disturbance is just superficial. There was no difference in BD caused by fertilization treatments in any soil layer (Tables 2 and 3).

No statistical difference in AS was found between tillage systems or fertilization. However, the AS expressed as MWD was 24% higher under CT (0.78 $\pm$ 0.14 in NT and 0.63 $\pm$ 0.07 in CT). This lack of response to management practices can be explained by the results found for TOC. This biochemical property is a crucial factor in soil stabilization, as it increases inter-particle cohesion within aggregates and their hydrophobicity (Abiven et al., 2009). Although the TOC varied between tillage systems, this difference was only observed on the surface, and was not significant in the full arable layer where AS was measured. Moreover, the impact of increased C input over AS is lower in soils with high TOC content (Fortun et al., 1996), such as those found in the Southern Pampas.

3.3. Chemical properties

A significant interaction in soil pH, between fertilization treatments and tillage systems, was determined in the first 5 cm of the soil (Table 2). Under NT, plots not fertilized with N (Control and PS) had higher values than those with a history of N fertilization. The difference between these two groups of treatments was 0.23 units under CT and 0.42 under NT. These results agree with those of Fabrizzi et al. (1998), who found a reduction of 0.39 units after eight years applying 120 kg N ha^{-1} in NT. However, when N was applied with lime this trend was reversed and the pH was even higher than the one observed in the Control. Under the NT system, because the soil is not disturbed, the effect of N fertilizer is accumulated in the surface layer, generating a pH gradient through soil depth, and a higher contrast among treatments. Under CT, the tendency was the same, but as the arable layer was mechanically mixed, the differences were not so clear. In the 5–20 cm layer, tillage systems did not affect pH, and the NPS + Mi + Li did not differ from the Control (Table 3).

The increase in soil pH caused by liming was 0.49 units in CT and 0.88 in NT for the surface layer, and 0.2 at 5–20 cm for all tillage systems. This agrees with the concept that soil acidity correction is lower as the depth increases, when lime is applied on the surface of the soil (Caires et al., 2005). This happens because alkalinity must be transported from the surface by mass flow to lower layers, in the form of HCO_3^- or OH^- (Sumner, 1995). The differences in soil pH correction among tillage systems can be explained by the fact that under NT the lime accumulates on the surface. In contrast, as soil is mixed in CT, the liming effect reaches a higher depth, but it is also diluted by the higher soil volume. So, the difference is not significant at 5–20 cm.

Even surface pH in N fertilized plots was close to the theoretical threshold for plants and micro-organism development (pH = 5.5) (Brady and Weil, 1999); below 5 cm, soil pH values were close to the optimum values. Therefore, soil acidification should not be considered an immediate problem, but a potential one. There are reports of yield increases in alfalfa (*Medicago sativa* L.) in the area due to liming (Vazquez et al., 2010), but there is no published information about the effect of this practice on crops.

Table 5
Nitrate and sulphate content in soil profile before 2008–2009 sowing. Average between tillage systems and fertilization treatments.

Depth (cm)	N-NO_3^- (kg ha^{-1})	S-SO_4^{2-} (kg ha^{-1})
0–5	19.1 ± 3.4[a]	3.5 ± 0.7
5–20	25.3 ± 3.9	8.2 ± 1.5
20–40	17.0 ± 2.7	10.6 ± 3.1
40–60	12.9 ± 3.1	10.7 ± 3.4
Total	74.4 ± 9.5	32.8 ± 5.7

[a] Average ± standard deviation.

At the beginning of the 2008–2009 season, nitrate and sulphate content were not affected by medium-term fertilization or tillage (Table 5). This result does not agree with those obtained by Alvarez and Steinbach (2009). They analyzed data from 35 essays in the Central Pampas zone and found an increase in nitrate content before sowing of 21 kg ha^{-1} under CT compared with NT. This behaviour was explained by the higher nutrient mineralization in CT. However, the high precipitation in the months prior to soil sampling may have caused N losses by leaching (423 mm between 2007 double cropped soybean harvest and 2008 soil sampling). This process is the main cause of N losses in the Southern Pampas region, where up to 22% of the N applied as urea at a rate of 140 kg ha^{-1} was leached beyond the soil rooting profile (Sainz Rozas et al., 2004).

