OPTIMISING NITROGEN INPUTS IN RESPONSE TO CLIMATIC RISK

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ABSTRACT

Supply of nitrogen (N) to a crop involves many complex states, flows and regulatory processes, most of which are strongly influenced by climate and management. Rainfall (generally the lack of it) exerts a dominant influence on the N economy of cereal cropping systems in semiarid regions. The combination of a complex system with many interactions, operating under a highly variable rainfall regime, requires models to deal with this complexity and variability. This paper briefly reviews the modelling approaches taken to the study of N fertiliser use on crops, and proceeds to use a simulation study involving maize production in semiarid Kenya to highlight some principles and possibilities. The CERES-maize model was tested and a revised version (CM-KEN) was found to provide accurate predictions of grain yield under a wide range of water, N and management regimes. This model was then used in conjunction with historical weather data for Katumani, Kenya to investigate the factors influencing response to N in the region. Soil properties investigated included organic matter, mineral N at planting, soil water at planting, and runoff characteristics. Management factors examined included plant density, timing of N applications and timing of the onset of the rains. The model was shown to have potential as a tool to investigate the residual effects of fertiliser application in a previous season. In all cases, responses to applied N varied markedly with the amount and pattern of rainfall in any season. Model output provided an assessment of the long-term average effects of these factors, as well as the probabilistic information needed to assess risk. The understanding of the interactions between soil, management and weather that arose through model application provided a credible basis for a quantitative hypothesis as to how farmers in the region might develop more productive systems. N input was shown to be a critical element in this hypothetical development pathway and its role as a focus for future research is highlighted.

INTRODUCTION

Nitrogen (N) supply places a major constraint on productivity and profitability in most cropping systems of both the developed and developing world. In the former, N output from agriculture can be a major pollutant beyond the farm. The cycling of N in the soil/plant system is complex and involves many pathways, states and regulatory processes. All of these flows and transformations are influenced by weather. In semiarid tropical and subtropical regions, rainfall is the dominant climatic factor influencing the N economy of cropping systems. Other important non-climatic factors include soil type, cropping history, and crop management. N inputs to systems can arise from inorganic fertilisers, organic residues or biological fixation. This paper deals with the impact of weather, primarily rainfall, on the N economy of a cereal cropping system. Arguments are presented for the need for models, and after reviewing the approaches that have been taken, a simulation study is presented which employs a dynamic simulation model to investigate the role of N fertiliser in a maize production system in semiarid Kenya.

THE NEED FOR MODELS

When N fertiliser is used in the semiarid tropics and subtropics, its efficiency of use is highly variable. Crasswell and Godwin (1984), in a survey of experiments in these regions, found efficiencies ranged from 0 to 32 kg additional grain per hectare per kg N applied. In many circumstances, low efficiencies are due to drought. Periodic inundation of soil from intense rainfall events can also result in losses via leaching or denitrification. Seasonal variation in moisture regime cause substantial variation in the rates of mineralisation of organic matter. Nitrogen can be lost from the soil-crop system by ammonia volatilisation or rendered temporarily unavailable to a crop by immobilisation. These processes will vary in importance in the different climatic and edaphic environments of the semiarid tropics and subtropics. Nitrogen not used during one cropping season may have substantial residual value for the subsequent season. Inadequate supply of N is a common cause of reduced yield, but excess N supply can cause yield losses, particularly in tillering crops in environments limited by water supply after anthesis (e.g. the "haying off" effect reported on wheat in Australia (Syme 1972)). In other situations, N supply may be adequate, but any mismatch between N supply from the soil and demand by the crop, either spatially in the soil profile, or temporally during the growing season, will lead to reduced yield (Myers 1987). Other crop and soil management factors will also interact strongly with responses of crops to N fertiliser.

Given the many different N transformations that are possible, and the large impact of climate on fertiliser use efficiency in these regions, it is impossible to identify a single fertiliser strategy that is optimal in all seasons. While sensible experiments can be conducted on individual processes that influence N supply to crops, an overall assessment of the role of N inputs in a cropping system subject to high climatic risk cannot be developed experimentally. Simulation models which describe the effects of weather on the major transformations of N in the soil, the processes of crop growth and development, and the balance of water in the soil can provide valuable insight into N fertiliser management practices for water-limited environments.

TYPES OF MODELS

A great profusion of models exist that deal fully or in part with N and plant growth (see Godwin 1987 and Myers 1988 for reviews). Four major approaches can be identified:

(i) Empirical response models such as regressions of yield or some other crop parameter against fertiliser applied. Examples include the quadratic model of wheat yield in Virginia in relation to N rate (Baethgen *et al.* 1989) and the quadratic and modified exponential models used for sugar beet and potato in the Netherlands (Neeteson and Wadman 1987). Various enhancements have been proposed to deal with more than one growth factor (Tisdale and Nelson 1975) or to account for the residual value of previous applications (Helyer and Godden 1976).

(ii) Response-weather-soil test models combine regression models with modifying factors, such as soil test data or expected rainfall. Examples include the model of Myers (1984) for N fertiliser use on sorghum crops in Queensland, the regression model of Hollinger and Hoeft (1986) relating maize yield to weather and N fertilisation in Illinois and the regression models relating polynomial fertiliser-yield functions to site variables developed for wheat in southern Australia (Colwell and Morton 1984).

(iii) Crop-soil-system models have been developed which incorporate descriptions of how crop growth, water, and nutrient supply processes are affected by the environment. These models incorporate procedures to simulate crop growth in relation to radiation interception, as modified by the status of nutrient and water balances. Examples of this level of model for cereals include: the spring wheat model of van Keulen and Seligman (1987); the CERES group of models for maize, wheat, sorghum and rice (Ritchie 1984; Godwin and Vlek 1984; Jones and Kiniry 1986; Godwin and Singh 1990) and the winter wheat model of the USDA-ARS (Willis 1985).

(iv) Process-orientated models dealing with nutrient transformations or uptake, include models of C/N dynamics in soils (McGill *et al.* 1981; Molina *et al.* 1983) and various nutrient uptake models (Claassen and Barber 1976; Nye and Tinker 1977).

