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RESEARCH ARTICLE

Simulating phosphorus responses in annual crops using APSIM: model evaluation on contrasting soil types

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Abstract Crop simulation models have been used successfully to evaluate many systems and the impact of change on these systems, e.g. for climatic risk and the use of alternative management options, including the use of nitrogen fertilisers. However, for low input systems in tropical and subtropical regions where organic inputs rather than fertilisers are the predominant nutrient management option and other nutrients besides nitrogen (particular phosphorus) constrain crop growth, these models are not up to the task. This paper describes progress towards developing a capability to simulate response to phosphorus (P) within the APSIM (Agricultural Production Systems Simulator) framework. It reports the development of the P routines based on maize crops grown in semi-arid eastern Kenya, and validation in contrasting soils in western Kenya and South-western Colombia to demonstrate the robustness of the routines. The creation of this capability required: (1) a new module (APSIM SoilP) that simulates the dynamics of P in soil and is able to account for effectiveness of alternative fertiliser management (i.e. water-soluble versus rock phosphate sources, placement effects); (2) a link to the modules simulating the dynamics of carbon and nitrogen in soil organic matter, crop residues, etc., in order that the P present in such materials can be accounted for; and (3) modification to crop modules to represent the P uptake process, estimation of the P stress in the crop, and consequent restrictions to the plant growth processes of photosynthesis, leaf expansion, phenology and grain filling. Modelling results show that the P routines in APSIM can be specified to produce output that matches multi-season rotations of different crops, on a contrasting soil type to previous evaluations, with very few changes to the parameterization files. Model performance in predicting the growth of maize and bean crops grown in rotation on an Andisol with different sources and rates of P was good (75–87% of variance could be explained). This is the first published example of extending APSIM P routines to another crop (beans) from maize.

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Introduction

Models of agricultural systems, particularly the simulation of nutrient dynamics, have a history of evolving as they have been applied to a more diverse range of farming systems. Early crop models, such as those of the CERES family, e.g. CERES-Maize (Jones and Kiniry 1986), were developed primarily to simulate the growth of crops in high input systems, where the only nutrient considered was nitrogen (N). As long as N fertiliser inputs met a substantial proportion of the crop nutrient needs there was little pressure on the model to accurately predict N mineralization from soil. When these models were applied to low input systems, the N supply from soil became critical and led to efforts to improve the soil mineralization routines (Probert et al. 1998a). In particular it was recognised that a full accounting of both carbon (C) and N was needed, and that all soil organic matter (SOM) was not the same in terms of its rate of decomposition; this is particularly important with regards to SOM in subsoil layers.

Crop models that focused on the growth of single crops, with the model being initialized just before sowing, masked whether the models were able to adequately represent the effects of crop residues and roots on nutrient cycling. Real farming systems are concerned with sequences of crops, intercrops and rotations (rather than a single crop) and the desire to model these systems focused attention on the roots and residues remaining after a crop, their quality, and their effects on the N supply to following crops (Probert et al. 1998b). These can be positive in the case of a legume-cereal sequence or detrimental when decomposition of cereal residues with high C:N ratio cause immobilisation of N.

Even following these modelling advances soil constraints represented in models were still restricted to water and N (Probert and Keating 2000). To be useful in tropical and sub-tropical farming systems it was clear that there was need to simulate effects of phosphorus (P) and the nutrient release from a wider range of organic inputs, including animal manures that are often the only nutrient management option for resource-poor farmers. Palm et al. (1997) asserted: “…current simulation models do not yet fully meet the needs of research and extension workers in developing countries… The major issues that need attention are the capacity to simulate P dynamics and the decomposition of the range of crop residues and organic materials that are encountered in tropical farming systems.” The range of materials found in tropical systems brings new challenges for modelling. In particular there are other “quality factors” that influence the decomposition and nutrient release processes (Heal et al. 1997), whilst the animal manures encountered are quite different, both physically and chemically, from plant residues.

The APSIM SoilP module and the necessary modifications to the Maize module to provide a capability to simulate P-constrained maize crops have been described previously (Probert 2004; Kinyangi et al. 2004; Micheni et al. 2004). There remained a need to test the applicability of the model under a wider range of environments, on different soil types, and for other crops. To this end the phosphorus routines in the Maize module have been incorporated into the APSIM Plant module so that the simulation of any crop that uses this module can, in principle, respond to P. In order to use this capability, the parameter set for the crop needs values for the critical P concentrations in the crop. These are used to estimate P demand by the crop to meet its daily growth requirements. Where the supply from soil is inadequate, the critical P concentrations determine the P stress being experienced, which is then used to reduce crop growth.

This paper reports progress in the development and testing of the APSIM modelling framework (Agricultural Production Systems Simulation Model; Keating et al. 2003; website www.apsim.info) towards functionality that can capture the release of N and P from various organic inputs, represent the behaviour of P in soil, and predict the growth of crops in situations where N and/or P is limiting.

Materials and methods

The APSIM SoilP module

The central concept of the SoilP module is that it is possible to describe P availability in soil in terms of a

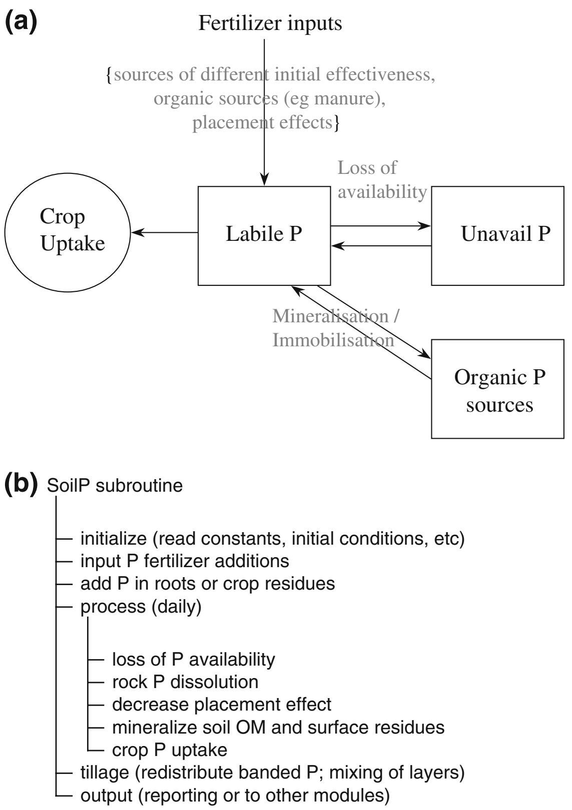


Fig. 1 The APSIM SoilP module. The *upper part* of the figure (**a**) shows in diagrammatic form the processes that are considered in the module. The *lower part* (**b**) shows the simplified subroutine structure of the model where some actions are event based (e.g. initialisation, add fertiliser, tillage) whereas the ‘process’ activities occur on a daily time step

