



# Approaching environmental phosphorus limits on a volcanic soil of Southern Chile



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## ABSTRACT

Unexpected incidental phosphorus (P) losses from volcanic soils recently threatened water quality in Southern Chile. Such soils are generally thought of as P sinks and no rapid indicators exist that reliably predict the potential for these soils to release P to water supplies. In this study we propose a local buffering capacity indicator ( $BC_p$ ) already in use for agronomic purposes to determine a threshold  $BC_p$  value to predict the onset of significant P loss. The  $BC_p$  represents the amount of P required to increase the value of Olsen-P by  $1 \text{ mg kg}^{-1}$  at 0.2 m soil depth per hectare ( $\text{kg P ha}^{-1}$ ). Changes in  $BC_p$ , and soil P variables were evaluated in a volcanic soil from the Osorno series in Southern Chile. The treated soil was incubated for 90 days with increasing P rates (0, 10, 25, 50, 100, 500 and  $1000 \text{ mg P kg}^{-1}$  soil). A segmented linear model was used to identify the  $BC_p$  threshold value from the relationship between the  $BC_p$  and water-soluble soil P ( $P_w$ ). Significant changes in soil P status and P sorption parameters were evident only after the soil was treated with the highest P rates, denoting the high P sorption capacity of the soil. Ammonium oxalate extractable P ( $P_{ox}$ ), Olsen-P,  $P_w$ , and the degree of P saturation (DPS) increased with P rates higher than  $500 \text{ mg kg}^{-1}$ . This was coincident with a significant decrease of the  $BC_p$  value. For this particular soil, the segmented model gave a  $BC_p$  threshold of  $15.1 \text{ kg ha}^{-1}$  ( $R^2 = 0.96$ ,  $P < 0.05$ ) below which  $P_w$  increased abruptly. This  $BC_p$  was equivalent to an Olsen-P of  $53.4 \text{ mg P kg}^{-1}$ , which is two times higher than the optimum agronomic value recommended for most crops and pastures of Southern Chile. Given that the  $BC_p$  is already in widespread use as an agronomic indicator in this region, we show that it also has promise as an environmental indicator of a soil's susceptibility to soil P loss.

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## 1. Introduction

Historically, Southern Chile has led the nation in dairy, livestock, and cereal crop production. This area represents more than 70% of the milk, 50% of the beef cattle, and about 80% of cereal crop production of Chile (INE, 2007). Animal and agricultural productive activities occur mostly in volcanic soils characterized by low pH, high organic matter content (OM), and extremely high P fixation capacity meaning that most of the inorganic P added to soil (85–90%) remains unavailable for crop uptake (Borie and Rubio, 2003; Escudey et al., 2001). Thereby, high P immobilization is a major constraining factor for plant production, forcing the use of significant amounts of phosphate fertilizers to counteract the slow release of P to the soil solution and obtain suitable yield targets (Besoain, 1985). Accordingly, local research emphasizes the development of management strategies to

provide sufficient P to meet nutritional crop demands (Bonomelli et al., 2003; Carrasco and Opazo, 1996; Carrasco et al., 1993; Sadzawka and Carrasco, 1985). Although most of the agricultural soils in the area require high P inputs, there is evidence that soils under more intensive management have reached P concentration levels that potentially can be of environmental concern (Alfaro and Salazar, 2005). While P release and loss from soil to water in this type of soils is expected to be low under most conditions, the soil P holding capacity is still finite and continuous P inputs over the long term increase the risk for P losses (Maguire and Sims, 2002).

Preserving the outstanding quality standards of water resources in Southern Chile is critical for sustaining tourism, agricultural production, and food security. Recently, unexpected incidental P losses between 3 and  $14 \text{ g of dissolved P ha}^{-1} \text{ year}^{-1}$  occurred through surface runoff in volcanic soils of Southern Chile (Alfaro and Salazar, 2007; Alfaro et al., 2008, 2009). These findings are consequential because P concentrations in surface runoff were found above  $0.01 \text{ mg P L}^{-1}$  which can trigger the accelerated growth of algae and aquatic plants in freshwater systems (Sharpley et al., 1999). Determining environmental P concentration limits in soils receiving long-term P applications is worthy of

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investigation to avoid impacting susceptible water bodies (Alfaro and Salazar, 2005; D'Angelo et al., 2003). Consequently, consistent environmental indicators are needed to predict P susceptibility to runoff loss in volcanic soils of Southern Chile.

