Modelling the effect of phosphorus on maize production and nitrogen use efficiency on smallholder farms in sub-humid Zimbabwe

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Abstract

The variation in response to the application of fertilizer N in smallholder agriculture is related strongly to temporal and spatial variability in soil moisture, soil fertility and crop management history. Smallholder farmers in many parts of sub-Saharan Africa create fertility gradients across landscapes through their management of limited nutrient and organic residue resources. Using a previously published dataset described in Mushayi (2001), the on-farm investigations of maize response to N were simulated using a prototype 'P-aware' maize model in APSIM. The differences in nitrogen response efficiency measured across several on-farm sites were strongly related to soil P status and seasonal conditions. Although it was assumed in the model that all sites had similar soil water characteristics, the general responses in maize grain yield to additions of N were well represented by the "P-aware" maize model. This new capability in APSIM is being used to refine nutrient management strategies for smallholder farmers in Southern Africa.

Media summary

A new P modelling capability in APSIM delivers better capacity to simulate maize production under the marginal soil fertility faced by smallholder farmers and results in more robust fertiliser recommendations.

Key Words

Maize production, phosphorus modelling, APSIM, smallholder farmers, Zimbabwe.

Introduction

Most of the soils used by smallholder farmers in Zimbabwe are coarse sands derived from granite and generally contain very low available P concentrations. While nitrogen is usually the most limiting nutrient, the nitrogen use efficiency from applied inorganic fertilizer is often found to be very low (<15 kg grain/kg N applied) and therefore uneconomic to apply. A study by Mushayi (2001) and Mushayi et al. (1998) found that there was a large variation in the response of maize production to applications of N fertilizer on researcher-managed and farmer-managed on-farm field trials. In these experiments, the highest amount of maize grain (kg) produced per kg of applied N averaged 3.6 on the farmer-managed crops while in the researcher-managed crops it averaged 12.4 kg/kg. The data presented in Mushayi et al. (1998) studies suggests that the low response to N was strongly related to low soil P.

The development and application of crop simulation models to date has commonly focussed on water and nitrogen as the main constraints to crop growth. While such models have been useful for evaluating alternative management strategies and effects of climatic conditions, their use assumes that other factors such as nutrients other than N, pests and disease are not limiting. In low input systems, this assumption is flawed. A prototype version of the APSIM-Maize model responsive to soil P has recently been developed in the APSIM framework (Probert 2004). This P-aware crop module represents the plant P uptake process, estimates P stress in the crop, and the consequent restrictions to the key plant growth processes – photosynthesis, leaf expansion, phenology, grain filling. It is used in association with a new module (APSIM SoilP) that simulates the dynamics of P in soil and is linked 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. (website: www.apsim.info).

The objective of this paper is to assess the extent to which a P-responsive maize model can capture the variable response to N fertilizer observed under smallholder farming conditions in Zimbabwe. The original data sets of the field experiments described in Mushayi (2001) and Mushayi et al. (1998) were simulated using the APSIM P-responsive maize model. By applying the validated model under other environmental circumstances, further extrapolation of the N x P interactions were undertaken.

Methods

Complete details of these experiments are found in Mushayi (2001). Briefly, on-farm trials were conducted in communal and resettled farming districts in Zimbabwe natural region II (rainfall 750-1000 mm) and region III (rainfall 650-800 mm) during the seasons 1996/97 and 1997/98. Only data for season 1 is presented here. In the first year, researcher managed on-farm experiments were undertaken at 6 sites namely, Wedza (Wedza1, Wedza2) and Gokwe South (Gokwe1 and Gokwe2) communal areas and at two sites in the Chinyika (Chinyudze and Bingaguru) resettlement area. The Domboshawa agricultural research station was also used as another site. All sites were located on medium-grained loamy sands and sandy loams derived from granite with the exception of the Gokwe1 and Gokwe2 sites which were located on Kalahari sands. The soils derived from Kalahari sands are low in clay (<5%) contain virtually no silt and are hence very low in potassium (Table 1). According to the Zimbabwean Classification of Bray extracted P, available P was considered to be low (less than 7 mg/g Bray-1 P) at the Gokwe and Chinyika sites, low to moderate at Wedza and Bingaguru sites and high at the Domboshawa site reflecting long-term fertilizer P applications to this on-station site.

Three maize varieties (SC401, SC601 and ZM607) were planted by hand between 1 and 28 December 1996 into cultivated soil in 0.9 m rows with 0.3 m spacing between plants resulting in a plant population of between 2 and 4 plants/m2. The net plot harvested by hand was from 2 rows of 5 m long. Six rates of N from 0 to 125 kg N/ha (at 25 kg N/ha intervals) were applied as ammonium nitrate (34.5% N). One third of the N was applied at planting and the remaining two thirds at 42 days after planting (DAP). At planting all treatments received 13.5 kg P/ha, banded beside the seed, in the form of single super phosphate in both seasons. Weeds were regularly controlled by hand. All on-farm and on station experiments had 3 replicates per site and plots were arranged in a randomized complete block design.

