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Testing the APSIM Model with Data from a Phosphorus and Nitrogen Replenishment Experiment on an Oxisol in Western Kenya

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Abstract

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 10 cropping seasons between 1996 and 2000. An additional factor studied was the source of N, either as urea or tithonia biomass-N 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 APSIM model has been tested against this data set. The effects of P treatments were large in the long rain season, but in the short rain season the inadequate supply of N greatly reduced growth and P effects. The yields of the maize crops were predicted well ($r^2 = 0.88$) with respect to both the P treatments (as TSP) and the N inputs (as urea). The predicted water, N and P stresses were informative in understanding the contrasting pattern of response observed in the two seasons. The simulation of this long-term experiment shows that the APSIM SoilP module is robust, in as much as it extends the testing of the model to a very different environment where there were both N and P stresses affecting plant growth, and on a very different soil type to where the concepts in the APSIM phosphorus routines were originally developed and tested.

Crop production on many soils in western Kenya is limited by both nitrogen (N) and phosphorus (P). The concept of recapitalisation of soil P has focused attention on the use of rock phosphate materials rather than commercial forms of processed fertilisers, and the feasibility of raising soil P through large, one-time application rather than a gradual increase with smaller, but regular inputs (Buresh et al. 1997). Such strategies have been evaluated in long-term experiments in western Kenya.

Probert (2004) describes how a capability to simulate P limited maize crops has been developed within the APSIM modelling framework. The data used to derive the parameter set defining the P status of maize through its growth cycle were from experiments at Katumani in the semi-arid region of eastern Kenya, on soils with low P sorption. There is a need to test the applicability of the model under a much wider range of environments and on different soil types.

In this paper, we describe the testing of the APSIM P routines using an experiment that provides suitable data for testing some aspects of the model. The annual rainfall and soil type, especially with regards to its phosphorus sorption properties, are

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extreme contrasts to those on which the model was first developed.

The Experiment

Site description

A field experiment was conducted at Olwenyi, Ondele and Julius farms near Maseno in western Kenya (0°06' N, 34°34' E, 1420 m above sea level). The annual rainfall in the region is typically 1800–2000 mm, with bimodal distribution and two growing seasons; the long rain season between March and July (LR) and the short rain season between September and January (SR).

The soil type is a very fine isohyperthermic Kandiudalfic Eutrudox (USDA 1992). It has few chemical or physical barriers to rooting in the top 4 m (Mekonen et al. 1997). Air-dried soil (0–15 cm) had a pH of 5.2 (1:2.5 soil:water suspension); organic carbon 18 g kg^{-1}; exchangeable acidity (1 M KCl) 1.0 $cmol_c$ kg^{-1}, calcium 3.5 $cmol_c$ kg^{-1}, magnesium 1.3 $cmol_c$ kg^{-1}, potassium 0.12 $cmol_c$ kg^{-1}; bicarbonate–EDTA extractable phosphorus 1.7 mg kg^{-1}. Clay, silt and sand contents were 35%, 20% and 45%, respectively. P sorption is very high; based on sorption isotherms 250 mg P kg^{-1} of soil was required to raise soil solution P to 0.2 mg L^{-1} for 0–15 cm soil.

Treatments

The experiment began in 1996. It was designed as a balanced factorial combination comparing a one-time application versus repeated annual additions of P, with two P sources (triple superphosphate (TSP) and Minjingu rock phosphate from Arusha, northern Tanzania) plus a control treatment that did not receive any P, and two nitrogen sources (urea and tithonia biomass to supply 60 kg N ha^{-1}). The annual P application was 50 kg ha^{-1} applied in March–April before the LR crop, while the one-time application rate was 250 kg ha^{-1} applied before the 1996 LR crop only. The P sources were broadcast and incorporated into the soil before planting. After 10 seasons, the total P applied was the same for the one-time and annual applications.

The N inputs as urea or tithonia biomass (3.3% N) were applied to only the LR crops. Urea was split-applied, one-third at sowing and two-thirds at 5 weeks after sowing. The tithonia was chopped and incorporated into soil before planting maize in the LR season.

