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Evaluation of APSIM to Simulate Plant Growth Response to Applications of Organic and Inorganic N and P on an Alfisol and Vertisol in India

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Abstract

Field experiments in India examined the response of sorghum and pigeonpea to inputs of low and high quality manures on N and P-responsive alfisol and vertisol soils. A special feature of the work was that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal. For this preliminary evaluation, the model performed poorly in simulating the observed P response of the cereal (sorghum) at low N levels. However, further modifications to input parameters for the P model, especially in relation to P supply and uptake for deeper soil layers, may improve the fit between observed and predicted results. In contrast, APSIM performed well in predicting the growth of pigeonpea well supplied with P, and the residual N benefits to a following cereal crop, including the response to additional inputs of N fertiliser.

Manures can contain appreciable amounts of P as well as N. In some instances, P is an additional, and sometimes greater, constraint to crop growth than N in low-input farming systems. With the generally low N content of manures found in smallholder farming systems (Motavalli and Anders 1991; Probert et al. 1995; Mugwira and Murwira 1997), questions arise as to whether a farmer would get a higher return from application of manure to a legume crop instead of a cereal, and to what degree is the residual N benefit of the legume to the following cereal crop enhanced by the legume responding to the applied manure?

Experimentation in India has examined these two questions for the case of low and high-quality manures applied to sorghum and pigeonpea crops grown on alfisol and vertisol soils (Revanuru 2002). A special feature of this work is that inorganic fertiliser treatments were included to help quantify the cereal and legume responses to the N and P content of the manure. Another is that monitoring of the experiments was quite extensive and many of the input parameters for simulation were known, especially for the soil and manure characterisation.

The data set was thought ideal for evaluating the performance of APSIM and its new modules, SoilP and Manure, to simulate the complex of climate, soil and plant interactions and effects on crop growth and yield. A complication, however, is that currently only the APSIM Maize module is able to respond to low soil P conditions to simulate P stress on plant growth (Probert 2004). Nevertheless, it was felt that

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the simulated total biomass response of APSIM Maize could be used as a surrogate for the observed sorghum responses. Within APSIM, the maize and sorghum models are based on a common crop template and share the same routines for interacting with the soil water and nutrient (N and P) modules to supply growth demand.

This paper provides a brief overview of the Indian experiments and results, and reports on the performance of APSIM to simulate aspects of the observed legume and cereal crop responses to N and P inputs, and the residual legume benefits to a following cereal crop.

Materials and Methods

Field experiments

Experiments were conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, in southern India (17.5°N, 78.3°E, 545 m above sea level) during the kharif (rainy) and rabi (dry) seasons of 1998. The experiments were conducted on two soils: an alfisol (Udic Rhodustalf) and a vertisol (Typic Pellustert).

Manure

Manure used in the experiments was collected from the bullock shed on the ICRISAT farm and from a local supplier in a nearby village. Manure was applied (11 June) to treatment plots on a fresh weight basis (10 t ha^{-1}). Dry weights and chemical characteristics of the manures applied are shown in Table 1. For the purpose of this paper, the two manures are referred to as high quality (HQM – narrow C:N, high P, from bullock shed) and low quality (LQM – wide C:N, low P, from village supplier).

Experimental design and treatments

Experiments investigated sorghum *(Sorghum bicolor*) and pigeonpea (*Cajanus cajan*) response to inputs of manure and fertiliser N and P on the two soils. For each crop, a split-plot design was implemented with soil type as main plots and nutrient treatments as sub-plots. For sorghum, there were six nutrient treatments: control, LQM, HQM, single superphosphate fertiliser at 20 kg P ha^{-1} (P20), ammonium nitrate fertiliser at 80 kg N ha^{-1} (N80), and N and P fertiliser at 80 kg N and 20 kg P ha^{-1} (N×P) with six replicates. For pigeonpea there were four treatments: control, LQM, HQM and P20 with three replicates.

