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Long-term phosphorus fertilization of wheat, soybean and maize on Mollisols: Soil test trends, critical levels and balances

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ABSTRACT

Few reports have compared the P critical level between different crops under equivalent growing conditions and the impact of P balance and P fertilization practices on the long term dynamics of soil available P. The objectives of this study were: i) to determine and compare, under similar field conditions, the P critical values for soybean, maize and wheat; and ii) to evaluate the effect of long-term application of P fertilizer on P balance and soil-test P. Results from a long-term experiment (2000/01 and 2013/14) involving soybean, maize and wheat crops in five experimental sites located at the Pampean Region (Argentina) were analyzed. Phosphorus levels included a −P treatment without P application and a +P treatment with continuous P fertilization (annual average 37 kg P ha^{-1}).

The critical Bray-P thresholds were 14.3, 12.5 and 19 mg kg^{-1} for soybean, maize and wheat, respectively. The rate of decline of the Bray-P pool in the −P treatments was described by an exponential decay function common to the five study sites. Obtained results indicated that a net extraction of 327 kg P per hectare is needed to reduce their initial Bray-P values by half, regardless of the initial soil Bray-P value. The soils fertilized with P showed a significant and linear increase in Bray-P. It was possible to fit a single function after pooling the data of the five sites. This combined function indicated that 3.2 kg P ha^{-1} were necessary to increase Bray-P in 1 mg kg^{-1}. Obtained data on crop P critical levels and rates at which soil-test P declines or increases according to the P balance constitutes a useful tool for sustainable use of P resources in Mollisols and related soil units. They can help to monitor future changes of soil P levels and to estimate the P demand of croplands.

1. Introduction

In order to achieve optimum crop yields, soil phosphorus (P) availability should be above the critical level, defined as the value of soil P test above which no fertilizer response can be expected (Fixen and Grove, 1990). If the soil P test value is below the critical level, P is assumed to be a constraint to crop yield and positive responses to P fertilization are expected. Critical P values vary greatly according to the soil-test, the soil sampling depth, and the statistical model employed (Mallarino and Blackmer, 1992; Dodd and Mallarino, 2005; Gutiérrez Boem et al., 2011; Jordan-Meille et al., 2012). Among the several soil P tests that have been proposed, Bray-P is widely used in soils with acidic to neutral pH (Dodd and Mallarino, 2005; Rubio et al., 2008; Jordan-Meille et al., 2012).

The definition of accurate P critical levels is essential when planning P fertilization programs by providing a safe target soil P test level so that yields are not constrained by soil P and environmentally harmful excesses are minimized (Dodds et al., 2008). Phosphorus critical levels are generally obtained from on-farm experiments that relate soil P tests to relative yields (RY), defined as the crop yield in the control treatment as percentage of crop yield in the fertilized treatment. In rotated cropping systems, it is particularly relevant to know the P critical level of the different crops to identify the convenient P level to be used as the target for the whole rotation (usually the highest P critical level). It is generally accepted that P critical levels vary among crops. This assumption comes mainly from data sets involving different areas and soils. However, the fact that critical levels are affected by soil properties and other environmental and management factors (Bray, 1954; Bell et al., 2013), suggests that accurate interspecific comparisons can be best evaluated through specific trials performed at the same experimental sites and growing conditions. However, only few reports meeting these conditions have been published so far (e.g. Dodd and

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Table 1
Soil classification, location and properties (0–20-cm depth) at the beginning of the experimental period (September 2000) for the five experimental sites. Balducchi and San Alfredo followed a bi-annual rotation: maize (first year) and double cropping wheat/soybean (second year). La Blanca, La Hansa and Lambare followed a tri-annual rotation: maize (first year), full season soybean (second year), and double cropping wheat/soybean (third year). In all cases the rootable depth exceeded 2 m.

Experimental site	Balducchi	San Alfredo	La Blanca	La Hansa	Lambare
Soil classification	Typic Hapludoll	Typic Argiudoll	Typic Hapludoll	Aquic Argiudoll	Typic Argiudoll
Location	34°09.461‘S; 61°36.465‘W	33°51′35.57“S; 61°28′7.84“W	33°29.923 S; 62°37.958‘W	32°38.405‘S; 61°19.967‘W	32° 10.236‘S; 61° 48.674‘W
Agricultural history (years)	+60	8	6	+20	12
Soil series	Santa Isabel	Hughes	La Belgica	Bustinza	Los Cardos
Bray-P (mg kg^{-1})	10.8	11.5	16.2	17.7	67.7
Total organic C (g kg^{-1})	13.5	19.8	13.3	12.2	18.7
C: N ratio	11.6	11.1	10.3	11.6	10.9
pH	5.9	6.0	6.6	5.5	5.6
Ca (cmol kg^{-1})	8.1	11.0	7.2	7.6	9.9
Mg (cmol kg^{-1})	2.0	2.1	2.0	1.6	3.0
K (cmol kg^{-1})	1.4	1.7	1.9	1.7	2.6
Clay (g kg^{-1})	118	180	155	180	205
Silt (g kg^{-1})	531	620	564	789	765
Sand (kg^{-1})	351	200	281	31	30
Textural class	silt loam	silt loam	silt loam	silt loam	silt loam
Rotation	Bi-annual: maize-wheat/soybean		Tri-annual: maize-soybean-wheat/soybean		

Mallarino, 2005; Poulton et al., 2013).

