

# Phosphorus Budget and Soil Extractable Dynamics in Field Crop Rotations in Mollisols

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A better understanding of the P cycle is necessary to provide insights into management strategies that could enhance P bioavailability for crops. Our objectives were to evaluate the effects of continuous P fertilization on (i) the P budget, (ii) soil-extractable P (Pe) dynamics, and (iii) the relationship between these variables. Two crop rotations during a 6-yr period were analyzed in seven on-farm experiments: corn (*Zea mays* L.)–double cropped wheat (*Triticum aestivum*)/soybean [*Glycine max* (L.) Merr.] (C-W/S), and corn–soybean–double cropped wheat/soybean (C-S-W/S). Calculations of net P input considered only P removal (output) and fertilization (input). Initial soil-test P was 13.4 mg P kg<sup>-1</sup> (average for the four sites) for the C-W/S rotation and 37.9 mg P kg<sup>-1</sup> for the C-S-W/S rotation (average for the three sites). Treatment combinations were two annual rates: unfertilized and grain P removal estimation +10% (average 34 kg P ha<sup>-1</sup> yr<sup>-1</sup>). Not applying P to soils testing 45 to 68 mg kg<sup>-1</sup> of initial Pe resulted in a steep Pe decline (slope 0.2 mg kg<sup>-1</sup> per unit of negative P budget). Nevertheless, soils with <25 mg kg<sup>-1</sup> of initial Pe levels resulted in a very small and gradual decline (slope 0.02 mg kg<sup>-1</sup>). Use of current P rates applied by local farmers probably results in a small soil-test P buildup with time. The P required to increase Pe by 1 mg P kg<sup>-1</sup> was 11 and 8 kg P ha<sup>-1</sup> yr<sup>-1</sup> for the C-W/S and C-S-W/S rotations, respectively.

**Abbreviations:** Pe, Bray-1 extractable phosphorus; Pi, initial Bray-1 phosphorus.

Phosphorus fertilizer recommendations are usually based on the relationship between crop yield and soil P availability measured by specific soil tests. These tests mainly quantify the inorganic labile P fraction, and Bray-1, Mehlich-1 or -3, and Olsen are the most widespread available P indices (Cox, 1994). In Argentina, the Bray-1 extractable P (Pe) index has been calibrated and validated as the standard method for P fertilization recommendations (Rubio et al., 2008). The soil test P availability value between deficiency and sufficiency is usually termed the *P critical level*. Plant species have a great variability in P critical levels, reflecting differences in crop demand, rooting patterns, and processes that lead to enhanced uptake (Vance et al., 2003).

A great number of soil factors regulate P availability, ranging from chemical (soil mineralogy, pH, organic matter, adsorption capacity, interactions with other chemicals), to physical (texture, impedances, temperature, aeration, soil moisture), and to biological (presence of roots, residues, bacteria, and fungi). On the other hand, plant factors such as root architecture, rhizosphere alterations, and mycorrhizal symbiosis may increase the accessibility to soil P sources (Vance et al., 2003). Because of low fertilizer P recovery (usually <25% in the first year), P may accumulate in the soil under continuous addition of P fertilizers. Residual effects generate positive responses in successive crops, which depend on the P rate, crop P removal, soil type (precipitation and adsorption effects), immobilization with organic matter, and erosion and leaching losses (Halvorson and Black, 1985). If no fertilizers are added or P rates are lower than P exports, soil P availability declines, which will ultimately lead to soil degradation and a reduced capacity to sustain high crop yields.

Nutrient-budget studies are usually based on a short time scale and necessarily depend on a number of assumptions related to the nutrient's cycling. Accurate P

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budgets are relatively simple to calculate because most inputs and outputs can be quantified in most agricultural situations. Pools of P can easily be estimated by means of the P concentrations and mass of each component of the P budget. The main components of the P inputs are fertilizers and manures, whereas grain harvested, animals sold, erosion, and leaching losses are the main outputs to be considered. A positive budget indicates P accumulation on a total soil P basis, while a negative budget indicates P depletion. This is not necessarily the case for available soil P, however, which has a particular dynamic different from the total soil P. As a consequence, the relationship between them is far from linear. Therefore, information about soil Pe changes in long-term rotations with different P fertilization strategies and initial soil P ( $P_i$ ) availability can aid growers in managing nutrients more efficiently. In that regard, long-term field experiments constitute a valuable tool to quantify the impact of P nutrient management practices on increasing or decreasing the Pe.

In a 29-yr study on Ultisols in Alabama, Cope (1981) found that 24 and 20 kg P ha<sup>-1</sup> yr<sup>-1</sup> raised Mehlich-1 soil test P by 1 mg P kg<sup>-1</sup> in a 2-yr rotation of cotton (*Gossypium hirsutum* L.), vetch (*Vicia villosa* L.) for green manure, and corn (both cotton and corn for grain harvest). After 14 yr of annual P application in a Webster soil (a fine-loamy, mixed, superactive, mesic Typic Endoaquoll) and a Canisteo soil (a fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll) located in north-central Iowa, Webb et al. (1992) conducted a study to evaluate changes in Pe values under a corn-soybean rotation for grain harvest (18 mg P kg<sup>-1</sup> initial Bray-1 P; 0–15-cm soil depth). They found that the annual P additions required to maintain Pe levels were approximately 16.8 kg P ha<sup>-1</sup> for plots that received no initial P fertilizers and >33.6 kg P ha<sup>-1</sup> for plots that received 291 kg P ha<sup>-1</sup>. Cox (1994), working with soils from North Carolina and Brazil, found that increases in Mehlich-3 P with each unit of applied P were 0.7 units in soils with 10% clay, which exponentially decreased to 0.2 units in soils with >50% clay (crop P removal effects were not considered). A study performed by Randall et al. (1997) in Minnesota showed that every 1 mg P kg<sup>-1</sup> increase in Bray-1 P required from 20 to 35 kg P ha<sup>-1</sup> in a Webster clay loam soil and from 26 to 58 kg P ha<sup>-1</sup> in an Aastad clay loam soil (a fine-loamy, mixed, superactive, frigid Pachic Argiudoll) when P fertilizer was added at rates of 24 and 49 kg P ha<sup>-1</sup>, respectively, where continuous corn was grown for 7 yr followed by 11 yr of a corn-soybean rotation for grain harvest. Clearly, the amount of P fertilizer or positive P budget required for each milligram of P per kilogram increase in soil P test varies with climatic conditions, soil type (pH, organic matter, soil texture, etc.), soil test method, evaluation time, crop removal, as well as the rate of P fertilizer applied (Sato et al., 2005; Haden et al., 2007).

Originally, Pe was not uniform across the Pampas region (Argentina). It was low (Bray-1 P <10 mg P kg<sup>-1</sup>) toward the south and east, and high toward the north and west (>20 mg P kg<sup>-1</sup>) (Hall et al., 1992). Continual P removal by grains and forages and low rates of fertilization resulted in low soil P replenishment

(i.e., only 40–50% of P removed by crop harvest; Ciampitti and García, 2007) in the decade of the '90s. Although fertilization rates showed a slight increase during the period of 2000 to 2006, the P budget in the region is still negative. During the last three growing seasons, the replenishment of P ranged from 46 to 52% for the four main annual crops (corn, wheat, soybean, and sunflower [*Helianthus annuus* L.]) (Ciampitti and García, 2007). As a consequence, soil Pe is expected to suffer a continuous decline. Currently, many soils of the region have Bray-1 P values <10 mg P kg<sup>-1</sup> (Rubio et al., 2008).

The objectives of this study were: (i) to evaluate the influence of continuous P fertilization on the Pe change with time for different initial available soil P levels; (ii) to quantify and determine the P budget; and (iii) to relate the soil P budget (P removal minus P fertilization) to soil-test P trends. Our approach was to analyze the results from seven field fertilization trials located on the northern Pampas of Argentina during a 6-yr period.

