Critical value of soil Olsen-P for potato production systems in volcanic soils of Chile

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Abstract

The critical value of soil Olsen-P (mg Olsen-P kg⁻¹) is the value of soil Olsen-P above which the probability of crop response to P fertilization is small or null. The aim of the present study was to determine the critical value of soil Olsen-P for potato tuber yield in volcanic soils. The data used in this study were taken from 41 experiments of P fertilization conducted in southern Chile from 1977 to 2015 by the National Potato Center at the Instituto de Investigaciones Agropecuarias (INIA). To identify the critical values of soil Olsen-P, relationships between relative yields and initial soil P-Olsen were assessed using three models (linear-plateau, boundary and Mitscherlich function). Across experiments, the average fresh tuber yield was 41.9 Mg ha⁻¹ and varied between 4 and 89 Mg ha⁻¹. Fresh tuber yield decreased up to 92% by P deficiency; however, yield reduction was concentrated between 20 and 40%. The critical Olsen P values determined were 41, 33 and 11 mg Olsen-P kg⁻¹ obtained ($P < 0.01$) with linear-plateau, boundary function and Mitscherlich function, respectively. However, linear-plateau and Mitscherlich functions showed lower coefficient of determinations ($R^2 = 0.23 - 0.31$) than the boundary function ($R^2 = 0.97$). Therefore, we suggest that the critical Olsen-P value of 33 mg P kg⁻¹ determined with the boundary function is more appropriate for potato growers than the critical value determined with the other models. This information will be valuable for optimizing strategies for P fertilizer management in potato production systems aimed at achieving optimal crop yield and minimizing potential environmental risk.

Keywords: Tuber yield, Phosphorus deficiency, P-Olsen, P supply, P rate.

1. Introduction

Phosphorus (P) has been considered a major factor limiting crop productivity, and large amounts of P have been applied to soils since the Green Revolution to sustain production of agricultural systems (Tilman *et al.*, 2001, 2002). Relative to nitrogen and potassium, the recovery of P fertilizers by crop plants is usually very low due to the high capacity of soils to fix P (Manske *et al.*, 2001; Balemi and

Negisho, 2012). Potato is particularly sensitive to P-deficient soils, indicating a low P uptake efficiency (Sandaña, 2016) and, therefore, P fertilization is a critical component of profitable potato production as many soils lack sufficient P to optimize crop growth (Rosen *et al.*, 2014; Hopkins *et al.*, 2014; Thornton *et al.*, 2014; Sandaña and Kalazich, 2015; Sandaña, 2016). However, there

are some trends likely to drive the effort to improve P management in this crop, since i) phosphate rock will be much less available (Cordell *et al.*, 2009), ii) P prices are likely to increase as it becomes more difficult to extract from phosphate rock (Elser and Bennett, 2011), and iii) the environmental concern regarding the effect of P fertilization given that repeated applications of P fertilizers has a direct negative impact on surface waters that influence the functioning of ecosystems (Tilman *et al.*, 2001). Thus, to realize a sustainable P use in agriculture, it is important to optimize soil P management to achieve optimal crop yield, minimize potential adverse effects on environment and limit the accumulation of soil P to certain target levels (Rowe *et al.*, 2016). Therefore, for a better P management, determining the critical value of soil Olsen-P to optimize P fertilization in potato crops is crucial.

The critical value of soil Olsen-P is the value of soil Olsen-P above which the probability of crop response to P fertilization is small or null (Tang *et al.*, 2009; Bai *et al.*, 2013; Sucunza *et al.*, 2018). Critical values of soil Olsen-P differ among crops because of different P requirements and P uptake efficiencies (Colomb *et al.*, 2007; Sandaña and Pinochet, 2016). The critical values of soil Olsen-P range from 3.9 to 15 mg kg⁻¹ for maize (Mallarino and Atia, 2005; Colomb *et al.*, 2007) and from 4.9 to 20 mg kg⁻¹ for winter wheat (Johnston *et al.*, 1986; Bollons and Barraclough, 1999; Colomb *et al.*, 2007). For potato, Maier *et al.* (1989) determined a critical value of Olsen-P of 17 mg P kg⁻¹, whereas Johnston *et al.* (1986) concluded that potato yield generally plateaued when soil Olsen-P test reached 25 mg P kg⁻¹, but this value varied between 10 and 54 mg P kg⁻¹ across years. The critical values of soil Olsen-P differ among sites because of differences in soil properties, with the soil texture being an important component (Redulla *et al.*, 2002; Johnston *et al.*, 2013). In addition, critical values of soil Olsen-P vary according to statistical model used for its determination. The statistical models such as the Mitscherlich, linear-linear, and linear-plateau are among the most used to determine criti-