Some of these models are static (largely groups (i) and (ii)) in that they do not contain time as a variable (France and Thornley 1984). The models we are concerned with are dynamic in that they describe variation of the system or its components with time. Among the dynamic models in group (iii), some describe phenomena that operate over very long periods of time (e.g. 50 to 2000 years in the case of the CENTURY model of Parton *et al.* 1987), whilst others deal with plant processes that operate over time periods of less than one day (e.g. models dealing with root growth in response to water potential (Grenetz and List 1973)).

Empirical response models can be quite accurate in specific circumstances, but they tend to lack generality when any part of the production system changes or when they are used in a different region from where they were developed. Their general lack of sensitivity to the timing of rainfall in relation to crop development places a major limit on their precision in semiarid areas. At the other extreme, process models provide a useful framework for basic research, but their demand for inputs, and the fact that they generally deal with only part of the production system, means that they have little role as applied research or management tools at present.

To simulate N dynamics and responses to fertiliser adequately in diverse cropping systems, it is our contention that a model capable of describing the major soil nitrogen transformations, as well as plant processes on a daily time-step is required. For a model to be useful, it must also operate with a minimum of commonly available inputs. The CERES model used in this study meets these criteria in that it simulates phenology, water and nitrogen balance, growth, and yield in relation to a minimum of soil, climate, management and genetic inputs. This class of model has been well documented elsewhere (Godwin and Vlek 1984; Ritchie 1984; Jones and Kiniry 1986).

SIMULATION STUDY: N FERTILISER USE ON MAIZE UNDER INTERMITTENT DROUGHT

The farming systems of eastern Kenya are characterised by continuous cultivation of maize or maize intercrops in a 500 to 700 mm annual rainfall regime on low fertility alfisols. The bimodal rainfall regime allows two crops to be planted each year, but the risk of drought is high with rainfall less than 250 mm in 40% of seasons. However, even in good seasons, yields are low because of the low soil N levels and minimal use of fertiliser (Rukandema 1984). The high risk of drought and the poor returns likely under such circumstances from expensive outlays such as fertiliser are often thought to be major deterrents to fertiliser use. Adequate description of the response to fertiliser has been plagued by high seasonal rainfall variability and the impracticality of conducting experiments in an adequate sample of years and sites (Nadar and Faught 1984; Fig. 1). Even though Nadar and Faught (1984) obtained vastly different results in each of the seven seasons examined, an examination of the rainfall records at this site (Fig. 2) shows that they conducted their experiments over a relatively uniform period of seasonal rainfall. They missed a series of high rainfall seasons in the late 1970s and the low rainfall seasons of 1983-84 which resulted in widespread drought and famine in East Africa. Even this extensive series of field trials (seven seasons) was not sufficient to sample rainfall variability adequately in this region.

The existence of rapid population growth and degrading land resources in this region have created an intense interest in the prospects for more productive farming systems. We report on a simulation approach to assess the potential contribution of N fertiliser in improving grain production and farmer income.

Modelling Goals

The contributions which simulation modelling could make to the resolution of problems in semiarid Kenya are:

(i) Quantification of the interactions between weather, management and soil properties which control either N supply or N demand; and

(ii) Identification of the factors or processes which offer the greatest potential to improve system performance.

Model Testing, Calibration and Validation

A number of revisions were made to the CERES-Maize model to deal with problems encountered during its application in semiarid Kenya. Failure to simulate crop death was a weakness, and modifications were made to kill crops in response to severe water stress (e.g. Carberry and Abrecht 1991).

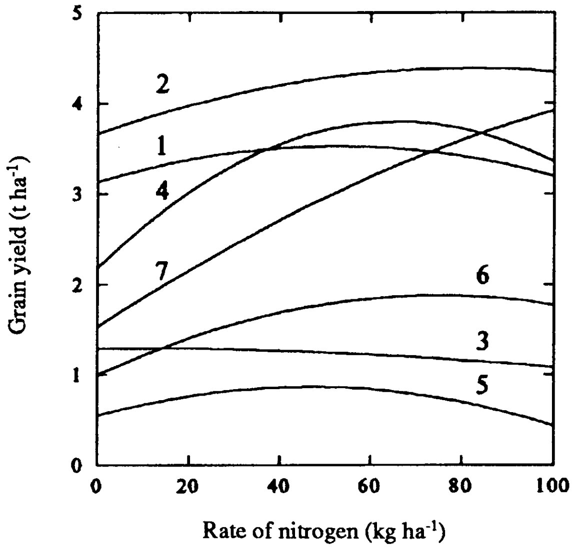

Fig. 1. Responses of maize grain yield to N fertiliser recorded in seven seasons at Katumani, Kenya. (after Nadar and Faught 1984). 1=1979SR, 2=1980LR, 3=1980SR, 4=1981LR, 5=1981SR, 6=1982LR, 7=1982SR (SR = short rains; LR = long rains).

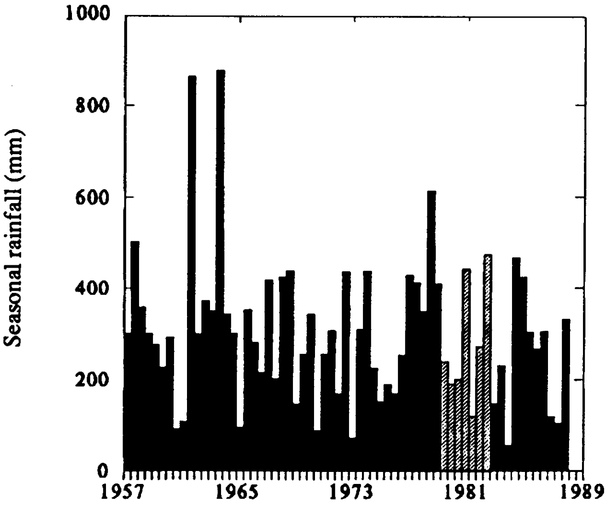

Fig. 2. Seasonal rainfall at Katumani over the 1957 to 1988 period. Hatched bars refer to period of N fertiliser experiments shown in Fig. 1.