## MATERIALS AND METHODS

### Field Trials

The Pampas region is located in the east-central part of Argentina. Around half of the surface occupied by this region (55 Mha) is dedicated to cereal or oil crops. The climate of the region is temperate and the regional mean temperatures of the coldest and warmest months are 15 and 25°C, respectively. The rainfall regime is humid in the eastern part of the region and semiarid in the western part. In both areas, rainfall has no clear seasonal pattern, although the interannual variations are large (Soriano et al., 1991). From west to east, Pampean soils present an increase in the clay content (predominantly illite), from sandy Entic Hapludolls and Quartzipsamments in the west to clayey Vertisols and Vertic Argiudolls in the east. The most common soils are Typic Argiudolls and Typic Hapludolls (Soriano et al., 1991). Soils in the northern Pampas present a lower amorphous Al, Fe, and inorganic P (IP) content (0.8 g Al kg<sup>-1</sup>, 1.4 g Fe kg<sup>-1</sup>, and 128 mg IP kg<sup>-1</sup>) than soils located in the southern Pampas region (1.2 g Al kg<sup>-1</sup>, 1.9 g Fe kg<sup>-1</sup>, and 125 mg IP kg<sup>-1</sup>) (Gutiérrez Boem et al., 2010). Before the introduction of agriculture, the Pampas region was covered by temperate prairies in the northeast and dry grassland steppes of moderate continental climate in the west and southwest.

In the northern Pampas, corn is usually planted at the beginning of the spring season (September–October), while soybean is usually planted later in the spring (November–December). Both crops are frequently harvested at the beginning of the fall season (March–April). Winter wheat is commonly planted at the beginning of the winter season (June–July) and harvested at the start of the summer season (November–December). Corn and wheat are usually fertilized with N and P, and S fertilization has been incorporated as a standard practice in several farms in the last 4 to 5 yr (García et al., 2007). Fertilizer rates have traditionally been lower than crop nutrient removal, resulting in continuous depletion of the native soil fertility. Fertilization management focuses on the immediate crop, without regard for the long-term effects of improved fertilization strategies.

In 2000, a long-term fertilization study was established in 11 farms of the Consorcios Rurales de Experimentación Agrícola (CREA)–

Southern Santa Fe. After the first year, the farms were divided into two groups: five sites continued under a C-W/S rotation and six sites under a C-S-W/S rotation. From this network, seven experimental sites (three C-W/S sites and four C-S-W/S sites) under stabilized no-till systems, showing variation across sites in soil types, Pi, and soil management history, were selected for this study (Table 1). The evaluation period considered in our work was between the 2000–2001 and the 2006–2007 growing seasons. Soils at the different sites are classified as Typic Argiudolls or Typic Hapludolls (Table 1).

A similar experimental protocol was performed in all sites. The experimental design was a randomized complete block design with three replicates. The plots were 25 to 30 m wide and 65 to 70 m long. Treatments compared in this research were a control without P and continuous P fertilization. Each crop phase was not present each year nor were the two crop rotations replicated at each experimental site. In addition, only the fertilizer treatments were replicated within each rotation. The P rate was decided annually according to the expected crop yield (which changed with the environment, mainly due to differences in annual precipitation) through the estimation of P removal. For each year and experimental site, a constant P concentration (calculated to 0% moisture content) was assumed for the different crops: 4.0, 5.0, and 7.0 g P uptake kg<sup>-1</sup> grain yield for maize, wheat, and soybean, respectively (Ciampitti and García, 2007). The final P rate for each crop was 10% higher than the estimated P removal. The goal of the fertilization rate was to obtain a slightly positive P budget to gradually build up soil P levels.

Monoammonium phosphate (12–52–0, N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O) was the source of P. For all crops at planting time, P was banded with a seed-fertilizer minimum tillage planter 5 cm below and to the side of the seed. For the C-W/S rotation, annual P rates applied for corn were 20, 37, and 36 kg P ha<sup>-1</sup> for growing seasons 2000–2001, 2002–2003, and 2004–2005, respectively. In the same rotation, the annual P rates for the wheat crop were 37 kg P ha<sup>-1</sup> in all growing seasons. The double-cropped soybean did not receive any P application. For the C-S-W/S rotation, the annual P rates applied for corn were 20 and 37 kg P ha<sup>-1</sup> for growing seasons 2000–2001 and 2003–2004, respectively. Wheat annual P rates were 37 and 46 kg P ha<sup>-1</sup> for growing seasons 2002–2003

and 2005–2006, respectively. For the full soybean crop, annual P rates applied were 30 and 34 kg P ha<sup>-1</sup> for growing seasons 2001–2002 and 2004–2005, respectively. The annual P rate averaged 34 kg P ha<sup>-1</sup>.

At the beginning of the experiment, soil samples (0–20-cm depth) were collected to perform a complete soil test analyses (Table 1). These samples were air dried at 40°C and sieved to 2 mm. The soil properties measured were: total organic C, pH (1:2.5 soil/distilled water suspension), Bray-1 P, and exchangeable cations (pH 7 NH<sub>4</sub>OAc method; Chapman, 1965). Phosphorus was evaluated colorimetrically by the Bray-1 method using a 1:8 (w/v) soil/solution ratio and an extraction time of 5 min. All extractions were performed in duplicate. For total organic C, a titration was performed and the coefficient to estimate total C was 1.724. The gravimetric soil moisture content was determined by the difference between the fresh weight and dry weight after drying at 105°C to constant weight. Soil texture was determined by the pipette method (Gee and Bauder, 1986).

Soil samples (0–20 cm) were collected for Bray-1 P analysis every cropping season approximately 1 wk before planting time. Each composite sample consisted of 10 to 12 cores (1.9-cm diameter) and three soil samples, one per block. Soil P budgets were calculated as the difference between P inputs and outputs. The P inputs were calculated from the rate and P concentration of the fertilizer applied. The P outputs were calculated from crop yields and grain P concentrations, determined each growing season by chemical analysis of the grain (on a composite basis).

For corn, hybrids DK 696 (growing season 2000–2001) and DK 682 (growing seasons 2002–2003, 2003–2004, and 2004–2005) were used. The hybrids used for soybean were DM 4800 (growing seasons 2001–2002 through 2002–2003 and 2003–2004) and DM 3700 (growing season 2005–2006). For wheat, the cultivars Klein Don Enrique (growing season 2001–2002 and 2002–2003) and ProINTA Gaucho (growing seasons 2003–2004 and 2005–2006) were used. For all crops, the hybrids and cultivars used were the best available commercial materials in terms of genetic yield achievable.

**Table 1. Experimental sites, previous management, and soil properties (0–20 cm) at the beginning of the experiment period (September 2000) at the seven sites under corn–double-cropped wheat/soybean (C-W/S) or corn–soybean–double-cropped wheat/soybean (C-S-W/S) rotations. Each determination is the average of three replications.**

Soil property	C-W/S rotation			C-S-W/S rotation			
	La Marta	Balducci	San Alfredo	La Blanca	La Hansa	Lambaré	Santo Domingo
Experimental farm	La Marta	Balducci	San Alfredo	La Blanca	La Hansa	Lambaré	Santo Domingo
Soil classification	Entic Haplustoll	Typic Hapludoll	Typic Argiudoll	Typic Hapludoll	Aquic Argiudoll	Typic Argiudoll	Typic Argiudoll
Agricultural yearst	40	+60	8	6	+20	12	5
Previous crop	W/S	W/S	W/S	W/S	S	W/S	S
Extractable P, mg kg <sup>-1</sup>	11.2	10.8	18.3	16.2	45.5	67.7	22.5
Total organic C, g kg <sup>-1</sup>	12.1	13.5	19.8	13.3	12.2	18.7	14.8
pH	6.3	5.9	6.0	6.6	5.5	5.6	6.3
Ca, cmol kg <sup>-1</sup>	6.9	8.1	11.0	7.2	7.6	9.9	10.8
Mg, cmol kg <sup>-1</sup>	2.1	2.0	2.1	2.0	1.6	3.0	2.9
K, cmol kg <sup>-1</sup>	2.4	1.4	1.7	1.9	1.7	2.6	2.3
Clay, %	8.0	11.8	18.0	15.5	18.0	20.5	19.0
Silt, %	35.4	53.2	62.0	56.4	78.9	76.5	69.3
Sand, %	56.6	35.1	20.0	28.1	3.1	3.0	11.7
Textural class	sandy loam	silt loam	silt loam	silt loam	silt loam	silt loam	silt loam

† The number of continuous years of growing agriculture crops.