Management

Fallow pastures that preceded the experiments were incorporated in early May 1998. Extra-short duration pigeonpea, cultivar ICPL 88039, was planted (alfisol – 20 June, vertisol – 23 June) on 60 cm ridge spacing. Sorghum hybrid, CSH 9, was planted (alfisol – 20 June, vertisol – 23 June, both re-sown on 29 June) on similar ridges. Pigeonpea and sorghum plots were treated with pre-emergence herbicides and hand weeded twice during the season. During excessively wet conditions, pigeonpea plots were drenched to combat blight. Application of P fertiliser was banded at sowing, whereas application of N fertiliser was split; 40 kg N ha^{-1} banded at sowing and 20 kg N ha^{-1} side-banded at 30 and 60 days after sowing. Three irrigations were applied to help crop emergence and establishment.

Following harvest of grain and removal of stalks, kharif pigeonpea plots were planted with a medium duration sorghum variety, Maldandi-35-1 (9 November, both soils). The treatment plots were further subdivided into three sub-plots to accommodate three N levels (0, 40 and 80 kg N ha^{-1}) applied

Table 1. Nutrient content and application rates of manures applied to pigeonpea and sorghum at the start of the 1998 kharif season, at ICRISAT, Patancheru, India.

Manure type	%C	%N	%P	C:N	Dry weight applied (kg ha^{-1})	N applied kg ha^{-1}	P applied kg ha^{-1}	C applied kg ha^{-1}
LQM[a]	25.3	0.7	0.3	35.0	2350	16.9	11.6	848.4
HQM	16.3	0.8	0.6	22.0	2870	21.7	17.3	469.1

[a] LQM, low quality manure; HQM, high quality manure.

to the following sorghum crop. Application of N fertiliser was split; 40 kg N ha^{-1} side-banded at 14 and 37 days after sowing. The rabi sorghum was irrigated throughout the crop cycle.

Measurements and analysis

Soil and manure samples were analysed for per cent organic carbon (OC) (Walkley and Black 1934), total N (Keeney and Nelson 1982), total P (Tandon et al. 1962), mineral N (Keeney and Nelson 1982) and extractable P (Olsen and Sommers 1982). Soils layers were sampled to 90 cm for the alfisol and 150 cm for the vertisol. Gravimetric water content of soil layers was monitored regularly throughout the kharif and rabi crop cycle for each experiment. Total plant biomass was harvested at maturity. Meteorological data were collected at the ICRISAT weather station. Treatment differences were analysed using ANOVA for a split-plot design.

Simulations

Soil descriptions

Soil parameters and initial conditions used to simulate experiments on the two soils are set out in Tables 2 and 3. Analysis of the gravimetric moisture determinations taken throughout the kharif and rabi crops provided estimates for the crop lower limit and the drained upper limit water contents in layers for each soil. Concentrations of OC, and NO_3-N and the amounts of soil water were measured. Bulk density and NH_4-N values were estimated. P sorption characteristics for surface layers were known (Sahrawat and Warren 1989), data for the other layers were estimates. Finert values (stable SOM not contributing to mineral N supply) have been set using %OC in the bottom layer as a guide and based on experience in setting this parameter (Probert et al. 1998b).

High atmospheric N contributions to the crop–soil budget have been reported for the Patancheru environment (up to 12 kg N ha^{-1} $year^{-1}$ in rainfall (Murthy et al. 2000)), resulting in unexpectedly high biomass yields on the N impoverished soils. To increase the soil N supply and include the effects of N additions from the atmosphere, labile N (f_biom) in the soil surface layer was adjusted upwards until there was agreement between simulated and measured biomass yield for the control treatments. Similarly, labile P values in Tables 2 and 3 were calibrated for the two soils, to give reasonable prediction of observed yields in the presence of adequate N.