cal values. (Colomb *et al.*, 2007; Tang *et al.*, 2009; Bai *et al.*, 2013; Sucunza *et al.*, 2018). However, the linear-linear and linear-plateau methods do not require an arbitrarily defined relative yield level (i.e.: 95 % maximum attainable yield) to define the critical value of soil P test as required in the Mitscherlich model (Colomb *et al.*, 2007; Tang *et al.*, 2009).

To our knowledge there is no information about the critical value of soil Olsen-P for potato crops cultivated in volcanic soils (Andisols) such as those in southern Chile, where most potato crops are planted (Haverkort *et al.*, 2014). Andisol soils, derived from volcanic materials, are characterized by their high P retention capacities, this being the main constraint of crop productivity in these soils (Valle *et al.*, 2015). Although Andisols are very productive, they are often deficient in P; therefore, large doses of P fertilizers should be applied to maximize yields (Dahlgren *et al.*, 2004; Sandaña and Pinochet, 2014). However, this is in contrast with the global challenge of increasing crop productivity with a lower input of P fertilizers (Gregory and George, 2011, Thornton *et al.*, 2014). Therefore, the aim of the present study was to determine the critical value of soil Olsen-P for potato tuber yield in volcanic soils in southern Chile.

2. Materials and methods

2.1. Sites, experiments and experimental design

The data used in this study were taken from 41 experiments conducted in southern Chile from 1977 to 2015 by the National Potato Center at the Instituto de Investigaciones Agropecuarias (INIA), Osorno, Chile. Experiments were performed in Andisol soils in different environments from Chillán (36°36'47 S; 72°05'54 W) to Castro (42°28'44 S; 73°45'58 W) on Chiloe Island (Figure 1). 80% of the total potato area is cultivated from the regions of Maule to Los Lagos (ODEPA, 2017). Most potatoes are cultivated from October to March. However, early (September) and late (November) planting

dates are also found in this zone. The data set comprised experiments where the yield responses of one or more cultivars were assessed under different levels of P fertilization (from two to five P levels) (Table 1). In total, eleven cultivars were assessed in the experiments. Five cultivars (Patagonia-INIA, Karu-INIA, Yagana-INIA, Pukara-INIA, Puyehue-INIA, Puren-INIA) created in the INIA potato breeding program since 1980 and three introduced cultivars (Desiree, Spartan, Rodeo and Asterix) (Table 1). Patagonia-INIA, Karu-INIA, Pukara-INIA,

Desiree and Rodeo are popular among potato growers in Chile. Almost all experiments were carried out under rainfed conditions. In experiments where only one cultivar was assessed under different levels of P fertilization, treatments were arranged in a three randomized complete block designs. On the other hand, a split-plot design was used in factorial experiments in which different genotypes and different levels of P fertilization were assessed, where P rates were assigned to main plots and genotypes to subplots randomized into three blocks.

Table 1. Year, experiments, initial soil Olsen-P, cultivar, water supply and phosphorus rate assessed under field experiments conducted by INIA in southern Chile from 1977 to 2015. In the experiments, different rates of phosphorus fertilization were evaluated, from two to five levels of phosphorus rates.