## Statistical Analysis

The annual budget and  $P_e$  were analyzed by a procedure of replicate measures with time, using the PROC MIXED procedure of SAS (SAS Institute, 1996; Littell et al., 2000). The variables of experimental site, year, and fertilization treatment were considered as fixed effects of the model, while blocks and all interactions were considered random effects. Medians and all significant interactions were obtained using the LSMEAN/PDIFF procedure using the SLICE option. The best fixed parameters of covariance structure for each model were the Akaike information criterion (AIC) and the Bayesian information criterion (BIC).

The P removal and yields of each crop rotation were analyzed by ANOVA performed by site-year and Duncan's multiple comparisons test. For the  $P_e$  change adjusted by  $P_i$  and for the two groups of sites defined according to the relationship between  $P_e$  and accumulated P budget, differences between linear functions were determined by the  $F$  test (Mead et al., 1993). The AIC for the selected model was used; this criterion derives from the logarithm of the verisimilitude function. The correct model election responds to a minimization of the AIC value, minimizing the prediction of the error.

Model fitting for the relationship between the relative  $P_e$  difference and the accumulated soil P budget (both calculated as the difference between fertilized and unfertilized treatments) for each experimental site was implemented with GraphPad Prism 4 software (Motulski and Christopoulos, 2003) using this (componentized) GraphPad equation:  $Y_1 = I_1 + B_1 X + B_2 X^2$ . Model fitting was robust with an  $R^2$  value of 0.65 and  $P$  value  $< 0.001$ . Models were selected by comparing independent fits with a global fit that shared the selected parameters. In addition, all parameters were selected (intercepts, linear, and quadratic coefficients) to test whether one curve adequately fit all the data set

(different experimental sites). This analysis was performed with GraphPad Prism 4 software with the nonlinear regression function using the extra sum-of-squares  $F$  test ( $P < 0.05$ ) for the comparison method.

## RESULTS AND DISCUSSION

### Phosphorus Budget

The total amount of P applied during the 6 yr of study averaged  $204 \text{ kg P ha}^{-1}$  (Fig. 1). In general, the observed yields were considered from adequate to high for the local standards (Table 2). As expected, P fertilization promoted higher crop yields in most cases. The grain yield response to annual P applications varied among treatments and with time. In the C-S-W/S rotation, the addition of P produced yield increases of 896, 473, and  $158 \text{ kg grain ha}^{-1}$  for corn, wheat and soybean (average between full-season and double-cropped soybean), respectively. Significant P responses were mainly observed at the La Blanca and La Hansa locations (3 yr, three and four crops, respectively), only for wheat at Santo Domingo (2005), and a nonsignificant P response was observed at the Lambaré site (Table 2). In the C-W/S rotation, significant P responses were mainly observed at La Marta and Balducci (6 yr, eight crops). After the fourth year at the San Alfredo site, however, significant P responses (2 yr, three crops) were observed (Table 2). Responses varied according to  $P_i$  values and local calibrations.

The average P grain concentration, expressed on a dry-matter basis (0% moisture), was higher in soybean than in wheat, while corn presented the lowest values. Corn grain P concentrations were  $2.0$  to  $3.5 \text{ g P kg}^{-1}$ , with  $2.9$  to  $4.0 \text{ g P kg}^{-1}$  for wheat and  $4.7$  to  $6.2 \text{ g P kg}^{-1}$  for soybean.

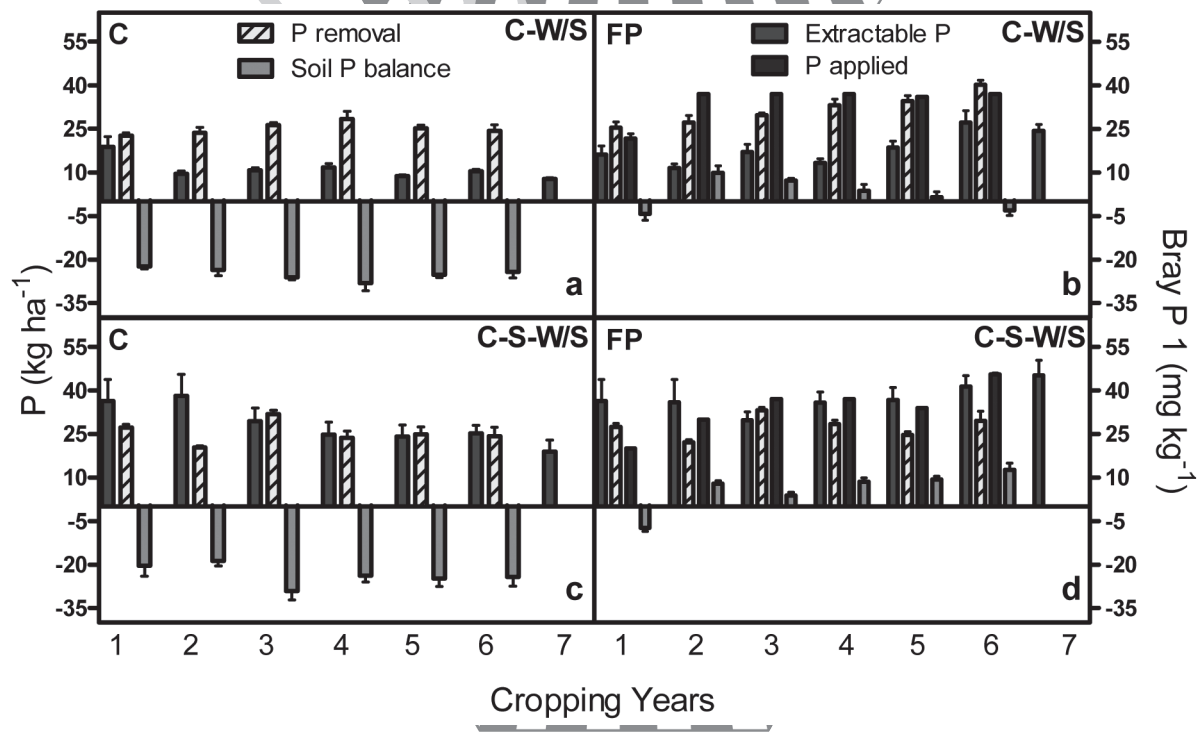


Fig. 1. Changes in P removal by grain, P fertilizer added, soil P balance, and extractable P for (a) unfertilized (C) and (b) P fertilized (FP) corn-double-cropped wheat/soybean (C-W/S) rotation and (c) unfertilized and (d) P fertilized corn-soybean-double-cropped wheat/soybean (C-S-W/S) rotation during seven cropping years. Each observation is the average of three replications for each experimental site. Bars represent standard errors of the mean.

**Table 2. Crop yields for unfertilized treatments (C) and continuous P application (FP) for each crop-year under corn–double-cropped wheat/soybean (C-W/S) or corn–soybean–double-cropped wheat/soybean (C-S-W/S) rotations during the 6 yr of evaluation.**

Crop, year	Fertilizer treatment	Grain yield								
		C-W/S rotation				C-S-W/S rotation				
		La Marta	Balducci	San Alfredo	Avg.	La Blanca	La Hansa	Lambaré	Santo Domingo	Avg.
kg ha <sup>-1</sup>										
Corn, 2000	C	11,138	7,970	9,962	9,690	8,444	‡	11,760	9,787	9,997
	FP	12,073*	9,028*	9,283	10,128	8,664	‡	11,971	10,175	10,270
Wheat, 2001	C	2,455	3,089	2,976	2,840	–§	–	–	–	–
	FP	3,390*	3,648*	3,231	3,423	–	–	–	–	–
Soybean, 2001	C	–	–	–	–	3,875	4,093	3,796	2,709	3,618
	FP	–	–	–	–	3,953	4,193	3,766	2,735	3,662
Soybean II, 2001	C	2,967	3,210	3,329	3,169	–	–	–	–	–
	FP	2,942	3,278	3,445	3,222	–	–	–	–	–
Wheat, 2002	C	–	–	–	–	2,624	1,481	3,633	1,345	2,271
	P	–	–	–	–	2,909*	1,741	3,668	1,569	2,472
Corn, 2002	C	9,374	10,857	9,572	9,934	–	–	–	–	–
	FP	11,717*	11,924	10,064	11,235	–	–	–	–	–
Soybean II, 2002	C	–	–	–	–	4,137	3,629	4,352	4,061	4,045
	FP	–	–	–	–	4,052	4,038*	4,350	4,190	4,158
Wheat, 2003	C	1,116	4,130	5,054	3,433	–	–	–	–	–
	FP	3,531*	5,160*	5,329	4,673	–	–	–	–	–
Soybean II, 2003	C	2,826	3,026	3,302	3,051	–	–	–	–	–
	FP	3,136*	3,351*	3,566	3,351	–	–	–	–	–
Corn, 2003	C	–	–	–	–	11,025	9,027	9,366	10,143	9,890
	FP	–	–	–	–	11,478	11,921*	8,856	10,005	10,565
Corn, 2004	C	10,837	9,046	8,732	9,538	–	–	–	–	–
	FP	13,770*	9,886*	10,395*	11,350	–	–	–	–	–
Soybean, 2004	C	–	–	–	–	4,958	3,615	4,383	5,606	4,640
	FP	–	–	–	–	56,008	3,948	4,407	5,841	4,949
Wheat, 2005	C	1,636	4,092	3,483	3,070	3,029	2,854	4,386	1,988	3,064
	FP	3,683*	5,476*	4,355*	4,505	3,762*	4,051*	4,264	3,161*	3,809
Soybean II, 2005	C	2,874	2,534	3,224	2,877	2,303	3,133	2,357	‡	2,598
	FP	3,625*	2,951*	4,053*	3,543	2,654*	3,170	2,455	‡	2,760

