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Research Article

Soil Phosphorus Dynamics of Wheat-Based Cropping Systems in the Semiarid Region of Argentina

Liliana Suñer,^{1,2} Juan Galantini,¹ and Gabriela Minoldo²

¹ Comisión de Investigaciones Científicas (CIC), CERZOS-UNS, 8000 Bahía Blanca, Argentina

² Departamento de Agronomía, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina

Correspondence should be addressed to Liliana Suñer; lsuner@criba.edu.ar

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The dynamics of soil P forms and particle size fractions was studied under three wheat-based cropping sequences in production systems of Argentina. The whole soil and its coarse (100–2000 μm) and fine (0–100 μm) fractions were analyzed to determine Bray-Kurtz extractable (Pe), organic (Po), inorganic (Pi), and total (Pte) phosphorus. The reference soil was determined at time 0 and compared to a four-year period (time 9 to 12) in three crop sequences: wheat (*Triticum aestivum* L.)-cattle grazing on natural grasses (WG), continuous wheat (WW), and wheat-legume (WL). Levels of Pe showed differences over time, from 10 to 16 $\mu\text{g g}^{-1}$ in WG, in line with agriculture and cattle grazing alternate sequences. In WW, P level increased with time, while in WL systems a significant decrease in P from 33.7 to 10.4 $\mu\text{g P g}^{-1}$ was found during the legume period. Soil P values varied between reference soil and soil samples in year nine and between treatments. Pi was significantly lower in WW, and its concentration increased with time. The coarse fraction of the reference plots had significantly higher levels of Po and Pi than the cultivated treatments, probably a consequence of the particulate organic matter decomposition and coarse mineral particle weathering. The observed changes in Pi content could be attributed to differences in occluded P equilibrium under different soil environments (mainly pH) and crop-tillage-climatic interaction.

1. Introduction

Plants absorb mainly inorganic phosphorus (Pi) but the organic phosphorus (Po) is also an important reservoir for plant nutrition [1, 2]. Several studies have reported reduction in soil organic P fraction during crop growth [3, 4]. The Po can be found in chemically or physically protected forms, which can be slowly mineralized into available forms for plant uptake, mainly as a product of soil organic matter (SOM) decomposition or by the action of specific enzymes [5, 6]. A continuous loss of the soil P reservoir due to crop harvesting can rapidly consume Po and Pi forms [5, 7, 8], which may eventually lead to plant P deficiencies.

Several soil studies have shown P deficiencies in the semiarid and semihumid regions of Argentina, and that extractable P content is lower due to soil pedogenetic characteristics and the agricultural history of the region [9–11]. Agricultural and cattle breeding systems of the semiarid Pampas region revealed negative P balances [12]. While P in the soil has been widely studied, little information is

available on its organic fractions [13]. In the western area of the Province of Buenos Aires, Po represents between 29% and 51% of the total P reserve [14]. Soil total phosphorus (Pt) reserve from the soil largely exceeds crop requirements, however plants could suffer deficiencies. Thus, the ability of soils to provide P can be variable. While soil Pt content in the soil may be relatively high (200 to 5000 $\mu\text{g g}^{-1}$; [8, 15]) only a small and variable fraction is available for crops. This may vary from 5 to 20 $\mu\text{g P g}^{-1}$ in Pampaeian soils [10]. However deficiencies do not take place when the soils contain adequate quantities of plant-available or rapidly usable P forms (such as fertilizers or labile organic P compounds).

McKenzie et al. [16] found that the wheat (*Triticum aestivum* L.)-fallow sequence was the most effective for P mineralization. When a legume crop was added to the cropping rotation, soil Pi values decreased [17]. Some studies [18, 19] quantified soil Po and Pi contents in the soils, others analyzed their dynamics over time [8], but little information is available about their distribution in different soil particle sizes and their relationship with the available P.