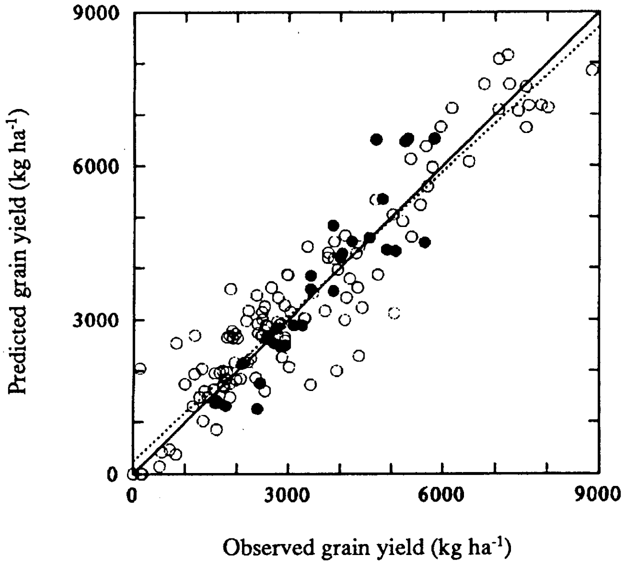

Fig. 3. Comparison of observed maize grain yield with that predicted by CM-KEN. Solid symbols refer to experiments incorporating residual N fertiliser treatments. Solid line is 1:1; Broken line is fitted; slope (s.e.) = 0.94 (0.03); Intercept (s.e.) = 249 (103); r^2 = 0.88.

Phenological development was found to be delayed by extreme water and N stress, and changes were made to the model to accommodate these responses. When the model was run for more than one cropping season, patterns of N mineralisation were not adequately simulated. Routines were therefore introduced to simulate the flush of mineral N commonly associated with drying and rewetting cycles in soils of the region (Birch 1960).

The revised model, CM-KEN, was found to provide accurate simulations of maize yield in relation to water, N and plant population (B.A. Keating , B.M. Wafula and J.M. Watiki, unpubl. data; Fig. 3). A total of 159 datasets, with yields ranging from 0 to 8000 kg ha^{-1}, were simulated with a root mean squared deviation of 689 kg ha^{-1}. These datasets were mostly based on single-season crops, although two experiments consisting of 20 datasets examined the residual effects of various rates of fertiliser N applied to the previous crop (Fig. 3). Earlier validation of the model had been undertaken by Jones and Kiniry (1986) under temperate conditions in the US and by Singh (1985) under tropical conditions in Hawaii. More extensive testing of the N and water routines has been reported in the evaluation of the CERES-Wheat model (Otter-Nacke *et al.* 1986).

Methods Used In The Simulation Study

All simulations were conducted using daily rainfall data for the National Dryland Farming Research Centre, Katumani, Machakos, Kenya (lat. 1° 35'S; long. 37°14'E; alt. 1601 m). Mean monthly maximum and minimum temperature and radiation were used throughout. The short rains (SR) occur from October to January and the long rains (LR) from March to July. In total, 63 seasons were examined, made up of 32 LR and 31 SR.

Standard inputs. Unless otherwise specified, the following inputs were assumed. The maize cultivar, Katumani Composite B was simulated at a plant population of 4.4 plants m^{-2}. The standard soil profile used was that of a chromic luvisol which is typical of the region (Table 1). Onset of the season was deemed to occur when 40 mm of rain was recorded within an 8 day period, with no more than one contiguous dry day. Onset periods or "windows" were defined from calendar day 276 to 320 and calendar day 62 to 120, for the SR and LR, respectively. Planting was assumed to take place immediately season onset was detected. The crop was assumed to have been planted into dry soil at the end of the onset window if onset was not detected in any particular season.

In summary, the standard soil profile had an organic carbon content of 1.1% in the surface layer, an initial mineral N content of 54 kg ha^{-1} at the beginning of the onset window, and an available water holding capacity of 173 mm over its 130 cm depth. Soil water was initialised at one fifth of the available range, and initial values of mineral N are given in Table 1. The fertiliser response investigated was to 0, 10, 20, 40, 80 and 160 kg N ha^{-1}, applied at planting, as

Table 1. Profile information † for the standard soil used in the simulation study.

DLAYR	LL	DUL	SAT	WR	BD	C	NH_4	NO_3
10.0	.140	.250	.300	1.00	1.35	1.10	1.0	2.0
10.0	.140	.250	.300	0.86	1.35	1.10	1.0	3.0
10.0	.140	.290	.320	0.64	1.35	1.00	1.0	3.0
20.0	.150	.300	.330	0.47	1.40	0.80	1.0	2.0
20.0	.170	.300	.340	0.35	1.40	0.70	1.0	1.0
20.0	.170	.310	.350	0.25	1.40	0.65	1.0	1.0
20.0	.170	.310	.360	0.15	1.40	0.60	1.0	1.0
20.0	.170	.310	.370	0.08	1.40	0.60	1.0	1.0

† DLAYR is the layer depth in cm, LL is the lower limit of plant extractable soil water (volumetric), DUL and SAT are the corresponding drained upper limit and saturated water contents respectively, WR is a weighting factor for root growth, BD is the layer bulk density in g cm^{-3}, C is the organic carbon in percent, NH_4 and NO_3 are the ammonium and nitrate mineral-N (in ug g^{-1}) at onset of the season.

Whole profile properties: SALB, the soil surface albedo =0.13; U, the soil evaporation coefficient for stage 1 = 9 mm; SWCON, the whole profile drainage coefficient = 0.50; CN2, the runoff curve number = 60.

calcium ammonium nitrate. Each season was modelled independently of other seasons with reinitialisation of input parameters at the start of the onset window unless otherwise specified.

Factors investigated. The effects of the following factors on the yield response to applied N were investigated:

(i) Initial mineral N present in the soil when the seasonal onset window was opened (levels varied from 54 to 81 to 103 kg N ha^{-1}).

(ii) Initial soil water present in the profile at the start of the onset window (increased from 0.2 to 0.4 to 0.6 of the available range).

(iii) Runoff curve number (increased from 60 to 70 to 80; the model uses a curve number approach to partition rainfall between runoff and infiltration and the curve numbers used increased the simulated runoff from a mean of 23 to 41 and 62 mm respectively).

(iv) Plant population (varied in 6 steps over the range 1.1 to 6.6 plants m^{-2}).

(v) Splitting the N application (20 kg ha^{-1} at planting and 20 kg ha^{-1} at 28 days was compared to applying 40 kg N ha^{-1} at planting). Another splitting tactic investigated, was the application of 10 kg N ha^{-1} at planting, followed by a further 30 kg N ha^{-1} at 28 days in those seasons that recorded rainfall in excess of 150 mm from onset. This resulted in a mean fertilisation rate of 22 kg N ha^{-1} over the 63 seasons. The tactical splitting regime was compared to a fixed regime of 22 kg N ha^{-1} at planting every season.