Table 1. Surface soil characteristics (0-10cm) for the 6 on-farm experimental sites and Domboshawa station site.

				[c]Exchangeable cations		
	[a]Organic C (%)	[b]Bray P (ppm)	pH ($CaCl_2$)	K	Ca	Mg
					cmol(+)/L	
Wedza1	0.51	13	4.5	0.19	0.72	0.20
Wedza2	0.81	11	4.4	0.19	0.43	0.11
Chinyudze	0.61	6	4.7	0.21	1.69	0.30
Bingaguru	0.51	12	4.6	0.15	0.91	0.40

Gokwe1	0.31	2	4.8	0.01	0.16	0.07
Gokwe2	0.51	1	4.8	<0.01	0.13	0.06
Domboshawa	0.71	44	4.4	0.08	-	0.12

[a]Fluoride extractable phosphorus Bray1-P (Bray and Kurtz, 1945).
[b]Walkley-Black (Walkley 1947)
[c]1 M ammonium chloride extraction (Rayment and Higginson 1992)

Simulation

Using the raw data from Mushayi (2001), the individual treatment yields for the SC401 and SC601 genotypes (ZM607 was not parameterized in APSIM-Maize) were obtained along with the soil characterization and climatic data for each site in the wet season of 1996/97. Daily rainfall data was collected by farmers at each of the on-farm sites and was used along with the temperature data measured at the Domboshawa station and calculated radiation data. As there were no soil analyses for the Domboshawa station site, records from samplings of adjacent plots were obtained. For Gokwe1 and Gokwe2 and Domboshawa sites, organic C, pH and available P data were available for intervals to 1 m depth and were used to set up the profiles in the simulations (data not shown). Since pre-sowing mineral nitrogen was not analysed, it was initialized in the model at a concentration that produced a yield similar to that measured in the 0N treatment of the field experiments. Since there was no information available on the soil physical characterisation of the sites, all sites used the same soil water holding profile parameters with a depth of 1.7 m, a plant available water holding capacity of 80 mm and a drainable capacity (saturation- drained upper limit) of 264 mm. Site slope characteristics such as slope, runoff and soil water conductivity were also considered to be the same across all sites. The soil characterization described by Shamudzarira and Robertson (2002) for a granitic sand at Makoholi research station was used as the basis of the soil water simulation setup. The management parameters in the model mimicked the actual field experimentation.

Results

Field experiments

There was a highly significant (p<0.001) site ? N treatment interaction. Linear responses to N were found at the Bingaguru and Domboshawa sites with nitrogen use efficiencies (NUE's) of between 17 and 33 kg grain/kg N at all rates of N (Figure1). At all other sites, the response to N was generally poor with a maximum grain yield of 1633 kg/ha produced at the Wedza sites with 75 kg/ha of fertiliser N. Rainfall received at Bingaguru and Domboshawa was 963 and 1340 mm (November-April), respectively, whilst the other sites received between 607 and 894. Much of this rainfall was concentrated in late January and early February leading to waterlogging at some of the sites. The addition of 13.5 kg/ha basal P at planting appears to be inadequate to overcome the low available soil P measured at the smallholder sites. Although the measured soil P concentration is similar at the Bingaguru and Wedza sites (11-13 ppm) grain production at Wedza 1 and 2 was much lower and due to the effect of low and poorly distributed rainfall at the Wedza (within crop rainfall was 442 at Wedza and 830 mm at Bingaguru). It is hypothesised that as a consequence of lower soil water, the maize crop at Wedza was unable to take up soil P and was more severely limited by P stress in the second half of the crop growth period.