The P compounds strongly bound to soil fine fraction have been shown to be unaffected by tillage treatments [14, 20]. Phosphorus in the coarse fraction, however, sharply decreases due to cultivation. Results of these studies suggested that the greater decomposition of the SOM in the coarse fraction facilitated availability of Po and Pi for subsequent crops. Particle size fractions of SOM may help characterize nutrient dynamics and soil quality status [6]. Understanding Po dynamics within the soil system is useful to assess P availability and to avoid excessive fertilization with undesirable environmental consequences [21, 22]. In addition, quantification of P mineralization in different environment-management conditions will allow the inclusion of true data in the simulation models [23].

When organic and inorganic phosphorus are determined, in both fine and coarse fractions, it will expect that Po content in the coarse fraction would be the most sensitive to crop-tillage management changes. This Po is associated with particulate organic matter, a labile SOM fraction. However, Pi content in the coarse fraction would be more stable because of its relationship with sand size. On the other hand, Po content in the fine fraction would be stable because of its relationship with humified organic materials, while the Pi content would be more strongly linked to plant P availability due to its relationship with fine size minerals of soil.

We hypothesized that crop sequences can modify the P distribution within different soil particle sizes, affecting its availability for plants. The main objective of this study was to evaluate the changes caused by different wheat-based cropping sequences on the distribution of P forms in particle size fractions in an entic Haplustoll of the semiarid Pampas.

2. Materials and Methods

This study was carried out at the Agricultural Experimental Research Station of INTA, Bordenave (63° 01' 20" W and 37° 51' 55" S), Province of Buenos Aires, Argentina. The climate in this area is temperate (continental moderated), with a mean annual temperature of 15°C. Mean annual rainfall is about 667 mm (1928–2013), concentrated in autumn and spring, with a dry period at the end of the winter and semidry period in the middle of summer. During the studied period mean annual precipitation was around 900 mm. Mean annual evapotranspiration rate is 28% more than the climatic offer. The main soil subgroup is entic Haplustoll (FAO: Haplic Kastanozem), which is a thermal, sandy loam, typically of this region, which has low to medium fertility and is sensitive to wind erosion, with a calcareous layer located between 0.8 and 1.0 m in depth [24]. Three cropping sequences were established on 12 ha of pasture land in 1983. They included:

- (i) WG, one year wheat and one year cattle grazing on natural grasses (*Lolium* sp., *Avena* sp., and other weeds). Wheat was in conventional tillage: short or without fallow; disk plough (0.15–0.20 m) and harrowing; regular seeding at 4–5 cm deep.
- (ii) WW, continuous wheat. Following harvest, there was a 4–6-month fallow (January–June) under stubble mulch used for soil moisture storage, mechanical

TABLE 1: Crop sequences in the studied production systems and mean annual rainfall.

Years from the beginning	WG	WW	WL	Annual rainfall (mm)
0				
1	Grass/oat	Wheat	Wheat	683.7
2	Wheat	Wheat	Wheat	998.1
3	Grass/oat	Wheat	Wheat	965
4	Wheat	Wheat	Red clover	611.9
5	Grass	Wheat	Red clover	781.8
6	Wheat	Wheat	Red clover	647.1
7	Grass	Wheat	Wheat	697.1
8	Wheat	Wheat	Wheat	612
9	Grass	Wheat	Wheat	1194.7
10	Wheat	Wheat	Red clover	1108.3
11	Grass	Wheat	Red clover	678.9
12	Wheat	Wheat	Red clover	641.6

Wheat (*Triticum aestivum*); red clover (*Trifolium repens*).

weed control using chisel ploughing to a depth of 0.20 m preceded wheat deep-furrow seeding, which deposits the seed 8–10 cm deep.

- (iii) WL, 3 years of wheat and 3 years of red clover (*Trifolium repens*). Tillage was the same as WW rotation.

Crop sequence for each cropping system is shown in Table 1. A reference (Ref) plot adjacent to treatments was maintained with native grasses for over 25 years. Fertilizers were not applied in any of the rotations.

