Simulating the Response of Maize
to Nitrogen Fertilizer in Semiarid Zimbabwe

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Risk Management Working Paper Series 00/03

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Abstract: Crop yield responses to inorganic fertilizers are variable under low and erratic rainfall characteristic of the semiarid tropics. Risks are especially high on the infertile granitic sands in many smallholder communal areas of Zimbabwe. There is a need to develop fertilizer recommendations taking account of climatic variability, the price of maize and the cost of fertilizer, that are relevant to the low rates of fertilizer that smallholder farmers are willing to apply. The aim of this paper is to validate a cropping systems simulation model using experimental results of maize response to N, and then to apply the model to explore the risk associated with N fertilizer use and management strategies to minimise risk. Data for model validation came from a long-term maize N fertilizer rate trial (1991/92-1997/98) at Makoholi near Masvingo in semi-arid Zimbabwe. On average, maize growth and development in response to N was simulated with a degree of accuracy that justifies its use in analysis of risk associated with N use in these semi-arid regions of Zimbabwe. APSIM was then configured to simulate the response to N over a 46-year climate record in order to assess the long-term risks associated with N use. The simulated long-term distribution indicated that negative responses to N could be expected in 15% of years, whereas no negative response to N was recorded in the experiments at Makoholi. Median responses were 20-30 kg maize grain/kg N for observed and simulated results. In terms of return on fertilizer investment, the observed and simulated distributions were also similar: in about 20% of years, a negative return could be expected, while in the best 20% of years a return of $Z5000 or more could be expected, given the grain:fertilizer price ratio, which at March 2000 was about 1:7. The model analysis has suggested moderate rates (ca. 30 kg N/ha) of N fertilizer use would give greater responses per unit N applied that smaller rates (15 kg N/ha). There was no evidence that conditional fertilizer strategies based on early-season rainfall would offer significant benefits over fixed application strategies. Early sowing at recommended population densities gave higher responses to N than that for late sown and/or low density crops.

Simulating the Response of Maize to Nitrogen Fertilizer in Semiarid Zimbabwe

1. Introduction

Maize (*Zea mays* L.) is the most important crop in communal lands of semi-arid Natural Regions III and IV of Zimbabwe (e.g. Mackenzie, 1987). A substantial amount of agronomic research on maize has been conducted in semi-arid areas of Zimbabwe (see Metelerkamp, 1987; Waddington and Kunjeku, 1989), but much was not appropriate to smallholder needs (Waddington and Kunjeku, 1989). In addition, appropriate fertilizer recommendations have not been developed for the smallholder sector. Prior to 1980, fertilizer recommendations for maize were based on generated response curves from work done in intensive cropping areas on heavy soils. After 1980 however, a concerted effort was made by the Agronomy Institute of the Department of Research and Specialist Services to develop appropriate fertilizer recommendations for the smallholder farmers through conducting on-farm and on-station trials with lower rates of N (Agronomy Institute, 1989; Mataruka and Whingwiri, 1988; Shamudzarira, 1994; Shumba, 1988). Nitrogen (N) has been the element of major focus in such work because it is the major limitation in smallholder fields and its availability interacts strongly with climate. A major limitation in using results from this work has been the variability in treatment response from season to season and across sites (e.g. Hikwa, Mataruka and Natarajan, 1989). Much of the seasonal variability is due to low and uncertain rainfall coupled with soils of low plant available water capacity.

Given the difficulties in devising agronomic recommendations in environments with high seasonal variability, a number of workers have examined the application of crop simulation modelling to issues of N management in maize in smallholder agriculture (Keating *et al.* 1991; Thornton *et al.* 1995). These studies were useful in defining the risks of applying N. However, in these studies relatively high yields in the absence of fertilizer were obtained, whereas little attention has been given to highly infertile situations where yields in the absence of fertilizer can be as low as 500 kg/ha. In wet years, yields from unfertilized crops on the granitic sands in Zimbabwe can be even lower at 300-400 kg/ha due to the low availability of soil N (Low and Waddington, 1991). If simulation models are going to be applied to such situations, then they must demonstrate an ability to simulate such low yields as well as the yield response to small inputs of N fertilizer that are typical of smallholder farmers in this region.

In semi-arid regions, rainfall deficits impose a major risk to achieving responses to N fertilizer. Without a means of anticipating the "goodness" of the upcoming season, the best a farmer can do is to apply fertilizer tailored for a typical season. Such a strategy unavoidably results in lost opportunities for high yield in good seasons and wasted inputs in poor seasons. One strategy to minimise risk is to apply fertilizer conditional upon antecedent rainfall. This principle underlies the operation of "response farming" type strategies. A variant of this approach has been developed for Zimbabwe (Piha, 1994) where N fertilizer rates are adjusted according to the rainfall pattern during the on-going season. N is applied on up to three occasions during the season, with the amount at emergence fixed and the size of subsequent applications varied depending upon the degree of visible crop drought stress. It is possible to evaluate the benefits of such strategies using

crop simulation coupled with historical climate data, as was done by McCown *et al.* (1991) for the Machakos district in semi-arid Kenya. Here we attempt a similar analysis for a semi-arid location in Zimbabwe.

This paper reports on the validation of the capability of the APSIM cropping systems model to simulate the response of maize to N fertilizer, using a long-term experiment conducted at Makoholi Research Station near Masvingo in semi-arid Zimbabwe. A second objective is to use the validated model to study the long term returns (in yield and income) associated with low fertilizer applications, including strategies that are conditional upon early-season rainfall.

2. Materials and methods

2.1. Sites, soils and crop management

The experiment was conducted from 1991/2 to 1997/8 at Makoholi Research Station (latitude 19.8 °S, 30.8°E, elev. 1204 masl), which is situated in Natural Region IV of Zimbabwe. The climate is semi-arid and characterized by a unimodal wet season from October to March. The 30-year average seasonal rainfall at Makoholi is 583 mm, but this ranges from 260 to 1150 mm (Bruneau and Twomlow, 1999), as a result of the high inter- and intra-seasonal variability of the rainfall. The soil type at the site is classified as a moderately deep (100-150 cm) fersiallitic coarse sand derived from granite, classified as a Ferralic Arenosol (FAO) or an Ustic Quartzipsamment (USDA). This soil is representative of *Topland* soils within the geomorphological catena of the Zimbabwean landscape (Nyamapfene, 1991). Soil pH (in water) varies little with depth at this site being on average 6.4 throughout the 100-cm profile. The site had been previously under fallow for two years.

