Phosphorus dynamics in Vertosols: improving fertilizer management

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Abstract

Phosphorus (P) increasingly constrains crop productivity in Australian Vertosols (Australian Soil Classification, Isbell et al., 2021). However, P behaviour and dynamics in Vertosols are still not well understood especially within complex cropping systems. To complement our knowledge in P dynamics in Vertosols and collect critical information as a baseline for future agricultural model development, nine Vertosols were incubated with various P fertilizer treatments. Phosphorus dynamics were modelled in relation to physical and chemical properties. Results indicate that physical and chemical properties and P dynamics of the Vertosols are highly variable and differ substantially from the other soil types. This suggests that inclusion of selected soil properties to current soil P models could help to improve the understanding of the fate of applied P in Vertosols. This will be critical for future development of sustainable P fertilizer management strategies.

Keywords

Phosphorus, fertilizer, simulation, modelling, APSIM

Introduction

Cropping systems often rely on phosphorus (P) fertilizers to balance crop removal and maintain productivity. This is increasingly the case in Vertosols that represent a large proportion of cropping land in the Northern Grain Region (NGR) of Australia. The resulting P removal by the crop has exceeded the P applied in fertilizers and this has led to a decrease in soil P reserves. Crop responses to the addition of P fertilizers is now commonly observed as an indicator that soil P reserves are too low (Bell et al., 2013a; Bell et al., 2013b).

Vertosols are often characterised by alkaline pH, high clay content and a relatively high cation exchange capacity that is dominated by calcium (Ca). Studies suggest that dissolution and precipitation of Ca-P minerals can play a critical role in supplying P for crop uptake in these soils (Wang et al., 2007; McLaren et al., 2014; Andersson et al., 2016). Regardless of whether or not dissolution and precipitation of Ca-P minerals influence the pool of bioavailable P in these soils, the implications for crop P acquisition and the fate of applied fertiliser P remain uncertain. Additionally, environmental variables such as fluctuating soil water content (rainfall incidence), together with soil P reserves that are increasingly concentrated in shallow topsoil layers; often lead to confounding effects that contribute to the perception that crop P fertiliser responses are unreliable in such soils.

The complexity of the interactions between (a) crop P demands, (b) the size and spatial distribution of bioavailable P in the soil profile, (c) soil chemical and physical characteristics and (d) environmental conditions; introduce considerable complexity to development of effective P fertilization strategies. Considering the complexity and the lack of understanding of P bioavailability in Vertosols, there is a need to develop better decision support frameworks to account for these complex interactions. Agricultural systems modelling can improve our understanding of complex soil-plant-environment interactions and thereby assist in decision making (Jones et al., 2017; Keating and Thorburn, 2018). Modelling changes in the P cycle relative to plant-availability and plant growth is a difficult task. The modelling is difficult because the key chemical processes may differ greatly between soil types, fertilizer products, application strategies and environmental conditions.

The main objective of the present study is to complement our knowledge in P dynamics in Vertosols and collect critical baseline information for future model development. The specific aims are (1) to determine which specific soil properties affect P sorption in Vertosols, (2) to determine the extent to which P dynamics and availability can be explained by differences in key soil characteristics, (3) to evaluate the ability of The Agricultural Production Systems sIMulator (APSIM) to simulate P dynamics.

Methods

Soil collection and characterization

Soil samples from the subsurface layer (10-30 cm) were collected from 12 sites across the NGR. All the collected soils have a long-term cropping history with little or no P application. Nine soils are typical Vertosols found in this region. Other soil types were also collected, including two Ferrosols from Kingaroy and Redvale and a Chromosol from Nyngan. Soil physical and chemical properties likely to influence P sorption properties (e.g. pH, PBI, CEC) were determined (Table 1). Phosphorus sorption curves were generated using methodology from Rayment and Lyons (2011).

Table 1: Summary of selected soil properties

Soil	pH_{H2O}[1]	Total C[2]	Clay[3]	Total P[4]	Colwell-P[5]	BSES-P[6]	$PBI_{Colwell-P}$[7]	$CaCO_{3\ eq}$[8]	CEC[9]
		%			mg kg^{-1}				cmol_c kg^{-1}
Vertosols	5.7-8.8	0.5-1.7	15-58	132-1006	<2-40	4-112	52-246	<1-50	17-69
Ferrosols	5.3-6	0.9-8.2	35-74	340-630	4-55	30-36	155-967	<1	9.3-19.3
Chromosol	6.8	0.7	22.6	250	12	16		60	12.4