\* Significant ( $P < 0.05$ ) yield difference between the unfertilized and the fertilized treatments.

† Soybean = full-season soybean, Soybean II = double-cropped soybean.

‡ No crop planted.

§ No information.

The average grain P removal by site and year is shown in Table 3. In the C-S-W/S rotation, the annual P removal in treatments without P fertilization (control), averaged across years, was 20.4, 23.3, 26.8, and 28.3 kg P ha<sup>-1</sup> yr<sup>-1</sup> for the experimental sites La Hansa, Santo Domingo, La Blanca, and Lambaré, respectively. The unfertilized plots from the C-W/S rotation, averaged across years, had an annual P removal of 23.2, 26.7, and 28.1 kg P ha<sup>-1</sup> at La Marta, Balducci, and San Alfredo, respectively (Table 3; Fig. 1). In the C-W/S rotation, the total P removed averaged 155.9 and 194.5 kg P ha<sup>-1</sup> for the unfertilized and fertilized treatments, respectively. In the C-S-W/S rotation, P removal was 158.7 and 165.4 kg P ha<sup>-1</sup> for the unfertilized and fertilized treatments, respectively (Table 3; Fig. 1). Particularly in the C-W/S rotation, significant P removal differences between treatments were observed mainly at the La Marta site (5 yr, six crops); in addition, after the fourth year at the San Alfredo site, significant P responses (2 yr, two crops) were observed (Table 3). For the other rotation, C-S-W/S, significant P removal

differences were mainly observed at La Blanca (2 yr, two crops), at La Hansa (3 yr, three crops), and for double-cropped soybean at the Santo Domingo location (2004); no significant P removal differences were observed at the Lambaré site (Table 3). The average P fertilization rate was 34 kg P ha<sup>-1</sup> yr<sup>-1</sup>, and the final P removed in the fertilized treatment (anticipated grain removal plus 10%) was 30.3 kg P ha<sup>-1</sup> yr<sup>-1</sup> for the C-S-W/S and 35.7 kg P ha<sup>-1</sup> yr<sup>-1</sup> for the C-W/S rotations (Table 3). The average P removed at harvest represented 81.1 and 95.3% of the P applied in the C-S-W/S and C-W/S rotations, respectively—close to the proposed aim of applying rates equivalent to grain P removal +10%.

The annual P budget presented a significant ( $P < 0.05$ ) three-way year × fertilization × site interaction for the C-S-W/S rotation, whereas the two-way year × fertilization and year × site interactions were significant for the C-W/S rotation (Table 4). The unfertilized treatment presented, on average, an accumulated negative P budget of 155.9 and 148.1 kg P ha<sup>-1</sup>

**Table 3. Phosphorus removal by grain for unfertilized treatments (C) and continuous P application (FP) for each crop-year under corn–double-cropped wheat/soybean (C-W/S) or corn–soybean–double-cropped wheat/soybean (C-S-W/S) rotations during the 6 yr of evaluation.**

Crop, year†	Fertilizer treatment	P removal by crop								
		C-W/S rotation				C-S-W/S rotation				
		La Marta	Balducci	San Alfredo	Avg.	La Blanca	La Hansa	Lambaré	Santo Domingo	Avg.
kg P ha <sup>-1</sup>										
Corn, 2000	C	22	21	26	23	26	‡	31	24	27
	FP	28*	20	30	26	28	‡	31	25	28
Wheat, 2001	C	7	11	10	9	–§	–	–	–	–
	FP	13	13	13	13	–	–	–	–	–
Soybean, 2001	C	–	–	–	–	18	22	20	21	20
	FP	–	–	–	–	21	24	20	23	22
Soybean II, 2001	C	18	19	20	19	–	–	–	–	–
	FP	17	19	20	19	–	–	–	–	–
Wheat, 2002	C	–	–	–	–	9	5	12	4	7
	FP	–	–	–	–	10	6	12	5	8
Corn, 2002	C	25	28	25	26	–	–	–	–	–
	FP	31*	31	26	29	–	–	–	–	–
Soybean II, 2002	C	–	–	–	–	24	21	26	24	24
	FP	–	–	–	–	24	24*	26	25	25
Wheat, 2003	C	4	14	17	11	–	–	–	–	–
	FP	12*	17	18	15	–	–	–	–	–
Soybean II, 2003	C	17	18	20	18	–	–	–	–	–
	FP	19	20	21	20	–	–	–	–	–
Corn, 2003	C	–	–	–	–	29	24	24	27	26
	FP	–	–	–	–	30	31*	23	26	28
Corn, 2004	C	28	24	23	25	–	–	–	–	–
	FP	39*	28	37*	35*	–	–	–	–	–
Soybean, 2004	C	–	–	–	–	29	21	26	33	27
	FP	–	–	–	–	24*	21	23	29*	24
Wheat, 2005	C	6	13	10	10	11	11	16	6	11
	FP	14*	17	15	15	14	16*	16	10*	14
Soybean II, 2005	C	13	12	18	14	13	18	14	‡	15
	FP	22*	18	25*	22*	16*	19	15	‡	16

\* Significant ( $P < 0.05$ ) yield difference between the unfertilized and the fertilized treatments.

† Soybean = full-season soybean, soybean II = double-cropped soybean.

‡ No crop planted.

§ No information.

in the C-W/S and C-S-W/S rotations, respectively (Fig. 1). The fertilized treatment presented both negative and positive budgets in the C-W/S rotation, depending on the site and year; whereas positive budgets for all experimental sites and years were observed in the C-S-W/S rotation (Fig. 1). The mean, minimum, and maximum annual P budgets averaged across sites and presented by year and fertilization treatment are shown in Table 5. In the C-S-W/S rotation, the fertilized treatment showed a negative P budget ( $-6$  kg P ha<sup>-1</sup>) only in the first year, with an increasing trend in subsequent years. For the C-W/S rotation, a similar situation was observed during the first year, presenting an equivalent negative P budget ( $-6$  kg P ha<sup>-1</sup>). In addition, these positive P budget values were  $< 10$  kg P ha<sup>-1</sup> yr<sup>-1</sup> (with a neutral P budget in the sixth year) (Table 5).

The accumulated P budget for corn presented negative values in the unfertilized treatment, averaged across growing seasons and sites, of 53.0 and 49.1 kg P ha<sup>-1</sup> for the C-S-W/S

(two crops) and C-W/S (three crops) rotations, respectively. In the fertilized treatment, a positive budget of 4.3 and 4.5 kg P ha<sup>-1</sup> was observed after the corn growing seasons for the C-S-W/S and C-W/S rotations, respectively. In the case of soybean (including single and double-cropped soybean), the unfertilized treatment resulted in negative budgets of 87.2 and 53.8 kg P ha<sup>-1</sup> for the C-S-W/S and C-W/S rotations, respectively. Moreover, in the P fertilized treatment, a negative budget was observed of 22.9 and 59.9 kg P ha<sup>-1</sup> for the C-S-W/S and C-W/S rotations, respectively. This situation resulted because only full-season soybean crops received P fertilizer, while double-cropped soybean was not fertilized with P. For wheat, continuous P fertilization resulted in an accumulated P budget of 62.4 kg P ha<sup>-1</sup> in the C-S-W/S rotation and 68.1 kg P ha<sup>-1</sup> in the C-W/S rotation. In the unfertilized treatment, negative budgets were 17.6 and 30.9 kg P ha<sup>-1</sup> for the C-S-W/S and C-W/S crop rotations, respectively. Clearly, the different accumulated P budget trends are related to the application of P

to the full-season soybean crop (C-S-W/S rotation), in which specifically 18 kg P ha<sup>-1</sup> were accumulated after P removal in the fertilized plots (two full-season soybean crops; Table 3).

