

## 4.3

# A Capability in APSIM to Model Phosphorus Responses in Crops

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### *Abstract*

Crop simulation models can be used to evaluate climatic risk and alternative management options, including the use of nitrogen fertilisers. However, they have not met the needs of researchers for low-input systems in tropical regions where organic inputs rather than fertilisers are often the only nutrient management option, and other nutrients besides nitrogen (particular phosphorus) frequently constrain crop growth.

This paper describes progress towards developing a capability to simulate response to P within the APSIM (Agricultural Production Systems Simulator) framework, and initial attempts to parameterise such a model to simulate the growth of maize crops grown in semi-arid eastern Kenya. The creation of this capability requires: (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, e.g. water-soluble versus rock phosphate sources, and 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; (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.

To a large extent, the behaviour of P in the plant and in soil organic matter is modelled in a similar manner to nitrogen. However, that this can lead to a situation where predicted mineralisation of P from crop residues is contrary to experimental observations. It is suggested that the reason lies in the fact that C:P ratios are not common across the sub-fractions of organic matter, with a high proportion of the P being present in the water-soluble components.

The development and application of crop simulation models has focused on water and nitrogen as the main constraints to crop growth (Probert and Keating 2000). Such models have been useful for evaluating alternative management strategies and the effects of climatic conditions. However, their use assumes that other factors (e.g. nutrients other than N, pests, disease) are not limiting. In the case of nutrients, for high-input systems where fertiliser is used to correct nutrient deficiencies the assumption is acceptable. But in low-input systems, as occur in many tropical farming systems,

the assumption is untenable, and these models fail to meet the needs of researchers and extension workers (Palm et al. 1997).

Phosphorus is a limiting nutrient that frequently affects crop growth thereby reducing the usefulness of models. One situation where models have been less than adequate concerns use of scarce manure supplies, which are often the only input of nutrients to the cropping system, and can be a source of both N and P (McCown et al. 1992). It was in response to this particular need that efforts began towards developing a capability within APSIM (McCown et al. 1996; Keating et al. 2003; web site <[www.apsim.info](http://www.apsim.info)>) to simulate growth of crops that were constrained due to P deficiency.

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In order for this to be achieved, a new APSIM module (SoilP) was needed, to describe the dynamics of P in soil; modifications were needed to existing modules to describe the mineralisation of P from manures and other organic inputs; and modifications were needed in the various crop models to describe the P uptake process, together with the extent of P stress in the plant, and its effects on crop growth. This paper sets out how this has been achieved to develop a 'P-aware' APSIM maize module. We use 'P-aware' to distinguish a crop module that has the necessary enhancements to be constrained under low P conditions.

The experimental data set used to derive parameters for the model had been collected during an earlier ACIAR project, from experiments carried out in the Kenyan semi-arid tropics and described by Probert and Okalebo (1992). The testing of the model under a wider range of soils and climate is the subject of other papers in these proceedings (e.g. Kinyangi et al. 2004; Micheni et al. 2004).

## Modelling Phosphorus in Cropping Systems

Phosphorus uptake by plants involves diffusion of phosphate to roots, and is increased by the presence of mycorrhizae. Models of diffusion to plant roots (e.g. Claassen and Barber 1976; Nye and Tinker 1977) show that root density is a controlling factor in P uptake. But models of the diffusion process are at a greater level of detail (in both time and space) than what is found in most crop models. Crop models typically assume that water and nitrogen are homogeneous throughout each soil layer with a dimension of centimetres, in marked contrast with the diffusion models where concentration gradients exist around individual roots with dimension of fractions of a millimetre.

More general system models, like EPIC (Jones et al. 1984) and CENTURY (Parton et al. 1988), have included P routines, but the generic crop routines in these models have limited ability to address crop management issues requiring accurate simulation of crop growth in response to weather, genotype, soil and management practices. They have not been widely used to explore management strategies involving P. It has been reported that the P routines in CENTURY were not able to describe the dynamics of P in tropical soils (Gijssman et al. 1996).