[1]measured 1:5 soil:water ratio (Rayment and Lyons, 2011); [2]total carbon content (Dumas method); [3]particle size analyser; [4]total phosphorus content (aqua regia method); [5]0.5M $NaHCO_3$ pH8.5 (Rayment and Lyons, 2011); [6]0.001M H_2SO_4 (Rayment and Lyons, 2011); [7]Phosphorus buffering index (Burkitt et al., 2002); [8]Titration (Rayment and Lyons, 2011); [9]cation exchange capacity (Rayment and Lyons, 2011)

Soil incubation

Soils were incubated at constant temperature (25°C) and moisture with 50 mg P kg^{-1} (equivalent to 60 kg P ha^{-1}) applied as mono-ammonium phosphate (MAP). Phosphorus availability using Colwell-P (Rayment and Lyons, 2011) test was measured after 10, 30, 90 and 365 days incubations. The decrease in P-availability was modelled using a non-linear exponential decay model:

$$y = a + b*\exp(-cx)$$

where "y" is Colwell-P (mg P kg-1) and "x" is time (number of incubation days).

Phosphorus dynamics and APSIM modelling

The coefficients (a, b and c) obtained in the exponential decay model were then related to soil properties to determine if any specific soil properties affect the dynamics of P. The labile P simulations for the various soils were set up using soil water characteristic curves from existing soils in the APSOIL database. Soils from APSOIL database were selected for their geographical proximity and similar properties to the incubated soil samples. Soil characteristics in the model were modified with the measured data (e.g. OC, NO3/NH4 etc.) Weather data was created based on constant minimum and maximum temperatures with climate control management adding a 1°C variation; with no rain events and radiation set to 0 MJ m^{-2}. The simulations were started on the 1st January with a maximum available water corresponding to field capacity. For each soil, two simulations were generated: one for the unfertilised control (0P) and one for the fertilised treatment (60P), with fertilizer added on the 2nd of January. Phosphorus was applied as water soluble form of fertilizer broadcast in the top 15 cm. For each soil, the Soil-P sorption coefficients ("a" and "b") were derived from Freundlich sorption curves and the initial labile-P was derived from measured Colwell-P. The rate loss available P ("r") could not be experimentally estimated, so various values were tested for each soil (0.1; 0.3; 0.6).

Results

The variability in soil properties observed in Table 1 was also illustrated in the P-sorption curves following Freundlich equations (Fig. 1). Most of the Vertosols reached a plateau as the equilibrium concentration of P in solution increased in the sorption phase, which differentiated them from the strongly P sorbing Ferrosol (Kingaroy). However, the level of saturation for sorption also varies between the Vertosols. For example, V5 quickly reached a saturation level below 400 mgP kg^{-1}, suggesting that very small amounts of P were "fixed"; on the other hand, V2 barely reached a plateau after "fixing" more than 1500 mgP kg^{-1}. This means, Vertosols drastically differ in their ability to "fix" P and the sorption curves were reflective of the wide range of soil properties observed in Table 1. Stepwise regression analysis for the "a" sorption coefficient indicated a significant correlation with soil clay content, pH and $PBI_{Colwell-P}$ ($r^2 = 0.92$, $p < 0.001$). The "b" sorption coefficient was significant correlated with pyrophosphate extractable Al and Fe (Pyr) ($r^2 = 0.20$, $p < 0.01$).

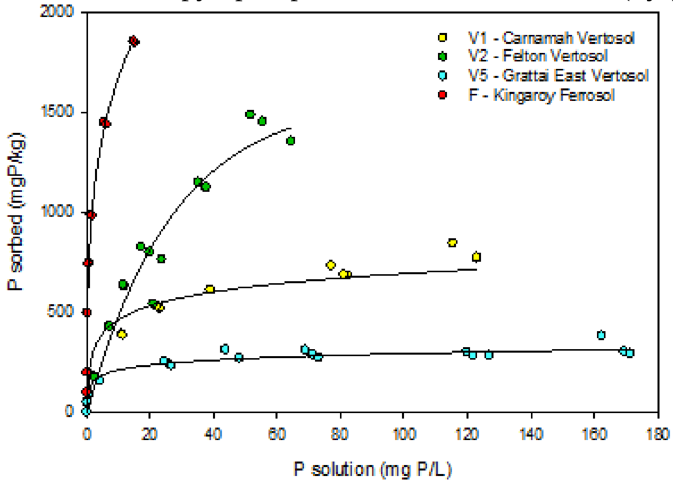

Figure 1. Sorption curves for three Vertisols and one Ferrosol derived from non-linear regression model (Freundlich; $P_{sorbed} = a \times P_{Solution}^{b}$ a and b are Freundlich sorption coefficients)

Overall, P fertilizer addition increased Colwell-P concentration in all the soils after 10 days incubation (Fig. 2). Within the Vertosols, the quantum of increase in P-availability was variable. For example, V2 had lower increase in Colwell-P 10 days after P fertilizer addition compared with V1 and V5. Using stepwise regression, increase in Colwell-P after P fertilizer addition was only significantly correlated with soil clay content ($p < 0.01$). In most of the soil samples, Colwell-P decreased over time, with the sharpest decrease occurring between day 10 and day 30 of the incubation. A three parameters exponential decay function significantly modelled the decrease in Colwell-P over time. Preliminary results indicated that the coefficients defining the shape of the Colwell-P decay curve were not significantly correlated with specific measured soil properties.