Overall, the absence of P fertilization during 6 yr of continuous cropping (i.e., the unfertilized treatment) led to an average (across sites and years) annual net P loss of 26.4 and 24.9 kg P ha<sup>-1</sup> yr<sup>-1</sup> in the C-S-W/S and the C-W/S rotations, respectively. Selles et al. (2007), in an Aridic Boroll soil after 27 yr of a wheat-fallow rotation, observed an average negative annual budget of 5.2 kg P ha<sup>-1</sup> without P fertilization (0–15-cm soil depth), with average wheat yields of 1.8 Mg ha<sup>-1</sup> and annual P uptake of 6 kg P ha<sup>-1</sup>.

### Extractable Phosphorus Change

The initial average Pi (2000–2001 growing season) was 13.4 mg P kg<sup>-1</sup> for the C-W/S rotation and 37.9 mg P kg<sup>-1</sup> for the C-S-W/S rotation. The Pe change showed a significant three-way year × fertilization × site interaction for the C-W/S rotation. For the C-S-W/S rotation, significant year × site and year × fertilization interactions (*P* < 0.001) were verified (Table 4).

At the end of the evaluation (2006), the C-S-W/S rotation presented Pe values that averaged, across fertilization treatments and years, 20.0, 34.7, 55.5, and 16.2 mg P kg<sup>-1</sup> for La Blanca, La Hansa, Lambaré, and Santo Domingo, respectively. For the other crop rotation, C-W/S, Pe values averaged 11.3, 11.4, and 17.2 mg P kg<sup>-1</sup> for Balducci, La Marta, and San Alfredo, respectively.

For the C-S-W/S rotation, the Pe values averaged across sites and fertilization treatments were 38, 37, 27, 30, 31, 33, and 32 mg P kg<sup>-1</sup> for 2000, 2001, 2002, 2003, 2004, 2005, and 2006, respectively. For the crop rotation C-W/S, the Pe values averaged 13, 10, 14, 12, 13, 18, and 16 mg P kg<sup>-1</sup> for 2000, 2001, 2002, 2003, 2004, 2005, and 2006, respectively (Table 6). Moreover, for the C-S-W/S rotation during the 6-yr period, 5 yr resulted in significant Pe differences between the unfertilized and fertilized treatments. Similarly, for the C-W/S crop sequence, 4 yr during the entire evaluation period presented significant differences in the Pe values between contrasting P environments.

During the 6-yr period, the fertilized treatment increased by 2.3 and 1.3 mg Pe kg<sup>-1</sup> yr<sup>-1</sup> on average for the C-W/S and C-S-W/S rotations, respectively (Fig. 2a and 2b). The unfertilized treatment declined by 0.4 and 3.1 mg P kg<sup>-1</sup> yr<sup>-1</sup>, on average, for the C-W/S and the C-S-W/S crop rotations, respectively. Mallarino et al. (1991) showed that rates of 20 kg P ha<sup>-1</sup> applied annually for corn and soybean grown in rotation on a Typic Hapludoll soil (in Iowa) produced an average increase in Pe of 0.93 mg kg<sup>-1</sup> yr<sup>-1</sup> (0–15-cm soil depth). In the unfertilized plots, they observed a decrease of 1 mg P kg<sup>-1</sup> yr<sup>-1</sup>. The increasing soil test P trends were always linear (Fig. 2), as reported

**Table 4. Analysis of variance of annual P budget and extractable P (Pe) for the corn-soybean-double-cropped wheat/soybean (C-S-W/S, four sites) and corn-double-cropped wheat/soybean (C-W/S, three sites) rotations, considering the variables of site, fertilization, and year as statistical sources of variation.**

Variables	F value	
	P Budget	Extractable P (Pe)
	<u>C-W/S rotation</u>	
Experimental site	NS	70.0***
Fertilization	1,415.8***	196.9***
Year	9.8***	16.2***
Site × fertilization	NS	25.6***
Year × site	7.2***	7.0***
Year × fertilization	12.8***	24.6***
Year × fertilization × site	NS	5.3***
	<u>C-S-W/S rotation</u>	
Experimental site	10.7**	110.3***
Fertilization	14,996.1***	49.1***
Year	155.2***	3.2**
Site × fertilization	15.4***	NS
Year × site	45.1***	5.2***
Year × fertilization	115.2***	9.2***
Year × fertilization × site	1.9*	NS

\* Significant at the 0.05 probability level; NS = not significant.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

for other long-term studies (Cope, 1981; McCallister et al., 1987; McCollum, 1991; Dodd and Mallarino, 2005).

The relative Pe difference was estimated as a quotient between the Pe of each year and the initial Pe measured in 2000 (Fig. 2c). Using this quotient for the C-W/S rotation, the fertilized treatment presented a relative average increase of 74%, and the unfertilized treatment showed an average decline of 50%. The C-S-W/S rotation showed an increase of 58% in the fertilized treatment and a decrease of 42% in the unfertilized plots during the evaluated period (Fig. 2c). Furthermore, Pi exerted a large influence on the Pe change; note that the data fitted into statistically significant (*P* > 0.05) linear functions when the Pe change was adjusted by the Pi (Fig. 2c). This constitutes one of the

**Table 5. Mean, median, minimum, and maximum of annual P budget for the corn-soybean-double-cropped wheat/soybean (C-S-W/S, four sites) and corn-double-cropped wheat/soybean (C-W/S, three sites) rotations, considering the variables of fertilization treatment (unfertilized, C, and annual P fertilization, FP) and year. Data resulted from means across the three replications at each experimental site.**

Year	Annual P Budget											
	C-S-W/S Rotation						C-W/S Rotation					
	Mean		Min.		Max.		Mean		Min.		Max.	
	C	FP	C	FP	C	FP	C	FP	C	FP	C	FP
	kg P ha <sup>-1</sup>											
2000	0	0	0	0	0	0	0	0	0	0	0	0
2001	-20	-6	-31	-11	0	0	-23	-6	-26	-10	-21	-1
2002	-20	8	-22	6	-19	9	-28	5	-30	4	-25	7
2003	-31	4	-38	-1	-26	3	-26	8	-28	6	-25	11
2004	-26	9	-29	6	-24	7	-29	2	-36	-2	-20	7
2005	-28	10	-33	5	-21	10	-25	1	-28	-3	-23	8
2006	-23	19	-30	10	-7	16	-24	0	-28	-3	-19	2

**Table 6.** Mean, median, minimum, maximum of annual extractable P for the corn–soybean–double-cropped wheat/soybean (C-S-W/S, four sites) and corn–double-cropped wheat/soybean (C-W/S, three sites) rotations, considering the variables of fertilization treatment (unfertilized, C, and annual P fertilization, FP) and year. Data resulted from means across the three replications at each experimental site.