labile P pool, and fluxes into and out of this pool (Fig. 1a). These fluxes are: inputs; crop uptake; transformation between available and organic forms of P; and transformation between available and unavailable forms of P. The model later calculates the P balance between the different forms of P present in this system (Fig. 1b). Thus, the labile P in a given soil layer has units of kg ha^{-1} and responds quantitatively to inputs and removal. It cannot therefore be directly equated with any particular soil P test (which in general do not respond quantitatively to inputs and removal), though we shall return to the topic of how there is need to use soil P tests to initialise such a model.

Fertiliser inputs

Different forms of P fertiliser and different placement options are handled by specifying fertiliser as either immediately available (e.g. water-soluble forms, such as mono-ammonium phosphate) or as a non-water soluble source (e.g. rock phosphate) which must break down before its P enters the labile P pool at a rate that is specified for a particular simulation run. Placement effects are allowed for by accounting for placed (banded) P separately from the rest of the labile P that is distributed within a soil layer.

Loss of availability

Transformations between labile P and unavailable P are assumed to be first-order processes that are dependent on increasing temperature. The relative rates of the forward and reverse processes (Jones et al. 1984) determine the magnitude of the unavailable pool relative to the labile P at steady-state conditions.

Soil organic P

The APSIM SoilN module accounts for C and N in different soil organic matter pools; the APSIM SurfaceOM module does likewise for the surface residues (see Probert and Dimes 2004). SoilP module assumes that these pools also contain P and that decomposition of any pool (controlled by the SoilN or SurfaceOM modules) results in release of C, N and P in proportion to the composition of the pool. SoilP assumes that the C:P ratios of the soil BIOM (microbial biomass) and HUM (soil humus) pools are invariant (as is the case for the corresponding C:N ratios), but the C:P ratio of the surface residues and FOM (fresh organic matter) will vary depending on the materials being added to the system.

Crop uptake of P

SoilP module calculates a potential daily supply of P from all soil layers. This involves: (1) estimation of the effective P in a soil layer (the sum of labile P and placed P, with a premium being assigned to the latter); (2) conversion to a notional concentration in solution based on the P sorption characteristics of the soil; (3) summation across the soil profile weighted according to the presence of roots, soil water status of the layer, and layer thickness; and (4) application of a P uptake factor (p_supply_factor) that can be crop or cultivar dependent. The P uptake factor, as used here, has similarities with the root absorbing power of Nye and Tinker (1977) in that it is the proportionality between P uptake and concentration in solution. Actual uptake is then the minimum of the potential supply and the demand calculated by the crop module. P uptake is apportioned between labile and placed P in the different layers in the proportion to which they contribute to the potential supply.

Simulating crop growth and development under P limiting conditions

The routines introduced into the Maize module to restrict growth under P limiting conditions are similar to the corresponding N routines. The relative P concentration in the plant (or plant parts) is calculated with reference to defined optimal and minimal concentrations. This is then used to calculate P stress factors for photosynthesis, leaf expansion, phenology and grain filling, which are combined (law of minimum) with corresponding stress factors for water and nitrogen to modify crop growth.

Data are scarce on how P deficiency affects plant growth. Compared with the effects of nitrogen there seems to be a lack of information on leaf expansion, and only passing references to the fact that P deficiency delays flowering in maize (Probert and Okalebo 1992) and in sorghum (Sahrawat et al. 1995). Accordingly, the model currently assumes the dominant effect of P is expressed through a reduction in photosynthesis.

The plant demand for P is calculated from (a) the P requirement for today's growth (at the optimal P concentrations of the various plant components), and (b) the overall P deficit of the crop, being the amount of P required to raise the whole of the plant mass to its optimal P concentration. Provided the soil supply (see above) is adequate, the model allows part (a) to be met. Further, in order that a plant can 'recover' from a P-deficient condition, the uptake is allowed to exceed the requirement for today's growth by a factor [a value of 1.5 is currently used (Jones et al. 1984)], thereby reducing the overall deficit.

Datasets used for testing the model

Alfisol in eastern Kenya

The first data set used to test the assumptions that underlie the P capability developed within the APSIM framework was collected on an Alfisol with low P sorption characteristics at Mutua Farm, near Katumani, in eastern Kenya and has been published previously by Probert and Okalebo (1992). Briefly, bicarbonate extractable P (Olsen) in the surface 0–15 cm soil was 4 mg kg^{-1} and maize (Katumani Composite B) was grown over two seasons (short rains 1989–1990; long rains 1990) with different inputs of P as single superphosphate and adequate N. Several harvests were made through the duration of the crop, and the plant biomass was separated into its components (leaf, stem, cobs and, at maturity, grain), dried and analysed for P and N.

Oxisol in western Kenya

An experiment was conducted on an Oxisol near Maseno in western Kenya, to compare the growth of maize crops to inputs of two phosphorus sources. Commercial triple superphosphate (TSP) and Minjingu phosphate rock were applied either at a once–only rate of 250 kg P ha^{-1} or as five annual inputs of 50 kg P ha^{-1}. The experiment was carried out over ten cropping seasons between 1996 and 2000, so that the total P applied was the same for the one-time and annual applications. An additional factor studied was the source of N, as urea, to supply 60 kg N ha^{-1}. Both N and P sources were applied only to the crops grown in the long rain season. The annual rainfall and soil type, especially with regards to its phosphorus sorption properties, are extreme contrasts to those on which the model was first developed. This work has been published by Kinyangi et al. (2004).

