Prediction of Available Soil Phosphorus Increases after Fertilization in Mollisols

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Accurate critical levels should be accompanied by predictive models on the amount of P required to increase P availability to a target value to obtain reliable P recommendations. Based on information on soil properties, we estimated the increase in soil available P after the addition of a unit of P, in pot studies, in an area of homogeneous though geographically distant loess-derived Mollisols of the Pampean Region in Argentina.

Reliable P fertilizer recommendations are needed for both economic and environmental reasons. They are usually based on the relationship between crop yield and soil P availability measured by specific soil tests (i.e. Bray 1, Olsen, Mehlich III). The soil test level separating deficiency and sufficiency is usually termed the critical level. At values below the critical level, P is assumed to be a constraint to crop yield and positive responses to P fertilization are expected. Plant species vary in P-critical levels, reflecting differences in crop demand, rooting patterns, and processes that lead to enhanced uptake.

In build-up and maintenance recommendation systems, critical levels must be accompanied by predictive models on the amount of P required to increase soil P concentration from an initial value to a target value (i.e. the agronomic or environmental critical level). These predictive models are much less abundant than the information referring to critical levels. Fertilizer requirement is largely dependent on the same chemical and physical characteristics of the soil that regulate P availability and sorption properties (Withers and Sharpley, 1995).

Most works studying the increase in available soil P after the addition of P have been developed using data sets including soils with extreme variation in one or more properties expected to strongly influence P response, as clay content (Cox, 1994), clay content and type (Quintero et al., 1999), or extractable aluminum (Haden et al., 2007). However, Beauchemin and Simard (1999) suggested that predictive models are best developed using homogeneous soils to account for their individual characteristics. Thus, current models may not be useful in areas with homogeneous soils, having small variability in clay and other basic soil characteristics. The large differences among soils may mask out the subtle differences that can be found in sets of homogeneous soils.

The soils of the Pampean Region (Argentina)–taxonomically similar, but distributed over a wide geographic area–can provide a data set that may allow an evaluation of the different soil characteristics that regulate the increase in available P. This region is the most productive agricultural area in Argentina and many of its soils are among the most fertile of the world. Cultivated Pampean soils are relatively homogeneous in terms of taxonomy and topsoil pH and clay content. The objective of this study was to estimate the increase in soil P availability after P additions under laboratory conditions, using information on soil properties.

Seventy-one soils were chosen from 31 representative agricultural areas of the Pampean Region (**Figure 1**). For the present study, 43 and 28 agricultural soils located North and South of the Flooding Pampa, respectively, were selected. All selected soils were non-calcareous, loess-derived Mollisols. Typic Argiudolls (26 soils) predominated among the Northern Pampean soils, followed by Typic Hapludolls (7); Entic Haplustolls (5), Thapto-Argic Hapludolls (4), and Abruptic Argiudolls (1). Typic Argiudolls (18) also predominated among the Southern soils, followed by Typic Haplustolls (5), Petrocalcic Paleudolls (3) and Thapto-Argic Hapludolls (2). Soils were sampled from the top 20 cm of the soil profile because that is the layer considered in local experiments for estimating P-critical levels for crops.

Soil samples were air dried, sieved to 2 mm and characterized for parameters related to soil P availability: pH, particle size distribution, organic C, total P, initial soil-available P, and P retention indices. In order to evaluate the sorption properties

Abbreviations and notes for this article: P = phosphorus; PRI-I = P retention index I; PRI-II = P retention index II; C = carbon; ppm = parts per million; h = hour.

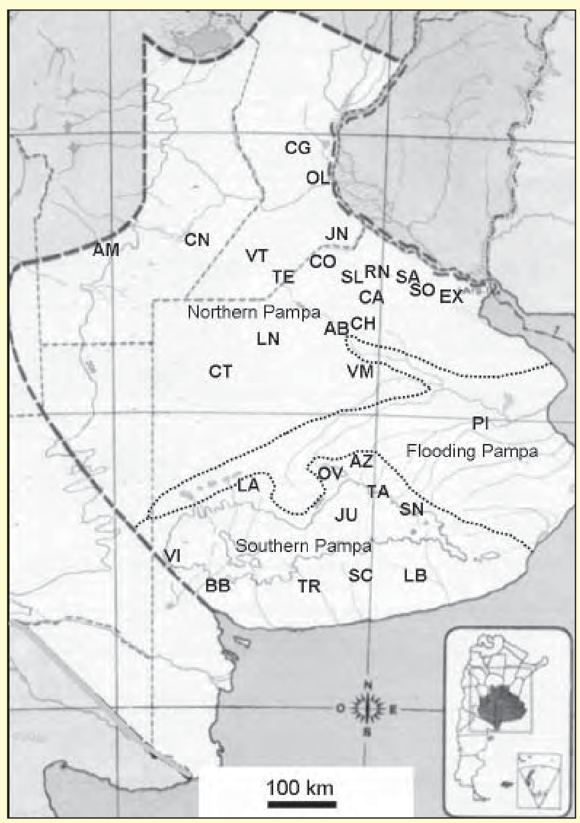

Figure 1. Sampling sites of the soils utilized in the present study. For each site, one to six soils were selected. Northern and Southern soils are those located above and below the straight line, respectively.