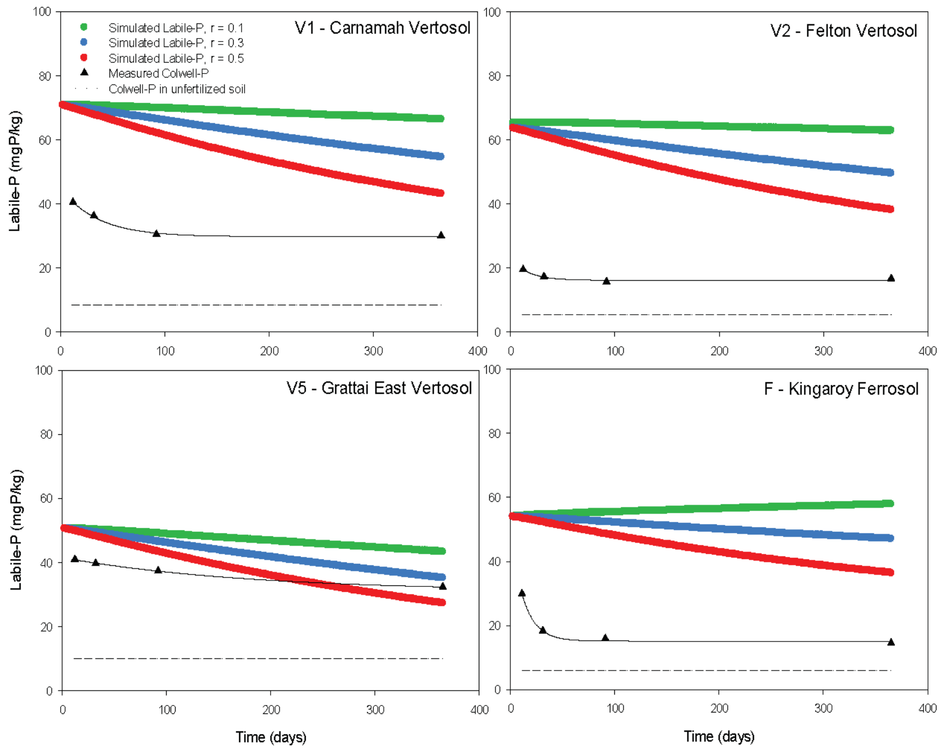

Figure 2. Actual (black line) and APSIM-simulated (coloured lines) decrease of available P over time after P-fertilizer addition.

For most of the soils, APSIM modelling simulated a decrease in Labile-P over time after P fertilizer addition (Fig. 2). The value assigned to the “r” coefficient had a substantial effect on the decrease of Labile-P over-time, with a larger “r” resulting in a steeper decrease in Labile-P. The model consistently simulated a linear decrease of Labile-P over time however this differs to the measured values which show an exponential decay in Colwell-P. The key to simulating the relative increases in Labile-P in response to applied P fertilizer and the further decrease over time seemed to rely on choice of the “r” coefficient. Further data analysis is required to potentially relate “r” to soil properties.

Conclusion

Soil P dynamics are governed by complex interactions between soil physical and chemical characteristics, seasonal moisture availability, crop root distribution and root activity. This is particularly true for alkaline Vertosols in northeast Australia, where the limited P mobility together with the effects of tillage and fertiliser management have major impacts on the distribution of soil solution P. At a fundamental level, the soil P availability in these Vertosols is not well understood and research is limited. The preliminary results presented in this study suggest that physical and chemical characteristics in Vertosol are highly variable and this translates into differences in P-sorption and P availability. APSIM modelling was able to simulate a decrease in P availability after the addition of P-fertilizer although it did not equate to the decrease in observed Colwell-P. This study has suggested that the “r” coefficient may be a key factor in allowing the Labile-P pool dynamics to be simulated in soils, and may reflect the importance of precipitation/dissolution reactions in determining labile-P. Further research linking key soil properties to soil P dynamics are necessary and on-going. These linkages would help develop a more mechanistic framework against which different P management practices can be considered. Ultimately, this would facilitate the development of decision support tools that would help make crop responses to applied P fertiliser more reliable in dryland cropping systems.

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