The experiment was comprised of a factorial of plant spacing at the same plant density (0.90 X 0.30m, 0.75 x 0.35m, 0.54 x 0.50m), tillage (reduced and conventional) and nitrogen fertilizer rate (0, 30 and 60 kg N/ha). In this paper only those results from the conventional tillage treatment are used for model validation. "Conventional" tillage involved preparing the seedbed with an ox-drawn mouldboard plough. After harvest, residues were incorporated into the soil.

Gross plots were 6m x 4.5m, with three replications. The target plant population was 3.7 plants/m^2, but established densities varied between seasons. Therefore, the plant counts at the anthesis biomass sampling provided an indication of the final established plant population density. From 1991/2 to 1996/7 cultivar R201 was used and in 1997/8 cultivar SC501. In the 30 kg N/ha treatment, N fertilizer was applied as a basal dressing at sowing, whereas in the 60 kg N/ha treatment an additional topdressing of 30 kg N/ha was applied 30-40 days after emergence. Weed control in all treatments was done by hoe weeding 2-3 times during the season. A uniform application of lime at a rate of 600 kg/ha was applied to all plots about 2 months before planting in 1992, 1994 and in 1997.

2.2. Measurements

Before sowing two or four auger holes per plot were made to 100cm to determine soil water content, nitrate, and organic carbon. Samples were analysed in the following increments: 0-15, 15-30, 30-60, 60-90, 90-100cm. Bulk density was determined from two pits dug adjacent to the experimental site. Measurements of organic carbon and pH were done on the soil samples taken at planting.

Observations were made when 50% of the maize in each plot had reached the following cardinal stages: emergence, anthesis and physiological maturity (black layer formation). Final grain yield and biomass was measured from a quadrat measuring 2.7 x 3.6m (9.72 m^2).

The drained upper limit (DUL) was determined at the site in 1995. A ponded area measuring 2 x 2m was marked out just outside the experimental area and flooded with water. The area was then covered with a plastic sheet to prevent drying of the soil surface and left to freely drain for 24 hours. Soil moisture contents were measured gravimetrically at 15-cm depth intervals to variable depths that averaged about 100cm. A well-fertilized maize crop was established in the ponded area and the crop allowed to deplete the soil moisture within the profile. The lower limit (LL) was determined in 1996 after a prolonged spell of dry weather when it was assumed that the established crop had extracted the maximum possible available soil water.

Climate data (daily minimum and maximum temperature, rainfall and solar radiation) was recorded at a site 10 km away from the experiment. Sunshine hours were used as a surrogate measure of solar radiation receipts.

2.3 Simulation set-up for model validation

In order to simulate the experiments, the APSIM-Maize module was linked with the soil water module SOILWAT (Probert *et al.* 1997), the soil nitrogen module SOILN (Probert *et al.* 1997), and the surface residue module RESIDUE (Probert *et al.* 1997).
The genetic coefficients for R201 and SC501 used for CERES-Maize were obtained from Dr A du Toit (Potchefstroom Agricultural Research Station, Republic of South Africa).

Soil water parameters (Table 1) were derived from soil samples taken at the site, and the values of DUL and LL determined during the experiment (see above). It was assumed that maize roots were able to reach 100cm as there would have been little plant available water in the rocky material below 100cm. A runoff curve number of 85 was used and the parameters for soil evaporation were set at 8 and 3.5 mm for first and second stage drying, respectively. Soil nitrogen parameters were taken from measurements at the site (Table 2). The fraction of organic N at sowing that was in the readily mineralisable and inert fractions was set to 0.02 and 0.5 in the soil surface, respectively, changing to 0.01 and 0.95 at depth. The amount of surface crop residues was initialised as zero as residues were absent at the start of the simulation in 1992.

Weather data were derived from measurements at the site. Management information (date of sowing, established plant population, dates and amounts of fertilizer application) was also input (Table 3). Simulations were run from the date of pre-sowing soil sampling in 1992 until the observed date of maize physiological maturity in 1998. No soil or crop residue variables were reset during the simulation, thus testing the ability of the model to simulate changes of soil water and nitrogen over the seven cropping seasons and intervening fallow periods.

Table 1: Soil water parameters used in the simulation of the Makoholi experiment. The total plant available water (DUL-LL) to 1000 mm depth was 59 mm and drainable porosity was 220 mm. Air_Dry, LL15, DUL, SAT and SW are the volumetric soil water contents at air dryness, lower and upper limits of plant available water, saturation and the start of the simulation, respectively; BD is the bulk density and SWCON is the drainage coefficient.

Depth mm	Air_Dry	LL15	DUL	SAT	SW	BD	SWCON
			mm/mm			g/cm^3	
0 - 50	0.03	0.04	0.14	0.44	0.17	1.431	0.7
150 - 300	0.07	0.07	0.15	0.45	0.13	1.420	0.7
300 - 450	0.09	0.13	0.20	0.45	0.13	1.418	0.7
450 - 600	0.09	0.13	0.20	0.40	0.12	1.546	0.7
600 - 750	0.09	0.18	0.22	0.40	0.12	1.551	0.7
750 -1000	0.09	0.22	0.24	0.38	0.12	1.610	0.7

Table 2: Parameters for the soil nitrogen module used to simulate the Makoholi experiment. The total mineral N to 1000 mm depth was 14.4 kgN/ha