(vi) Effect of the timing of seasonal onset was investigated by comparing the simulated response to N in those seasons which started early (i.e. in the first half of the onset window) with that from those that started late (i.e. in the second half of the onset window).

(vii) Residual effects. The residual effects of applied fertiliser were assessed by simulating the response to fertiliser N in the current season as influenced by the rate of N applied in the previous season. This analysis involved: (a) carrying the soil N and soil water over from one season to the next; and (b) adjusting the onset window (and consequently sowing dates) in those seasons when a previous crop overlapped the onset/sowing window of the current crop.

Analysis and interpretation of simulation output. Because the different scenarios simulated involved different input costs, all yields were converted to a gross margin in Kenyan shillings (Kshs ha^{-1}) using the following assumptions. Grain was valued at 3 Kshs kg^{-1} and N fertiliser was assigned a value of 16.3 Kshs kg^{-1}. Seed costs varied with plant density and all gross margins were adjusted to reflect this, assuming that seed for planting was valued at 4 Kshs kg^{-1} and two seeds of average weight of 0.32 g are planted per planting position, prior to thinning to one plant. Planting, harvesting and weeding costs were not likely to be influenced in any predictable way by the scenarios investigated and these costs have been excluded. The analysis assumes that phosphorus or other nutrients were not limiting. Although the value of the grain is likely to be influenced by general seasonal conditions (e.g. higher value during times of short supply), we felt our understanding was not sufficiently developed at this stage to incorporate this effect. The standard presentation of these results is either as a mean response to the applied fertiliser rate over the 63 seasons or as a cumulative distribution function (CDF) to highlight the risk implications of the scenarios examined. A CDF specifies the probability (y axis) of obtaining less than the specified outcome (e.g. yield or gross margin on the x axis). The concepts of generalised stochastic dominance with respect to a function (SDWRF - Meyer 1977) were used where appropriate to differentiate between CDFs using the software of Goh *et al.* (1989). Values of the risk aversion coefficient (r) were determined at which the different strategies could be deemed stochastically efficient (i.e. likely to be chosen by a farmer whose attitudes to risk are described by r). Units for r are Kshs^{-1} and the outcome space of the analysis is maize grain yield ha^{-1}. Further details on the interpretation of values of r can be found in Raskin and Cochran (1986) and a comparison with other methods of risk analysis is provided by Bailey and Boisvert (1989). Put simply, a value of $r = 0.0001$ describes the risk aversion characteristics of a farmer whose marginal utility declines at 1% per 100 Kshs of income (or value of output for subsistence production) from 1 ha of maize. Marginal utility is the value the farmer in question places on a unit of additional income.

Results of Simulation Study

Response to added N. Long-term average grain yield increased from 1000 to 2700 kg ha^{-1} as seasonal N fertiliser additions increased from 0 to 160 kg ha^{-1} (Fig. 4a). Gross margins were on average maximised (6400 to 6600 Kshs ha^{-1}) at N rates between 40 and 80 kg N ha^{-1} (Fig. 4b). Variability in response to N was extreme, ranging from positive increases in gross margin of 11000 Kshs ha^{-1} (above the crops receiving no fertiliser) in some seasons to a loss of 2600 Kshs ha^{-1} associated with high rates of fertiliser use in other seasons (Fig. 5). In general, response to added N was correlated with seasonal rainfall (Fig. 6). The two seasons which showed the largest losses from N fertiliser (Fig. 6) were situations when crop death was simulated under N fertilised conditions. Large leaching losses were predicted in the two seasons where rainfall exceeded 800 mm, and consequently yields and gross margins fell short of the general relationship with rainfall (Fig. 6).

Under the soil and management conditions assumed as standard, the 40 kg N ha^{-1} strategy appears to offer a greater probability of high returns, with only marginally increased risk of greater losses compared with lower rates of N. The model predicted zero yield and negative gross margins in approximately 20% of seasons (Fig. 7). While, as will be seen later, this failure rate will be strongly influenced by other management factors, crop failure rates of 15 to 25 % are consistent with local experience. Farmers would see no immediate return for their 640 Kshs ha^{-1} investment in 40 kg ha^{-1} fertiliser N in such seasons ; this risk may be too great for some whose annual household cash flow may be as little as 3000 Kshs (Rukandema 1984).

Both the probabilities of a positive increase in gross margins and the magnitude of this increase arising from the application of 40 kg N ha^{-1} were greater for the LR than the SR (Fig. 8a). The prospects for large positive responses to fertiliser N were markedly enhanced in those seasons that started