Kharif sorghum (maize)

Simulation of the kharif experiment began on 11 June 1998, which coincided with application of the manure treatments. The applied manure was fully incorporated into the surface soil layer. A maize planting was simulated on 29 June (the re-sowing date for both soils, see Management above), with plant population set to 10 plants m^{-2} (the observed plant stand at harvest, both soils). Crop parameters for maize cultivar Hybrid 614 were found to best approximate the duration of the kharif sorghum crop. Fertiliser applications were made on 21 June (P20 banded and 40N), 21 July (20N) and 3 Sept (20N). Irrigation was applied on 29 June (63 mm), 1 July (63 mm) and 13 July (50 mm). To assess model predictions, simulated maize biomass was compared with the observed total biomass of kharif sorghum.

Pigeonpea–sorghum (maize) sequence

Pigeonpea–maize sequences for the kharif–rabi seasons were simulated for each soil using the data in Tables 2 and 3, except in this case it was assumed that there was no P constraint. Simulations began on 11 June 11 and an extra short duration pigeonpea was planted on 20 June, with a population of 33 plants m^{-2}. After grain harvest, removal of pigeonpea stover was simulated on 4 November. Maize cultivar Hybrid 511 was planted on 9 November with a population of 13.8 plants m^{-2} for the alfisol, and 14.7 for the vertisol. Three N fertiliser treatments for the rabi maize were simulated; 0, 40 and 80 kg N ha^{-1}, with fertiliser applied as per the experimental details described above for rabi sorghum. A total of 260 mm of irrigation was applied for the simulated rabi crop. To assess model predictions for pigeonpea, simulated biomass is compared to observed biomass from the P20 treatment (i.e. adequate P conditions). To assess simulation of maize response in the rabi following pigeonpea, simulated biomass is compared to observed biomass for rabi sorghum following pigeonpea receiving 20 kg P ha^{-1} in the kharif season.

Table 2. Soil properties and initial conditions for simulation of the alfisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was 8.6.

Layer no.	1	2	3	4	5
SoilWat parameters[a]					
Layer thickness (mm)	150	150	300	300	300
Bulk density (g cm^{-3})	1.50	1.45	1.40	1.40	1.40
SAT	0.36	0.40	0.42	0.42	0.42
DUL	0.21	0.21	0.23	0.23	0.24
LL15	0.09	0.09	0.11	0.14	0.18
Soil water	0.09	0.09	0.11	0.14	0.18
SoilN parameters					
Organic C (%)	0.57	0.42	0.31	0.24	0.18
Finert[b]	0.35	0.47	0.52	0.62	0.74
Fbiom	0.04	0.020	0.015	0.01	0.01
Nitrate-N (mg kg^{-1})	1.60	1.40	1.80	1.30	1.00
Ammonium-N (mg kg^{-1})	0.50	0.10	0.10	0.10	0.10
SoilP parameters					
Labile P (mg kg^{-1})	10	10	10	10	10
P sorption (mg kg^{-1})[c]	30	60	100	150	200

[a] The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).
[b] Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.
[c] P sorbed at 0.2 mg L^{-1} in solution.

Table 3. Soil properties and initial conditions for simulation of the vertisol experiments at ICRISAT, Patancheru, India. C:N ratio for all layers was set at 12.

Layer no.	1	2	3	4	5	6
SoilWat parameters[a]						
Layer thickness (mm)	150	150	300	300	300	300
Bulk density (g cm^{-3})	1.00	1.10	1.20	1.20	1.20	1.20
SAT	0.55	0.54	0.50	0.50	0.50	0.50
DUL	0.37	0.37	0.42	0.42	0.46	0.46
LL15	0.17	0.23	0.29	0.32	0.37	0.41
Soil water	0.12	0.27	0.34	0.38	0.41	0.41
SoilN parameters						
Organic C (%)	0.57	0.47	0.43	0.37	0.19	0.17
Finert[b]	0.31	0.37	0.50	0.62	0.74	0.83
Fbiom	0.04	0.02	0.015	0.01	0.01	0.04
Nitrate-N (mg kg^{-1})	3.00	2.00	1.50	1.30	1.00	1.00
Ammonium-N (mg kg^{-1})	0.50	0.10	0.10	0.10	0.10	0.10
SoilP parameters						
Labile P (mg kg^{-1})	6.0	5.0	4.0	3.0	2.0	1.0
P sorption (mg kg^{-1})[c]	50	100	100	100	100	100