Depth mm	pH	Org C. (%)	Initial mineral N (kgN/ha)	
			NO$_3$	NH$_4$
0 - 150	6.5	0.76	4.29	1.29
150 - 300	6.2	0.71	2.13	0.21
300 - 450	6.3	0.57	1.06	0.21
450 - 600	6.4	0.57	1.16	0.23
600 - 750	6.5	0.66	1.16	0.23
750 -1000	6.6	0.55	2.01	0.4

2.4. Extension of experimental results using long-term simulation

The validated model was used to assess the long-term risks associated with applying N fertilizer in these semi-arid regions of Zimbabwe. As the rates of N applied at Makoholi were also not typical of those used by smallholder farmers (< 16 kg N/ha), there was a need to assess the yield response and dollar return to smaller rates of N application. Accordingly, APSIM was configured to simulate the response to N application over the long-term climate record. The simulation was configured as follows:

Climate data: No long-term climate data are available prior to 1991 for Makoholi. However, the Masvingo climate record, a nearby station (20.1°S,30.8°E, elev. 1081m asl), does exist for 1951 to 1991. Therefore, the Masvingo climate record was appended to the Makoholi record to give a 46-year record from 1951 to 1998.

Soil inputs: The soil type used was that described above and used to simulate the Makoholi experiment. Soil N was re-initialised every year after harvest to eliminate long-term changes in soil fertility as a consequence of the scenarios. Nitrate-N at sowing typically varied between 10 and 25 kg N/ha, due to variable rates of simulated net mineralisation occurring between soil N re-initialisation and sowing. Soil water was allowed to carry over between seasons.

Crop management: Cultivar SC501 was sown at 3.5 plants/m^2 in each season on the first date after 1 November that had received at least 25mm rainfall over the previous 10 day period, and the soil water content in the 10-30 cm layer was at least halfway between the drained upper limit and lower limit. Using this rule, maize could be sown every season in the 46 year run. About 50% of the simulated sowing dates occurred before 15 November, another 40% before 30 November and the remaining dates were in December. Some simulations were conducted with the sowing window constrained to occur after 1 December, to reflect draft animal constraints on timeliness of sowing in communal areas (Ellis-Jones and Mudhara, 1995). In this late sowing scenario, about 70% of sowing dates occurred in the first few days of December, with the remaining occurring before the end of the year. There was one season where sowing did not occur because of insufficient rain before the end of the window on 15 January. Some simulations were also conducted with a lower population (2 plants/m^2) to reflect the lower densities commonly encountered in smallholder's fields. Residues were removed after harvest in every year.

Fertilizer management: Various application strategies were simulated: no fertilizer applications as a baseline, applications that occurred on fixed dates after sowing in every season, and applications that were conditional upon rainfall. In the conditional strategies, 3 windows for application were defined: 1-10, 20-30 and 40-50 days after sowing during which 15 kg N/ha could be applied if 20 mm occurred over a 20 day period.

Table 3: Details of the seasonal conditions in the experiment at Makoholi.

Season	In-crop rainfall (mm)	Sowing date	Established plant population (m^2)	Anthesis days after sowing	Silking days after sowing	Harvest date
1991/2	83	22-Jan-92	Na*	78	80	7-Jun-92
1992/3	625	23-Nov-92	3.5	70	78	17-May-93
1993/4	445	29-Nov-93	3.6	63	72	5-May-94
1994/5	359	24-Nov-94	3.4	71	79	21-Jun-95
1995/6	637	27-Nov-95	3.6	74	81	21-Jun-96
1996/7	628	27-Nov-96	3.7	75	82	8–Apr-97
1997/8	305	27-Nov-97	Na	61	74	7-Apr-98

* data not available

In total 12 scenarios were simulated:

1. No fertilizer applied.
2. 15 kg N always applied at sowing.
3. 15 kg N always applied at sowing and 20 days after sowing (total 30 kg N).
4. 15 kg N applied conditional upon rainfall in the 1-10 day window.
5. 15 kg N applied conditional upon rainfall in the 1-10 day window, and the 20-30 day window (total up to 30 kg N).
6. 15 kg N applied conditional upon rainfall in the 1-10 day, the 20-30 day, and the 40-50 day window (total up to 45 kg N).
7. No fertilizer applied in late sowing.
8. No fertilizer applied in low population.
9. 15 kg N applied conditional upon rainfall in the 1-10 day, the 20-30 day, and the 40-50 day window (total up to 45 kg N) in the late sowing.
10. 15 kg N applied conditional upon rainfall in the 1-10 day, the 20-30 day, and the 40-50 day window (total up to 45 kg N) in the low population.
11. No fertilizer applied in late sowing and low population.
12. 15 kg N applied conditional upon rainfall in the 1-10 day, the 20-30 day, and the 40-50 day window (total up to 45 kg N) in the late sowing and low population.

Economic calculations: Return on fertilizer applied was calculated as the yield multiplied by price per kg minus the fertilizer rate multiplied by the cost of fertilizer per kg. As most maize in smallholder areas in Zimbabwe is produced for home consumption, the price based used was based on the cost of buying maize for home consumption.

3. Results and discussion

3.1. Observed response to applied N

Figure 1 shows that the observed response to N was variable among seasons. In 1991/92 severe drought resulted in no grain being harvested from any of the N treatments. The in-crop rain during this season was both low in total amount (Table 1) and poorly distributed (Figure 2). By contrast, in 1993/4 a substantial response to N was observed with a maximum yield of 3.9 t/ha achieved in the 60 kg N/ha treatment. In this season, 445 mm of well-distributed in-crop rain was received (Table 1 and Figure 2). In the other seasons, with in-crop rain varying between 305 and 637mm, the response to N was more repeatable.

There was considerable variability in the agronomic response to fertilizer applied (extra kg grain per kg N applied) (Table 4). For instance, the agronomic efficiency for the first 30 kg N applied varied between 9 and 59 kg/kg, and the response to 60 kg N varied between 13 and 34 kg/kg. Over all the seasons and N rates, the lowest efficiency was recorded in 1991/2 (0 kg/kg) and the highest in the 30 kg N rate in 1993/4 (59 kg/kg).