Year	Extractable P											
	C-S-W/S rotation						C-W/S rotation					
	Mean		Min.		Max.		Mean		Min.		Max.	
	C	FP	C	FP	C	FP	C	FP	C	FP	C	FP
2000	38.0	38.0	16.2	16.2	67.7	67.7	13.4	13.4	10.8	10.8	18.3	18.3
2001	38.2	36.0	16.7	12.1	71.5	71.5	10.7	9.7	8.0	8.5	12.5	11.6
2002	24.8	29.7	14.3	19.6	48.0	43.0	11.3	16.3	8.0	10.0	14.0	26.0
2003	24.6	35.9	13.9	23.3	48.6	50.8	11.0	12.7	8.0	10.0	16.0	18.0
2004	24.1	37.1	13.4	19.3	45.0	53.0	8.8	17.8	7.3	12.2	9.9	26.1
2005	24.3	41.2	12.9	28.7	39.7	60.0	10.5	26.0	8.7	15.6	12.1	40.3
2006	19.0	45.2	10.9	28.4	41.5	72.2	7.4	24.3	7.1	19.8	7.7	28.3

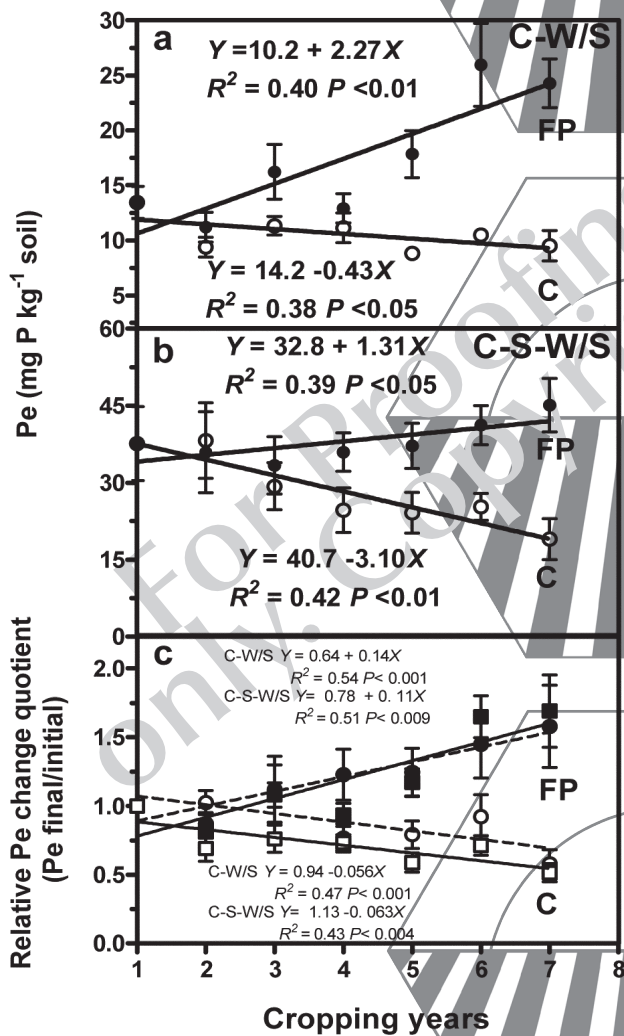
most intriguing findings of our research. After this standardization, we observed that differences between rotations and sites were almost negligible in both unfertilized and fertilized treatments (Fig. 2c). Therefore, Pi standardization allowed us to obtain an accurate model to explain the Pe change for both unfertilized and fertilized Mollisols.

### Extractable Phosphorus and Soil Phosphorus Budget Relationship

The association between the annual change in P budget and Pe allowed the quantification of the P required annually to increase the Pe level by 1 mg P kg<sup>-1</sup> (including P removal) (Fig. 3; Table 7).

The net positive P budget required for an increase of 1 mg P kg<sup>-1</sup> in the Pe level varied among experimental sites and ranged from 6.3 to 13.6 kg P ha<sup>-1</sup> for both crop rotations evaluated (Table 7). The net P budget required for an increase of 1 mg P kg<sup>-1</sup> was 10.8 and 7.5 kg P ha<sup>-1</sup> in the C-W/S rotation and C-S-W/S rotations, respectively (Table 7). Randall et al. (1997) reported that 26 kg P ha<sup>-1</sup> yr<sup>-1</sup> were needed to raise soil-test P by 1 mg P kg<sup>-1</sup> yr<sup>-1</sup> on a Minnesota Webster soil where continuous corn was grown for 7 yr followed by 11 yr of a corn–soybean rotation. In a corn–soybean long-term rotation study, Dodd and Mallarino (2005) reported that the annual P rate needed to increase soil-test P by 1 mg P kg<sup>-1</sup> yr<sup>-1</sup> ranged from 17 to 28 kg ha<sup>-1</sup> yr<sup>-1</sup> for the highest annual P rate (44 kg ha<sup>-1</sup> yr<sup>-1</sup>). Furthermore, Pi varied greatly among the study sites and was a main factor controlling the Pe change. The positive P budget requirement to obtain an increase in Pe levels of 1 mg kg<sup>-1</sup> was greater in soils with <25 mg kg<sup>-1</sup> initial soil-test P (10.3–13.6 kg P ha<sup>-1</sup>/mg P kg<sup>-1</sup>) than in soils with >45 mg kg<sup>-1</sup> initial soil Pe (6.3–6.8 kg P ha<sup>-1</sup>/mg P kg<sup>-1</sup>) (Table 7).

The relationship between Pe and the accumulated P budget is shown in Fig. 3. The fitted regression lines were significant ( $P < 0.001$ ), and the coefficients of determination ( $r^2$ ) were generally >0.50, with the exception of San Alfredo for the unfertilized treatment and San Alfredo, Balducci, Lambaré, and La Hansa for the fertilized treatments ( $r^2 > 0.25$ ). All experimental sites demonstrated a linear association (statistically significant or apparent nonsignificant trends) between Pe levels and the net P budget (Fig. 3). The Pe decrease was greater at La Hansa and Lambaré than at Santo Domingo and La Blanca (C-S-W/S rotation) (Fig. 3). Similar tendencies were observed in plots with continuous P addition: Santo Domingo and La Blanca demonstrated a greater increase than occurred at La Hansa and Lambaré, which did not show a defined trend (statistically nonsignificant plateau), resulting in low or no increase in Pe (net positive P budget). In the C-W/S rotation, the experimental sites of Balducci and La Marta presented similar statistically significant ( $P < 0.05$ ) increasing and decreasing trends for the unfertilized and fertilized treatments, while San Alfredo and Santo Domingo



**Fig. 2.** Change in extractable P (Pe) under (a) corn–double-cropped wheat/soybean (C-W/S) and (b) corn–soybean–double-cropped wheat/soybean (C-S-W/S) rotations with P fertilization (FP) and unfertilized (C), and (c) relative Pe change quotient, calculated as the rate between Pe values of each year adjusted for the initial Pe level on an annual basis for C-W/S (filled lines and squares) and C-S-W/S (dotted lines and circles) rotations for FP (filled symbols) and C treatments (open symbols). Each observation is the average of three replications for each experimental site. Bars represent standard errors.

showed similar response trends (none statistically significant at the San Alfredo site) for both treatments (Fig. 3).

Two main groups of sites were defined according to the relationship between  $P_e$  and the accumulated P budget. San Alfredo was excluded mainly because the soil-test P decrease and increase were steeper and not significant ( $P > 0.05$ ), which did not fit in any of the groups, and thus it was considered as a third group (Fig. 3g). The first group includes those sites with  $P_i$  values  $< 25 \text{ mg P kg}^{-1}$  soil: La Marta, Balducci, La Blanca, and Santo Domingo (Fig. 3a, 3b, 3c, and 3d). In this group, unfertilized plots showed a slow or negligible soil-test P decline. Fertilized plots belonging to this group showed a steeper increase in soil-test P levels. The second group included those sites with  $P_i > 40 \text{ mg P kg}^{-1}$  soil: La Hansa and Lambaré (Fig. 3e and 3f). In this group, unfertilized plots exhibited a rapid decline in soil-test P values, while fertilized plots showed nonsignificant trends in available soil P. In the last site-group, different soil-test P trends might be related to the organic P content (NaOH- and  $\text{NaHCO}_3\text{-P}$ ) associated with high organic C content (Table 1). Furthermore, when P was applied, the organic P content was observed to increase compared with the check plot (Ciampitti, 2009). Differences between group responses might be associated with P movement from the surface soil horizon to deeper soil layers and P loss through erosion or leaching. In addition, P removal was further associated with the potential yield rather than soil-test P levels (annual P removal of  $20\text{--}28 \text{ kg P ha}^{-1}$ ).