P Bray concentration in the 0–5 cm layer was affected by fertilization and tillage systems, with interaction between them (Table 2). Those plots that were never fertilized with this nutrient (Control and NS) showed lower levels of available P. Under CT, average concentration was 2.7 times higher in fertilized plots, and 4.5 times higher under NT. As P is highly retained by the soil matrix, its mobility is reduced and it tends to accumulate at the surface if mechanical mixture is not used (Hussain et al., 1999). In agreement with Hussain et al. (1999), no difference between tillage systems was found at the 5–20 cm layer (Table 3). At this depth, the trend of P Bray among fertilization treatments was the same as in the 0–5 cm layer.

Under NT and in the surface layer, the NPS + Mi + Li treatment had a P Bray concentration slightly higher than the one in the other P-fertilized plots (12 mg kg^{-1} difference). This situation coincides with a pH increase of 0.77 units. A relationship between available P, pH and liming was determined by other authors (Haynes, 1982; Naidu et al., 1990). This phenomenon is explained by the fact that available P in soil is controlled by sorption and desorption processes and, as pH increases, the electrostatic charge of those surfaces capable of sorbing it is reduced (Barrow, 1984). Therefore, the affinity to the phosphate ion is limited and so it remains in available forms.

If the P Bray concentration (mg kg^{-1}) is calculated as a pondered average in the entire arable layer (0–20 cm), the value determined for treatments never fertilized with P (13 mg kg^{-1}) can be compared with the critical threshold for crops in the region: 20 mg kg^{-1} for wheat (García et al., 2006), 16 mg kg^{-1} for maize (Echeverría and Sainz Rozas, 2006a,b), and 9 mg kg^{-1} for soybean (García et al., 2006). So, it is expected to find yield response in all the crops involved in the sequence analyzed, except for soybean.

In order to understand the P accumulation in soil during the experiment, it is important to study the historic P balance in the system. As the P-fertilizer rate was always 30 kg ha^{-1}, all variations in the balance were caused by plant extraction. Accumulated balance was similar under NT and CT. P-fertilized treatments (P and NP) had a linear increase of approximately 10 kg ha^{-1} year^{-1}, while unfertilized plots decreased at a 19 kg ha^{-1} year^{-1} rate (Fig. 1). The extraction of P was higher in N plots relative to the Control, due to the increase in crops yield.

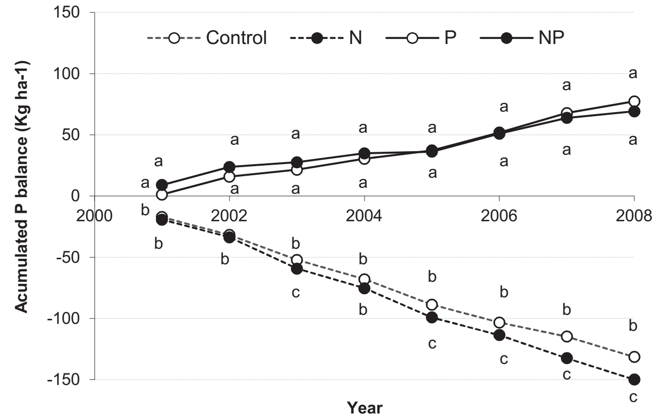

Fig. 1. Phosphorus accumulated balance in different fertilization treatments (Control, N, P and P) and tillage systems (NT and CT). Different letters indicate differences among treatments in the same year.

Although the P Bray concentration tended to increase with time, it suffered fluctuations and did not show the clear trend of the balance (Fig. 2). In the second year (2002), no difference between treatments was detected, and values were lower than the originals. The balance was positive that year, but it must be considered that P-fertilizers recuperation efficiency in soils of the area is lower than 10% (Divito et al., 2010). Then, crop extraction exceeded the income generated by the fertilizer and available P tended to decrease. From the third year onwards, fertilized treatments increased linearly their available P concentration ($y = 1.46x + 18.33$; $R^2 = 0.53$) due to annual and residual fertilization. Other authors (Dodd and Mallarino, 2005; Zhang et al., 2004) determined closer relationships between time and available P improvement. However, these results were obtained in monoculture systems or simpler crop sequences, and in areas with a higher climatic stability. Then, P extraction by crops was similar each year, stabilizing the tendency.