Surface soil samples (0–15 cm depth) were obtained after wheat growing cycle during November of each sampling year; 3 subsampling points were located using GPS for subsequent sampling. Three blocks were randomly located in the three production systems and in reference soil; three composite samples consisting of three soil sample each were obtained from each block. Soil texture differences were not observed between different blocks or treatments, with mean values for clay and silt of 101 and 218 g kg⁻¹, respectively. The samples were returned to the lab, air dried, sieved (<2 mm), and stored for analysis. Soil was sampled 9 years after initiating crop rotations and the subsequent years.

2.1. Soil Chemical Determinations. Soil pH with a glass electrode at a 1:2.5 water ratio [25], total soil organic carbon (SOC) by dry combustion (LECO carbon analyzer), and the following P forms were determined:

- (i) extractable (Pe) by Bray-Kurtz 1 [26]: extraction with hydrochloric acid (HCl) 0.025 M and ammonium fluoride (NH₄F) 0.03 M (pH 2.9), soil/solution ratio 1:7, shaking time 1 min; this method is indicated for soils with neutral to slightly acidic pH [27];
- (ii) total extractable (Pte), [28] with a perchloric acid digestion to 270°C;
- (iii) total (Pt) with sodium carbonate [29]; 0.1–1 g sample is fussed in sodium carbonate (Na₂CO₃) to 900°C

TABLE 2: Soil organic carbon (SOC), organic (Po), inorganic (Pi), total extractable (Pte), total and extractable phosphorus (Pe), Po : (Po + Pi) relationships, and pH of different cropping systems (CS).

Year	CS	SOC %	Po mg kg ⁻¹	Pi mg kg ⁻¹	Po : (Po + Pi)	Pte	Pt mg kg ⁻¹	Pe	pH
0	Ref	1.28	189.0	328.0	0.37	529.0	562.1	30.9	6.7
	WG	1.13 ^{a*}	77.7 ^{a**}	294.7 ^{a*}	0.20 ^{a**}	289.6 ^{b**}	412.2 ^{b*}	14.3 ^{b**}	6.8 ^a ns
9	WW	0.89 ^{b**}	50.4 ^{b**}	172.0 ^{b**}	0.22 ^{a**}	230.0 ^{b**}	396.3 ^{b*}	11.7 ^{b**}	6.6 ^b ns
	WL	1.14 ^{a*}	82.2 ^{a**}	290.5 ^{a*}	0.22 ^{a**}	417.3 ^{a*}	456.3 ^{a*}	33.7 ^a ns	6.6 ^b ns
	WG	1.08 ^a	133.7 ^a	231.1 ^a	0.37 ^a	396.7 ^a	418.0 ^a	10.2 ^b	6.4 ^{ab}
10	WW	0.84 ^b	75.5 ^b	159.0 ^b	0.33 ^b	344.1 ^b	378.2 ^{ab}	13.1 ^b	6.3 ^b
	WL	1.11 ^a	107.3 ^{ab}	230.5 ^a	0.32 ^b	339.7 ^b	362.1 ^b	21.2 ^a	6.5 ^a
	WG	1.07 ^a	86.7	217.5 ^b	0.38 ^a	350.2 ^a	440.0 ^a	15.7 ^b	6.3 ^a
11	WW	0.85 ^b	84.0	176.3 ^c	0.32 ^b	316.8 ^b	407.2 ^a	18.8 ^b	6.3 ^a
	WL	1.12 ^a	81.5	245.7 ^a	0.33 ^b	289.7 ^b	328.4 ^b	26.0 ^a	6.1 ^b
	WG	1.16 ^a	85.4	218.1 ^b	0.28 ^a	343.0 ^a	420.0 ^a	11.6 ^b	6.4 ^a
12	WW	0.95 ^b	65.7	233.7 ^{ab}	0.22 ^b	365.2 ^a	411.3 ^a	27.2 ^a	6.1 ^b
	WL	1.27 ^a	78.3	250.2 ^a	0.24 ^b	280.1 ^b	321.6 ^b	10.4 ^b	6.2 ^b