An  $F$  test was performed on the first and second groups, for each fertilization treatment, to examine whether slopes and intercepts were significantly different (Mead et al., 1993). In the first group, soils with  $P_i < 25 \text{ mg P kg}^{-1}$  soil, the unfertilized treatments did not differ in their slope in the negative section of the soil P budget. The unified slope was  $0.018 \text{ mg P kg}^{-1}$  soil per unit of change (Fig. 3). In the fertilized treatment, we did

not observe significant differences among sites and the unified slope value was  $0.37 \text{ mg P kg}^{-1}$  soil per unit of change in the positive soil P budget. Intercepts varied significantly ( $P < 0.001$ ), however, among experimental sites. As was observed for the unfertilized treatments, the intercepts were different ( $P < 0.001$ ) among experimental sites. In the second group, soils

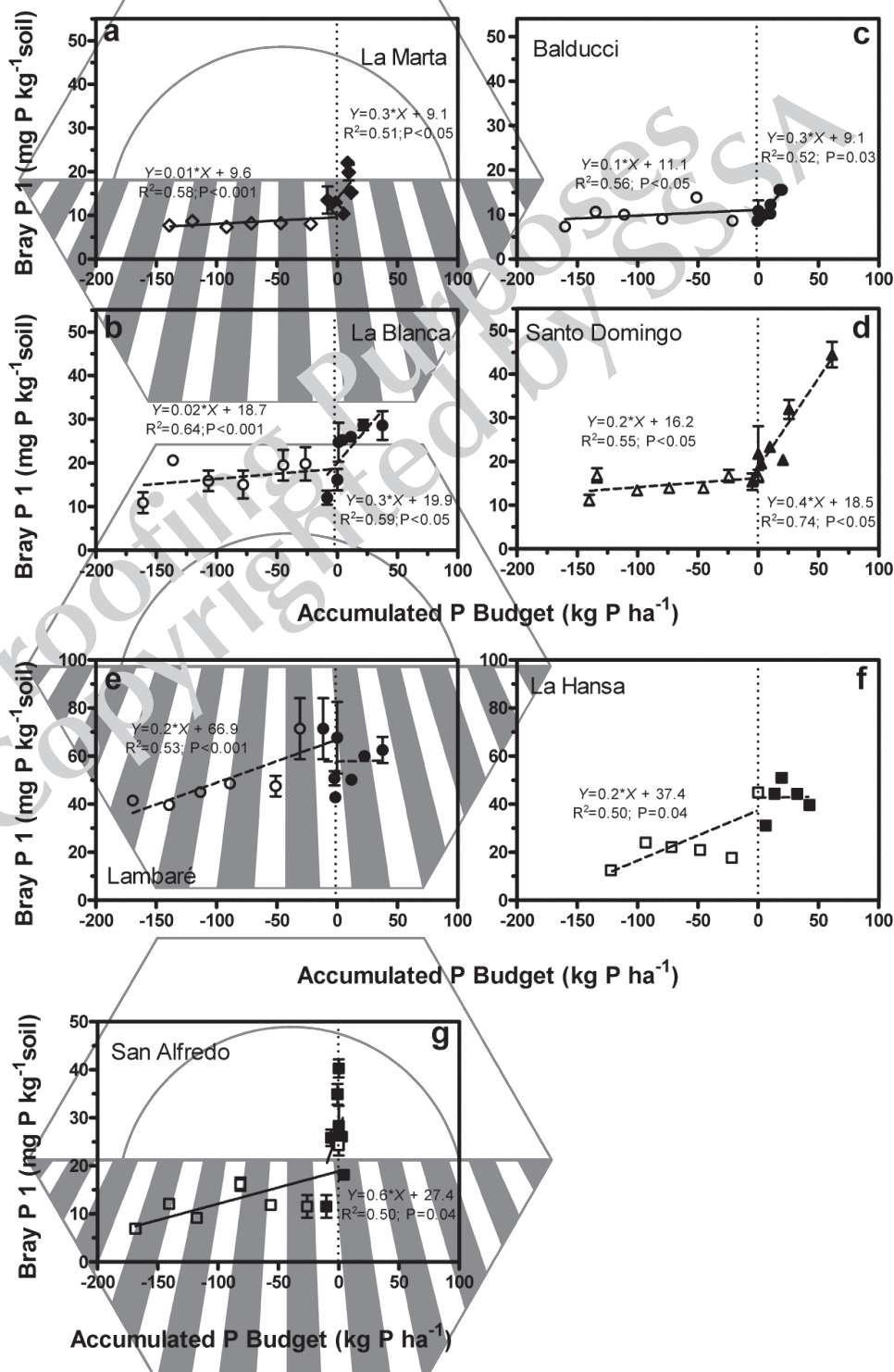


Fig. 3. Relationship between Bray-1 extractable P and the accumulated P budget during the experiment (6 yr) for both corn-double-cropped wheat/soybean (C-W/S) or corn-soybean-double-cropped wheat/soybean (C-S-W/S) rotations. Sites were grouped according to the initial available P: (a-d) low-P group, (e-f) high-P group, and (g) unclassified site. Filled symbols corresponding to the P fertilizer treatment and open ones to the unfertilized treatment. Bars represent standard errors. Only statistically significant ( $P < 0.05$ ) equations are presented.

**Table 7. Differences between P fertilized and unfertilized treatments in P budget, extractable P (Pe), and the estimated average P rate required for an increase in the soil Pe levels of 1 mg P kg<sup>-1</sup> for all experimental sites evaluated under corn–soybean–double-cropped wheat/soybean (C-S-W/S) and corn–double-cropped wheat/soybean (C-W/S) rotations.**

Site	Accumulated P budget	Annual P budget	Annual ΔPe	Net P budget†
	kg ha <sup>-1</sup>	mg P kg <sup>-1</sup>	mg P kg <sup>-1</sup>	kg P ha <sup>-1</sup> /mg P kg <sup>-1</sup>
	C-W/S rotation			
Balducci	179.7	30.0	2.2	13.6
La Marta	148.9	24.8	2.0	12.4
San Alfredo	167.5	27.9	4.4	6.3
Avg.	165.4	27.6	2.9	10.8
	C-S-W/S rotation			
La Blanca	198.4	33.1	3.2	10.3
La Hansa	165.0	27.5	4.4	6.3
Lambaré	207.2	34.5	5.1	6.8
Santo Domingo	201.3	33.6	5.1	6.6
Avg.	193.0	32.2	4.5	7.5

† Positive budget needed for an increase in Pe concentration of 1 mg P kg<sup>-1</sup> soil.

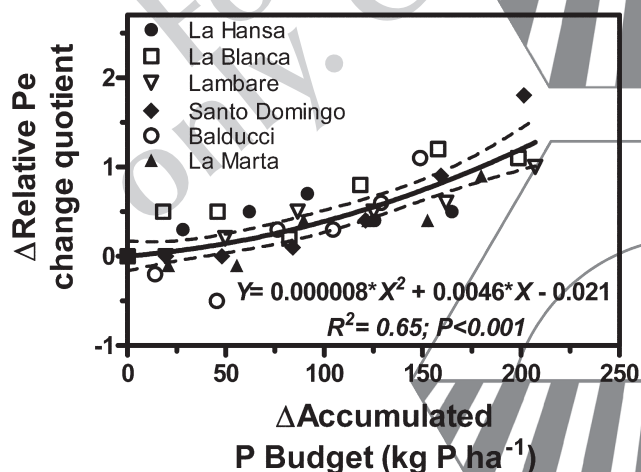
with  $P_i > 40$  mg P kg<sup>-1</sup> soil, the unfertilized treatments did not show significant slope differences and the unified slope was 0.19 mg P kg<sup>-1</sup> soil per unit of change in the negative accumulated P budget; however, the intercepts showed significant statistical differences ( $P < 0.001$ ) among experimental sites. In the fertilized treatments, the slopes were not significantly different and the unified slope was 0.0068 mg P kg<sup>-1</sup> soil per unit of change in the positive accumulated soil P budget. Finally, in the third group, the slope of the change in Pe was not significant for either unfertilized or fertilized treatments.