[a] The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL).
[b] Finert is the proportion of soil carbon assumed not to decompose; Fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.
[c] sorbed at 0.2 mg L^{-1} in solution.

Results

In-crop rainfall (980 mm) for the kharif (Figure 1) exceeded the long-term annual rainfall (899 mm) and waterlogging was observed in both soils for pigeonpea plots. There was little rainfall during the rabi crops, which were grown under irrigation.

Sorghum experiments

The simulated and observed biomass responses of kharif sorghum crops on alfisol and vertisol soils are shown in Figure 2. Observed biomass responses on the alfisol were significantly ($p < 0.05$) greater than those on the vertisol. For the alfisol, biomass yields for the manure and fertiliser treatments are significantly ($p < 0.05$) higher than the control. In contrast, only the fertiliser treatments provided statistically significant responses on the vertisol. Results for both soils show a stronger response to N fertiliser (N80) than to P fertiliser ($p < 0.05$) and an increased N response ($p < 0.05$) in the presence of P ($N \times P$ treatment).

The simulated trends in Figure 2 are less responsive, with almost no change in predicted yields for the application of manures or inorganic P on either soil. In fact, simulated biomass yields with addition of LQM are lower than that simulated for the control on each soil, indicating that the model simulated net immobilisation and a reduced N supply for crop growth with the addition of the LQM. Simulated

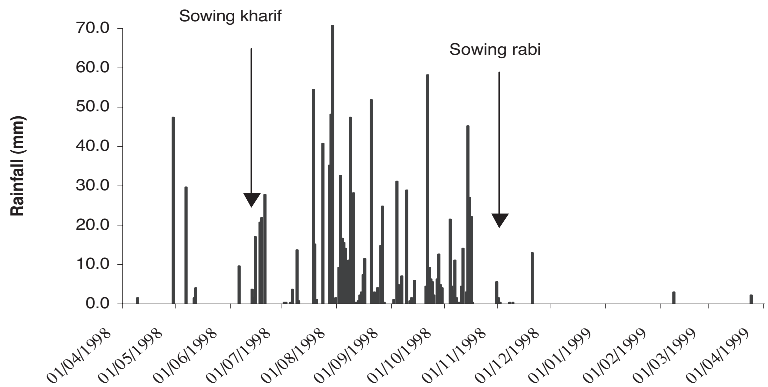

Figure 1. Rainfall during the kharif and rabi seasons in 1998 at Patancheru, India. Sowing of kharif and rabi crops shown by arrows.

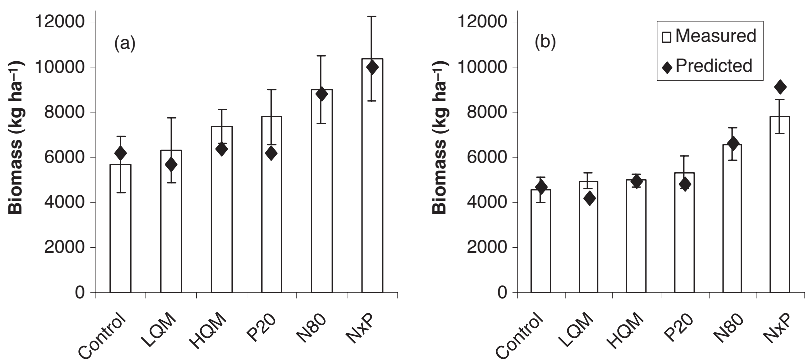

Figure 2. Measured (sorghum, bar) and simulated (maize, symbols) total crop biomass for kharif crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure, fertiliser P (P20), fertiliser N (N80) and fertiliser N and P ($N \times P$). Error bars are standard deviations of treatment means.

responses to application of fertiliser N on both soils and N+P for the alfisol are close to the observed responses, but there is a large over-prediction for the N+P treatment on the vertisol. What the model was able to simulate reasonably well were the differences in biomass yields between soils.