In brief, sole maize crop was planted at 0.75 × 0.25 m spacing using medium to short duration hybrid varieties. The long rainy season (LR) crops were sown in March–April, the short rainy season (SR) crops in August–September. During maize harvest, all stover was removed from the plots. Between crops, soil was ploughed to 15 cm depth.

The model was specified to simulate the experimental treatments involving TSP and urea. We used the genetic coefficients for the maize hybrid HB 511 for all seasons, these being available from other studies. For most crops, the predicted maturity of the crop agreed reasonably with the date of harvest. An exception was the LR crop in 2000 (sown 7–8 April), which the model predicted to be mature on 10 September, later than the sowing date (29–30 August) for the next SR crop. This was accommodated by delaying the sowing of the SR crop until 12 September. The simulation runs were initialised on 15 March 1996, corresponding to the start of the experiment. A continuous simulation was run for the ten seasons. The soil's plant available water capacity to the rooting depth of 1.8 m was 155 mm. The soil organic carbon in the surface soil layer was the measured value. The soil labile P in the surface layer was based on the sum of resin and bicarbonate-P measured in the sequential fractionation of soil P. Both organic carbon and soil P were assumed to decrease with depth, while P sorption was assumed to be higher in the subsoil layers.

Andisol in Colombia

Experiments involving P inputs as fertiliser or chicken manure to a maize-bean cropping system were carried out to provide a data set that would be suitable for further testing of the model and extending its application to a different crop (namely bean). The environment and soil (a very high P-fixing Andisol) at the Colombian location is a strong contrast to the two Kenyan soil types described above. As this work has not been published to date a more detailed description follows.

The experimental site was located in the Andean hillsides of the Department of Cauca, Colombia (2°48′N, 76°33′W, 1,500 m.a.s.l.). The area has a mean temperature of 19.3°C and a mean annual rainfall of 1,900 mm with bimodal distribution and two growing seasons. The soil is derived from volcanic ashes and is classified as an Oxic Dystropept (Inceptisol) in the USDA soil classification system (USDA 1998) and an Andic Dystric Cambisol in the FAO classification (FAO/UNESCO 1990). Air-dried soil (0–15 cm) had a pH of 5.3 (1:2.5 soil:water); organic carbon 105 g kg^{-1}; exchangeable calcium 3.05 cmol$_c$ kg^{-1}, magnesium 0.96 cmol$_c$ kg^{-1}, potassium 0.28 cmol$_c$ kg^{-1}; bicarbonate–EDTA extractable phosphorus 1.27 mg kg^{-1}. P sorption is very high; based on sorption isotherms, 1,000 mg P kg^{-1} of soil was required to raise soil solution P to 0.2 mg l^{-1} for 0−15 cm soil (Le Mare and Leon 1989).

The land had previously been cultivated with cassava (*Manihot esculenta* Crantz) for 8 years, followed by 5 years of fallow and converted to a maize mono-crop for two seasons before the start of experimentation. The maize-bean rotation commenced with maize (*Zea mays* L.) sown in September 2001 followed by bean (*Phaseolus vulgaris* L.) in the next March–June season (2002).

Treatments Two adjacent randomised block experiments included the following treatments. The TSP experiment had nine treatments with P fertiliser as triple super phosphate applied: once at the beginning of the experiment (20, 40, 80 and 160 kg P ha^{-1}, identified as 20R, 40R, 80R and 160R, respectively) or annually (5, 10, 20 and 40 kg P ha^{-1}, identified as 5A, 10A, 20A and 40A, respectively), with a zero P control (0 kg P ha^{-1}) to a sole maize crop in rotation with a sole crop of beans. With this combination of treatments, after 4 years there are treatments where total P applied is equal for the one-time and annual applications (e.g. 160R and 40A). The Manure experiment comprised annual applications of 0, 3, 6, 12 t ha^{-1} of chicken manure (CM) (identified as 0M, 3M, 6M and 12M, respectively) prior to the maize crops, in the same two-crops-per-year rotation as for TSP. In both experiments the P sources were broadcast and incorporated into the soil (10 cm depth) using hand tools before sowing.

Management A medium to short duration maize hybrid variety (cv Cresemillas), was planted in September 2001 at 0.8 × 0.5 m (50,000 plants ha^{-1}), and a medium duration bean variety (ICA Caucayá, PVA 773) was planted in March 2002 at 0.6 × 0.1 m (166,666 plants ha^{-1}). This variety has been used by farmers in the region because of its superior grain quality although it has been sensitive to diseases.

For TSP Experiment, N was applied as urea. The maize crops received 120 kg N ha^{-1} in three equal splits 14, 42 and 63 days after sowing (DAS); the bean crop received 20 kg N ha^{-1} at 14 DAS. Basal nutrients (dolomite, potassium, and micronutrients) were also applied to the maize and bean crops. For Manure Experiment there were no inputs of N or basal nutrients. At harvest all stover remained on the plots and was arranged in rows between the crops to facilitate planting of crops and weed control.

The soil (0–10 cm) was sampled before and after each maize crop and samples air-dried, sieved through 2 mm, and fractionated for soil P using a method that employs a series of increasingly aggressive extractants to remove labile inorganic and organic P (Pi and Po) followed by more stable Pi and Po forms. The method is modified from the procedure of Tiessen and Moir (1993), which in turn is based on the fractionation procedure of Hedley et al. (1982).

The model The simulations were done with APSIM v3.6. The model was specified to simulate the experimental treatments involving TSP, CM and urea assuming common starting conditions for all treatments. The simulations were initialized on 18 August 2001 (after harvest of the maize crop prior to commencement of the experiments) and carried out as a continuous run until maturity of the bean crop in June 2005 (i.e. there was no resetting of any variables between crops). Measured data were used to specify the soil characteristics for the APSIM SoilWat and SoilN modules (Table 1) at initialization. Based on the data in Table 1 the soil's plant available water capacity for maize (rooting depth 1.5 m) was 121 mm. The weather file to run the model used daily rainfall and maximum and minimum temperatures measured at the experiment site. Radiation data were estimated using MarkSim (Jones and Thornton 1999; Jones et al. 2002).