The risk for P loss has been assessed through the use of indicators of dissolved P concentration in surface or subsurface runoff (Hesketh and Brookes, 2000; Maguire and Sims, 2002; Vadas et al., 2005; Wang et al., 2010). Soil test P values (STP), such as Olsen-P, Mehlich-P3, and Bray-P1, determined by short-term extractions, have been well correlated to dissolved P losses (Heckrath et al., 1995; Hesketh and Brookes, 2000; Maguire and Sims, 2002). However, STP methodologies fail to discriminate whether a given soil acts as a P “sink” or source (Hesketh and Brookes, 2000). Particularly, Chilean volcanic soils having the same Olsen-P can present different P buffering capacity values (Sadzawka and Molina, 2005). The DPS has been also used as a tool to detect risk of P losses (Beauchemin and Simard, 1999). The ratio of ammonium oxalate-extractable P to the sum of oxalate extractable Fe and Al (DPS<sub>ox</sub>) was found to be a reliable indicator of P loss in sandy Netherland soils (Breeuwsma et al., 1995; Van der Zee and Van Riemsdijk, 1988). The ratio of STP to PSC is postulated as an indirect way to estimate DPS (Nair et al., 2004). Although PSC can sometimes be obtained directly from P sorption isotherms, indirect methods, such as estimating the P sorption maximum ( $q_m$ ) from the Langmuir sorption model (Pautler and Sims, 2000), are generally preferred. The P sorption index (PSI) – the ratio of sorbed P to solution P following the addition of a single dose of P – is used as a P buffering capacity parameter (Bache and Williams, 1971). Its simplicity and acceptable accuracy has resulted in extensive use. Phosphorus losses by leaching and overland flow in grasslands have been predicted by the ratio between STP and PSI (Börling et al., 2001; Casson et al., 2006; Pautler and Sims, 2000), and the quotient of Olsen-P to PSI (Hughes et al., 2000; McDowell and Condon, 2004).

While the DPS is a reliable indicator of the risk of P loss from soil to fresh water bodies, the methods for its determination are time consuming and expensive for farmers and regulators. On the other hand, the BC<sub>p</sub> is an indicator used routinely in the Southern Chile region and has been shown to successfully assess agronomic P fertility (Sadzawka and Campillo, 2005; Sadzawka et al., 2006). For this reason, The National Degraded Soil Recuperation Program (PRSD) adopted the BC<sub>p</sub> as the official tool to achieve targeted soil P levels. PRSD is a governmental initiative implemented by the Chilean Ministry of Agriculture to recover degraded agricultural soils through financial incentives and technology transfer to farmers. Thus, BC<sub>p</sub> is a reliable indicator working across most volcanic soils in the region with practical/policy-relevance, addressing key agronomical issues. Because of the BC<sub>p</sub> gives the amount of P applied to one hectare (ha) of soil at 0.2 m depth that will increase Olsen-P by 1 mg kg<sup>-1</sup>, it reflects the rate of change of P status unlike most agronomic indicators. For this reason, the BC<sub>p</sub> could also serve as an indicator of environmental risk of P loss when the buffer capacity is met or exceeded by P additions.

It has been well established that soil P buffering capacity (PBC) changes as a function of soil P management and other agronomic practices (Barrow, 2000). As BC<sub>p</sub> represents an estimate of PBC, we hypothesize that its value decreases with increasing P rates and allows the determination of a threshold (change point) where the potential risk for P loss increases abruptly. The objective of this study was to evaluate the BC<sub>p</sub> as an indicator of the point where environmentally significant P release occurs on an Andisol of Southern Chile.