Year	Experiments	Initial Olsen-P (mg kg ⁻¹)	Cultivar	Water supply	Phosphorus rates (kg P ha ⁻¹)		
1977	1	7	Spartan	Rainfed	0	140	280
	2	29	Spartan	Rainfed	0	140	280
	3	12	Spartan	Rainfed	0	140	280
	4	10	Desiree	Rainfed	0	65	109 153
	5	10	Spartan	Rainfed	0	116	232 464
	6	2	Spartan	Rainfed	0	87	174 262
	7	8	Spartan	Rainfed	0	116	232 464
	8	10	Spartan	Rainfed	0	116	232 348
	9	23	Spartan	Rainfed	0	140	279 419 559
	10	17	Spartan	Rainfed	0	65	109 153 196
	11	17	Ultimus	Rainfed	0	87	175 350
2008	1	7.5	Karu-INIA	Rainfed	0	65	130 196
	2	70	Karu-INIA	Rainfed	0	65	130 196
	3	4.3	Karu-INIA	Rainfed	0	65	130 196
	4	12.1	Karu-INIA	Rainfed	0	65	130 196
	5	9.4	Karu-INIA	Rainfed	0	65	130 196
	6	6.6	Karu-INIA	Rainfed	0	65	130 196
	7	10	Karu-INIA	Rainfed	0	65	130 196
2009	1	7.7	Karu-INIA	Rainfed	0	65	130 196
	2	40	Karu-INIA	Rainfed	0	65	130 196
	3	19.5	Karu-INIA	Rainfed	0	65	130 196
	4	94	Karu-INIA	Rainfed	0	65	130 196
	5	10.7	Karu-INIA	Rainfed	0	65	130 196
2010	1	7.5	Patagonia-INIA	Rainfed	0	65	130 196
	2	7.8	Patagonia-INIA	Rainfed	0	65	130 196
	3	12.7	Patagonia-INIA	Rainfed	0	65	130 196
	4	23	Patagonia-INIA	Rainfed	0	65	130 196
2011	1	2.4	Karu-INIA	Rainfed	0	65	130 196
	2	15	Karu-INIA	Rainfed	0	65	130 196
	3	42	Karu-INIA	Irrigated	0	65	130 196
	4	27	Karu-INIA	Rainfed	0	65	130 196
	5	16.2	Puyehue-INIA	Irrigated	0	65	196
2012	6	43	Karu-INIA	Rainfed	0	65	
	1	48	Karu-INIA	Rainfed	0		130 196
	2	8.2	9 cultivars ¹	Rainfed	0		130
	3	10.7	9 cultivars ¹	Irrigated	0		130
2013	4	16	Karu-INIA	Rainfed	0	30	74 130
	1	7.2	9 cultivars ¹	Rainfed	0		130
	2	7.3	3 cultivars ²	Irrigated	0		130
2015	1	6.3	Patagonia-INIA	Rainfed	0		130
	2	4	Patagonia-INIA	Rainfed	0	65	196

Desiree, Patagonia-INIA, Karu-INIA, Yagana-INIA, Pukara-INIA, Puyehue-INIA, Puren-INIA, Rodeo and Asterix. ²Patagonia-INIA, Rodeo and Asterix.

Figure 1. Site distribution of experiments and average historical rainfall, maximum (T max.) and minimum (T min.) temperatures and incident solar radiation during the period October-March in five locations in southern Chile.

In general, in all experiments soils had high acidity (on average 5.5 pH in water), high organic matter content (on average 14.4%) and moderate to low P availability for potato production. Across experiments, the initial soil Olsen-P level (Olsen *et al.*, 1954) (20 cm depth) ranged between 2 and 70 mg Olsen-P kg⁻¹ (Table 1). Olsen-P has been shown to extract an amount of P that is representative of the phosphate released into the solution and taken up by the plants.

2.2. Crop culture and measurements

Each experimental plot consisted of 4 rows 5.6 m long placed 0.75 m apart. The planting density was 40,000 potato seeds ha⁻¹. Experiments received the same amount per hectare of N, K, Mg and Ca (150 kg N, 87 kg K, 22 kg Mg and 37 kg Ca). These nutrients plus the corresponding P fertilization rates were incorporated into each row by hand at planting. The fertilizer sources for N, P and K were Nitromag (27% N, 3%

Mg and 5% Ca), Triple Super Phosphate (20% P), and Potassium chloride (KCl) (31% K), respectively. The experiments were maintained free of biotic stresses. Thus, weeds, diseases and insects were prevented with the use of pesticides at the rates recommended by their manufacturers.

At harvest, fresh tuber yield was determined in each plot from two central rows 5 m long (7.5 m²) without edge effects. To eliminate the variability among years, sites and cultivars, the relative yields (RY) were calculated as (Bai *et al.*, 2013):

$$RY: Y_0/Y_m$$

Where Y_0 is the yield of treatments with no P fertilization and Y_m is the maximum yield obtained in the field trial during the same year with the best treatment fertilized with P.