Maize The maize cultivar had not previously been modelled using APSIM. Based on information that it is a medium to short duration hybrid we selected the parameter set for SC401, an early maturing hybrid from Zimbabwe. To improve fit of the maturity date simulated by the model with known harvest dates the only change made to the parameter file was to decrease the thermal time between crop emergence and end of juvenile stage (tt_emerg_to_endjuv) parameter

Table 1 Soil properties used for specification of APSIM for simulation of the experiments studying responses to P fertiliser and chicken manure

Layer no.	1	2	3	4	5	6	7
SoilWat parameters[a]							
Layer thickness (mm)	100	100	100	300	300	300	300
Bulk density (g cm^{-3})	0.55	0.55	0.66	0.90	0.90	1.10	1.15
SAT	0.71	0.71	0.71	0.65	0.65	0.57	0.55
DUL	0.56	0.56	0.56	0.56	0.56	0.52	0.50
LL15	0.40	0.40	0.45	0.45	0.45	0.45	0.45
Maize parameter							
LLmaize	0.40	0.40	0.45	0.45	0.47	0.48	0.48
Navybean parameter							
LLnavybean	0.40	0.40	0.45	0.45			
SoilN parameters[b]							
Organic C (%)	9.0	7.0	3.0	1.0	1.0	0.5	0.2
Finert	0.7	0.8	0.9	0.95	0.99	0.99	0.99
Fbiom	0.02	0.015	0.01	0.01	0.01	0.01	0.01
Nitrate–N (mg kg^{-1})	33	36	20	10	5	5	5
Ammonium–N (mg kg^{-1})	17	8	6	1	1	1	1
SoilP parameters[c]							
Labile P (mg kg^{-1})	15	9	6	4	4	4	4
Sorption (mg kg^{-1})	1,000	1,500	1,800	1,800	1,800	1,800	1,800

[a] The soil water characteristics are described in terms of the volumetric water content at saturation (SAT), at drained upper limit (DUL), and at lower limit of water extraction by the crop (LL15)

Maximum depth of water extraction 1.5 m for maize and 0.6 m for bean

[b] Finert defines the proportion of the soil organic matter that is not susceptible to decomposition; Fbiom is the proportion of the decomposable soil organic matter that is initially present in the more rapidly decomposing pool. The C:N ratio of the soil organic matter was set to 13

[c] Sorption is the P sorbed at a concentration in solution of 0.2 mg l^{-1}

from 230 to 220. No changes were made to the critical P concentrations that had been used for modelling maize crops in Kenya (Table 2). These concentrations had been derived from composition of samples taken from the experiment growing the short-duration cultivar Katumani Composite B in eastern Kenya (Probert and Okalebo 1992) together with the published data of Jones (1983).

Bean There has been no previous experience of modelling the common bean grown in Latin America using APSIM. We used the APSIM Plant module with the Navybean parameter set (Robertson et al. 2002) selecting the cultivar specific values for 'rb_short'. Changes were made to the parameters tt_emerg_to_endjuv (increased from 250 to 300 to make the simulated crop mature later) and to y_hi_max_pot (increased from 0.45 to 0.50 to increase the maximum harvest index potential of the simulated crops). Both changes were made to try to improve the fit with the observed data.

Table 2 Minimum (Min) and maximum (Max) critical P concentrations (%) in plant components used in APSIM for maize and bean module

Stage of growth	Emergence		Flowering		Grain-filling		Maturity	
	Min	Max	Min	Max	Min	Max	Min	Max
Maize								
Leaf	0.3	0.45	0.11	0.25	0.08	0.24	0.06	0.24
Stem	0.3	0.45	0.06	0.1	0.02	0.07	0.02	0.07
Flower	0.3	0.45	0.06	0.1	0.02	0.07	0.02	0.07
Grain					0.15	0.3	0.15	0.3
Root	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Beans								
Leaf	0.4	0.5	0.18	0.34	ND	ND	0.14	0.3
Stem	0.35	0.45	0.16	0.2	ND	ND	0.1	0.2
Pod			0.25	0.4	ND	ND	0.25	0.4
Grain					ND	ND	0.24	0.4
Root	0.15	0.15	0.15	0.15	ND	ND	0.15	0.15

Critical concentrations for beans were derived from composition of samples from the experiments: control treatments for minimum concentrations; 80R, 160R from TSP experiment, and 6M, 12M from CM experiment for maximum concentrations). Root P concentrations were assumed to be 0.15% at all stages of growth and independent of the crop's P status

ND not determined

In order to model a P response in bean it was necessary to create the parameter set defining the critical P concentrations in the components of the bean crop. These were derived from analytical data for samples from the experiment (available at flowering, pod-filling and maturity in 2002, and pod-filling in 2003 and 2004). The other parameter required was p_supply_factor for navybean in the SoilP module. This parameter is the proportionality between daily P uptake and the notional concentration of P in soil solution. In initial simulation runs we assumed the same value as used for maize (0.45). Subsequently, after inspection of output compared with measured yields, we reduced the value for navybean to 0.3. This is consistent with bean being more sensitive to P supply from soil than maize (Rao et al. 1999).

Manure The CM used each year in the experiment had been analysed for macro nutrients, these varied from year to year; average values were: 37% C, 3.3% N, 1.5% P, 2.0% K, 3.8% Ca, 0.9% Mg. Measured data for each year were used to specify the inputs of manure in the model. In the APSIM Manure module, manure is characterised in terms of the three pools corresponding with the FOM pools of the SoilN module. In other studies (Probert et al. 2005) attempts have been made to link these pools to proximate analyses of organic sources. Here we have assumed that the C was distributed in the ratio 0:0.5:0.5 between the three pools. Further we assumed that all pools had uniform composition of C, N and P (see Probert et al. 2005).

Soil phosphorus From soil P fractionation data (0–10 cm layer) the sum of resin P and bicarbonate Pi fractions were used as the estimate of initial labile P in soil. As no information was available for the subsoil layers, it was assumed that soil P decreases with depth and that P sorption increases in the subsoil (Table 1).