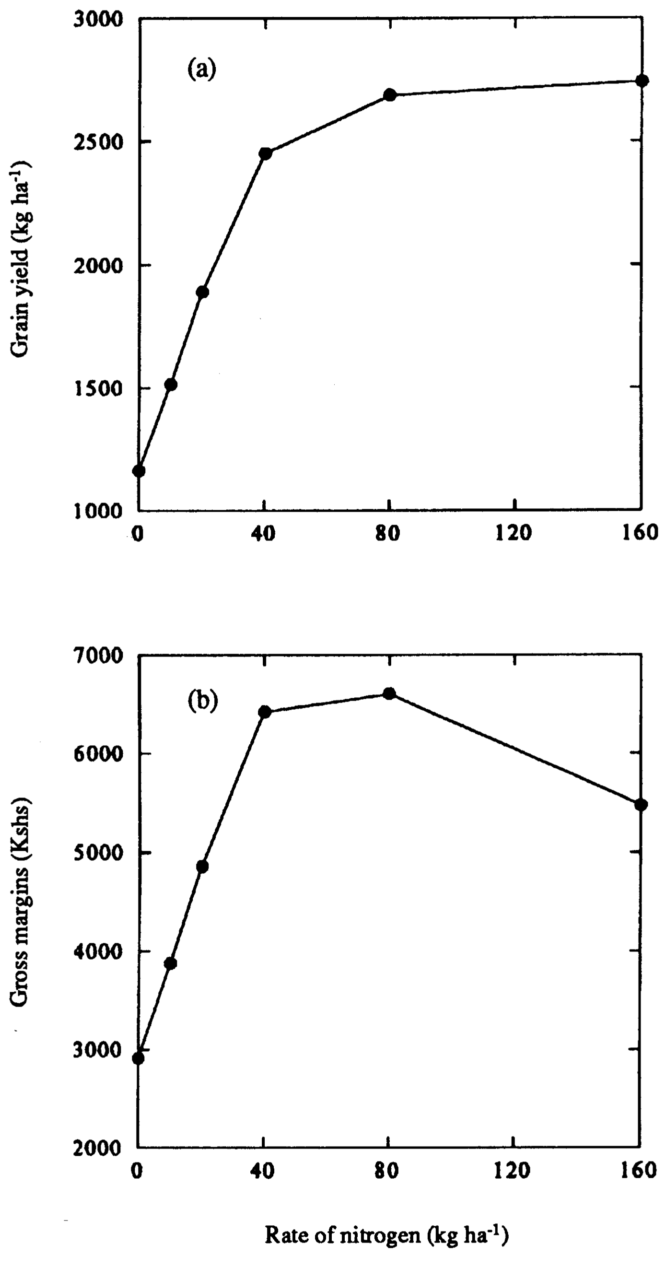

Fig. 4. Response of (a) mean grain yield and (b) mean gross margins of maize to rate of N fertiliser simulated at Katumani from 1957 to 1988.

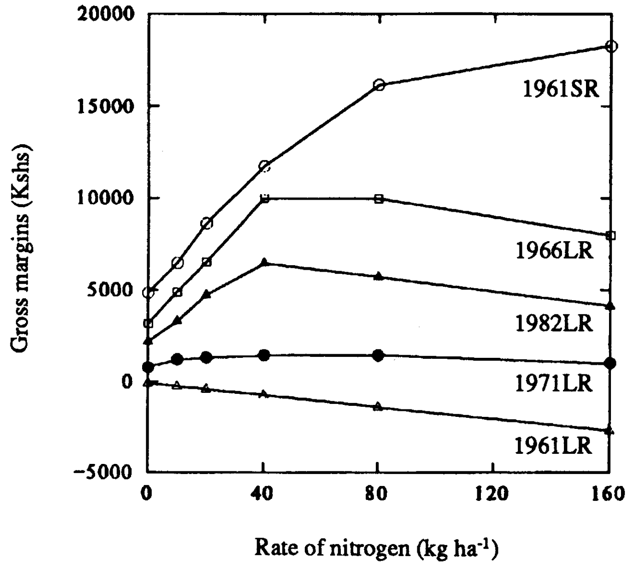

Fig. 5. Response in gross margins to rate of N fertiliser simulated in contrasting seasons (long rains, LR, or short rains, SR) at Katumani.

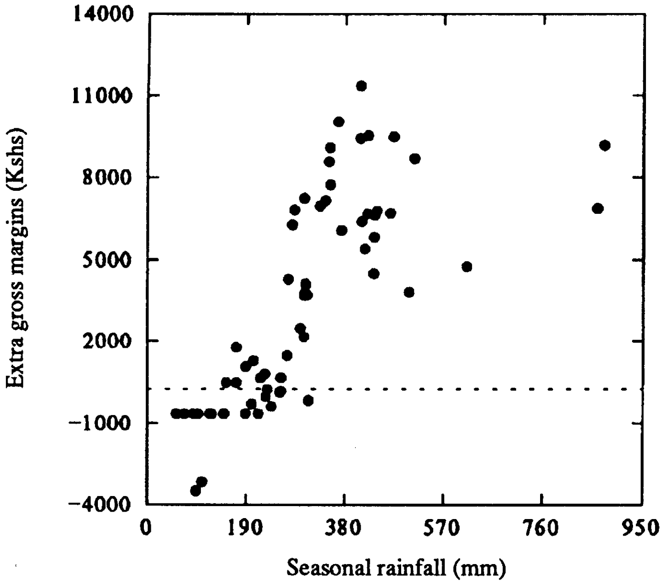

Fig. 6. Response in gross margins to the application of 40 kg N ha^{-1} (relative to zero N treatment) as a function of seasonal rainfall.

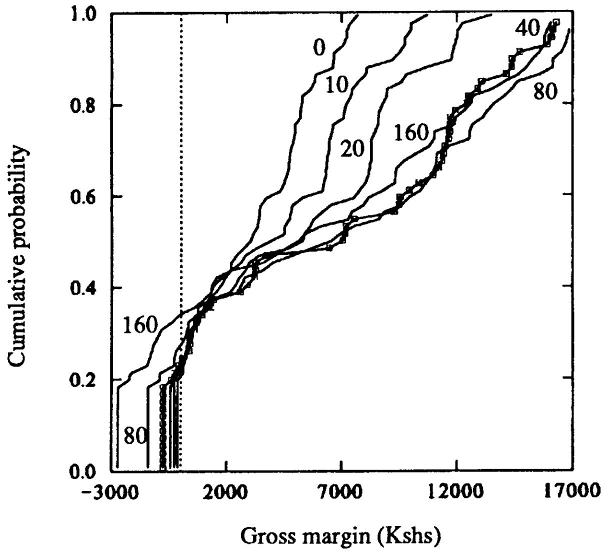

Fig. 7. CDFs for gross margins of maize grown at Katumani (1957 to 1988) at different rates of N fertiliser (as indicated in kg N ha^{-1}).

early (i.e. the first half of the onset window) compared to those that started late (Fig. 8b). Potential obviously exists to develop fertilisation tactics conditional on the timing of the seasonal rains and this subject is considered elsewhere in this symposium (e.g. Stewart 1991; McCown *et al.* 1991).

Effect of soil properties. The quantity of mineral-N present in the profile at planting strongly influenced the mean response to fertiliser N (Fig. 9a). There was little to be gained from using fertiliser N in situations when mineral N present in the profile at planting exceeded 100 kg N ha^{-1} (Fig. 9b).

Response to N fertiliser was enhanced in the presence of more soil water at planting (Fig. 10a). Long-term average gross margins increased from 2900 to 4700 Kshs ha^{-1} in unfertilised situations as the fraction of available soil water at planting increased from 20% to 60%. The corresponding increase in average return under adequate fertilisation was from 6600 to 10500 Kshs ha^{-1}.