Table 1. Mean, minimum, maximum, and coefficient of variation values for the analyzed soil properties for 71 soils (whole dataset) and for the Northern (43) and Southern (28) soils.

	--- All soils ---		---------- North ----------				----------- South ----------				North vs. South
	Mean	CV[1]	Mean	Min.	Max.	CV	Mean	Min.	Max.	CV	p value[4]
b coefficient	0.52	22.5	0.58	0.33	0.74	13.6	0.41	0.27	0.58	19.9	***
Clay, g/kg	23.2	27.5	21.0	8.7	30	30.4	26.1	15.1	37.6	19.8	***
pH	6.1	6.1	6.0	5.3	6.9	4.8	6.4	5.9	7.5	6.4	***
Total C, g/kg	21.8	32.9	18.3	11.5	26.9	22.6	27.3	12.8	38.6	27.6	***
P Bray 1, mg/kg	12.1	64.7	11.2	2.4	30.3	65.2	13.7	3.3	35.6	63.0	NS
P total, mg/kg	324	19.8	299	211	359	12.8	362	191	490	21.1	***
PRI-I [2]	251	6.8	246	220	296	5.2	260	218	303	7.6	***
PRI-II [3]	310	12.6	289	242	336	7.1	343	275	418	11.3	***

[1] Coefficient of variation.
[2] P retention index I (Quintero et al. 1999).
[3] P retention index II (Sims 2000).
[4] p value for the t test comparing Northern and Southern soils: NS Not significant ($p > 0.05$), *** Significant at $p < 0.001$.

of the soil, two P retention indices were calculated: PRI-I was measured by the method proposed by Quintero et al. (1999), and PRI-II was measured following the method proposed by Sims (2000).

PRI-I consists of equilibrating 2.5 g of soil for 1 h with 25 ml of 0.1 M $CaCl_2$ containing 60 mg P/L at 25°C. Sorbed P was calculated as the difference between the P content in the added solution and the P content in the equilibrium solution. The PRI-I was then calculated as the amount of sorbed P divided by the logarithm to base 10 of the concentration of P measured in the equilibrium solution (Quintero et al., 1999). In order to calculate PRI-II, 1 g soil was equilibrated with 20 ml of 0.1 M $CaCl_2$ containing 75 mg P/L at 25ºC for 18 h. The other steps were similar to those described for PRI-I.

Soils were incubated in duplicate for 45 days with five levels of P (KH_2PO_4): 0, 8, 16, 32, and 64 mg P/kg soil in PVC pots containing 150 g soil. Pre-wetted soil samples were thoroughly mixed with a solution of KH_2PO_4. Potassium phosphate was used as it is the P source usually used in P sorption studies and has an intermediate behavior compared to triple superphosphate and diammonium phosphate, the fertilizer sources commonly used in the Pampean Region (Jiao et al., 2007, Schefe et al., 2007). After the incubation period, Bray P-1 was determined using a 1:7 soil to solution ratio and colorimetric P development.

The increase in available P, defined as the difference between available P for the P-enriched and the average of the two control pots, was calculated for each P level. Simple linear regressions of available P increase vs. added P were evaluated for each soil. The function used was $y = bx$, where y is the increase in available P, b is the slope, and x the P rate. In practical terms, the higher the b coefficient, the lower the amount of P necessary to reach a determined value of available soil P. In order to develop predictive models, regression analysis was used relating obtained b coefficients to different soil parameters. The variable *zone* was included taking into account the described ecological sub-regions of our study site. Values for this variable were 1 for soils north of the Flooding Pampa and 0 for Southern soils (**Figure 1**). The other variables included in the analysis were: clay, silt, and sand percentages, initial Bray P, total P, PRI-I, PRI–II, C content, and pH.

Predicting Soil P Increases

The main differences among Mollisols of the Pampean Region occur in the subsurface horizons. Most topsoil properties (e.g. clay content, pH) vary only slightly, with the exception of those characteristics affected by soil management, such as C content and nutrient availability. This was reflected in our measurements: total C and soil available P were the variables with the highest coefficient of variation (**Table 1**). Although in general terms the selected soils were homogeneous, soils from the Northern Pampa ecological sub-region (**Figure 1**) presented consistently lower clay content, total C, total P, pH, and P retention index values than soils located in the South (**Table 1**).