Management

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

Potassium deficiency was observed to seriously affect the yield of the first crop. In March 1997, all plots were split to accommodate an additional factor testing the effect of 1) no addition of K fertiliser, and 2) annual application of 60 kg K ha^{-1} as KCl. In this paper, we consider only data from plots that received K, and yields are assumed to be unaffected by K deficiency.

The soil (0–15 cm) was sampled in 1996, 1997 and 2000 at the time of sowing the LR crop after all organic and inorganic fertiliser materials had been applied and incorporated into the soil. Samples were 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 (P_i and P_o) followed by more stable P_i and P_o 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).

Simulations

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, with the soil properties set out in Table 1. A continuous simulation was run for the 10 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.

Results and Discussion

Observed maize yields

The overall effects of the treatments on the total above-ground dry matter (DM) yield for maize are summarised in Table 2. Maize grain yields showed responses that were similar to the total DM yields and these data are not presented.

There is a very large response to P in the LR seasons, but only small differences between the two P sources or the frequency of application of the P fertiliser. This is consistent with Minjingu rock phosphate being recognised as an effective source of P, especially on an acidic soil.

The yields of the SR crops were much lower than for the LR. The stresses predicted in the simulations indicate that this is predominantly a nitrogen effect, because there were no N inputs to the SR crops (see Figure 3).

The apparent effects of the two N sources are complex. For the LR crops, the main effect of N source was not statistically significant ($p > 0.05$). The application of tithonia-N resulted in higher average DM yields, but this observation is due almost entirely to the 1996 LR crop. In the first year of the experiment, before the K treatments had commenced, the tithonia biomass (containing 56 kg ha^{-1} of K) largely overcame the K limitation that occurred when urea was the N source. The annual input of tithonia biomass also contained 6 kg ha^{-1} of P and this contributes to some of the difference between the two N sources in the absence of any P fertiliser. The SR crops, grown without additional inputs, show a residual effect from the tithonia-N compared with urea-N, maize DM yields being approximately 1 t ha^{-1} higher where P was applied ($p < 0.01$).

Comparison of observed versus predicted yields

Figure 1 compares the observed effects of the three P treatments with the output from the simulation, showing the response to P in each of the cropping

Table 1. Soil properties used for specifying APSIM simulation of the Maseno experiment.

Layer	1	2	3	4	5	6	7
SoilWat parameters[a]							
Layer thickness (mm)	150	150	300	300	300	300	300
BD (g cm^{-3})	1.10	1.22	1.31	1.23	1.19	1.15	1.21
SAT	0.50	0.49	0.46	0.48	0.50	0.50	0.49
DUL	0.35	0.38	0.40	0.37	0.36	0.35	0.37
SWCON	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Maize parameter							
LLmaize	0.22	0.24	0.28	0.30	0.30	0.29	0.30
SoilN parameters							
organic C (%)	1.8	1.0	0.72	0.57	0.45	0.35	0.30
finert[b]	0.35	0.7	0.8	0.9	0.95	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01	0.01
SoilP parameters							
labile P (mg kg^{-1})	8.5	5	2	2	2	2	2
P sorption (mg kg^{-1})[c]	260	400	400	400	400	400	400

[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); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.

[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 2. Effect of P treatments on maize biomass yields (t ha^{-1}) at Maseno for the two sources of nitrogen. Data averaged across the 5 years 1996–2000.

Phosphorus treatment	Long rain crops		Short rain crops	
	Urea	Tithonia	Urea	Tithonia
No added P	3.3	5.8	1.6	2.2
Annual addition (50 kg ha^{-1}) as TSP	9.6	10.3	2.2	3.1
Annual addition (50 kg ha^{-1}) as MPR	8.8	10.3	2.2	3.2
One time addition (250 kg ha^{-1}) as TSP	9.5	10.6	2.5	3.5
One time addition (250 kg ha^{-1}) as MPR	9.1	9.9	2.5	3.3
Analysis of variance:				
P treatment	$p < 0.001$		$p > 0.05$	
N source	$p > 0.05$		$p < 0.01$	
P treatment × N source	$p > 0.05$		$p > 0.05$	

