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Modelling crop response to phosphorus inputs and phosphorus use efficiency in a crop rotation

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ABSTRACT

Phosphorus (P) is one of the macro nutrients required by crops, and is deficient in many agricultural soils. Due to the low recovery and residual effects of applied P, long-term measurements are required to quantify crop response to P inputs. A modelling approach enables integration of available data to investigate response of crops to P additions in different soils. The APSIM agricultural production systems model has an ability to simulate crop response to soil P. However, the model has only been tested against a few datasets for maize, sorghum and bean crops outside Australia. It has not been applied to Australian conditions, nor against other crops. In this paper we derived the model parameters for wheat, soybean and peanut based on literature and measurement data. The parameterised model was tested for simulation of biomass growth, grain yield, P uptake and grain P contents of four crops (wheat, maize, soybean and peanut) in response to different levels of P addition in a 6-year rotation on a Red Ferrosol soil at Kingaroy, Queensland, Australia. Overall, the model could explain 87% of the variation in observed total aboveground biomass, 84% in grain yield, 75% in crop P uptake and 73% in P content in grain. It was also able to reflect the differential P recovery of crops in the rotation under the 5 different P input levels. In addition, a close relationship was found between modelled labile P and measured bicarbonate extractable P (Colwell P), which may help to initialise APSIM using Colwell P measurements in future studies. It is noted that much of the uncertainties in modelling crop response to phosphorus input arise from the uncertainties in input variables, particularly those describing soil P sorption capacities. Unless P sorption characteristics of a soil in a particular region are quantified, it remains difficult to conduct meaningful modelling research or develop model applications.

1. Introduction

Phosphorus (P) is one of the macro nutrients required by crops. In many agricultural areas it is often deficient and crop yields are constrained if no P fertilizers are applied. In a single season, the crop often only recovers a small fraction (10–20%) of added P, while the rest can be bound to soil particles as adsorbed P, forms sparingly-soluble P compounds or is incorporated into organic P pools (Cornish, 2009). Subsequent recovery of residual P by crops depends largely on soil type and management, but rarely exceeds 50% in most Australian soils (Holford, 1997; Bünemann et al., 2006). While with optimal management, the long-term recovery of applied P from some soils can reach 80% (Wang et al., 2010; Song et al., 2010), the recovery of applied P by crops is often much lower, due to sorption reactions of P with Al- and Fe-oxides (acidic soils) or reactions with Ca to form less soluble or insoluble compounds (alkaline soils). Due to the generally slow recovery of added P by crops, data from long term experiments on crop responses to P addition are required to develop an understanding of the phosphorus dynamics in the soil-plant system. However such data are rare and existing datasets have often only recorded crop biomass and yield at certain P fertilisation rates on a few soil types. It is difficult to extend the results to other locations because soils vary significantly in their P buffering capacity (a measure of the capacity to sorb P) and differences in climate lead to changes in crop productivity and P demand. Soil-plant systems modelling with a capability to model P response in crops provides an efficient means to integrate data from short and long-term experiments and to evaluate phosphorus use efficiency (PUE) of different crops across a wide range of climatic and soil conditions.

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The Agricultural Production Systems Simulator, APSIM (Keating et al., 2003; Wang, 2002) has been successfully used in Australia and China to simulate cropping systems performance as influenced by variable climate and management interventions, including various levels of water and nitrogen input (Probert et al., 1995, 1998; Wang et al., 2003, 2011; Asseng et al., 2007; Hochman et al., 2009; Chen et al., 2010). APSIM's SoilP module was developed to simulate the dynamics of P in soil and to account for effectiveness of P fertiliser applications. It works with the APSIM SoilN and crop modules to enable the simulation of crop response to P fertiliser application in environments where P availability in soil can be represented in terms of P sorption (Probert, 1985, 2004; Delve et al., 2009). The model has been tested against a few datasets in Africa for maize (Probert, 2004) and sorghum (MacCarthy et al., 2009), and in Colombia for maize and beans (Delve et al., 2009) since it was developed. The results indicated that under P-constrained conditions, the model was able to explain 75–87% of the variation in biomass and grain yield of maize and bean crops under varying P input levels (Probert, 2004; Delve et al., 2009). To the best of our knowledge, no study is available on the performance of APSIM to simulate crop response to P additions under Australian conditions. The recent escalation in the cost of both nitrogen and phosphate fertilisers has raised questions about their cost effectiveness and whether growers are using best practice for yield and profitability. A systems approach based on validated soil-plant process models will enable investigation of crop responses to P inputs in contrasting climate and soil conditions, thus assisting in to the development of management strategies to maximise phosphorus use efficiency.