In order to identify the critical values of soil Olsen-P, the relationship between RY in response to initial soil P-Olsen (mg Olsen-P kg⁻¹) was assessed by using three models (linear-plateau, boundary and Mitscherlich function).

The linear-plateau model was defined by Equations 1 and 2:

$$RY = a + b x, \text{ if } (x < c) \quad \text{Equation 1}$$

$$RY = P, \text{ if } (x \geq c) \quad \text{Equation 2}$$

where RY is the relative yield, a is the intercept, b is the slope, and c is the critical Olsen-P value (mg Olsen-P kg⁻¹) and P is the predicted relative plateau yield.

The boundary function was defined by the Equation (3):

$$RY = a + bx \quad \text{Equation 3}$$

where RY is the relative yield, a is the intercept, b is the slope and X is the initial concentration of soil Olsen-P (mg P kg⁻¹). This function was fitted only to the 15% lowest relative yields observed across experiments. The critical Olsen-P value was considered as the intercept of this function with the horizontal line showing the $RY = 1$.

The Mitscherlich model is given by Equation 4:

$$RY = A * (1 - e^{(-cx)}) \quad \text{Equation 4}$$

where RY is the relative yield, A is the maximum attainable RY when X is not limiting, c is a response factor and x is the concentration of soil Olsen-P. The critical value of Olsen-P was calculated following Tang *et al.* (2009) based on the Olsen-P value corresponding to 90% of maximum predicted relative yield (A).

2.3. Statistical analyses

In each experiment, an analysis of variance (ANOVA) was used to assess the effects of P treatments on fresh tuber yield. This was performed with the software Statistica 7.0. The linear-plateau and boundary regressions were performed using a routine TBL curve (Jandel Scientific). The Mitscherlich model was performed using the software SigmaPlot v.13. A least significant differences (LSD) test was calculated at 5% significance for mean comparison. Linear regression analyses and ANOVA were also performed with Statistica 7.0.

3. Results

Across experiments, the average fresh tuber yield was 41.9 Mg ha⁻¹ and varied between 4 and 89 Mg ha⁻¹, following a normal distribution (Figure 2a). Fresh tuber yield decreased up to 92% under no P fertilization; however, yield reduction was concentrated between

20 and 40% in response to P deficiency (Figure 2b).

The relationship between relative yield and initial soil Olsen-P content showed that, across all experiments, significant yield reductions were observed with soil Olsen-P values below 30 mg P-Olsen kg⁻¹ (Figure 3). Relative yield was significantly ($P < 0.01$) related to initial soil Olsen-P when described by the linear-plateau and Mitscherlich models. However, the coefficient of determinations of these models were lower ($R^2 = 0.23$ - 0.31) owing to the scatter of data below the 30 mg Olsen-P kg⁻¹ (Figure 3) than the boundary function fitted to the

lowest relative yields observed across experiments was significant ($P < 0.05$; $R^2 = 0.97$). The three models used made it possible to identify three critical values of soil Olsen-P for potato production. The critical values were 41, 33 and 11 mg Olsen-P kg⁻¹ using the linear-plateau, boundary function and Mitscherlich model, respectively (Figure 3). However, the linear-plateau and Mitscherlich functions are less suitable than the boundary function because they do not take into account the lower relative yields observed. In addition, the Mitscherlich model underestimates the maximum attainable relative yield by around 20%.

Figure 2. Frequency distribution of fresh tuber yield observed in all treatments across experiments (a) and frequency distribution of yield reduction in treatments with no P application (b).

Figure 3. Relationship between relative fresh tuber yield and initial soil Olsen-P content of each experiment fitted with the Mitscherlich, linear-plateau and boundary models. Boundary regression was fitted to the 15% lowest relative yields observed (circles with black dots). The size of the circles indicate the maximum yield observed under the highest P fertilization treatments. Arrows indicate the critical value of soil Olsen-P determined with each model.