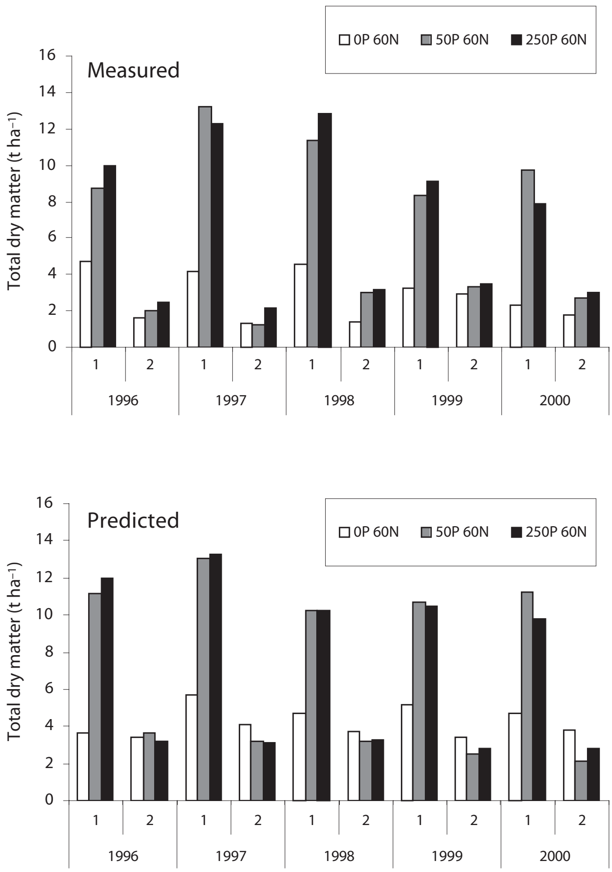

Figure 1. A comparison of the measured (upper pane) and simulated (lower pane) dry matter yields of maize through 10 seasons for the treatments receiving 60 kg ha^{-1} of N as urea and different inputs of P as TSP: none, 50 kg ha^{-1} annually, or 250 kg ha^{-1} as a single application before the 1996 crop. Note that for the measured data, the yields for the first crop in 1996 are for the treatments that received tithonia-biomass as the N source. For the later crops, the N source was urea, and potassium was also applied after 1997.

seasons. In Figure 2 the data are plotted in the more conventional 'observed versus predicted' manner.

The most marked feature of the pattern exhibited in Figure 1 is the difference in DM yields between the two seasons. This is captured well by the model. In the second (SR) season when no additional P and, more importantly, no N was applied, yields were very low (2–3 t ha^{-1}) and were little affected by P treatments. In the LR, the DM yields without P addition were around 4 t ha^{-1} increasing to ~10 t ha^{-1} where P was applied. There was reasonable agreement between the observed and fitted yields (r^2 = 0.88) with little indication of bias (Figure 2). However, the model provides no ability to discriminate between the treatments for the SR crops.

Where the P effects are not obscured because of limiting N, both the observed and predicted data show that, in the early years of the experiment, there was not much difference between the 50 and 250 kg ha^{-1} rates, though with a tendency for the measured yields to respond beyond the 50 kg ha^{-1} rate in 1996 and 1998 (Figure 1); but by the fifth year there is some suggestion that the annual application of 50 kg ha^{-1} is giving larger yield than the single input of 250 kg ha^{-1}.

Insights provided by the model

Stresses on crop growth

In this experiment, there is little indication of year-to-year variation in crop growth, but it is evident that there are great differences between the two seasons and due to the treatments. The output from the model is helpful in understanding the cause of these effects.