Yields in the absence of N varied between 0 (1991/2) and 1810 kg/ha (1993/4), with a mean of 850 kg/ha It is notable that the grain yield in the zero N treatment did not give a strong indication of the likelihood of a high agronomic response to N (Figure 3).
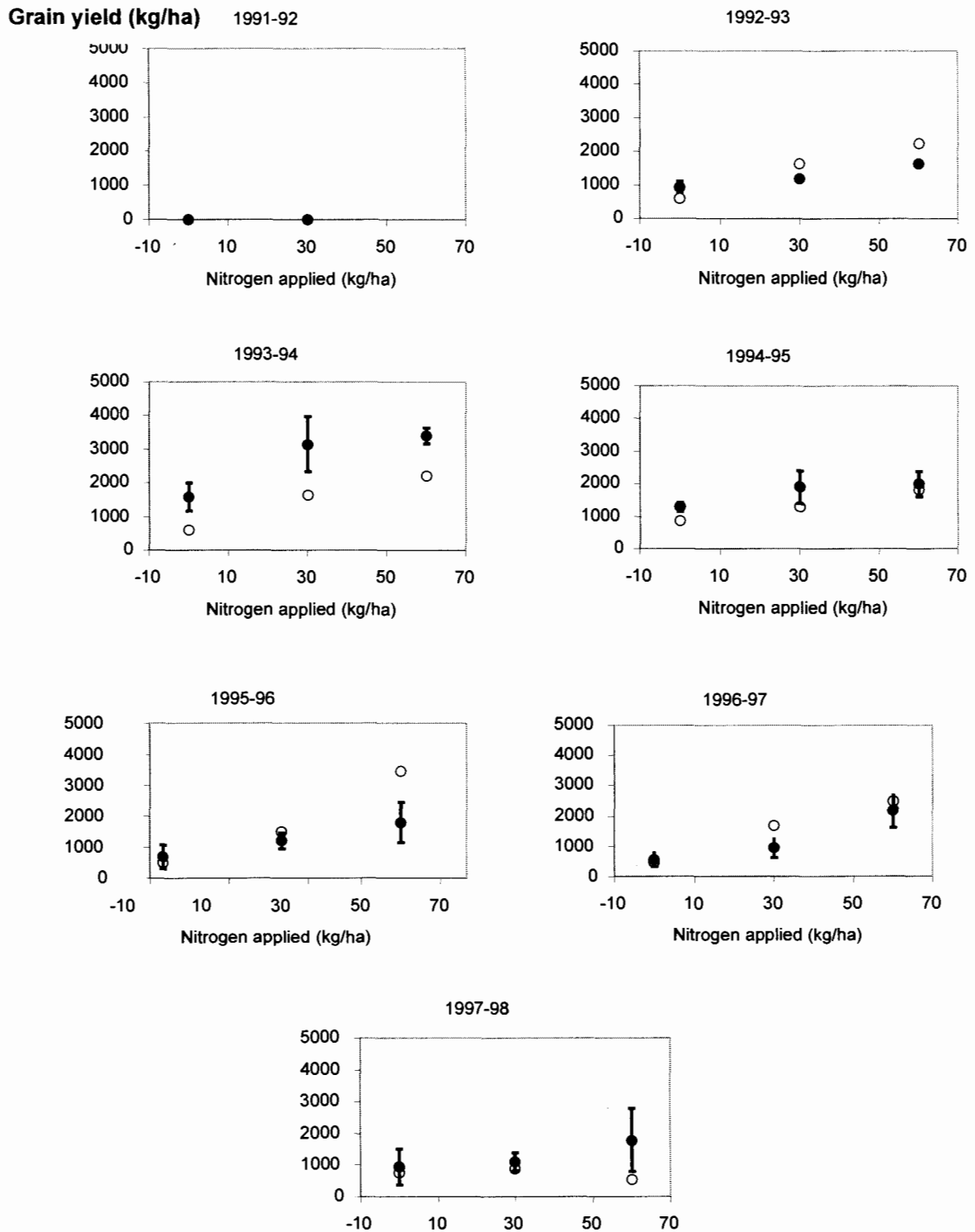
Figure 1: Observed (filled points with +/- standard errors) and simulated response (hollow points) to N fertilizer over 7 seasons at Makoholi.
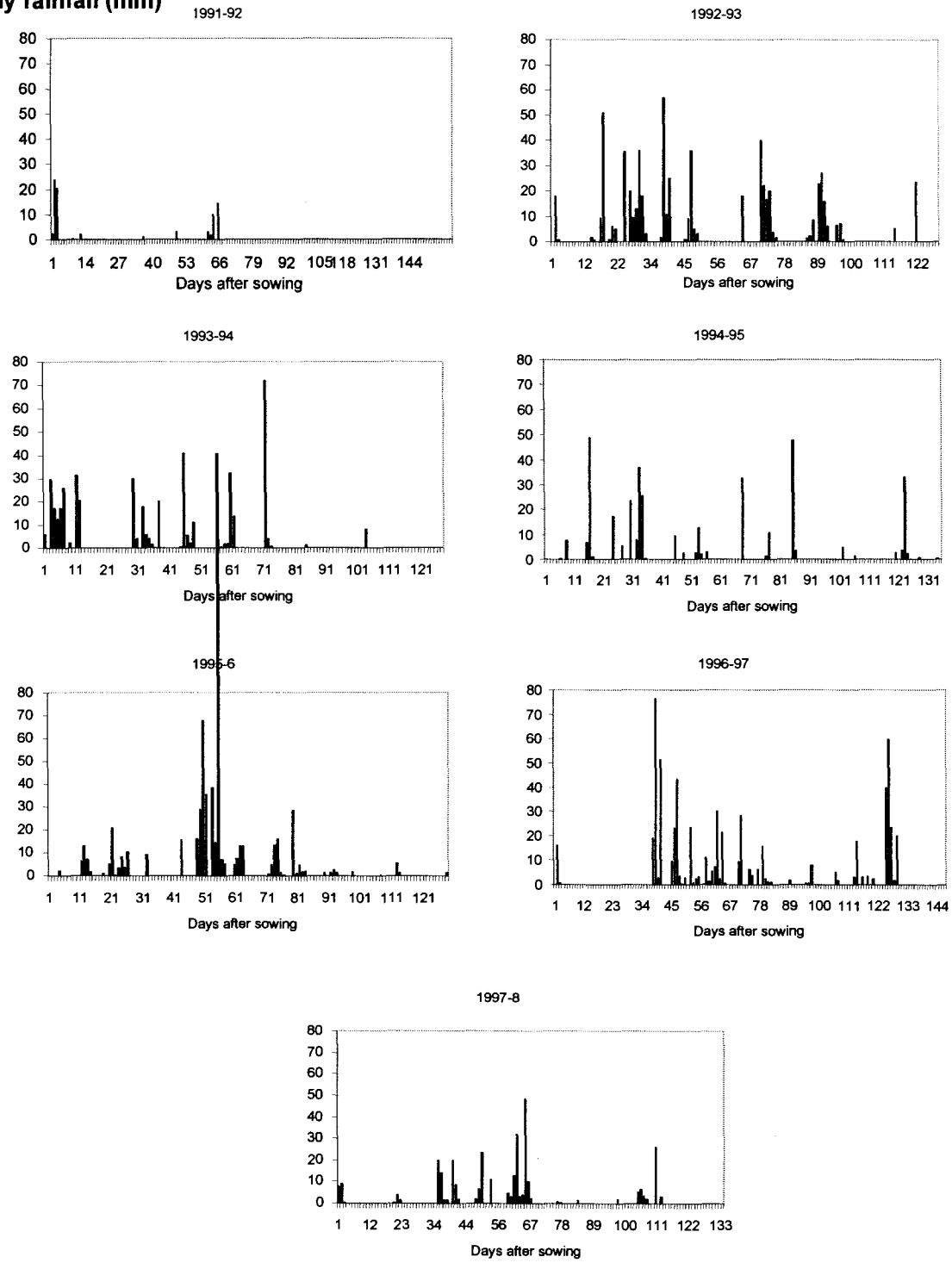
Daily rainfall (mm)