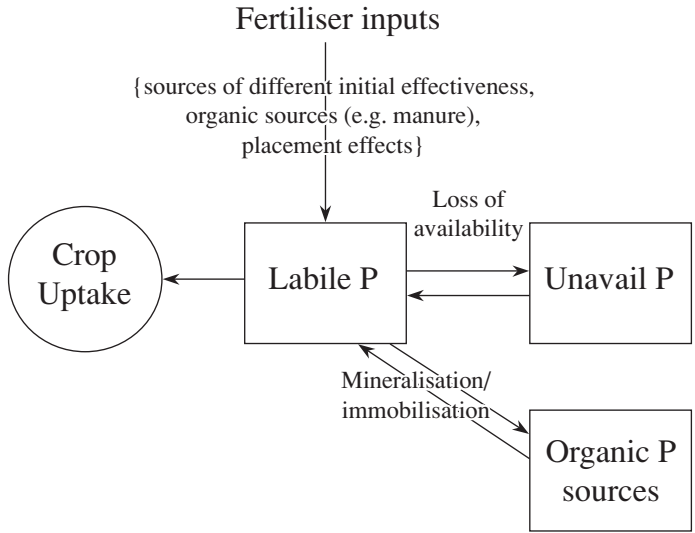
Management of soil P (especially in high-input agricultural systems) has focused on issues like whether to apply fertiliser, at what rate, evaluating placement and residual effects, and comparing relative effectiveness of water-soluble versus insoluble sources. Because P is immobile in soil (at least 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.

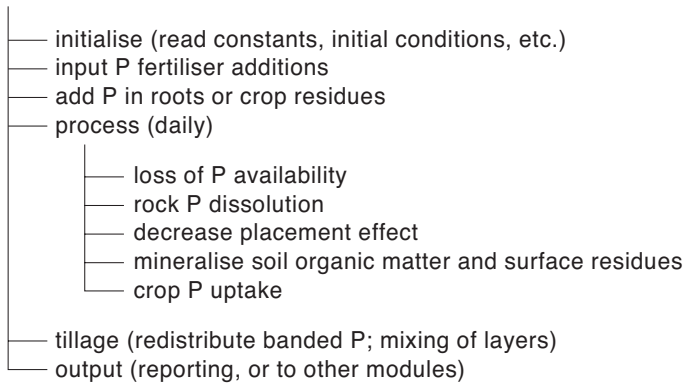
Crop models tend to perform best when there is a similar degree of detail for the various components of the overall model. At the time ACIAR project LW2/1999/003 commenced, it had not been demonstrated that this could be achieved for simulating a P constraint. It is noteworthy that the notion of including a P constraint into crop models has also been an activity for modellers using the DSSAT software. Their model has been published by Daroub et al. (2003).

### The APSIM SoilP module

The central concept of the SoilP module is that it is possible to describe the availability of P in soil in terms of a labile P pool. Figure 1 illustrates the processes that are considered to affect the amount of labile P in soil. These are: inputs (fertilisers, manures etc.); crop uptake; transformation between available and organic forms of P; and transformation between available and unavailable forms of P. The model of this system (see the subroutine structure in Figure 1b) is really a statement of the P balance between the different forms of P present. Thus, the labile P in a given soil layer has units of  $\text{kg ha}^{-1}$  and responds quantitatively to inputs and removal. It cannot therefore be directly equated with any particular soil P test, though we shall return to the topic of how there is need to specify such a model in terms of soil P tests.



SoilP subroutine



**Figure 1.** The APSIM SoilP module. The upper part of the figure shows in diagrammatic form the processes that are considered in the module. The lower part 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.

*Fertiliser inputs*

SoilP has been designed to accommodate different forms of P fertiliser and also placement effects in fertiliser application. This is achieved 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 needs to break down before P becomes

available, or some combination of the two. In the case of addition of an available form, if it is broadcast and mixed into soil its P content is immediately added to the soil labile P; but if it is banded, its P is accounted for separately so that it can be assigned a higher value than the rest of the labile P in terms of supplying P to a crop. Similarly, a rock phosphate source is accounted for separately and releases its P to the

labile P pool at a rate that is specified for a particular simulation run. To date, no effort has been made to make the rate of release of P from non-water soluble sources dependent on the source or soil properties.

#### *Loss of availability*

It is assumed that the transformations between labile P and unavailable P are first-order processes that are dependent on 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; it has been assumed that at steady state the unavailable pool is typically 10 times the labile pool. No attempt has been made to rationalise the sum of the soil P pools to measured total soil P.

#### *Soil organic P*

The APSIM SoilN module accounts for C and N in the various soil organic matter pools; the APSIM Residue module does likewise for the surface residues (see Probert and Dimes 2004). SoilP assumes that these pools also contain P. Decomposition of any pool (controlled by the SoilN or Residue 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 and HUM pools are invariant (as is the case for the corresponding C:N ratios), but the C:P ratio of the surface residues and FOM can vary depending on the materials being added to the system. Decomposition of soil organic matter can thus result in mineralisation or immobilisation of P depending on the C:P ratios of the pools decomposing and being synthesised.

