**A modelling approach to explore the impacts of root distribution and citrate release on phosphorus use efficiency of crops**

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**Introduction**

Phosphorus (P) is a macro nutrient required by crops, and addition of P through fertilisation is needed to maintain soil fertility. Modern agriculture is dependent on P derived from phosphate rock, which is a non-renewable resource. At present rates of consumption global P reserves may be depleted in 50-100 years (Cordell et al. 2009). Increasing P use efficiency (PUE) is therefore essential to maintain crop productivity, avoid negative impacts on the environment, and sustain the resource base. In addition to agronomic measures, such as precision application of P fertilisers, development of new crop varieties with enhanced root growth and increased root citrate efflux to solubilise soil P is considered to have great potential to increase PUE (Jones 1998). However, in spite of the assumed benefits of citrate efflux for mobilization of P in soils, it remains unclear: 1) what level of citrate efflux is needed to have significant impact on crop PUE in different soils, 2) how the citrate solubilisation effect on soil P interacts with enhanced root growth to affect crop P uptake, and 3) what data are needed to quantify these processes and their system-wide impacts. In this paper, we: 1) briefly review the current understanding and available data on citrate release from plant roots and its impact on PUE, 2) show how a modelling approach helps address these issues, and 3) discuss the potential of combining farming system modelling and crop breeding to advance our understanding.

**Methods**

A literature review was conducted with a strong focus on modelling of PUE as affected by citrate release from crop roots. The range of citrate efflux was collated, together with information available on citrate efficiency to solubilise P, citrate decomposition, and response of crop growth to citrate efflux in P deficient soils. This information was used to support the further development of the farming systems model APSIM (Keating et al., 2003). APSIM’s capability to model crop P responses was originally developed for soils where P availability can be represented in terms of P sorption using the Freundlich isotherm (Delve et al., 2009). It simulates P availability in soil and its impact on crop growth through the SoilP and crop modules. The new development here aims to enable APSIM to simulate the impacts of root length density (RLD) distribution and citrate release on soil P availability to crops. Modifications to APSIM-SoilP include: (1) linking the potential P supply in each soil layer to RLD and the P uptake power of unit length of root, (2) relating change in P concentration in the soil solution to the citrate efflux from roots, the efficiency of citrate to solubilise soil P and the citrate loss due to decomposition and sorption, and (3) P solubilised by citrate surplus to crop demand being added to the banded P pool. Parameters for (1) were derived by comparing the performance of the new model with the original one against three datasets, and parameters for (2) were based on information from the review. The new model was then used...
to explore the impact of citrate release on crop growth in soils that varied in their sorption capacities.

Results and Discussion

Our review revealed that the current understanding on the impact of root citrate release on plant PUE is limited. It seems to be clear that (1) citrate can enhance P mobilisation into soil solution (Jones, 1998), and (2) release of citrate (also malate and oxalate), mainly from root tips, increases with P deficiency (Ryan et al., 2001). The main mechanism in P solubilisation involves chelation of metal ions and formation of soluble citrate-metal-P complexes (Kirk et al., 1999). Plants with high citrate efflux from roots include Brassica napus, Lupinus albus (white lupin), and the Proteaceae family. The range of root citrate efflux for wheat and rice are lower, 5-185 (Bryan et al., 2009) and 155-360 nmol/g fresh weigh (FW)/h (Kirk et al., 1999), respectively, as compared to 1656-2373 in white lupin and 3600-9000 nmol/gFW/h in Proteaceae (Roelofs et al., 2001). Most of the data were from plants grown in hydroponics or artificial media. No data are currently available on comparison of genotype response under field conditions. There is also no field scale modelling conducted thus far. We found only one modelling study on rice P uptake in controlled laboratory conditions, and the limited data show that the rate of citrate decomposition is around 0.97d⁻¹ (Kirk et al., 1999), and the citrate efficiency to solubilise P varies significantly in different soils, ranging from 0.010 to 0.400 mol P/mol citrate (Gerke, 1994; Kirk et al., 1999).

Figure 1 shows the performance of the modified model as compared to the original model in term of simulating wheat yield in response to P fertiliser applications. Very similar model performance was achieved across the three sites and different levels of P fertiliser inputs. Figure 2 shows the simulated response of wheat growth to citrate efflux with the modified model and a citrate efficiency of 0.4 on four soils assuming four different sorption capacities. The results indicate that: (1) at any given citrate efflux, biomass is higher in soil with lower P sorption, consistent with observations, (2) If the citrate efflux is relatively low, the impact of citrate release on biomass is marginal (Fig 2b), (3) higher citrate release, either by more root or by higher effluxes, increases the biomass significantly, with the highest increase on soil with highest P sorption, and (4) the biomass increase resulting from citrate release diminishes with increased P fertilisation rates. The new development extends the capability of APSIM to explore the impact of plant root distribution and root exudates on the interaction between crop growth and P dynamics in soil.

The modified model provides a framework to evaluate the impacts of new plant traits (such as citrate release, root distribution change) and to assist in breeding efforts in the assessment of performance of new genotypes under different soil and climate conditions. Further measurement data are needed to quantify the citrate efficiency and crop performance in different soils, which can be obtained from growing plants in different soils, either in pots or the field. Further development and testing of APSIM is required for simulation of crop-P responses in acid and alkaline soils where P availability is controlled by sparingly soluble aluminium and calcium phosphates. Information is also needed to understand the efficiency of different organic anions to solubilise P, the diffusion, sorption characteristics, and decomposition of anions in different soil environments.

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Figure 1. Comparison of simulated and observed wheat grain yields under different levels of P fertiliser inputs at one QLD site and two NSW sites: (a) original model, (b) modified model.

Figure 2. Simulated impact of citrate efflux from wheat roots on wheat biomass in four soils with low (SP50), medium (SP100), high (SP500) and very high (SP1000) sorption capacity. Four levels of citrate efflux (0, 200, 1000, 2000 nmol/gFW/h) were simulated for P application rates ranging from 0 to 200 kg/ha.

References