**, * and ns indicate statistical differences $P < 0.01$, $P < 0.05$ and not significant, respectively, between each treatment sampled in year 9 and reference soil. For SOC, each P form and pH, different letters indicate differences among treatments in each year.

followed by disintegration of the melt in chlorhydric acid (HCl);

- (iv) and organic (Po) and inorganic (Pi) by Saunders and Williams [30] method extraction with sulphuric acid (H_2SO_4) 1 N, shaking time 16 hours; Po is determined by difference between a calcined soil sample (in muffle to 550°C) and another one without calcine.

Inorganic P in all extracts was determined by the ammonium vanadate colorimetric method [31]. All these methods are fully described in Sparks [32].

2.2. Soil Physical Determinations. For the size fractionation of soil, we used the wet sieving of soil [33, 34]. Briefly, 50 g of soil previously air-dried and sieved (2 mm) was dispersed in glass containers of 120 mL and mixed with 100 mL of distilled water. Ten glass beads (5 mm diameter) were added to increase aggregate destruction and reduce potential problems created by different content of sand [33]. The samples were subjected to mechanical dispersion through a rotary shaker for approximately 16 h (overnight at 40 rpm) to disintegrate the aggregates. The sieving was done with a sieve of 140 mesh, making moves back and forth until the water coming out through the sieve was clear to the naked eye. Two particle size fractions were obtained: the fine fraction (0–100 μm) and the coarse (100–2000 μm), both fractions were oven-dried at 65°C. The fine fraction contained clay, silt, very fine sands, and humified or mineral associated organic matter (MOM). The coarse fraction had sand and less transformed, young, or particulate organic matter (POM). The same chemical methods above were also applied to determinate Pte, Po, and Pi in both fractions. Pe was not determinate in the fractions because physical separation of the particles could wash some available P forms [20].

2.3. Statistical Analysis. Statistical analysis was performed using analysis of the variance (ANOVA) and InfoStat's least significant differences (LSD) procedure [23].

Comparisons among years were not made due to significant interactions over time, probably as a consequence of the crop-rainfall interaction. For that reason, the statistical analysis was performed in two ways: (1) by comparing the Ref soil with each treatment in year 9 and (2) by comparing the three treatments in each year (9, 10, 11, and 12 years).

3. Results

3.1. Soil Phosphorus. Soil organic and inorganic P concentrations decreased under the different cropping sequences with a sharp decline in the Po : (Po + Pi) ratio. Inorganic P was the most abundant form in both the reference and cultivated soils (Table 2). Soil Pi content was significantly lower in WW than in WG and WL. The Pte concentration (perchloric extraction) showed lower concentrations in cultivated than in the reference soil and variability was high among treatments and years. In comparison the Pt concentration (Na_2CO_3 digestion) showed low variability among soils and years. Different trends were observed in the variation of the Pe among the years in the analyzed cropping systems (Table 2). The pH showed differences among treatments.

3.2. Particle Size Fraction P. After years with different cropping systems, the Po in the fine fraction was stable among treatments throughout sampling years (Table 3). The Pi in the same fraction was significantly lower in WW than in WG and WL treatments. This difference did not change the next sampling years. The Pte in the fine fraction of all three treatments was different during the first year but there were no statistical significant differences in later years.

The most important changes in Po and Pi contents in coarse fractions were found between the reference soil and the treatments, mainly due to the Po content depletion (Table 3). Statistical differences over time were observed in the inorganic P forms, which tended to disappear with time. These differences were only found in Pi content under WW during the first three sampling years.

TABLE 3: Soil organic (Po), inorganic (Pi), and total extractable phosphorus (Pte) in the fine and coarse fraction of different cropping systems (CS).