#### *Crop uptake of P*

SoilP 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 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 dif-

ferent layers in the proportion to which they contribute to the potential supply.

The notion of assigning a premium to placed P is analogous to what has been referred to as substitution, whereby one unit of placed P might be considered to substitute for, say, two units of soil P. The justification for relating P uptake to a notional concentration in solution follows from Probert and Moody (1998) who showed how P uptake can be related to a measure of P quantity combined with an index of P buffer capacity.

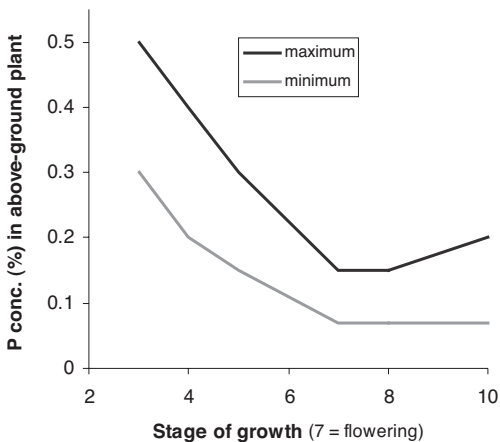
### **Simulating crop growth and development under P limiting conditions**

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.

Initial efforts to demonstrate that such a model might be feasible used P concentrations in the whole above-ground plant (see Figure 2) for calculating the P status of the plant. While this could work for a single crop, it is not compatible with simulating a sequence of crops where P in roots and residues must be considered. Accordingly, later efforts have endeavoured to partition P between the various plant components (leaf, stem, flower, grain, root) of the growing crop in a way similar to that in which N is modelled in APSIM crop modules. There is a dearth of information from which the appropriate critical P concentrations can be derived; current values are based on measurements on the short-duration cultivar Katumani Composite B (Probert and Okalebo, unpublished data) together with the published data of Jones (1983).

There are also few data on how P 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 concentration), 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. Because the predicted P supply from soil is strongly dependent on soil moisture, this approach to estimating uptake prevents the plant from rapidly meeting its P needs following a rainfall event.



**Figure 2.** The P concentrations in maize used to define the crops P status. The minimum P concentrations are derived from the experimental data of Probert and Okalebo (1992); the maximum concentration from Jones (1983).

### Parameterising the SoilP module

An example of a parameter file to initialise the APSIM SoilP module is shown in Table 1. In most circumstances it is envisaged that **banded\_p** and **rock\_p** would be zero in all layers (i.e. one would normally initialise the model before applying fertilisers); similarly in most unfertilised conditions it can be assumed that the labile P is in steady state with unavailable P (the default assumption if no values are provided for **unavailable\_p**). Information is needed for the C:P ratio of roots and residues and also the rate

at which P will be released from **rock\_p** (expressed on an annual basis).

The difficult business of specifying the soil with respect to its P status comes down to initialising the labile P pool and the soil's P sorption characteristics. For the latter the 'standard P requirement' is used, as defined by Beckwith (1965) and widely used by others (e.g. Fox and Kamprath 1970). It corresponds with the P sorbed at a final concentration of  $0.2 \text{ mg L}^{-1}$ . It has the advantage that it provides a scale for P sorption that is generally understood.

In most circumstances, it will be necessary to 'drive' the model using soil P test data to initialise the labile P pool. No effort has been made to include algorithms in the model code to specify how this should be done. Rather it is left to the discretion of the user. In experiences to date, we have used bicarbonate or resin extractable P. On low P sorbing soils it might be expected that these fractions will approximate the labile P, though more generally as P sorption increases it would be expected that the soil tests will extract a decreasing proportion of the soil's labile P.