Greater losses of soil water due to runoff depressed productivity and response to added N (Fig. 10b). The standard curve number used throughout this analysis (CN=60) resulted in an average runoff loss of 23 mm from an average seasonal rainfall of 306 mm. Curve numbers of 70 and 80 increased mean runoff to 40 and 62 mm, and they reduced long term average gross margins without fertiliser from 2900 Kshs ha^{-1} (CN=60) to 2300 and 1200 Kshs ha^{-1} respectively.

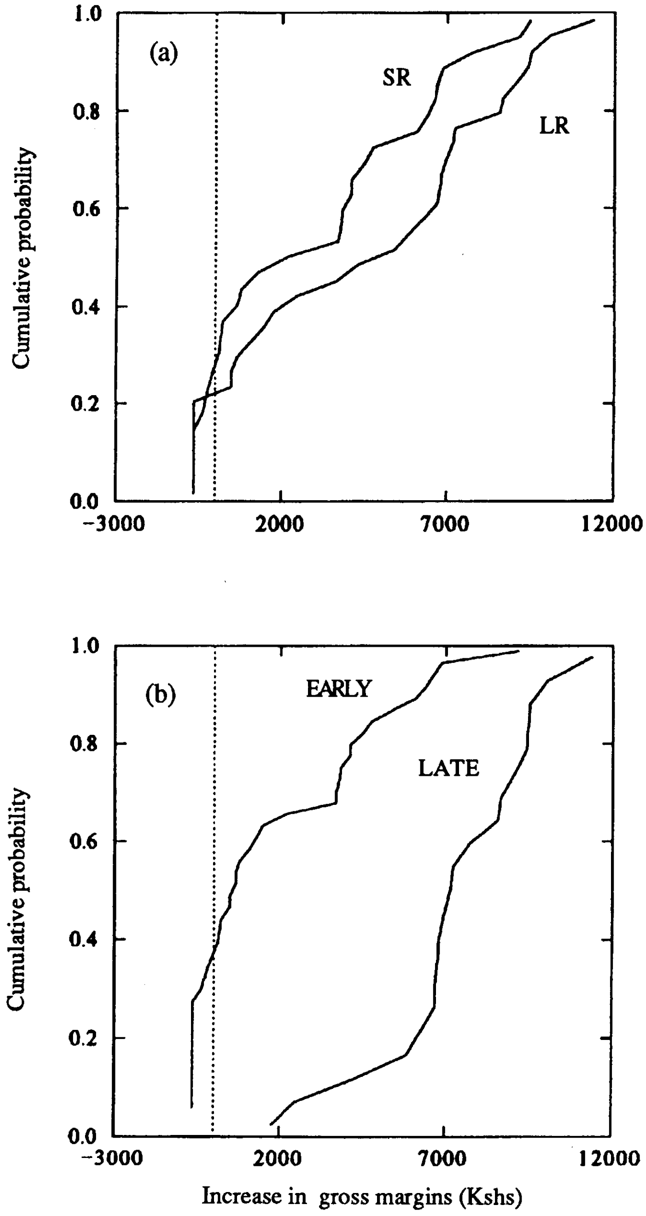

Fig. 8. Effects of (a) season (long rains, LR, or short rains, SR) and (b) timing of onset (early or late) on CDFs for additional gross margin associated with 40 kg N ha^{-1}.

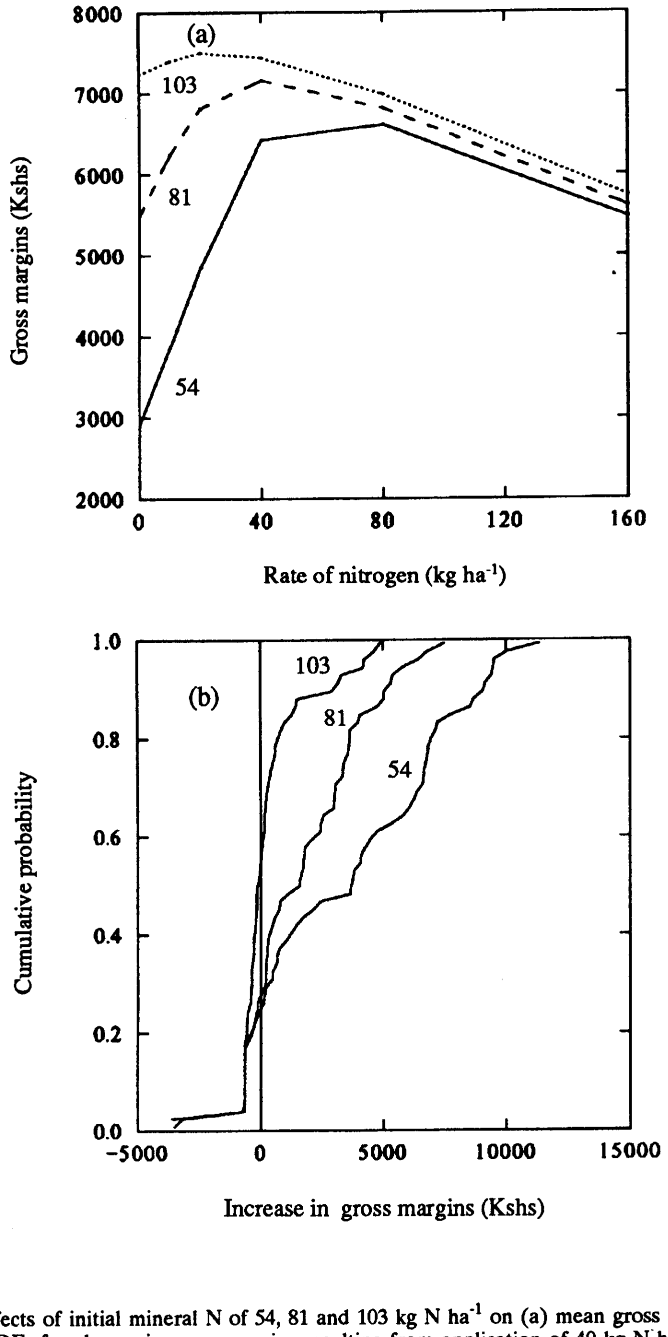

Fig. 9. Effects of initial mineral N of 54, 81 and 103 kg N ha^{-1} on (a) mean gross margins and (b) CDFs for change in gross margins resulting from application of 40 kg N ha^{-1}.