Initial simulations used identical parameters in the SoilP module as were used to simulate a long-term experiment on an Alfisol in Kenya (Micheni et al. 2004). However, inspection of the output indicated that the rate of loss of availability of P applied as TSP was considerably faster on the Andisol than on the Alfisol. This finding is supported by Iyamuremye and Dick (1996) and Takahashi and Shoji (2002) who found that high concentrations of allophane in Andisols strongly absorb phosphates, making them less available. The parameter rate_loss_avail_P (P availability loss per year at 25°C) was increased from 0.5 to 0.8 to improve the fit of the model to the observed data.

Statistical analysis

The closeness of the relationships between observed (O) and predicted (P) crop yields was estimated using:

1. the square of the correlation coefficient, R^2, which can be interpreted as the proportion of the variance in the observed data that is attributable to the variance in the simulated data
2. the median unbiased absolute percentage error, MdUAPE (%) calculated as

$$\text{MdUAPE} = 100 \times \text{median}(|\text{P}_i - \text{O}_i| / (0.5 \times (\text{P}_i + \text{O}_i)))$$

3. the modified coefficient of efficiency, E_1, calculated as

$$E_1 = 1 - \Sigma|\text{O}_i - \text{P}_i| / \Sigma|\text{O}_i - \text{O}_{\text{mean}}|$$

$E_1 = 1$ describes a perfect fit of observed and simulated data, whilst $E_1 = 0$ indicates the simulated data describe the observations as well as the average of the observed data.

Sommer et al. (2007) provide the rationale for the use of MdUAPE and E_1.

Results and discussion

Initial testing (Alfisol dataset)

The output from the model is compared with the measured data in Fig. 2. What is shown is not implied to be an independent test of the model. However, it does indicate that the model was able to capture the main features of the measured data in terms of total dry matter and grain yield. Other data (not shown) showed reasonable agreement in leaf area and P concentration in the tissues.

Testing with Oxisol dataset

The effects of P treatments on the Oxisol are illustrated in Fig. 3 for the total dry matter yield. Results were similar for grain yield (data not shown). The most marked feature of the results is the contrast in pattern of response between the two seasons. The P treatments, but even more importantly the N inputs, were applied prior to the crops grown in the long rains season. In this season there was a strong response to P each year. But in the short rains season there was little response to the treatments.

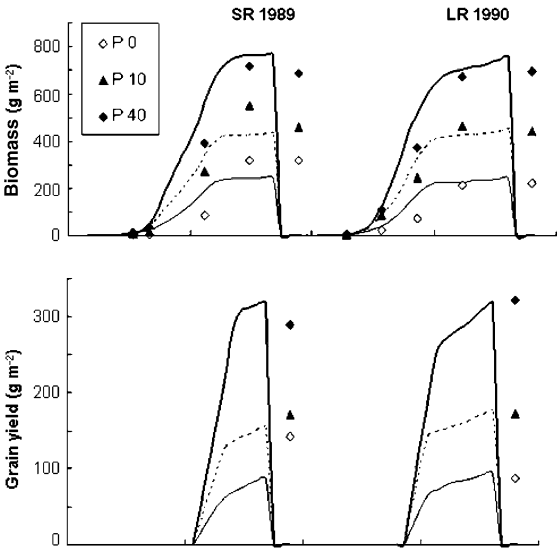


Fig. 2 Comparison of measured and simulated yields of the maize crops grown at Mutua Farm, near Katumani with different rates of P as superphosphate applied as a band below the seed and 90 kg ha^{-1} of N as calcium ammonium nitrate applied as three splits (Probert and Okalebo 1992). The observed data are shown as *symbols*, the predictions as continuous lines. Note that the crops were harvested several days later than physiological maturity as predicted by the model

In the first year there was additional response beyond the P50 rate. In second, third and fourth years, the yields were similar for the once only application (P250) and annual inputs (P50); but by the fifth year there is evidence that the P250 treatment was incapable of maintaining yields and the highest yield was obtained where there were annual applications (P50).

The simulated results captured these effects rather well. In fact it was only after early attempts to model the data that the experimenters realised the extreme consequences of not applying N to crops grown in both the long rains and short rains seasons. The model could be used to identify the factors limiting crop growth (water, N or P) (details not shown). It

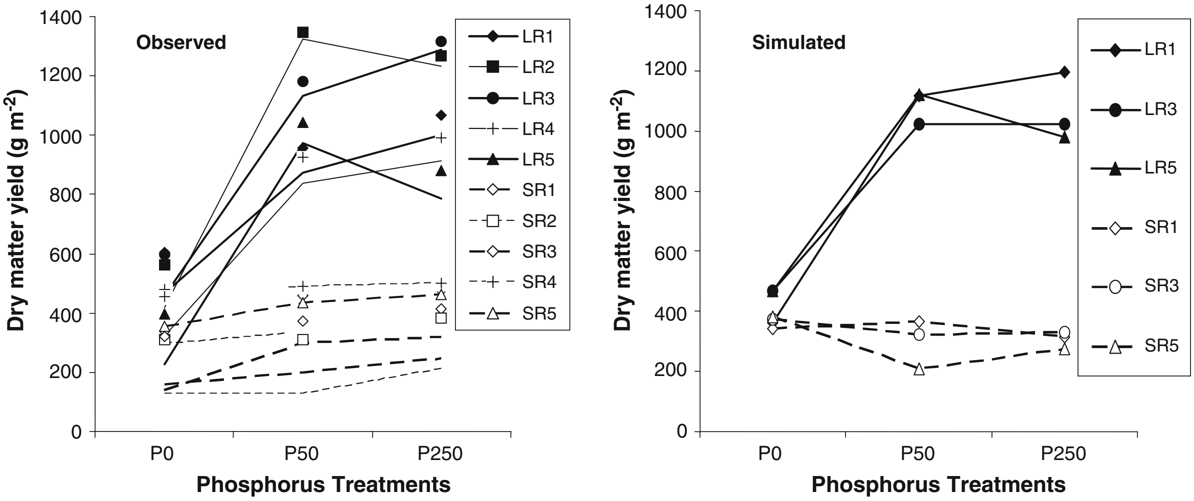


Fig. 3 Effect of phosphorus treatments on total biomass yields for the Oxisol dataset. *P50* refers to treatment that received 50 kg ha^{-1} of P annually; *P250* received 250 kg ha^{-1} as once only application. For the simulated yields, data are shown for the first, third and fifth seasons only

showed clearly that in this high rainfall environment there could be no residual effects from N because it would be leached beyond the rooting zone.