Pigeonpea–Sorghum

Observed responses of pigeonpea to manures and fertiliser P in the kharif are shown in Figure 3. In the case of pigeonpea, biomass yields are significantly higher ($p < 0.05$) for the vertisol than for the alfisol. There are significant ($p < 0.05$) increases in biomass response of pigeonpea to the three nutrient treatments (LQM, HQM and P20) compared with the control, and between the nutrient treatments, indicating that pigeonpea responded to the different levels of P input (12, 17 and 20 kg P ha^{-1}) and its availability.

As APSIM–Pigeonpea is not 'P-aware', simulated biomass can be compared only for the situation where P nutrition can be assumed adequate, in this case the P20 treatment. In Figure 3, simulated biomass of pigeonpea for the alfisol compares well with observed yield, but for the vertisol, the simulated yield is actually less than that for the alfisol, and substantially less than the observed. The Pigeonpea model used here (APSIM Version 1.61) has routines to simulate waterlogging stress on plant growth, and over-prediction of this stress seems to be responsible for simulation of the lower yield on the vertisol. For the vertisol, 87% of crop days are simulated to have profile water contents indicative of saturation, whereas for the alfisol it is less than 50% of days.

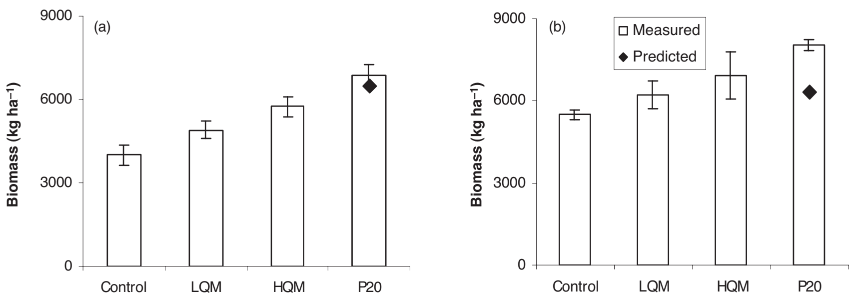

Figure 3. Measured (bar) and simulated (◆) total crop biomass for pigeonpea crops on (a) alfisol and (b) vertisol in response to low (LQM) and high (HQM) quality manure and fertiliser P (P20). Error bars are standard deviations of treatment means.

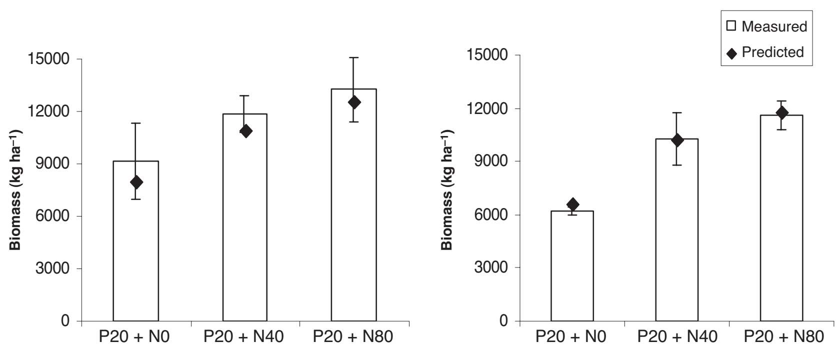

Figure 4. Measured (sorghum, bar) and simulated (maize, ◆) total crop biomass for rabi crops on (a) alfisol and (b) vertisol following kharif pigeonpea (fertilised with 20 kg P ha^{-1}). Rabi crops received zero (P20+N0), 40 (P20+N40) and 80 (P20+N80) kg N ha^{-1}. Error bars are standard deviations of treatment means.