In Figure 3 we show the predicted stresses on crop growth due to water, phosphorus and nitrogen. The experimental site enjoys high rainfall and the model predicts that, through the 10 crops, water stress was never limiting. For the no-P treatment, the simulation shows that P stress always dominates N stress, though for the SR crops after 1997 there are signs that N is also suboptimal. However, when P has been applied, the situation is reversed and N stress dominates. Particularly in the SR crops, N stress commences early and growth is severely restricted. Thus, the inference from the simulations is that the experiment was carried out under less than optimal N. Treatments with higher N inputs might well have accentuated the differences between the P treatments, especially in the SR crops.

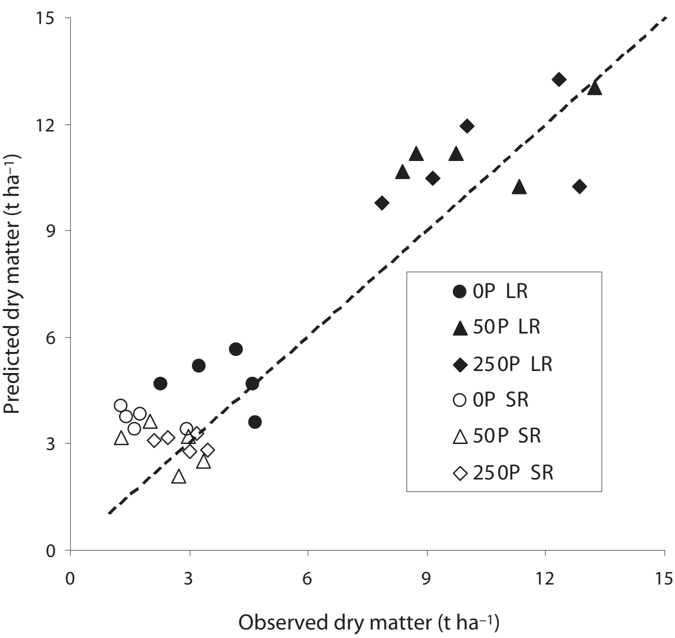

Figure 2. Plot of observed versus simulated maize dry matter yields in relation to the 1:1 line. The root-mean-square deviation between observed and predicted yields is 1.58 t ha^{-1}.

Figure 4 illustrates some aspects of the simulated water balance at the site. Over 25% of the rainfall is predicted to end up as drainage. Not much attention should be paid to the run-off values, because we deliberately parameterised the model to keep run-off low, based on the assertion that little run-off occurs on these soils. The large drainage reinforces that this is a very wet location where maize crops are not likely to be limited by water stress.

Another effect of the large drainage term is that it will effectively leach nitrate-N from the rooting zone. The lack of treatment effects in the second season is perhaps surprising, particularly where P-deficient crops have not fully exploited all of the applied N. However, such behaviour is understandable in light of the predicted water balance. Table 2 shows that there is a greater residual effect from tithonia-biomass than from urea. The inference to be drawn from the water balance is that this occurs because more of the tithonia-N is present in organic form and so is protected against leaching, and will become available when it is re-mineralised in the second season.

Soil P

The simulated changes in labile P in the topsoil layer are shown in Figure 5. Only small changes are predicted to occur in the treatment without P addition; the small increase in labile P is due to minerali-