Year	CS	Fine fraction mg kg ⁻¹			Coarse fraction mg kg ⁻¹		
		Po	Pi	Pte	Po	Pi	Pte
0	Ref	60.0	178.0	329.0	129.0	149.0	199.0
	WG	72.1 ^b ns	199.8 ^{a*}	221.5 ^{b**}	5.6 ^{a**}	95.2 ^{a**}	98.1 ^{a**}
9	WW	50.0 ^c ns	98.4 ^{b**}	149.7 ^{c**}	2.1 ^{a**}	73.6 ^{b**}	80.2 ^{b**}
	WL	88.1 ^{a*}	200.8 ^{a*}	331.4 ^a ns	1.2 ^{a**}	89.7 ^{a**}	85.9 ^{b**}
	WG	127.8 ^a	149.6 ^a	305.7 ^a	6.1 ^a	81.5 ^a	91.0 ^a
10	WW	72.2 ^b	93.8 ^b	256.3 ^b	3.3 ^a	65.2 ^b	87.8 ^a
	WL	101.6 ^a	144.3 ^a	263.2 ^{ab}	5.7 ^a	86.2 ^a	76.5 ^b
	WG	75.4 ^a	143.4 ^a	264.0 ^a	17.5 ^a	74.1 ^b	86.2 ^a
11	WW	75.4 ^a	121.0 ^b	239.5 ^{ab}	6.8 ^a	55.3 ^c	77.3 ^b
	WL	77.6 ^a	151.5 ^a	207.9 ^b	8.9 ^a	94.1 ^a	81.8 ^{ab}
	WG	84.8 ^a	133.9 ^b	259.2 ^a	1.6 ^a	84.2 ^a	83.8 ^a
12	WW	57.9 ^b	150.7 ^{ab}	256.6 ^{ab}	8.6 ^a	83.0 ^a	108.5 ^b
	WL	89.3 ^a	161.6 ^a	199.0 ^b	4.3 ^a	88.7 ^a	81.1 ^a

^{**}, ^{*} and ns indicate statistical differences $P < 0.01$, $P < 0.05$ and not significant, respectively, between each treatment sampled in year 9 and reference soil. For each P form different letters indicate differences among treatments in each year.

4. Discussion

4.1. Soil Phosphorus. The main differences in P fraction were observed between reference and cultivated soils. The highest variability of Po with respect to SOC suggests quality variations during crop sequences [6]. However, total SOC, as well as total Po, include fractions of a different quality and dynamics, which will individually be considered.

The effect of continuous wheat with fertilizer application on SOC content was a consequence of annual tillage and low residue input. A grassing period without tillage (WG and WL) and an increased residue input due to biological fixed N (WL) could explain the higher SOC in WG and WL as compared with WW [34, 35].

During the 4-year study period, treatments did not affect the dynamics of the organic P fraction. Other studies on Po in Pampas soils detected slight differences between management systems [36]. The characteristics of the method for Po determination, which estimates Po indirectly, could account for the difficulties in detecting statistical differences in these studies. In the applied method, Po was converted to Pi by high temperature oxidation and it was quantified by difference. Temperature effect on Pi solubility and acid extraction effect on Po hydrolysis could increase data variability [15]. The Po:(Po + Pi) ratio showed differences between years and treatments as a consequence of the cropping system characteristics and the rainfall variations during the study period. The abundant rainfalls in the 10th year favored plant uptake and dry matter production, which was reflected in higher Po:(Po + Pi) ratios in all treatments as compared with those in other years. The Pte values were more variable and, in some cases, showed differences with Pt values. This suggests that Pte extraction method depended on the soil conditions and physicochemical equilibrium.

Considering that the Po plus Pi quantity ranged between 222 and 373 mg kg⁻¹ and the Pte ranged from 230 to 417 mg kg⁻¹, a variable fraction of the soil P is not quantified

by the Saunders and Williams [30] method. The variations could be related to organo-mineral complexes and would seem to be associated with management practices [33].