## 2. Materials and methods

### 2.1. Field site characteristics

The soil was selected from a representative region in Southern Chile where dairy farming and beef production are among the

major economic activities. The soil under study was under permanent pasture with no fertilizer added (including P) over the last 20 years. The soil series was identified as the Osorno series, a medial, mesic typic hapludand, formed on slightly hilly topography, with 2–5% slopes. Soils in the Osorno series are deep and well drained with a high water holding capacity (CIREN, 2003). The average annual precipitation in the area ranges between 1200 and 1500 mm, and the mean annual air temperature is 12 °C (Mella and Kühne, 1985). These soils are characterized by low pH (4.8–6.2), high accumulation of OM (15–20%), and a large amount of exchangeable aluminum (Mella and Kühne, 1985). The mineral fraction is dominated by poorly crystalline materials with variable charge such as allophane and imogolite, which leads to low availability of inorganic P content in the soil solution (Besoain and Sadzawka, 1999; Escudey et al., 2001; Sadzawka and Carrasco, 1985).

### 2.2. Soil sampling and chemical analysis

Soil samples were obtained from the surface layer (0–10 cm) with an auger and bulked together to obtain an appropriate mass of soil for the experiment. Before analysis, composite soil samples were air-dried, ground, and sieved through a 2-mm sieve. Soil solution pH, OM, cation exchange capacity (CEC), exchangeable Al (Al<sub>ex</sub>), Al saturation (Al<sub>sat</sub>), sulfur (S), and nitrogen (N) were determined in four replicates according to standard procedures for Chilean volcanic soils (Sadzawka et al., 2006). Soil test P (Olsen-P) was extracted with 0.5 M NaHCO<sub>3</sub> at pH 8.5. Olsen-P is the standard method used in Chile to estimate plant available P. Water extractable P (P<sub>w</sub>), a measure of P susceptibility to P loss by runoff, was determined by shaking soils with nano-pure water at a soil/solution ratio of 1:10 (w/v) for 60 min, and filtration through a 0.45-µm filter (Kuo, 1996). Phosphate determination from the extracts was determined using the ammonium molybdate ascorbic acid reduction method (Murphy and Riley, 1962). Ammonium oxalate extractable P (P<sub>ox</sub>), iron (Fe<sub>ox</sub>), and aluminum (Al<sub>ox</sub>), which are associated with organic and poorly crystalline mineral phases, were obtained by extraction with pH = 3.0, 0.1 M oxalic acid + 0.175 M ammonium oxalate at a soil/solution ratio of 1:20 (w/v) in the dark (Loeppert and Inskeep, 1996). Iron and Al in the extracts were analyzed by atomic absorption spectrophotometry (AAS) and P<sub>ox</sub> concentration was measured colorimetrically (Wolf and Baker, 1990).

### 2.3. Soil incubation procedure

Individual pots with 100 g of air-dry soil each were spiked with increasing amounts of P. Seven rates of P (0, 10, 25, 50, 100, 500 and 1000 mg P kg<sup>-1</sup> soil) were added as KH<sub>2</sub>PO<sub>4</sub> solution and incubated at water field capacity under aerobic conditions over a 90 days period at room temperature (20–25 °C). The P solution was applied to each pot and the soil was thoroughly mixed using a glass-stirring rod. Field water capacity was obtained after watering the pots to saturation and draining for 48 h. During the incubation period each pot was weighed twice a week and the initial weight was maintained by the addition of extra P-free nano-pure water when required to return to the initial field capacity. This soil incubation procedure has been proposed in previous studies as a reliable methodology to evaluate P fertilizer availability (Barrow and Cox, 1990; Indiaty and Sharpley, 1997; Indiaty et al., 1999). Pots were arranged in a completely randomized experimental design with seven incubation treatments (seven P rates) and four replicates (total of 28 pots). Phosphate analyses (Olsen-P, P<sub>w</sub>, and P<sub>ox</sub>) and P sorption studies were performed before and at the end of the incubation period.

### 2.4. Phosphorus sorption studies

Soil P sorption curves were conducted in duplicate on air-dry soil sub-samples obtained from each incubation treatment. Sorption

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