The relationship trend between Pe change and P budget differed markedly between the first and second groups and also differed with Holford (1976) and Pote et al. (2003). These researchers observed that in poor P soils, a great proportion

of sorption sites remain vacant and the probability that the new P entering the soil was fixed is high. Therefore, P applied to a low-P soil would not necessarily translate to a proportional increase in Pe. In addition, Holford (1976) and Pote et al. (2003) supported the hypothesis that P application causes a greater increase in soil P when applied to soil that is initially higher in soil P. In our experiment, however, when initial soil Bray-1 P levels were  $< 25$  mg P kg<sup>-1</sup>, P application through inorganic fertilizer caused a greater increase than for the experimental sites of the second group ( $> 40$  mg P kg<sup>-1</sup>). In addition, our results show a higher P declination trend in the  $> 40$  mg kg<sup>-1</sup> P soils compared with the  $< 25$  mg kg<sup>-1</sup> P soils, with negative P budgets without continuous P applied. In this regard, our findings are in accordance to several researchers' previous research (Cope, 1981; McCallister et al., 1987; Mallarino et al., 1991; Webb et al., 1992; Dodd and Mallarino, 2005). In agreement with our results, Webb et al. (1992) found that soil-test P (Bray-1 P) decreased after 14 yr of crop production on two fine-loamy soils in north-central Iowa when no fertilizer P was added and the extent of decreases were enhanced with increases in the initial soil-test P levels. Recently, Dodd and Mallarino (2005), in three long-term field trials with corn–soybean rotations established in Iowa (1970s–2002) on Hapludoll and Endoaquoll soils with three different initial P rates that generated different initial Bray-1 P levels (20, 60, and 100 mg P kg<sup>-1</sup>), reported that P application increased soil-test P, with a greater response at a low initial P level (20 mg P kg<sup>-1</sup>). Furthermore, without applied P, the levels of decrease were enhanced with increases in the initial soil test P levels.

The absence of Pe increases after net P addition to the soil may indicate a saturation of the anion exchange matrix of the soil (Haden et al., 2007) and a conversion to nonlabile fractions, as suggested by McCollum (1991). It has been observed that high soil P levels may dissolve soil minerals (Low and Black, 1950; Kittrick and Jackson, 1955), which can promote a release of Fe and Al that potentially precipitates soil P. Aulakh et al. (2003) observed that the great sinks of excess continuous P applied through fertilizers were the moderately labile and recalcitrant soil P fractions, which could possibly be the case in our soils. This situation was also observed by Beauchemin et al. (2003) for soils enriched with P, and Peak et al. (2002) for soils enriched with poultry litter. We do not have enough information, however, to draw conclusions about these statements, a limitation of this research.

Figure 4 shows the relationship between the relative Pe difference and the accumulated soil P budget. Both parameters were calculated as the difference between fertilized and unfertilized treatments. The fitted equation was a second-order polynomial function ( $R^2 = 0.65$ ,  $P < 0.001$ ), with the exception of San Alfredo, which was excluded from the data analysis because its slope was not significant ( $P > 0.05$ ) (Fig. 4). The adjusted model did not show significant differences between sites



**Fig. 4. Relationship between the relative extractable P (Pe) change quotient (difference between the Pe final value and initial P level at the beginning of the experiment) and accumulated P budget during the experiment (6 yr) for both corn–double-cropped wheat/soybean (C-W/S) or corn–soybean–double-cropped wheat/soybean (C-S-W/S) rotations. Both parameters were calculated as the difference between P fertilized and unfertilized treatments. Each observation is the average of three replications for each experimental site. The dotted lines are the 95% confidence interval of the data set.**

and rotations ( $P = 0.75$ ). From the obtained function, it can be calculated that 97 kg P ha<sup>-1</sup> of accumulated soil P budget led to a 50% change in soil Pe. These results agree with those obtained by Dobermann et al. (2002) in a 2-yr study with a soybean–rice (*Oryza sativa* L.) rotation. They observed that the relationship between Pe and the accumulated P budget fitted a polynomial model, suggesting that with high P applications more P becomes extractable with low levels of Pe (<3.1 mg P kg<sup>-1</sup>). A net positive P budget of 200 kg P ha<sup>-1</sup> produced an increase of 15.9 mg P kg<sup>-1</sup>, and 12.5 kg P ha<sup>-1</sup> was required to raise the Pe by 1 mg P kg<sup>-1</sup> (Dobermann et al., 2002).

## CONCLUSIONS

The results from this 6-yr experiment showed that the Pe change in cropping sequences depended greatly on the Pi level, the amount of P removed in harvested products (cropping years' effect), and the annual P fertilization rate. Our results are constrained by our experimental conditions, which involved a P fertilization rate of 34 kg P yr<sup>-1</sup>, a Pi range from 11 to 68 mg P kg<sup>-1</sup>, a total P removal for 6 yr ranging from 148 to 194 kg P ha<sup>-1</sup>, and the inherent characteristics of the Mollisols used in our study.

Differences in the grain yield response to P fertilization were observed among different sites and years, mainly based on initial soil-test P values and local calibrations. The average P removed at harvest represented 81.1 and 95.3% of the P applied in the C-S-W/S and C-W/S rotations, respectively. The Pe change was also constrained to our range of Pi: from 10.8 to 67.7 mg P kg<sup>-1</sup>. The relative Pe difference, the quotient between the Pe of each year and the initial Pe, showed that the fertilized treatment increased 58 and 74% on average, while the unfertilized plots declined 42 and 50% on average, for the C-W/S and C-S-W/S crop sequences, respectively.

At all our experimental sites, not applying P through inorganic fertilizers resulted in a linear Pe decline with time during the 6 yr of evaluation. This decline was steeper for soils testing 45 to 68 mg P kg<sup>-1</sup> than for soils with <25 mg P kg<sup>-1</sup>. With continuous P applications, a linear significant and reliable relationship was obtained at sites with Pi <25 mg P kg<sup>-1</sup>. The use of current P rates probably results in a small soil-test P buildup with time in low-Pi soils. From this research, the P required to increase the Pe by 1 mg P kg<sup>-1</sup> was 11 and 8 kg P ha<sup>-1</sup> yr<sup>-1</sup> for the C-W/S and C-S-W/S crop rotations, respectively, if including the P removed at harvest.

The observed soil-test P and P budget relationships are practical for developing efficient P fertilization programs—specifically, for situations without applied P fertilizers in continuous no-till cropping systems.

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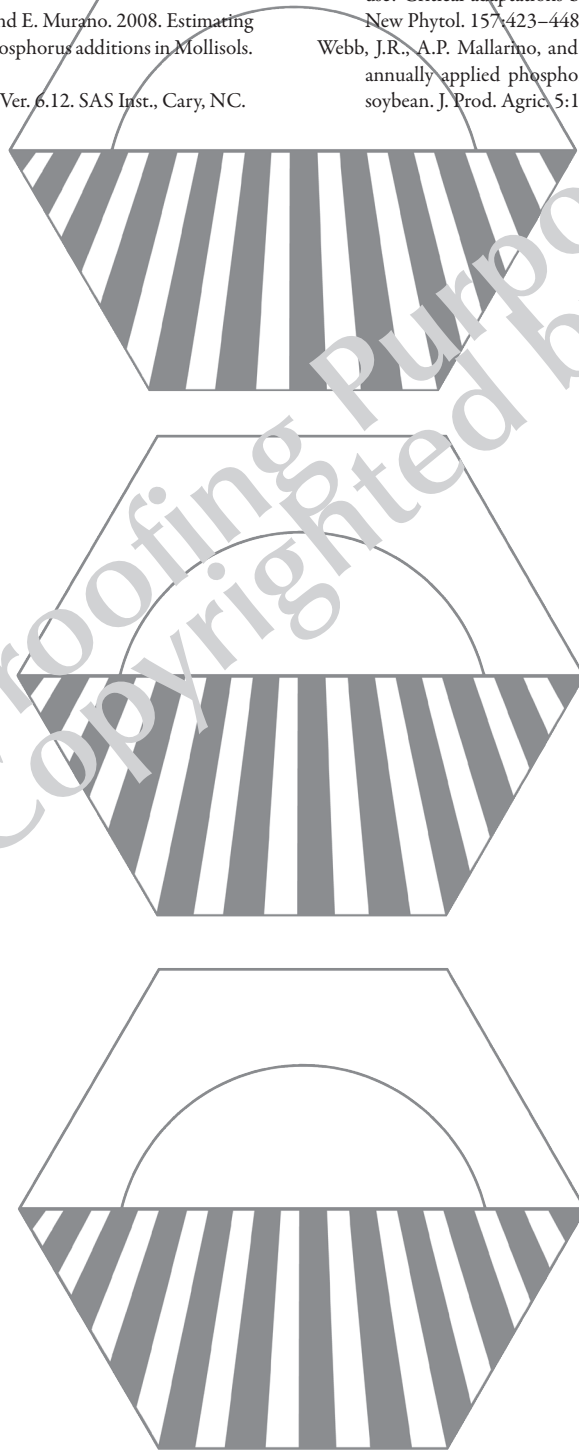
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