Figure 2: Pattern of in-crop rainfall in the 7 seasons at Makoholi.

Table 4: Observed agronomic efficiency (kg extra grain above 0 kg N/ha per kg N applied) for each season at Makoholi.

Season	Agronomic efficiency (kg grain/kg N)		Return to fertilizer application (Z$/ha)*	
	30 kg N/ha	60 kg N/ha	30 kg N/ha	60 kg N/ha
1991/2	0	0	-858	-858
1992/3	9	26	237	2469
1993/4	59	34	6589	7803
1994/5	23	13	2099	2536
1995/6	20	21	1619	4372
1996/7	15	30	1005	6759
1997/8	6	16	-129	3057
Mean	17	27	1509	3734

* Assuming a maize price of Z$4.20 per kg, and N price of Z$ 28.6 per kg.
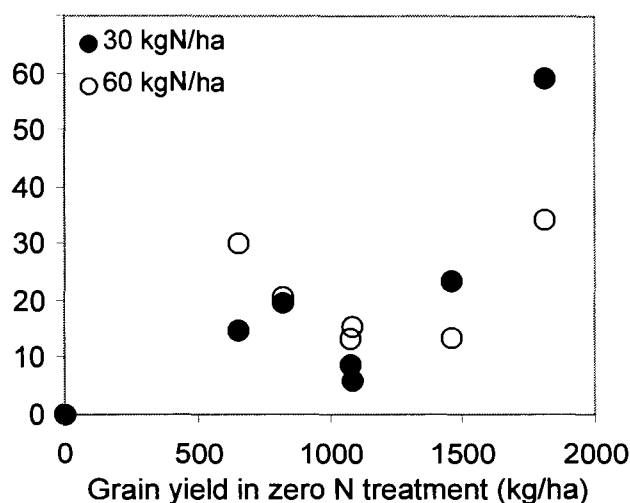
Agronomic response to N (kg/kg)

Figure 3: Correlation between agronomic response to fertilizer and grain yield in the two N rates at Makoholi over 7 seasons.

For instance, for 30 kg N applied, an agronomic response of 15-25 kg/kg N was achieved in seasons where the zero N yield varied between 600 and 1500 kg/ha. On the other hand, there is a suggestion that the total in-crop rainfall provided an indication of the response to N (Figure 4). There is a linear trend of increasing response between ca. 250 mm up to 450 mm, and a negative response beyond this. From first principles this makes sense: seasons of low rainfall limit the potential of the crop to respond to N, while seasons of high rainfall leach N from the root zone making N supply more limiting that water supply. Moreover, due to slow draining subsoils, these sandy soils are also prone to waterlogging under wet conditions, which can be expected to reduce the crop's efficiency of fertilizer N use.
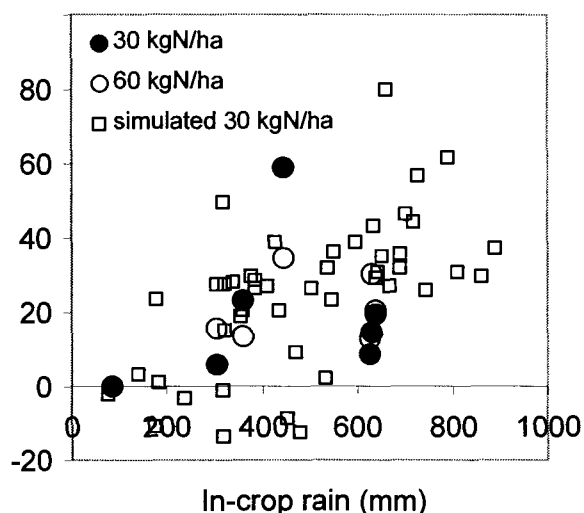
Agronomic response to N (kg/kg)

Figure 4: Correlation between agronomic response to fertilizer and in-crop rainfall.. Observed data are plotted for the 30 and 60 kgN ha^{-1} rates at Makoholi over 7 seasons as well as 46 seasons simulated for 30 kgN/ha.