Available P in those treatments never fertilized with this nutrient (Control and N) decreased in the first four years of the experiment, and then tended to stabilize in values close to 12 mg kg^{-1}. This happens because below a certain level, available P is maintained by organic P mineralization, sorption and desorption of inorganic P, and P cycling from lower layers that returns to the surface through vegetal residues (Zhang et al., 2004). Similar results were determined in the zone by Berardo et al. (1997) and Divito et al. (2010). In contrast to the trend observed in P balance, no statistical difference was observed between N and Control

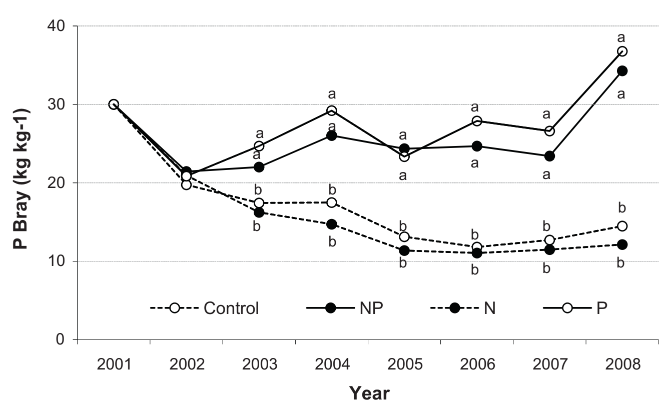

Fig. 2. Available P (P Bray) annual evolution in different fertilization treatments (Control, N, P and NP) and tillage systems (NT and CT). Different letters indicate differences among treatments in the same year.

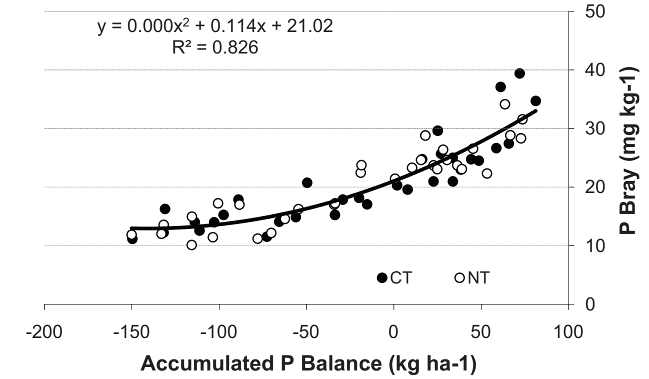

Fig. 3. Available P (P Bray) concentration as a function of accumulated P balance under different tillage systems (NT and CT).

treatments. However, P Bray concentration always tended to be lower in N plots.

When the accumulated P balance of previous crops was related to P Bray concentration measured before sowing the following year, a quadratic function was determined (Fig. 3). Available P tended to stabilize when the balance was lower than -100 kg ha^{-1}, while it rose if the balance was positive, due to the accumulation of P in readily available inorganic forms (Picone et al., 2007). Also, when P balance values were higher, P Bray concentration increased at a higher rate, because soil became saturated with P and the possibility of this nutrient to be sorbed was reduced (Rubio et al., 2008). This relationship was independent of the tillage system.

3.4. Maize response to soil properties modification

During the 2008–2009 growing season, incident radiation and temperature were similar to the historic data. However, accumulated rainfall (308 mm) was just 54% with respect to the historic average (576 mm). Even though complementary irrigation was applied during November and December (340 mm), soil moisture was below the physiological threshold during the critical period for maize.

Tillage systems did not alter maize yield. In the Argentinean Pampas, tillage systems affect yield mainly by altering water and nitrate content in soil (Alvarez and Steinbach, 2009). As the experiment was carried out in a humid region complemented by artificial irrigation, and there were no differences in nitrate accumulation at sowing, or noticeable changes in potentially mineralizable N, it is logical not to find response to tillage systems.

There were differences in maize yield between plots with different fertilization treatments in previous years but unfertilized during the 2008–2009 season (Fig. 4). This proves that there is a medium-term effect of this practice on crops. Lower values were observed in Control and NS, where the P Bray concentration in soil was lower (three and four times lower, respectively) than the average of the plots fertilized with P. There were no effects on yield from the medium-term application of N, S, micronutrients and lime. Considering that these treatments have not produced changes in the physical and biochemical soil properties and that, among the affected chemical properties, pH values did not reach pernicious values for plant growth and development, it is logical to conclude that the only soil property that affected crop yield was available P concentration. The residual effect of P-fertilizers caused an average 1000 kg ha^{-1} increase in maize yield, which is in line with the general improvement in yield in the area, 800 kg ha^{-1}, generated by P (Hernán Echeverría, personal communication, 2011). P-Bray in the arable layer (0–20 cm) correlated significantly with yield (Fig. 5), but the correlation coefficient was low, probably because other factors, such as N deficiency, were limiting.