Figure 4 shows the data plotted in observed versus predicted space. This again shows the lack of treatment effects in the SR season. Overall there was reasonable agreement between the observed and predicted yields with little indication of bias (Fig. 4). The statistics on the closeness of the relationship between observed and predicted yields are set out in Table 3.

Testing with Andisol dataset

Crop yields

In terms of plant growth, the annual inputs of the higher rates of CM provides a better "non-limiting nutrient" treatment than any of the treatments in the TSP experiment. Figure 5 shows a comparison of the observed and predicted crop yield through the eight seasons for selected treatments. For the 12 M treatment (Fig. 5a) there is good agreement for the maize crops that produced around 1,300 g m^{-2} total biomass and 600 g m^{-2} grain each year. The grain yield for bean was predicted well in 2002 and 2004 but not in 2003. Total biomass for bean was over-predicted (this is explored in more detail below). The 2003 bean crop was severely affected by diseases caused by *Rhizoctonia solani* and *Colletotricum lindemuthianum* which delayed maturity well beyond the normal 88 days and reduced yields. The simulation of the treatment without added P (Fig. 5d) has much smaller yields of maize and bean. Comparing this treatment with 12 M shows that the model predicted a large response to input of P in this soil. The other two treatments compare the effects of the one-time application of 160 kg P ha^{-1} as TSP (Fig. 5b) with the annual input of 40 kg P ha^{-1} (Fig. 5c). In both cases there is good agreement

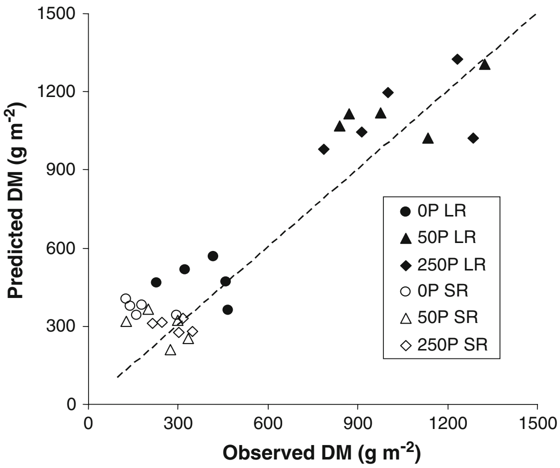


Fig. 4 Plot of observed versus simulated maize dry matter yields for the Oxisol dataset in relation to the 1:1 line. The root-mean-square deviation between observed and predicted yields is 158 g m^{-2}

Table 3 Statistics describing goodness of fit between observed and simulated crop yields

Experiment	N_{obs}	Variate	Mean observed yield (g m^{-2})	R^2	MdUAPE (%)	E_1
Oxisol	30	Maize grain	181	0.81	43	0.51
		Maize biomass	605	0.88	23	0.61
Andisol	40	Maize grain	237	0.74	38	0.50
		Maize biomass	648	0.83	22	0.63
		Bean grain	34	0.79	57	0.53
		Bean biomass	59	0.69	59	0.44

N_{obs}, number of observations (for Oxisol 3 treatments × 10 seasons; for Andisol 10 treatments × 4 seasons for each crop); R^2, square of correlation coefficient; MdUAPE, median unbiased absolute percentage error; E_1, modified coefficient of efficiency

between the observed and predicted data. For the 160R treatment the yield of maize in the first crop is close that for 12M, but the residual effect of P is not sufficient to maintain high yields in later seasons. These were the findings that led to the use of the higher rate of loss of available P in the model. With the parameterization used the model predicts the declining yields closely. In contrast, 40A was inadequate to achieve maize yields equivalent to 12M or 160R in the first season, but over the four seasons this treatment improves to yield better than 160R in the 2004 and 2005 maize crops. The contrasting trends for the 160R and 40A annually is simulated well by the model (Fig. 5b, c).

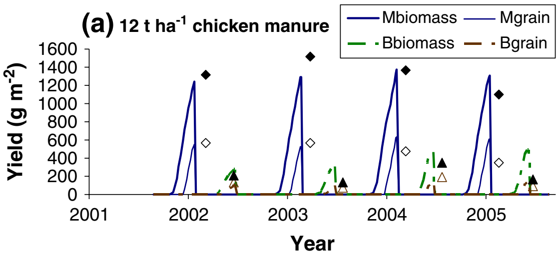
To illustrate a different aspect of model performance, there was generally good agreement between the observed and predicted yields of maize and beans in response to varying annual applications of CM (Fig. 6). There was some tendency to under-predict the yield response to the 3M and 6M treatments in the first year of the simulation, but with repeated annual applications all treatments tended to approach a yield plateau and this is well captured by the model.

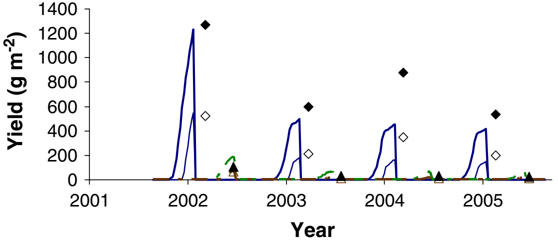
In contrast, the observed data for beans show a response to increasing inputs of CM throughout the experiment. This is the evidence that led us to use a different p_supply_factor for bean (0.3) than for maize (0.45). There is close agreement between measured and predicted grain yield of bean. For predicted bean biomass we show two lines. The upper dotted line is the model output for total biomass and there is clearly an over-prediction of the measured biomass in all cases. However, when the comparison is made with the simulated biomass less the simulated senesced leaves there is excellent agreement, apart from 2005. This adjustment of the simulated biomass is justifiable because at harvest in the field the bean crop is almost devoid of leaves but the APSIM bean module includes the senesced leaves in the total biomass. The shedding of senesced leaves also explains why the harvest index of the experimental crop is very high—over 66% in some treatments for the 2002 crop—whereas in the model the harvest index (HI) is constrained to a maximum potential of 50% (data not shown).