McCown *et al.* (1991) show similar positive relationships between maize yield and seasonal rainfall from ca. 200 to 500 mm for the short and long rains seasons in Kenya.

3.2. Simulation of response to applied N

Accurate simulation of the response to N fertilizer requires that the model is simulating satisfactorily associated aspects of crop growth and development. Crops were sown between 24 November and 22 January and flowered between 72 and 82 days after sowing. Table 5 shows that the model was achieving acceptable accuracy in simulating silking dates. Due to severe water stress in 1991/2 the simulated crop did not reach flowering, whereas in reality flowering was observed. In the other 6 seasons, the mean observed silking date was the same as the mean simulated (78 days after sowing), although there was some minor variation in phenology between seasons that the model did not simulate.

Table 5: Observed and simulated maize phenology.

Season	Sowing date	Silking DAS*	
		Observed	Simulated
1991/2	22-Jan-92	80	Did not flower
1992/3	23-Nov-92	78	72
1993/4	29-Nov-93	72	70
1994/5	24-Nov-94	79	81
1995/6	27-Nov-95	81	71
1996/7	27-Nov-96	82	89
1997/8	27-Nov-97	74	82

*days after sowing

The model simulated the grain yield response to N within one standard error of the mean in nearly all the seasons (Figure 1). Importantly, the model successfully simulated the crop failure in 1991/2, and the low biomass produced in that season (simulated 500 kg/ha biomass compared to 580 kg/ha observed). The low observed yields in the zero N treatment were also simulated well: the simulated grain yield across all seasons, but excluding the 1991/2 failure, was 675 kg/ha, while the observed was 1151 (+/- 173) kg/ha. On the other hand, the yields in the 60 kg N/ha rate were also simulated well: the simulated grain yield across all seasons, but excluding the 1991/2 failure, was 2453 kg/ha, while the observed was 2427 (+/- 301) kg/ha.

The most noticeable discrepancies between observed and simulated came in 1992/3 and 1993/4, where the model over-predicted and under-predicted yields, respectively. In season 1992/3 a good total (624 mm) and distribution (Figure 2) of rain occurred, so it is not surprising that the model should simulate a reasonable response to N. The fact that a poor response was observed, however, suggests that another factor may have been constraining yields in this season. The over-prediction in 1992/3 may explain, in part at least, the model under-prediction in 1993/4, through simulated over-depletion of both soil water and soil nitrate in 1992/3 leaving less than was actually available for the 1993/4 crop. In 1993/4 a medium amount of fairly well-distributed in-crop rain was received (445 mm), however the yields, including the N zero, were much higher than in other seasons. This suggests that nitrogen supply may have been higher in that year compared to other years. Biomass was also simulated with reasonable accuracy (Figure 5). With few exceptions, the simulated values were within two standard errors of the mean observed value.

3.3. Extension of Makoholi results using long-term simulation

The simulated response to 30 kg N/ha applied at sowing is compared with the responses observed at Makoholi from 1991/2 to 1997/8 in Figure 6. The 46-year simulated distribution of yields with no N applied had a yield range of 0 to 1200 kg/ ha. The lower half of the distribution was similar to that observed at Makoholi and the median was also similar at ca. 1000 kg/ha, however there were a number of observed yields that were higher than any simulated. This was probably a consequence of re-initialising soil mineral N to a low value before every season in the long term simulation, whereas in the case of the observed, soil N at sowing may have been higher, although this cannot be verified due to a lack of measurements. Distributions of simulated and observed yields with 30 kg N applied were also similar. Median yields were ca. 1500 kg/ha and maximum yields were ca 3000 kg/ha. The probability distribution for the agronomic response to N was also similar, although the simulated distribution indicated that negative responses could be expected in 15% of years, whereas no negative response to N was recorded at Makoholi. Median responses were 20-30 kg/kg N for observed and simulated results. In terms of return on fertilizer investment, the observed and simulated distributions were also similar. In about 20% of years, a negative return could be expected, while in the best 20% of years a return of $Z5000 or more could be expected. Of course, these results will be sensitive to the grain:fertilizer price ratio, which at March 2000 was about 1:7. The value of this ratio over the last 6 seasons has varied from 1: 4 to 1:6. Hence, the analyses reported here use a

pessimistic value for the ratio, nonetheless the short term prospects for an improvement in the ratio are not strong.
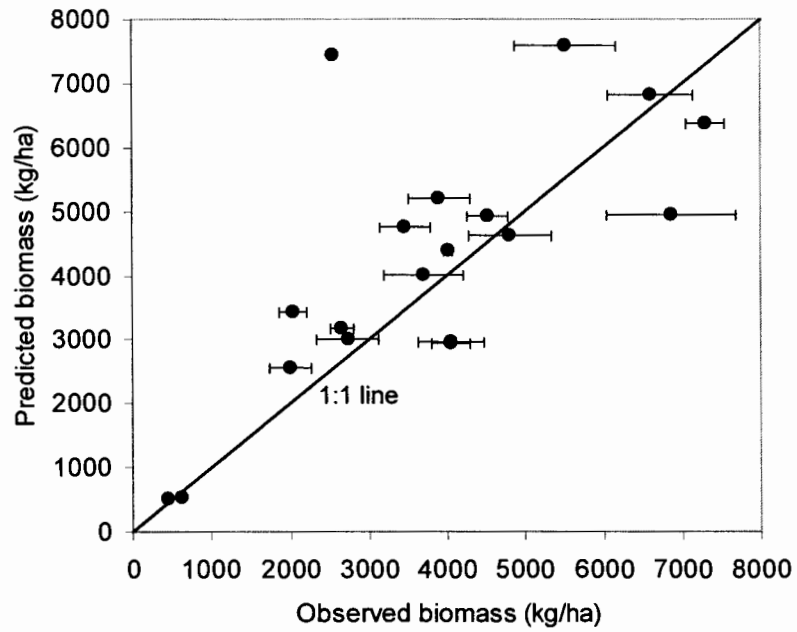