3.5. Results integration

Medium-term fertilization with N, P, S and Mi, and liming did not affect TOC content in the soil. Although the effect of N has already been studied in the area, with divergent results (Fabrizzi et al., 2003; Alvarez, 2005), the lack of response of TOC to P, S, Mi and lime represents an original contribution of this work.

Due to the high association between TOC and other soil properties (BD, AS and AN), it is reasonable to observe that they were also not altered by fertilization, and that the only detectable effects were direct: an increase in available soil P, due to P accumulation in the soil matrix, and a reduction in soil pH caused by N fertilization. Tillage systems interacted with these two properties, basically altering their distribution in the soil profile. Moreover, this management practice also altered physical properties (BD) and biochemical properties (TOC, POC, TN, PN), but only in the surface layer. These results agree with those of other authors (Fabrizzi et al., 2005; Domínguez et al., 2009).

Changes in soil properties generated by the use of fertilizers, lime and tillage systems did not affect maize yield (except for available P, which produced an average increase of 1000 kg ha^{-1}). However, the acidification in soil caused by N fertilizers is close to the theoretical threshold for plant and micro-organism development. It is, therefore, important to continue studying this trend for a longer period, in order to detect future effects on crop growth and development. The annual application of low doses of lime proved

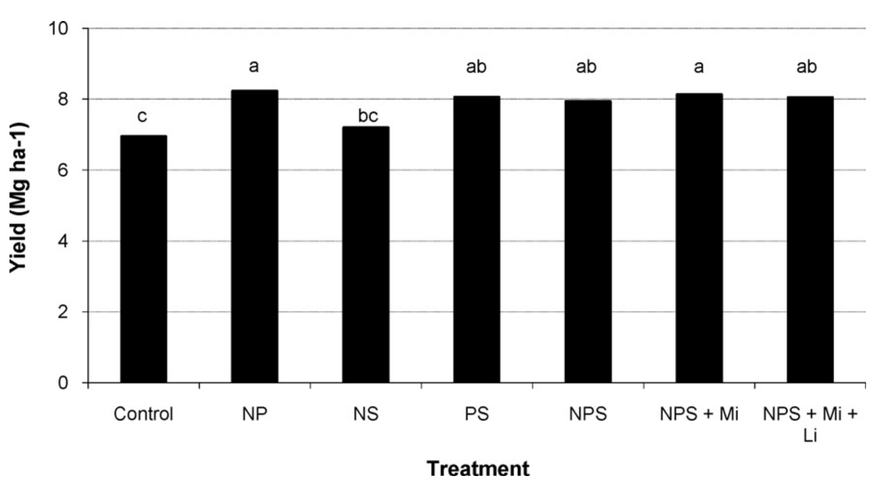

Fig. 4. Maize yield under different fertilization treatments not applied during that season (2007–2008).

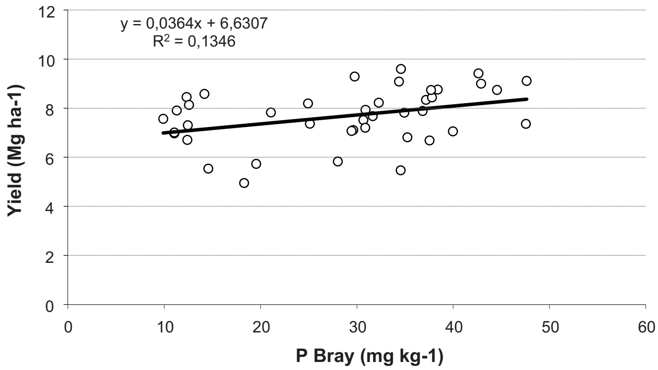

Fig. 5. Relationship between soil P Bray concentration in plots unfertilized during 2007–2008 season and yield.

to be an effective strategy to avoid acidification without altering other soil properties.

4. Conclusion

Contrary to the hypothesis, the medium-term use of N fertilizers did not affect any physical or biochemical property of a Typic Argiudoll in the Southern Pampas region under a crop rotation involving maize, soybean and wheat, but did cause soil acidification. Nor did the application of P, S, micronutrients and lime affect soil properties, except for an increase in soil available P.

Tillage systems interacted with both chemical properties affected by medium-term fertilization (P Bray and pH), basically altering their distribution in the soil profile. They also affected physical and biochemical properties, but only in the surface layer.

The magnitude of the changes generated by fertilization and tillage systems was not sufficient to generate maize response, except for available P. However, if the tendency of soil acidification continues, it may compromise soil health.

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