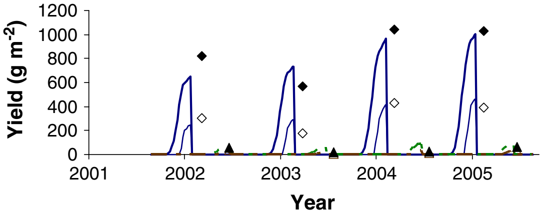
Comparison of observed versus predicted values shows highly significant agreement for all the treatments in all years (Fig. 7). In this figure the comparison for bean biomass is with the modelled output for non-senesced biomass. There is some tendency to over-predict maize biomass and grain for low yielding crops (when biomass $<\sim 400$ g m^{-2}), although overall agreement in the observed and simulated data is high ($r^2 = 0.75$–0.87). Statistics on the goodness of fit between observed and predicted yields are shown in Table 3.

Discussion

Phosphorus is a common limiting nutrient affecting crop growth in tropical areas, thereby reducing the usefulness of simulation models which do not have a capability to model both N and P limitations. The ‘P-aware’ maize model (Probert 2004) was a major breakthrough in our thinking of how to explicitly reflect soil P dynamics and especially P limitations in crop simulations. Although this capability has been tested in other soil types (e.g. Kinyangi et al. 2004; Micheni et al. 2004) there was still a clear need to


(a) 12 t ha^{-1} chicken manure


(b) 160 kg P ha^{-1} as TSP


(c) 40 kg P ha^{-1} yr^{-1} as TSP

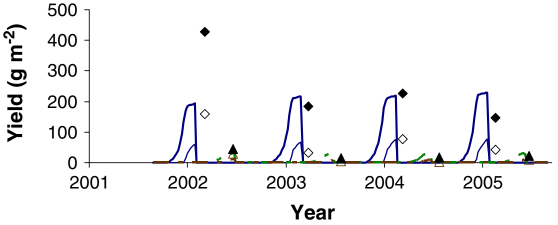

(d) Control

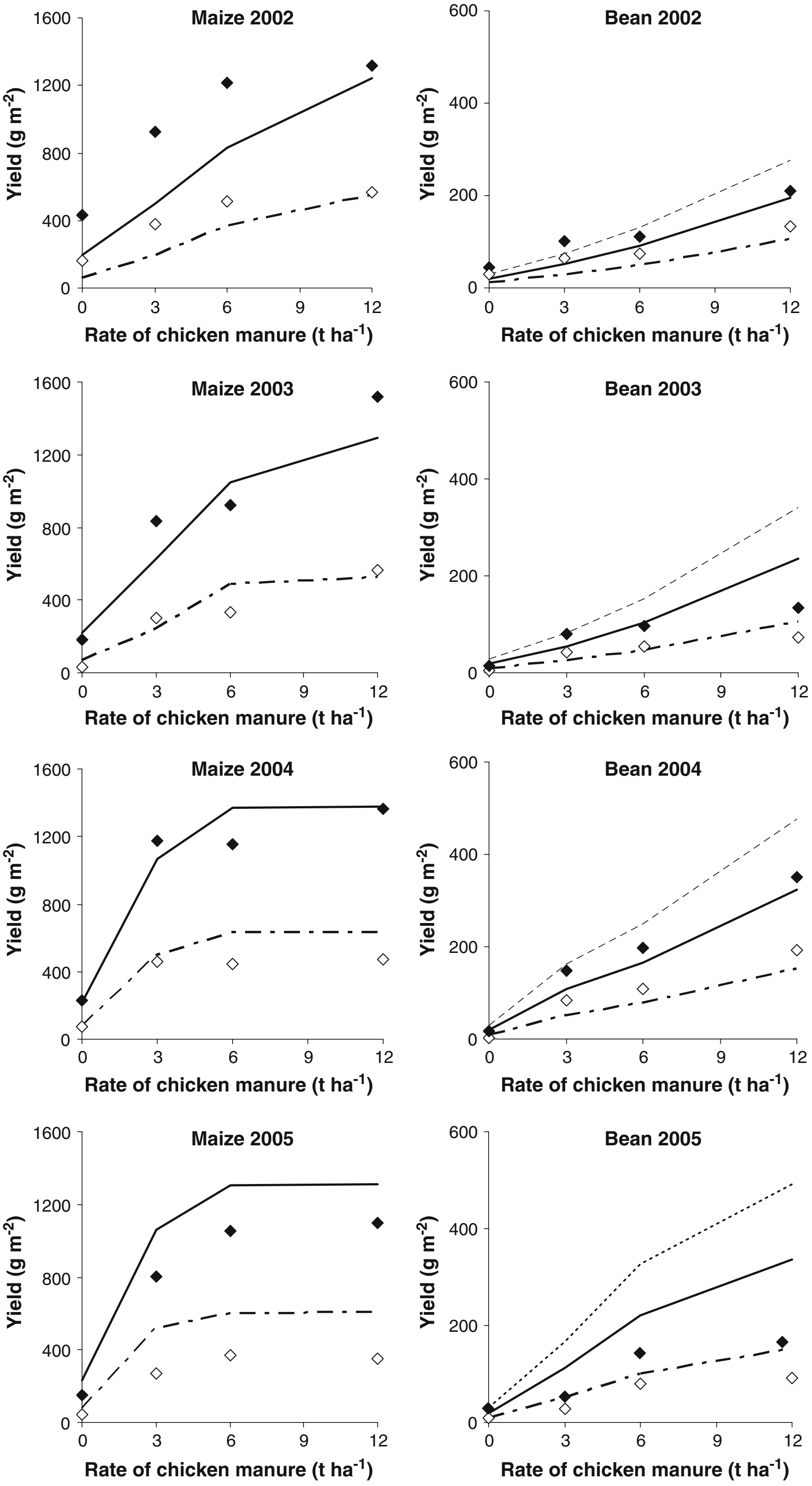
Fig. 5 Comparison of observed data (maize biomass (◆), maize grain (◇), bean biomass (▲) and bean grain (△) and predicted data (*lines*) for total biomass and grain yield of maize and bean crops (2001–2005) for selected treatments for the Andisol in Colombia dataset. Note that the *vertical scales* differ for different treatments

apply the new capability to other crops and on other more P-fixing soils. This study has provided opportunity to extend the capability to another crop (beans) and a soil with a much higher P-fixing capacity.