Figure 5: Overall observed and predicted biomass at maturity in the three N fertilizer treatments for the 7 seasons at Makoholi. Error bars represent +/- one standard error of the mean.
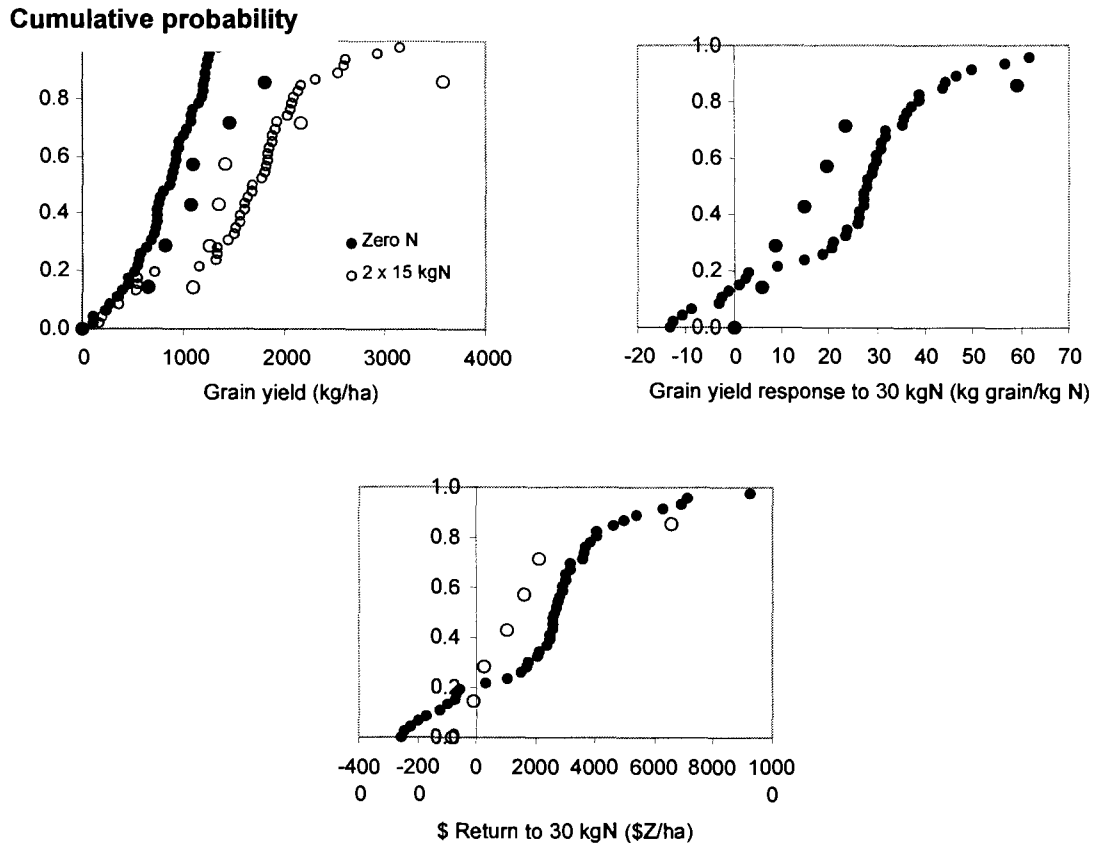
Figure 6: Comparison of observed and long-term simulated probability distributions of response and return to fertilizer . Observed (hollow points) are the values calculated from the seven seasons at Makoholi, and the long-term simulated are APSIM-derived values for 1951-1998. Return was calculated based on a maize price of $Z4.20 per kg and fertilizer cost of $Z28 per kgN.

In summary, Figure 6 indicates that APSIM, using the 46-year climate record for the district, captured the risk distribution of response to N fertilizer, similar to that observed in the Makoholi experiment. However, the model also indicated a significant proportion of years where there was a negative response in terms of yield and return, which was not observed in the experiment.

While the simulated response to N was weakly correlated with in-crop rainfall, some trends were apparent (Figure 4). With in-crop rainfall amounts of less than 250 mm, zero or negative responses to N were almost certain. Between 250 and 550 mm there was a weak positive correlation between yield response and rainfall. Responses tended to plateau with rainfall increasing above 550 mm. The scatter plot of simulated responses in Figure 4 agrees in part with the plot for the observed responses to the two rates over 7 seasons at Makoholi (Figure 4). A trend indicates a similar lower cut-off of 250 mm for a response to N, and an increasing trend from 250 to 550 mm. However, the simulated results do not indicate the downward trend of response to increasing rainfall above 550 mm that is apparent in the observed Makoholi results. This suggests that the simulations are not

accounting for factors that may be constraining N response under high rainfall. The model does account for N leaching and denitrification, and it is possible that these processes may be underestimated in wet seasons. It is also possible that disease or waterlogging may be constraining yields and APSIM does not simulate such effects. Grey leaf mould is a widespread disease in maize in Zimbabwe in wet years. It is also known that water tables lying on granite bedrock in communal areas in Zimbabwe are a feature of wet seasons. While the model can simulate wet root zone conditions under high rainfall and slow internal drainage, it is not possible to simulate water table fluctuations, especially if they occur as a consequence of lateral movement of water from higher positions in the landscape.

Table 6 gives summary statistics for a subset of the fertilizer strategies simulated, selected to allow a comparison of fixed and conditional application strategies. Interestingly, using the rainfall rules described above there was a modest saving in fertilizer when the conditional strategy was adopted. For example, where 30 kg N/ha could be applied, the conditional strategy gave a mean application rate over 46 years of 24.5 kg N/ha However, despite the savings in fertilizer application, the average grain yield is slightly less and, more importantly, the return to fertilizer is less, indicating that the conditional strategy while saving fertilizer doesn't improve mean return. Table 6 indicates that the yields using the conditional strategy in the 25th percentile were lower than in the fixed strategy. There was no fertilizer saved where 15 kg N/ha was applied conditionally versus a fixed rate at sowing, probably because in the simulation the rainfall rule to allow sowing would also permit fertilizer to be applied at sowing in most years.