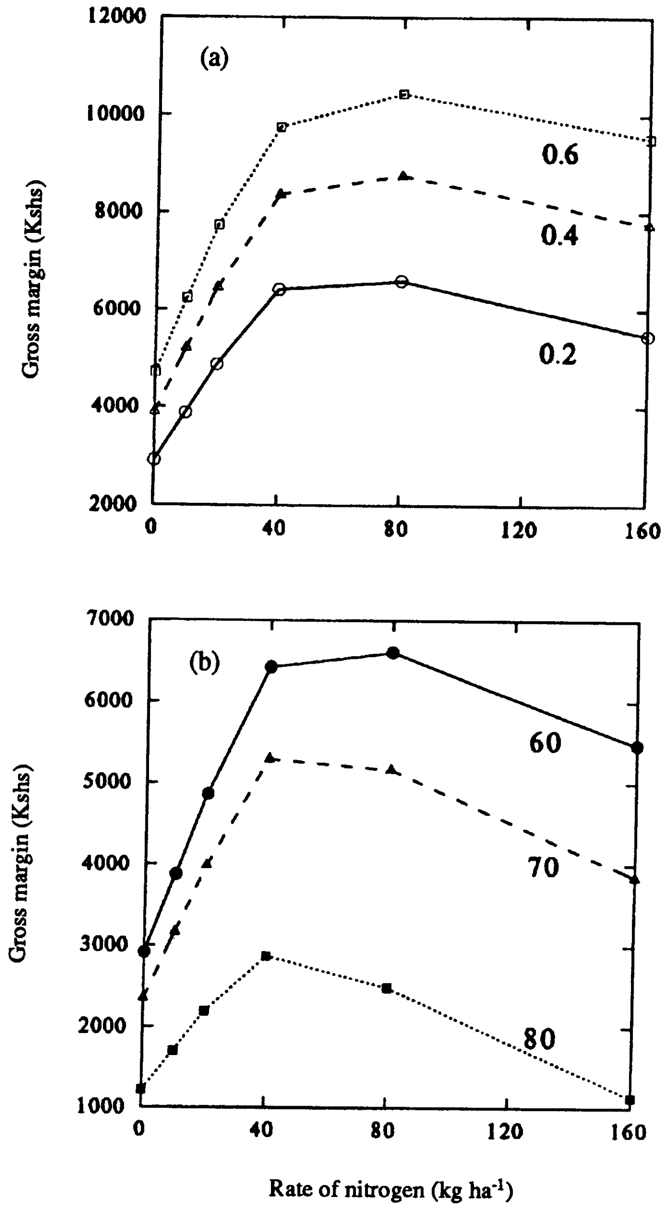

Fig. 10. Effects of (a) soil water at planting (fraction of the available water indicated), and (b) runoff curve number (as indicated) on the mean gross margins.

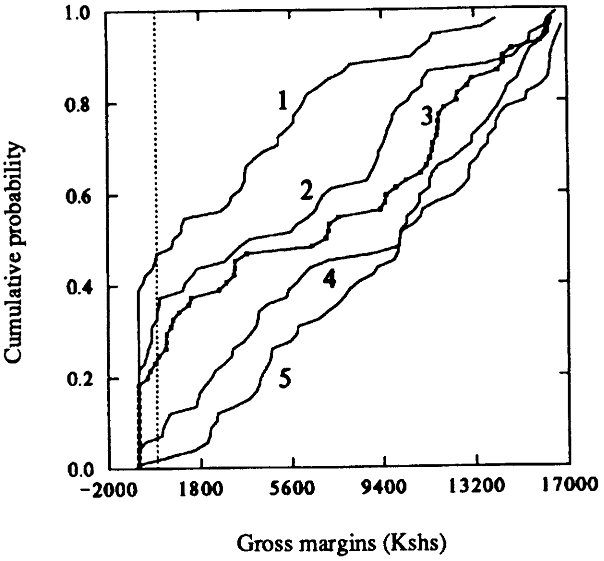

Fig. 11. CDFs for gross margins associated with 40 kg N ha^{-1} and various soil water scenarios. 3 (with symbols) is the standard regime CN=60, Initial SW=0.2; 2=CN of 70; 1=CN of 80; 4=Initial SW of 0.4; 5=initial SW of 0.6.

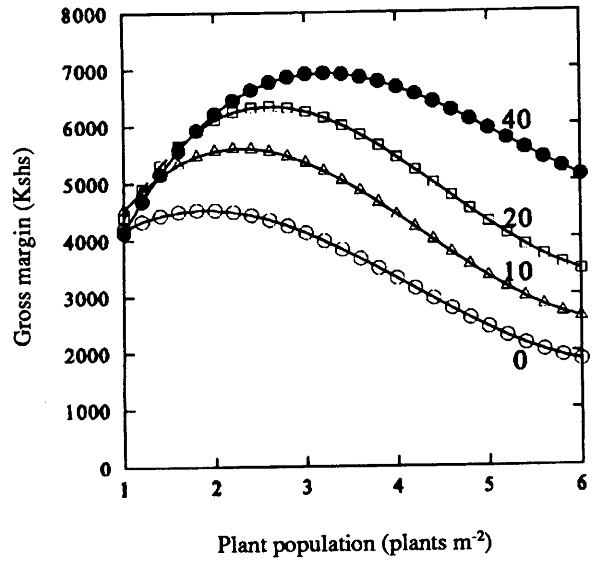

Fig. 12. Effects of plant population and rate of N fertiliser (in kg N ha^{-1} as indicated) on mean gross margins.

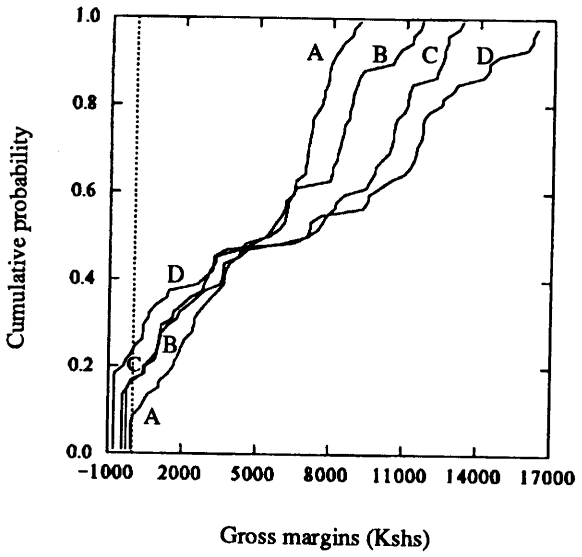

Fig. 13. CDFs for gross margins for optimal plant population (plants m^{-2}) / rate of N fertiliser (kg N ha^{-1}) combinations: A=2.2/0; B=3.3/10; C=3.3/20; and D=4.4/40.