Management of soil P (especially in high-input agricultural systems) has focused on issues like whether to apply fertiliser, at what rate, evaluating placement and residual effects, and comparing relative effectiveness of water-soluble versus insoluble sources. Because P is immobile in soil (at least over the time scale of an annual crop) interactions with climate are of little importance. Unlike the management of N, there has been no need for a detailed crop model to evaluate alternative strategies for management of P. Models operating with a time-step of a growing season and an empirical relationship between yield and soil P status are adequate to gain insights into crop responsiveness to alternative fertiliser P sources and their residual effects (Probert 1985). However, if there is a need for crop models to simulate response to manures and other organic sources in low-input systems, it is important that they respond to both N and P.

The development of a capability to model crop response to limited P supply requires code to describe the behaviour of P in both the soil and the plant. The approach adopted to create this capability in APSIM has similarities and conceptual differences from how the problem has been tackled in DSSAT (Daroub et al. 2003). The most obvious differences are in how the understanding of the behaviour of soil P is represented. Daroub et al. (2003) seek to specify numerous soil inorganic and organic P pools in terms of measured soil fractions. The philosophy in the APSIM approach has been that the availability of P to crops can described in terms of a labile P pool, whilst the organic P pools are identical to the C and N pools found elsewhere in the model. Thus, there will always be a linkage between mineralisation/immobilisation of N and P and decomposition of soil organic matter. Also, the conceptual labile P pool in the APSIM SoilP module has not been directly linked to any soil P test. In this manner we avoid the difficulty that labile P, as it is defined in the model, responds quantitatively to inputs and removal of P, whereas this is not the case with soil tests. Nevertheless, this is to admit that it is not yet clear how such a model should be initialised and/or validated against measured soil test data. Here we have used the sum of resin P and bicarbonate P_i (measured sequentially) to initialize the model with a degree of success. But the model could be initialized and tested with different assumptions concerning what constitutes labile P. Understanding of how labile P relates to soil test values will require study of the conformity between simulated labile P and measured soil test data.

Fig. 6 Total biomass and grain of maize and bean crops (2002–2005) in response to annual inputs of chicken manure for the Andisol in Colombia dataset



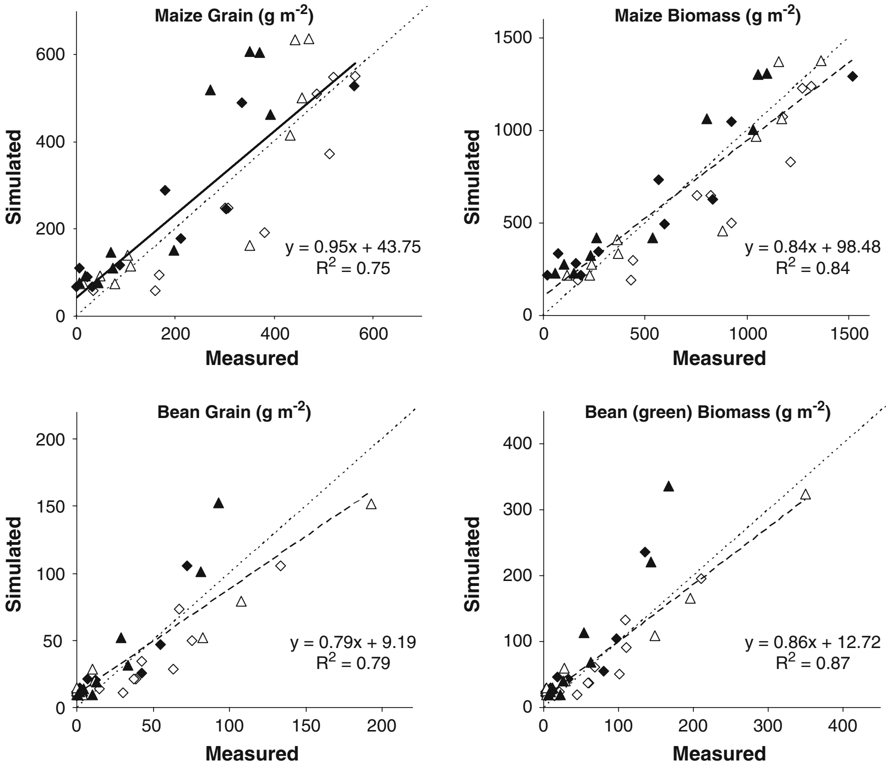


Fig. 7 Observed versus predicted grain and biomass for maize and bean crops for the Andisol in Colombia dataset. Based on data for crops harvested in 2002 (◇), 2003 (◆), 2004 (△) and 2005 (▲)

Conclusions

Here we have shown that the P routines in APSIM can be specified to produce output that matches multi-season rotations of different crops, on a contrasting soil type to previous evaluations, with very few changes to the parameterization files. The parameter set used to simulate the behaviour of P in the soil and the P concentrations and uptake by maize was that based on crops grown on a low P-fixing soil in a semi-arid environment. The model performed creditably in predicting the growth of maize and bean crops for the different P sources (fertiliser or chicken manure) and treatments (rates and frequency of application). The modified coefficient of efficiency E_1 for maize and bean yields for the experiments on the Oxisol and Andisol was between 0.44 and 0.63 with the simulated data accounting for more than 69% of the variance in the observed data. These results are even more notable when it is considered that there had been no previous experience of modelling beans with APSIM in Latin America or extending the P routines from maize to another crop.

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