Mean grain yield response, agronomic efficiency and return was similar for fixed and conditional strategies. There also seemed to be no advantage in terms of risk in using the conditional strategy. For example when considering downside risk, the 25th percentile for agronomic efficiency was 2 and 11 kg/kg N for the conditional strategies at 15 and 30 kg N, respectively, compared to 9 and 16 kg/kg N for the fixed strategy.

The dominant effect that is apparent in Table 6, is the higher grain yield response, agronomic efficiency and return from applying 30 versus 15 kg N. For example, mean agronomic efficiency was 24-25 versus 19 kg/kg for 30 versus 15 kg N applied. While the minimum return was more negative with 30 versus 15 kg N, the 25th percentile and median was higher. This seems to indicate that moderate rates of fertilizer are less risky than small rates. This result is in line with that observed in the experiment at Makoholi (Figure 1 and Table 4). This result defies the law of diminishing returns. The cause of such a response is unknown, but could arise due to a lower proportion of fertilizer N available for plant uptake at the low N rate, due to leaching losses, N immobilisation or denitrification.

A more complete economic analysis should also take cognisance of the association between price and type of season. Prices of commodities are usually much higher in dry years than in good years, giving rise to more severe cash-flow problems in dry years. If small amounts of fertilizer reduce the risk in dry years, but give lower returns in good years, the overall costs might not be very different between the conditional and fixed N-regimes. However, such an analysis is beyond the scope of this paper.

Table 6: Average results from long-term simulation over 46 years at Masvingo. Comparison of fixed with conditional strategies in applying 15 or 30 kg N/ha. Numbers in brackets refer to the fertilizer application strategy described in the Materials and Methods.

	No fertilizer applied (1)	15 kgN at sowing (2)	15 kgN at sowing + 15 kgN at 20 DAS (3)	15 kgN at sowing depending on rainfall 1-10 DAS (4)	15 kgN at sowing + 15 kgN at 20-30 DAS depending on rainfall (5)
			Fertilizer applied (kg N/ha)		
Mean	0.0	15.0	30.0	14.3	24.5
			Grain yield (kg/ha)		
Mean	797	1085	1560	1079	1433
Max	1355	1834	3144	1834	3159
Min	0	101	0	0	0
No. zero values	1	0	1	1	1
25th percentile	565	716	1322	716	768
Median	836	1172	1688	1172	1623
75th percentile	1070	1461	2000	1461	1952
			Grain yield response to fertilizer (kg/ha)		
Mean		288	762	281	636
Max		916	2398	916	2413
Min		-246	-398	-246	-402
No. values < zero		8	7	8	8
25th percentile		141	476	35	160
Median		327	827	327	794
75th percentile		449	1064	449	983
			Fertilizer agronomic efficiency (kg grain/kg N)		
Mean		19	25	19	24
Max		61	80	61	80
Min		-16	-13	-16	-14
No. values < zero		8	7	7	8
25th percentile		9	16	2	11
Median		22	28	22	28
75th percentile		30	35	30	37
			Return to fertilizer ($Z/ha)		
Mean		781	2317	772	1971
Max		3420	9213	3420	9276
Min		-1462	-2530	-1462	-2544
No. values < zero		11	10	12	11
25th percentile		164	1141	-1	244
Median		945	2615	945	2478
75th percentile		1459	3611	1456	3393

The above results assume good agronomic management with timely sowing and recommended plant populations. However, for a variety of reasons many smallholder farmers are unable to sow with the first sowing rains of the season, nor are they able to establish uniform plant populations at the recommended density (Waddington et al. 1991). Low yields result from late sowing due to a variety of reasons; e.g., lower crop yield potential, higher probability of crop water deficit, more weeds, and lower levels of farmer inputs. Table 7 gives an indication of how late sowing (after 1 December), low population (2 plants/m^2) or a combination of the two may impact on response to N applied. In this case, we compared the conditional strategy of 15 kg N/ha applied conditional upon rainfall in the 1-10, the 20-30, and the 40-50 day windows (total up to 45 kg N) for the three above crop management conditions. The mean results of the simulation indicate that late sowing and low population both depress agronomic response to N from 26 kg/kg N to 22 kg/kg N, while a combination of late sowing and low population further reduce it to 19 kg/kg N. While the maximum efficiencies that are achieved are similar for all four situations, the minimum values are less for the poor agronomy situations indicating greater downside risks are involved.

Table 7: Response to 3 x 15 kg N applied to early sown crops with high population, late sown crops, low population crops, and crops late sown with low population. Numbers in brackets refer to the fertilizer application strategy described in the Materials and Methods.

	High population, early sowing (6)	High population, late sowing (9)	Low population, early sowing (10)	Low population, late sowing (12)
	Fertilizer applied (kg N/ha)			
Mean	36	36	36	36
	Fertilizer agronomic efficiency (kg grain/kg N)			
Mean	26	22	22	19
Max	65	66	65	63
Min	-14	-11	-27	-16
no. values < zero	8	10	9	7
25th percentile	10	1	6	5
Median	29	24	27	21
75th percentile	39	37	34	32

4. Conclusions

This paper has shown that APSIM is capable of simulating the low yield levels and inter-seasonal variability observed on the sandy, low fertility soils in the semi-arid communal areas of Zimbabwe. The Makoholi results for 1991/2 to 1997/8 and the long-term simulations indicate that the climatic risk of poor returns to investment in to N fertilizer are considerable for smallholder farmers in semi-arid Zimbabwe. The model analysis has suggested moderate rates of N fertilizer use may give greater responses per unit N applied that smaller rates (i.e., 30 kg N/ha cf. 15 kg N/ha). The analysis gave no evidence that fertilizer strategies conditionally-based on rainfall would offer significant benefits over fixed application strategies, however good agronomy (recommended population density, early sowing) does assist in realisation of return on N fertilizer inputs.

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