### Predictive performance

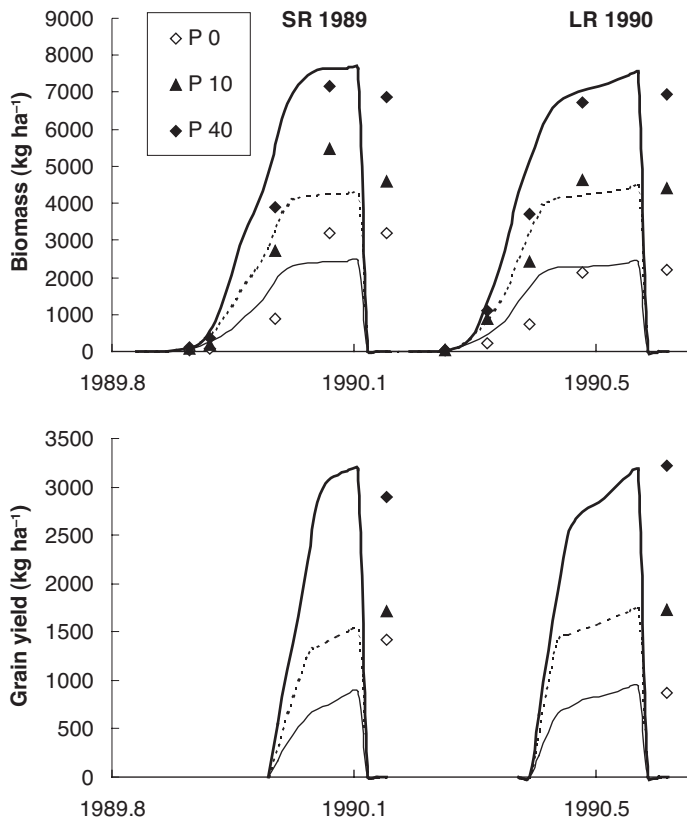
The data set that has been used to test the assumptions that underlie the P capability developed within the APSIM framework was collected on an Alfisol with low P sorption characteristics at Mutua Farm, near Katumani in eastern Kenya (Probert and Okalebo 1992). Bicarbonate extractable P (Olsen) in the surface 0–15 cm soil was  $4 \text{ mg kg}^{-1}$ . Briefly, 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.

The output from the model is compared with the measured data in Figure 3. 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.

A second experiment examined the effectiveness of different fertiliser sources of P (Figure 4). To demonstrate the potential of the model to simulate

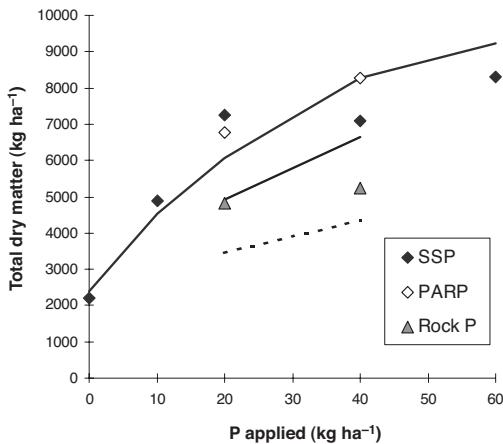
**Table 1.** An example of a SoilP parameter file to initialise an APSIM simulation. The layer structure (number of layers, layer thickness) used in the simulation is defined by the soil water module; the additional input relates only to the P pools.

[all.soilp.parameters]					
layer number	1	2	3	4	
labile_p =	5	4	3	3	(mg/kg)
unavailable_p =	50	40	30	30	! optional
banded_p =	0	0	0	0	(kg/ha)
rock_p =	0	0	0	0	(kg/ha)
sorption =	110	150	200	200	! p sorbed at 0.2 mg/L
residue_cp = 250					
root_cp = 200					
rate_dissol_rock_p = 0.40 (L/yr)					



**Figure 3.** 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<sup>-1</sup> 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 weeks later than physiological maturity as predicted by the model.

response to non-water-soluble sources, it was assumed that the Minjingu rock P had 20% of its P readily available and 80% unavailable; for the partially acidulated product, 60% was assumed available. No attempt was made to optimise values obtain a better fit. The simulated output shows that the model is able to predict a smaller response to P sources that are not immediately available. However, in this experiment the observed response to the partially acidulated product was similar to single superphosphate.



**Figure 4.** Simulation of total DM yield at maturity of maize fertilised with single superphosphate, partially acidulated (50%) rock phosphate, and Minjingu rock phosphate; all treatments received 90 kg ha<sup>-1</sup> of N as calcium ammonium nitrate. The observed data are shown as symbols, the predictions as continuous lines. The rock phosphate sources were only tested at rates of application of 20 and 40 kg P ha<sup>-1</sup>. Experimental data from Probert and Okalebo (1992).