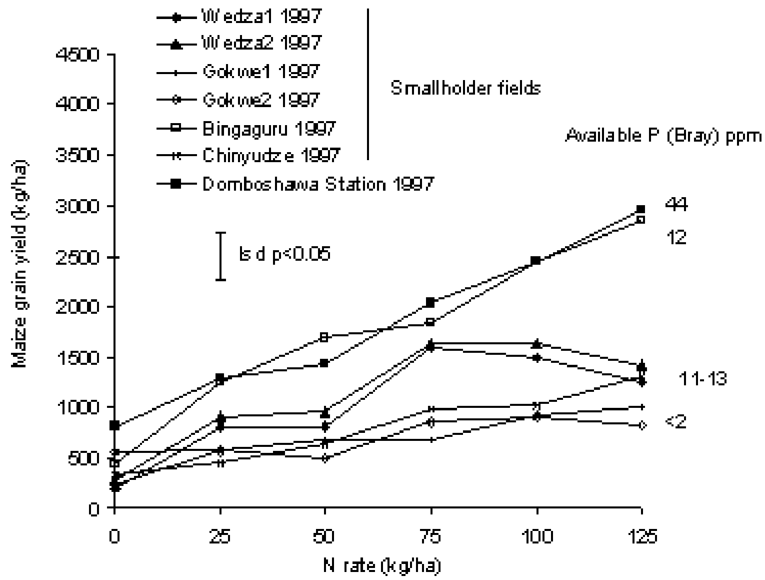

Figure 1. Maize grain response to N averaged over genotypes SC401 and SC601, Zimbabwe 1996/97 (Redrawn from Mushayi et al. 1998).

"P-aware" simulation of maize grain yield

The general responses in maize grain yield to additions of N were well represented by the "P-aware" maize model (Figure 2). Over prediction in grain yields of 525 to 1143 kg/ha on the 125 kg N/ha treatment at Bingaguru and Domboshawa was probably due to the model not responding negatively to the waterlogging events that occurred during late January and early February 1997 at these sites (Waddington, pers comm.). With the exception of Bingaguru, all smallholder sites demonstrated a flat response to N fertiliser additions above 25 kg/ha (Figure 2). Despite fertiliser P being applied in the simulation, the model suggested that the dry soil in the surface layer restricted P uptake from the fertiliser P applied to this layer. The observed dataset indicates that there may be small responses to N above 25 kg/ha and it is suggested that differences in soil type, history of manure application and fertiliser applications not represented by the model, may account for these.

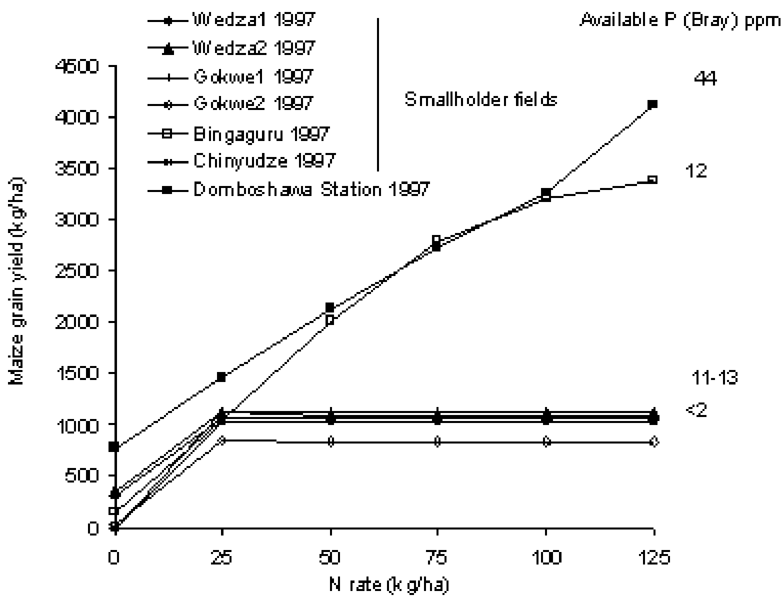

Figure 2. Simulated maize grain response to N averaged over genotypes SC401 and SC601, Zimbabwe 1996/97.

Conclusion

Smallholder producers in Zimbabwe and other Sub-Saharan nations face large temporal and spatial variations and are generally constrained by labour and cash shortages. While farmers are encouraged to use fertilisers, when responses to N are low, as described in the Mushayi et al. (1998) and Mushayi (2001) studies, it is not surprising that smallholder farmers are reluctant to invest in N fertiliser for maize. Recognition of other constraining factors is important, for example in soils with low available P, poor plant growth can limit the uptake of applied N resulting in low N use efficiency. Under high rainfall conditions, such as the 1996/97 cropping season in this study (Fig. 1a), leaching may also reduce N response. This can be partly remedied by smaller split applications of fertiliser N.

In many smallholder systems, water, N and P interactions can explain much of the yield variation in maize growth. The simulation of maize growth in response to fertiliser N under a range of available soil P concentrations was found to be promising, given the need in this study to make assumptions about the soil water characteristics of the sites. While simulations can never represent all of the factors that determine maize yield, it can be fruitful to apply models to scenarios of interest. Using this approach to investigating the N response functions on different field types and climatic situations, nutrient strategies can be modelled to assess likely yield increases. Further testing of the P-aware capability in APSIM is also underway for other datasets obtained from Africa and Australia.

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