The pigeonpea–maize sequence provides an assessment of how well the systems model is able to simulate the combined effects of organic and inorganic N supply. Figure 4 shows the observed and predicted biomass yield of the rabi cereal crops planted following pigeonpea (fertilised with P20) and receiving three rates of N fertiliser. From the observed responses to fertiliser N, it is clear that the preceding pigeonpea was unable to supply all of the rabi crop N requirements on either soil.

The model was able to predict very closely the observed biomass responses for the respective soils along with the response to N fertiliser inputs on each soil (Figure 4). It should be noted that, for both the simulated and observed rabi crops, all above-ground biomass from the preceding pigeonpea was removed, and the carryover of N from the kharif legume is via the pigeonpea root system and detached leaf material. Hence, results in Figure 4 suggest that the system model is able to simulate these residual organic N benefits, and interaction with inorganic N, with a high degree of accuracy.

Discussion

The measured yield responses for the legume and cereal crops in these experiments clearly indicate P and N responsive soils. However, the results of simulation of the observed P responses and interaction with N supply in the kharif cereal crop were disappointing, showing no sensitivity to inputs of organic or inorganic P at low N levels (i.e. LQM, HQM and P20 treatments). Application of APSIM to simulate the Indian data is one of the earliest attempts at using the new P capabilities on an independent data set. Results achieved here undoubtedly reflect a measure of inexperience with parameterising this new model.

Probert (2004) has suggested that the difficulty in parameterising the model is largely associated with specifying the P status in terms of P sorption and labile P in each soil layer. Further exploratory modifications to input parameters are no doubt warranted, especially in terms of the proportionality factor between measured Olsen P and labile P (Micheni et al. 2004) and how this may need to vary between soils, and perhaps with soil depth. Another parameter that may warrant attention is the P uptake factor that Probert (2004) suggests is crop and cultivar dependent. In this analysis, the p_supply_factor was set to 3.

However, the main concern with the model is the insensitivity of plant response to P inputs at the low N levels. Part of this problem is perhaps attributable to the calibration process used for labile P. For the kharif crop responses used in this study, moisture stress, at least due to deficits, can be discounted. Hence, the results suggest further testing of the model is required for conditions where both N and P are limiting plant growth. The ideal data set would have crop growth response to each element quantified in the presence of adequate levels of the other, in addition to limiting levels of both. This would help eliminate some of the calibration problems encountered in this current study.

The APSIM–Pigeonpea model (Robertson et al. 2001) is also relatively untested against observed growth responses in the field. While the P effects on pigeonpea growth in these experiments cannot be considered at this time, simulation of the P20 treatment for the two soils provided some useful insights. Clearly, the waterlogging stress routines in Pigeonpea and the soil drainage parameters for the vertisol warrants closer consideration. The close agreement between observed and predicted biomass at zero N for the rabi cereal crop (Figure 4) suggests that the model captures very well the key components contributing to enhanced soil N supply following a legume, in this case simulation of leaf senescence and detachment and residual root biomass of the pigeonpea.

In the past, APSIM has been shown to perform well in simulating mineral N supply following organic inputs (Probert et al. 1998b) and crop response to inorganic and organic N, including legume–cereal rotations (Probert et al. 1998a; Shamudzarira et al. 2000). Simulation of the pigeonpea–maize sequence in this study has extended evaluation to a tropical legume species and for two of the important soil types in semi-arid agricultural systems. The study has also highlighted the need to extend the P stress routines to other cereal and legume crops commonly grown by smallholder farmers in the tropics.

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