### A comment on modelling the mineralisation of P from organic inputs

It is generally recognised that the mineralisation of N from organic sources depends largely on the C:N ratio of the substrate. This can be expressed succinctly (Whitmore and Handayanto 1997):

$$N_{\text{mineralised}} = C_{\text{decomposed}} [1/C:N_{\text{substrate}} - E/C:N_{\text{SOM}}]$$

where  $C:N_{\text{SOM}}$  is the C:N ratio of the soil organic matter being synthesised; E is sometimes referred to

as the assimilation coefficient, which equates with the fraction of the decomposing carbon that is retained as soil organic matter and in APSIM SoilN is normally set at 0.4. If all the retained carbon is synthesised into the more labile soil carbon pool with a C:N ratio of 8, the C:N ratio of the substrate that determines whether net mineralisation or immobilisation occurs is 20. The essence of this relationship is the basis of the decomposition/mineralisation process in the APSIM SoilN module.

An assumption that the same principle would apply to the mineralisation of organic P leads to a relationship between the P mineralised and the C:P ratios of substrate and the soil organic matter being synthesised:

$$P_{\text{mineralised}} = C_{\text{decomposed}} [1/C:P_{\text{substrate}} - E/C:P_{\text{SOM}}]$$

From this equation, the P concentration determining net mineralisation/immobilisation can be calculated for different assumed C:P ratio of the soil organic matter (Table 2).

**Table 2.** Predicted phosphorus content of plant residues (expressed as C:P ratio and P concentration in dry matter) that would determine whether initial mineralisation or immobilisation of P occurs for different assumed values of the C:P ratio of the soil organic matter being formed.

C:P of organic matter	C:P of residues	P concentration (%) <sup>a</sup>
20	50	0.80
40	100	0.40
67	167	0.24
100	250	0.16
200	500	0.08

<sup>a</sup> Assuming 40% carbon in plant dry matter

Palm et al. (1999) suggest a critical P concentration of 0.24% below which immobilisation of P would occur, while Nguluu et al. (1996) reported that mineralisation of N from plant residues was reduced (presumably because the decomposition rate was limited by P) when P concentration in tissues dropped below 0.16%.

On the other hand, the C:P ratio of soil microbial biomass is generally in the range 10 to 35 (quoted by He et al. (1997)). For a Nitisol from Western Kenya, Nziguheba (2001) measured small changes in microbial C:P due to P inputs and through time, with an

overall average of 27. He et al. (1997) reported much larger variation in a soil under grassland, due to time of sampling and nutrient inputs (range 9–276), but it seems implausible that living organisms could vary so widely. For comparison, the C:N ratio of microbial biomass is higher for fungi (~12) than for bacteria (~8), but otherwise does not seem to vary much across diverse ecosystems.

Thus, there would seem to be some discrepancy between the mineralisation of P from plant residues and the soil microbial C:P ratio. At typical biomass C:P values, no crop residue with P concentration <0.4% would be expected to mineralise P. Why this does not happen can probably be explained by the fact that sub-fractions of the substrate have different C:P ratios (compare Probert et al. (2004) who suggest a similar explanation to account for the N mineralisation pattern from some manures). In the case of crop residues, the C:P ratio of the soluble fraction is much lower than that of the total dry matter. Nziguheba (2001, Table 1.2.1) reports soluble C:soluble P ranging from 12–50 for six organic inputs used as green manure, whereas total C:P was in the range 140–250. For most materials, at least 50% of total P was soluble. Similarly, Nguluu et al. (1996) reported approximately 75% of total P to be water extractable, even for materials that were grown under P limiting conditions.

In many situations where the model will be applied, the mineralisation of organic P is likely to be unimportant. But, clearly, any efforts to simulate the effectiveness as P sources of biomass transfer systems (as studied by Nziguheba (2001)) would need to be able to specify inputs of organic material that have sub-fractions with different C:P ratios.

## Discussion

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 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 can be initialised and/or validated against measured soil test data. It remains an open question as to what are the 'pros and cons' of the two approaches.

Here we have shown that the P-aware maize model can be specified to produce output that matches observations from a single site on an Alfisol. In particular, the desire has been to produce a tool that will perform sensibly with regards to issues like soluble versus non-water-soluble sources, placement effects, and soils with different P sorption characteristics. The challenges that are still to be faced are to show that the model with the same parameterisation is able to perform satisfactorily for different soils and environments, and ultimately can be parameterised for other crops. Other papers in these proceedings test this hypothesis on a wider range of soils.

The SoilP module has been developed with the aim that it will also respond sensibly to inputs of P in organic sources including manures, but validation against suitable data sets has not yet been undertaken. An omission from the model is that it does not explicitly deal with the effects of mycorrhizae on P nutrition of crops. However, it is expected that this will not be a limitation in the low-input farming systems where the model is likely to be used.

## Acknowledgment

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