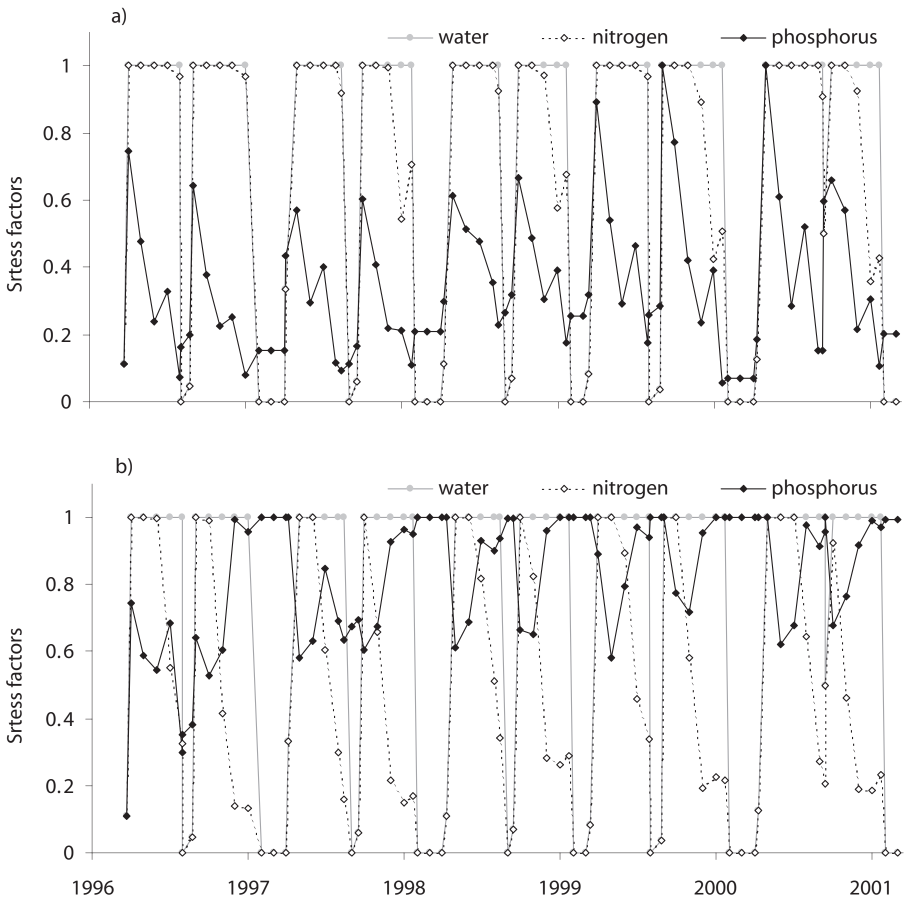

Figure 3. Illustration of the predicted stresses (1 – no stress, 0 – extreme stress) on the maize crops. The upper pane is for the treatment without applied P, the lower pane for the treatment with 50 kg ha^{-1} of P applied annually. Nitrogen as urea (60 kg ha^{-1}) was applied to only the LR crops.

sation of soil organic matter, which is predicted to decline during the course of the experiment. It is to be noted that all above-ground crop residues were removed from the plots. The inputs of P fertiliser in 1996 result in the increase in soil P being five times larger for the one-time application. However, the processes presumed to be occurring in soil, notably the loss of availability with time, result in declining labile P, so that by the end of the experiment the five annual applications results in higher labile P than for the one-time application. As mentioned above, some evidence to support this behaviour is found in the crop DM data.

Resin-P and bicarbonate extractable-P are generally considered to be the 'available' forms of P in soil. The measured data for the surface soil layer are

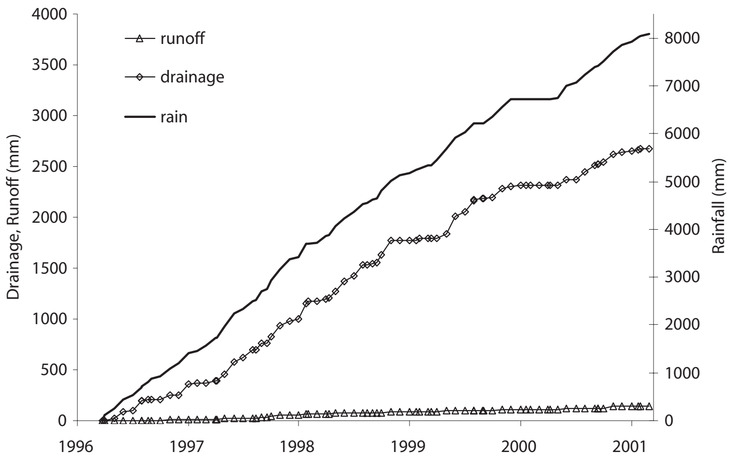

Figure 4. Cumulative rainfall and predicted drainage and run-off for the nil P treatment through the 10 seasons of the experiment. Note that rainfall is plotted on the right hand axis with a different scale to that used for drainage and run-off.