The objectives of this paper are to: (1) extend the parameterisation of APSIM model for simulation of P responses of wheat, soybean and peanut crops; (2) test the model performance for simulation of crop responses to P inputs against data collected from a rotation experiment in Queensland, Australia; and (3) discuss future research needs in terms of modelling P dynamics in soil-plant systems.

Table 2
Application of phosphorus fertilisers (kg P/ha) in each of the treatments.

Date	Fertiliser/application	P0	P20	P40	P60	P80	P160
28/10/97	Triphos, broadcast	0	20	40	60	80	160
21/10/99	Triphos, broadcast	0	10	60	30	40	160
26/04/01	Triphos, broadcast	0	15	70	30	55	20
24/05/02	DAP, broadcast	40	40	40	40	40	40

2. Materials and methods

2.1. Experimental design, soil and crop data

An experiment designed to investigate crop yield response to applications of inorganic P fertilisers was conducted for five years (1997–2002) on a Red Ferrosol soil (Ferralsols in FAO soil reference or Oxisols in USDA classification) at Kingaroy, Queensland, Australia. The experiment comprised a rotation sequence of maize, peanut, wheat and soybeans, with seven individual crops grown in the five year period. Detailed crop information including varieties, sowing and harvesting time and observed ranges of biomass and grain/pod yield is given in Table 1.

Details of P fertiliser applications are listed in Table 2. The first P applications were made before sowing the initial maize crop in 1997, with additional applications in 1999 (again pre maize) and in 2001 (prior to wheat). In the final crop season (2002) a common P rate (40 kg P/ha) was applied to all treatments prior to sowing the wheat crop, effectively testing whether a single application could

Table 1
Crops sown each year in the rotation experiment, and the ranges of measured biomass and grain/pod yields.

Sow year		1997	1998	1999	2000	2001	2002	2002
Crop name		Maize	Peanut	Maize	Peanut	Wheat[b]	Soybean[c]	Wheat[d]
Variety name		Hycorn-621T	Streeton	Pioneer-3270	Streeton	Hartog	Warrigal	Hartog
Sowing date (dd/mm/yy)		25/11/97	28/12/98	19/11/99	13/11/00	18/06/01	25/01/02	12/06/02
Harvest date (dd/mm/yy)		08/04/98	28/05/99	06/06/00	04/04/01	17/11/01	23/05/02	05/11/02
Biomass (Mg/ha)	P0[a]	5.6	3.8	7.2	6.9	1.7	2.2	13.8
	P20	10.6	5.2	13.4	8.8	3.9	3.6	14.4
	P40	12.8	5.7	18.8	11.8	10.2	5.7	11.6
	P60	15.9	7.0	17.7	10.6	7.3	4.9	13.7
	P80	15.1	7.1	19.1	11.3	10.6	5.5	14.2
	P160	16.7	8.0	23.6	12.6	10.3	6.3	13.4
Grain/pod (Mg/ha)	P0	2.8	1.8	3.4	3.6	1.1	0.8	4.5
	P20	5.8	2.0	6.8	4.8	2.7	1.2	4.8
	P40	7.2	2.4	9.7	6.3	5.4	2.3	4.6
	P60	8.3	2.5	9.2	6.0	4.5	1.6	4.7
	P80	7.9	2.6	10.0	6.1	5.3	2.1	4.7
	P160	8.4	2.6	11.3	6.5	5.8	2.6	4.9
Biomass P (kg/ha)	P0	4.2	5.9	6.3	8.5	3.3	2.9	13.8
	P20	12.1	7.9	12.5	11.9	7.2	5.0	14.4
	P40	14.8	8.0	22.2	16.5	17.8	7.7	12.8
	P60	17.8	10.5	19.0	14.2	12.7	6.0	13.7
	P80	20.8	11.4	20.6	16.3	17.8	7.2	17.0
	P160	28.4	13.6	35.8	24.5	20.2	9.1	17.4
Grain/pod P (kg/ha)	P0	3.5	3.4	5.1	5.7	2.6	2.6	13.0
	P20	10.6	4.1	10.2	8.2	6.1	4.2	13.9
	P40	13.4	4.8	19.0	13.5	13.0	10.2	13.4
	P80	21.3	5.3	15.6	11.5	9.8	6.2	13.7
	P60	18.2	5.8	17.0	12.6	12.7	8.5	13.6
	P160	23.2	6.9	25.9	18.8	15.0	12.1	14.1

[a] P0–P160 are the P treatments, see details in Table 2.
[b] Biomass at 126 days after sowing date.
[c] Biomass at 81 days after sowing date.
[d] Biomass at 141 days after sowing date.