Soybean, wheat and maize are three of the most important grain crops all over the world. In Argentina, they represent more than two thirds of the cropped area, mainly covered by highly fertile although P-deficient Mollisols (Rubio et al., 2008; Sainz Rozas et al., 2012). It has been reported that soybean is less responsive to P fertilization than maize and wheat (i.e. Colomb et al., 2007; Mallarino et al., 2013). In many cropping regions around the world, new farming systems have been progressively adopted in the last two decades (Pacini et al., 2003; Wezel et al., 2014). In Argentina, changes include the consolidation of soybean as the prevalent crop, the generalized adoption of no-tillage and the greater cropping intensity (Wingeyer et al., 2015; Andrade et al., 2017). Given these changes, there is a need to verify or fine-tune the currently accepted critical soil P levels. A long history of P exports without replenishment caused a widespread P depletion in most Argentinean agricultural soils (Sainz Rozas et al., 2012). This country does not have significant P reserves and must import almost all P fertilizers. At the international level, the depletion of P reserves makes uncertain the future of P fertilizer markets and an increase in extraction and manufacturing costs is expected (Gilbert, 2009). Therefore, P deficiency is a significant challenge for agricultural productivity and it is necessary to optimize the efficiency in the use of P by crops.

Besides accurate P critical levels, another key component for planning P management strategies is the rate at which soil P test declines or increases following the P balance of the system. Statistical functions or models are required to predict rates of change of soil P test driven by accumulated P balances over time. These functions help predict the rate of soil P test decline once P applications are ceased and also help at identifying limits to P rates to avoid risks of environmental pollution. Only a minor fraction of the P applied to the soil is absorbed by the target crop (about 5–25%, Morel and Fardeau, 1989; Benbi and Biswas, 1999). The remaining fertilizer P is retained by the soil matrix, and may eventually be available for subsequent crops. Residual effects of P fertilization mainly depend on the P balance and soil P sorption characteristics (Blake et al., 2003). In its simplest version, the P balance is calculated by subtracting the main output (P removed in harvested products: grain, forage) from the main input (fertilizer P or manure P). A positive or negative balance suggests an accumulation or a decline, respectively, of total soil P. However, because of the strong interaction of phosphates with the soil matrix, the relationship between P balance and available soil P is not directly predictable (Ciampitti et al., 2011). Whereas many field experiments reveal linear relationships between P balance and soil extractable P (Blake et al., 2000, 2003; Messiga et al., 2010; Ciampitti et al., 2011; Cao et al., 2012; Shen et al., 2014; Díaz and Torrent, 2016), Johnston et al. (2016) found exponential decay functions between time and soil available P. Some reports highlight that the net balance of P in the system is the preeminent factor regulating the dynamics of soil P test (e.g. Blake et al., 2003; Messiga et al., 2015). In such sense, using the accumulated P balance as the independent variable instead of time, the rate at which available soil P decreases or increases could be estimated independently of the factor time. The identification of the function that fit the soil P test decline is relevant to define the timescale over which the decline is produced. Very short periods of analysis are more likely to describe linear paths and may mask the presence of curvilinear tendencies. In this sense, long-term field experiments arise as the best tool for quantifying the impact of P balance and P fertilization practices on the dynamics of available soil P.

The objectives of this study were: i) to determine and compare, under similar field conditions, the P critical values for soybean, wheat and maize; and ii) to evaluate the effect of long-term application of P fertilizer on P balance and soil P test. To this end, we performed a study from 2000/01 to 2013/14 in five experimental sites located at the Pampean Region (Argentina) involving soybean/maize/wheat rotations.

2. Materials and methods

2.1. Long term P fertilization experiment

A long term network was established in private farms of the Regional Consortium for Agricultural Experimentation (CREA) to evaluate the long term effects of different fertilization regimes on crop yields and soil fertility. The network started in 2000 and at present comprises five sites managed under no-tillage whose soils show a range of variability in initial Bray-P and other characteristics (Table 1). Each site followed one of the following two crop rotations: 1) bi-annual rotation (C-W/S): maize (first year) and double cropping wheat/soybean (second year); 2) tri-annual rotation (C-S-W/S): maize (first year); full season soybean (second year), and double cropping wheat/soybean (third year). The bi-annual rotation was employed in two sites (Balducchi and San Alfredo) and the tri-annual rotation in three sites (La Blanca, La Hansa and Lambare). In the present study, we evaluated the period between the 2000/01 and 2013/14 growing seasons (Fig. 1).

A similar experimental protocol was performed in all sites. The experimental design was a randomized complete block design with three replicates (except San Alfredo: two replicates). The plots were 25–30 m wide and 65–70 m long. Two treatments were compared: a) −P treatment, without P fertilization; and b) +P treatment, with continuous annual P fertilization. P rate was determined every year according to the anticipated P removals plus a 5–10%. The anticipated P removals were estimated by multiplying the expected crop yield by the grain P concentration. The goal of adding a 5–10% to the