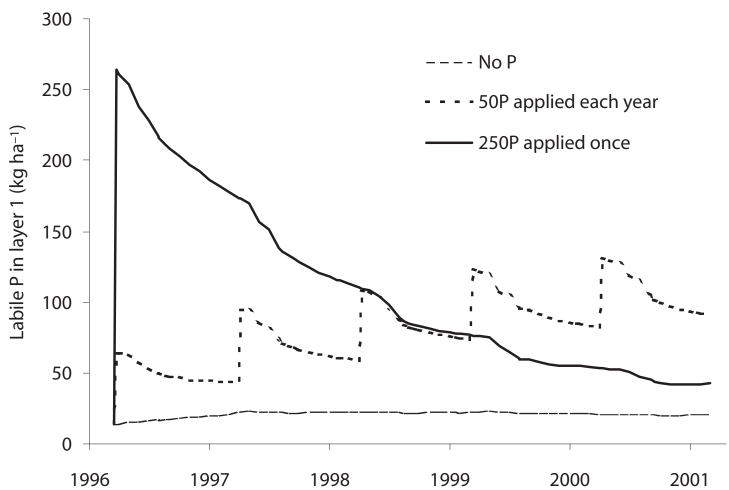

Figure 5. Simulated changes in labile P in the 0–15 cm layer of soil through the 10 crops for treatments that received different P treatment as specified in the legend.

Table 3. Measured soil P for the treatments receiving triple superphosphate (units: mg P kg^{-1} soil). Resin- and bicarbonate extractable-P (inorganic) were determined successively on the same aliquot of soil. Values reported are averaged across the two N treatments.

Phosphorus treatment	Resin-P			Bicarb-P			Resin + Bicarb-P		
	1996	1997	2000	1996	1997	2000	1996	1997	2000
No added P	4	3	1	5	7	6	9	10	7
Annual addition (50 kg ha^{-1})	16	7	5	12	13	18	27	21	23
One time addition (250 kg ha^{-1})	28	8	4	19	22	19	47	30	23

summarised in Table 3. Conformity with the pattern of the model output is not good for either resin or bicarbonate P. However, when the two fractions are summed there is some semblance of agreement: the nil treatment changed little through time; a clear decline for the one-time application of P was measured; the pattern suggests that the soil P for the annual application will eventually exceed that for the one-time application, though it does appear that this treatment reached a plateau rather than exhibiting a regular increase as shown in the model output.

Other fractions of soil P that were measured are difficult to interpret and are not reported here. The organic-P fraction of the bicarbonate extract was unaffected by treatment or time of sampling; it averaged 26 mg P kg^{-1} soil. Thus, for the treatment without P addition, a high proportion (~80%) of the bicarbonate extractable P was present as organic-P.

Conclusions

The Maseno experiment was carried out in a very different environment and on a very different soil to those on which the concepts in the APSIM phosphorus routines were originally developed and tested. Notably, this is a location with high rainfall where the model predicted that water stress did not affect crop growth, and the soil, an Oxisol, has high P-sorption characteristics. 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-sorbing soil in a semi-arid environment. The model performed creditably in predicting the growth of maize crops for the different P treatments. A second aspect of this data set was that the N inputs (applied to only the LR crops) resulted in very different crop growth between the two seasons. The predicted water, P and N stresses were informative in helping to understand the reasons for the differences in response to the N and P inputs in the two seasons. This is the first instance where the P version of the maize model has been tested under conditions where N stress was also a factor. Output from the model suggests that simulation of crop growth with two potential limiting nutrients was sensible.

Elsewhere Olsen P data have been used for initialising the labile P of the model. Here a fractionation procedure was used for the soil P data, and labile P has been equated to the sum of the resin and bicarbonate-P fractions. The soil P data were obtained for samples taken soon after the application of the fertilisers. There was poor agreement between the predicted changes in labile P and the soil P data.

Acknowledgments

The experiment was conducted by Bashir Jama and Roland Buresh of ICRAF, Nairobi. Obadiah Kyunguti and John Mailu are thanked for the management of the field trials.

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