After ploughing pasture soils, available P increased over the plant requirements suggesting that physicochemical equilibrium could result in precipitation of inorganic P forms such as apatite (Ca₅(PO₄)₃(OH,F,Cl)) or brushite (CaHPO₄·2(H₂O)) [35, 37, 38]. Under similar conditions, Galantini et al. [39] observed a sharp decrease in Pe during the first four years under continuous wheat and a slow increase after the 5th or 6th year. Physicochemical equilibrium of soil P was climatic (water regime) and management (phosphate status and tillage) dependent. As observed by others, this dynamics could mask biological effects on soil P changes [40].

In the WG treatment, Pe content ranged from 10 to 16 mg kg⁻¹ over time, showing higher values during grassing than wheat years. In continuous wheat, Pe level increased over time, whereas in WL they decreased significantly, from 33.7 mg kg⁻¹ at the end of the wheat period to 10.4 mg kg⁻¹ at the end of the legume period. A decrease during legume periods was also observed by other authors [17]. Statistical differences in pH values were observed among treatments in all sampling years. All three cropping systems showed a pH decrease over time; this might influence the P balance because a pH decrease could improve P solubility favoring flux from inorganic nonlabile to inorganic labile P forms.

4.2. Particle Size Fraction P. The inherent variability of Po, due to different plant residues and analysis method variability of this organic fraction, due to different plant residues and analysis method variability (obtained by difference between Pi and Po plus Pi), may explain the difficulty in detecting expected differences among sequences. Nine years under WW produced the lowest Pi content in the fine fraction, but no changes were found in WG and WL cropping systems. During the following sampling times, Pi concentrations

tended to increase in WW and to decrease in WG and WL treatments. The importance of the observed differences would suggest that it might be a consequence of the type and accessibility of P forms. This observation could be accounted for by the lower variability of P_{te} values. This increase of P_i in WW might occur because of the change from inorganic occluded or nondetected P to inorganic available forms, and later quantified in the analysis. In addition, losses due to plant uptake could be compensated with P from the coarse fraction.

More than 95% of the organic and 35% of the inorganic P as compared to the reference soil was lost in the coarse fraction due to cultivation. Probably, there was a combined effect of crop sequences (due to P requirement and residue input) and climatic condition effects on crop production and fresh organic matter mineralization [34, 39, 41]. Results revealed that the coarse fraction was mainly altered when the natural pastures were cultivated. Tillage effect on mineral weathering decreases were most likely related to faster decomposition of POM and the tillage influence on particle size and organomineral complex stability [41]. Previous results showed that tillage intensity modified humified SOM quantity and quality [6]. As tillage increases, humic substances decrease in quantity and reactivity. Some of the P changes were due to crop uptake and export through harvest, while other changes were linked to losses from the coarse fraction to the fine fraction by size reduction during tillage activities.

The effect of cropping system on P content in whole soil and its fine and coarse size fractions in a semiarid Haplustoll can be summarized as follows:

- (i) The major differences for all P forms were observed when cropping systems were compared with the reference soil.
- (ii) Reduction in the P_o : (P_o + P_i) ratio was mainly due to decomposition of SOM and this decomposition rate was dependent on moisture availability.
- (iii) The P_e content was modified by cropping system, increasing under a WW sequence and decreasing under WL or WG.
- (iv) The main effect of a cropping system on P dynamics was the rapid decomposition of the P in the soil coarse fraction with an increase of P_i in the fine fraction.
- (v) Soil P distribution depended mainly upon tillage effect on SOM mineralization and particle size distribution, as well as the cropping system and the potential changes in water availability modified physico-chemical equilibrium.

5. Conclusions

Soil cropping modifies P distribution within different soil particle sizes. A decrease of the P in coarse fraction (both organic and inorganic forms) was observed. As was hypothesized, crop sequences modify P distribution on soil particle size. The P_i form is mainly affected.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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