4. Discussion

A critical Olsen-P value can be defined as “a soil P status above which crop yield does not respond to P fertilization” (Tang *et al.*, 2009; Bai *et al.*, 2013; Xi *et al.*, 2016; Sucunza *et al.*, 2018). Variation in critical levels may stem from different models that have been used to estimate critical levels (Bai *et al.*, 2013). In the present study, different critical Olsen-P values (11, 33 and 41 mg P kg⁻¹) were identified depending on the model used. This is in agreement with previous studies, in which different models were used to assess the

yield response of different crops to soil P availability (Tang *et al.*, 2009; Sucunza *et al.*, 2018). Our results suggest that a critical Olsen-P value of 33 is less risky for potato growers than the critical values determined with the other models. Therefore, in order to reduce P accumulation in the soil and the risk of P for the environment, potato crops in volcanic soils with Olsen-P levels below or above the critical values reported in the present study (averaged 33 mg P kg⁻¹) will require corrections and maintenance fertilization rates (i.e.: the exported P from the field in product harvested), respectively.

Our critical Olsen-P value is higher than those previously reported. Previous studies have reported a critical value of Olsen-P for potato of 15 (Recke *et al.*, 1997), 17 (Maier *et al.*, 1989), 25-26 (Johnston *et al.*, 1986; Johnston *et al.*, 2013) and 27 mg P kg⁻¹ (Freeman *et al.*, 1998). However, Johnston *et al.* (1986) concluded that potato yield generally plateaued when the soil Olsen-P test reached 25 mg P kg⁻¹, but the value varied between 10 and 54 mg P kg⁻¹ across years. Differences in the critical Olsen-P level may be also affected by differences in soil properties such as soil type, soil structure, pH and organic matter (Bai *et al.*, 2013; Johnston *et al.*, 2013; Poulton *et al.*, 2013). Freeman *et al.* (1998) stated that their higher critical Olsen-P value compared to the critical value reported by Maier *et al.* (1989) reflects the

higher clay content of the krasnozem and duplex soils. Our results are in line with the Freeman *et al.* (1998) report (Figure 4), since the clay and silt content of Andisol soils are much higher than the sandy soil assessed by Maier *et al.* (1989), with 56-98% of sand content. From Figure 4 it is evident that sandy soils have lower critical Olsen-P values than soils with a high clay content such as those of Freeman *et al.* (1998) and soils of the present study. However, some of these differences could be also attributed to differences in soil sampling depth since, compared with our sampling depth (0-20 cm), in the study by Maier *et al.* (1989) and Freeman *et al.* (1998) the sampling depth was 0-15 and 0-10 cm, respectively.

Figure 4. Relationship between relative tuber yield and soil Olsen-P content in the studies by Maier *et al.* (1989) (white circles), Freeman *et al.* (1998) (black circles) and this study (grey circles). Boundary function was fitted by eye. Arrows indicate different critical values of soil Olsen-P depending on sand or clay soil content.

Critical Olsen-P values may differ among years and cultivars. In the present study, different genotypes were included to assess the critical Olsen-P value. Previous studies in potato have shown important genotypic differences in P uptake efficiency (Soratto *et al.*, 2015; Sandaña, 2016). This implies that the relationship between relative yield and soil Olsen-P and, as a result the critical Olsen-P value, can be affected by the genotype. This was observed in the study by Freeman *et al.* (1998), in which the yield deficit was greater for cv. Russet Burbank than for cv. Kennebec for Olsen-P concentrations higher than 10 mg kg⁻¹. The cultivar effects on critical Olsen-P, however, seem to be much lower than the effect of the soil type, since Maier *et al.* (1989) found from experiments at 33 sites that the critical soil P concentration ranges for various cultivars were not significantly different overall. On the other hand, critical Olsen-P values may differ due to seasonal variation in weather conditions, mainly rainfall (Johnston *et al.*, 2013; Poulton *et al.*, 2013). This can affect the growth and yield responses of potato crops for the same initial level of Olsen-P (e.g.: Figure 3).

5. Conclusions

The present study, across different experiments, demonstrated that the critical value of soil Olsen-P was better determinate by the boundary function model, with a critical value of 33 mg P kg⁻¹ for soils with high P fixing capacity. This value is less risky for potato growers than the critical value determined with the linear-plateau and Mitscherlich models. To maintain this critical value over time, the P removed in the product harvested from the field should be replaced through equivalent rates of P fertilization. This information will be useful for local potato growers, cropping in volcanic soils such as Andisols, to increase P use efficiency by

reducing P inputs, excess P accumulation in soils and potential risks of water contamination.

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