Values for the b coefficient can easily be converted to agronomic units (as the quantity of P in kg/ha to raise the soil test by 1 mg/kg) following the procedure shown in **Figure 2**. The relationship between the increase in available soil P and the amount of added P was linear and highly significant for each of the 71 analyzed soils (average $r^2 = 0.99$, minimum $r^2 = 0.94$). Thus, the b coefficient could be calculated directly from the slope of this relationship.

Obtained b coefficients ranged from 0.27 to 0.74, averaging 0.52 (**Table 1**). Southern soils had a significantly lower b coefficient than Northern soils. (**Table 1**) indicating that more P was needed to obtain a similar increase of available P in Southern soils. The b coefficient was negatively associated with the variable clay content, pH, total C, total P, and P retention indices, and positively related to Bray P-1. PRI–II was the best single independent variable for estimating b. As

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expected, the higher the P retention indices, the lower the coefficient b. Other measured properties associated with b were total C (r^2=0.31), PRI–I (r^2=0.30), clay (r^2=0.20), and pH (r^2=0.11). The majority of our soils fall in a very narrow range of pH values, which may explain the weak association observed between pH and b.

The best multiple regression model to predict the b coefficient (**Table 2**) included these variables: initial soil P, zone, and PRI–I (R^2 = 0.70). Because P retention indices and total P are not soil tests commonly provided by private or public laboratories, a second model excluding them was run (**Table 2**). This model retained a high coefficient of determination (R^2 = 0.61), and included these variables: clay content, initial soil P, and zone. A third model in which the zone variable was excluded and only measured soil variables were considered is also presented (**Table 2**). The variables selected by the model (R^2 = 0.62) were total P, initial soil P, pH, and P retention index II (**Table 2**).

Unlike previous studies that included more heterogeneous soils, initial P availability had an important role in predicting increases in soil available P due to P addition to the rather homogenous soils of the Pampean region. As expected, soil clay content and P retention indices also influenced the b coefficient. One of the main barriers to successfully mitigate the environmental damages caused by phosphates is the lack of precise estimation of the increase in available soil P due to the addition of P to soil, especially in agricultural areas of developing countries. Our information can strengthen P fertilization programs by providing a methodology to calculate reliable P requirements to keep P availability at a level sufficient for maximum crop yields while avoiding environmentally harmful excesses. Further research is needed to validate this method for other arrays of homogeneous soils that may differ in P dynamics. BC

Table 2. Multiple linear models for predicting b coefficient (n=71) according to Stepwise (R^2) methods. All models were significant at the 0.001 level.

	Equation	R^2
Model 1: all variables	0.95049 + 0.004826 Bray 1 P + 0.15450 Z[1] - 0.00233 PRI-I	0.70
Model 2: PRI and total P excluded	0.45369 + 0.00356 Bray 1 P + 0.16245 Z - 0.00344 Clay	0.61
Model 3: zone excluded	1.60087 + 0.00605 Bray 1 P - 0.08121 pH - 4.398E-04 total P - 0.00165 PRI-II	0.62

[1] Z is zone (0 for soils of the Southern Pampa and 1 for Northern soils).
Bray 1 P: extractable P (Bray 1). PRI-I: P retention index I. PRI-II: P retention index II.

In field crop ecosystems of Argentina, deficiencies of N, P, and S are frequently found.

Soil data

Top 20 cm:
P Bray: 11 mg/kg
Clay content: 28%
Bulk density: 1.2 t/m^3
Location: N Buenos Aires (Z = 1)

Estimation of b coefficient:

Coef b: 0.45369 + 0.00356 P Bray + 0.16245 Z - 0.00344 clay (%)
Coef b: 0.559

Objective of the fertilization

To reach P Bray: 15 mg/kg (topsoil 0 to 20 cm) It is necessary to increase 4 mg/kg P Bray (15 mg/kg to 11 mg/kg)

Phosphorus requirements to raise P Bray 1 ppm (kg P/ha) =

kg P/ha = 0.1 {Bulk density (t/m^3) x Deep (cm)}/Coef b
In our example
kg P/ha = {0.1 [1.2 (t/m^3) x 20 (cm)]/10}/0.559
kg P/ha = 24/0.559
kg P/ha = 4.29
It is required to raise 4 mg/kg P Bray 15 mg/kg - 11 mg/kg = 4 mg/kg. Fertilization rate: (4.29 kg/ha x 4) = 17.17 kg P/ha

Figure 2. Practical application of obtained results. The example from a field site located in the Northern Pampas. The farmer asked to raise the soil P test to 15 mg/kg, from an initial value of 11 mg/kg. Note: t/m^3 = metric ton per cubic meter.

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