While fertiliser had little effect on the probabilities of absolute crop failure and negative gross margins (Fig. 7), changes in water regime shifted the frequency of negative gross margins over the 5 to 40% range (Fig. 11).

Effect of plant population. The optimum plant population changed with N regime, increasing from below 2 plants m^{-2} in the absence of fertiliser, to above 3 plants m^{-2} when the N requirement was generally satisfied by 40 kg N ha^{-1} (Fig. 12). The important negative effects of high plant population under a strong N constraint have often been overlooked by scientists working in the region (e.g. Nadar 1984), but have been confirmed experimentally (J.M. Watiki and B.A. Keating, unpubl. data). Lower plant populations can reduce failure rates considerably but at the cost of lost yield potential in the wetter years, assuming N is available (Fig. 13). In this region, therefore, plant population can be seen as an important low cost tool available to farmers to manipulate demand for water and N resources. Optimum production will be achieved when this demand most closely matches supply.

Effect of timing of N application. Split N application had both positive and negative effects (Fig. 14a) depending on the distribution of rainfall. Overall, there was no gain from splitting a 40 kg N ha^{-1} fertiliser application at planting into two 20 kg N ha^{-1} doses at planting and 28 days later (Fig. 14b). Mean gross margins were 6425 and 6397 Kshs for the two management regimes respectively. This result reflects in part, the minimal leaching losses simulated for this soil in

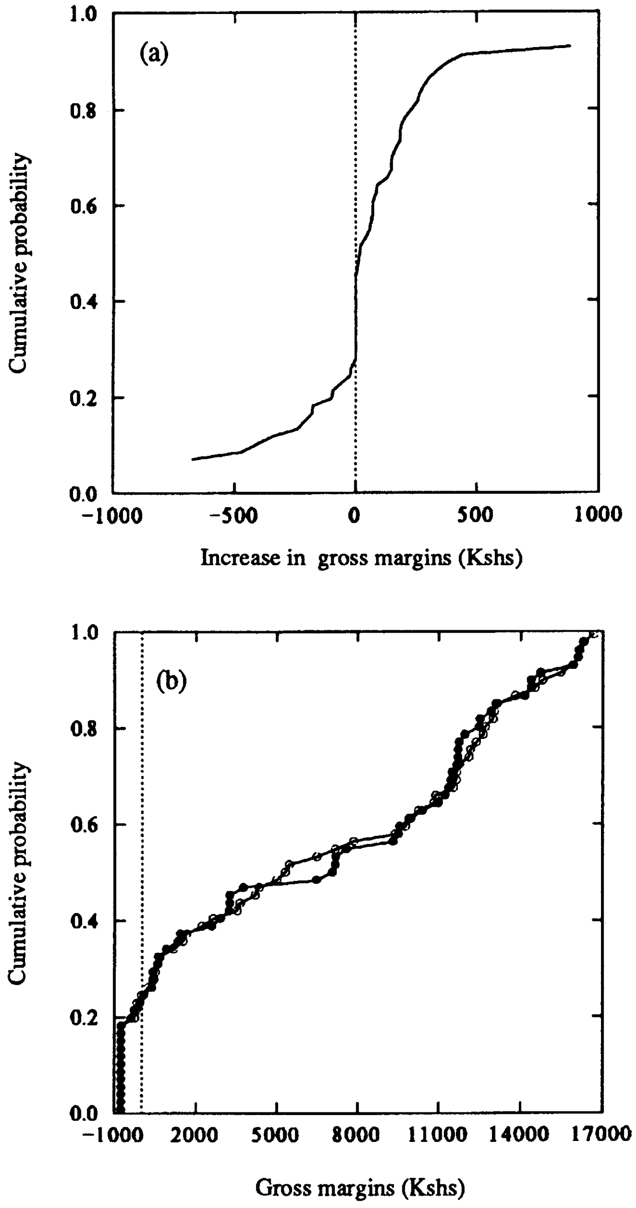

Fig. 14. CDFs for (a) difference in gross margins and (b) overall gross margins (solid symbols = single; open symbols = split) associated with splitting N fertiliser application (20 kg N ha^{-1} + 20 kg N ha^{-1}) relative to a single application (40 kg N ha^{-1}).

this climate. While leaching beyond the 1.3 m profile depth was simulated in 12 of the 63 seasons examined, losses were significant (>5 kg N) in only two seasons (see the two extremely wet seasons in Fig. 6). Markedly different effects of splitting N fertiliser applications have been simulated for sorghum grown on shallow light textured soils in a wetter Indian location (Godwin *et al.* 1990).

A small benefit was detected from a split application involving 10 kg N ha^{-1} at planting, followed by a further 30 kg N ha^{-1} in those seasons when rainfall exceeded 150 mm at 28 days from planting. This occurred in 25 of the 63 seasons examined, resulting in a mean seasonal N rate of 22 kg N ha^{-1}. The mean gross margin for the fixed strategy was 5060 Kshs ha^{-1} compared to 5450 Kshs for the conditional strategy. The fertiliser used in both cases was the same, the advantage coming from better matching the N requirement determined by rainfall with the N supplied from fertiliser. The differences in gross margin between the two strategies are both positive and negative (Fig. 15a) highlighting the fact that this matching was far from perfect in this simple example. The overall CDF (Fig. 15b) shows that the conditional strategy increased the probability of achieving high returns (> 10000 Kshs), but at the cost of lower probabilities of intermediate returns (5000 to 10000 Kshs) (Fig. 15b). Optimisation of fertiliser/plant population strategies when settings are made conditional on receipt of a forecast of season "goodness" is tested by McCown *et al.* (1991) and is a natural sequel to this paper.

Residual effect of previous fertiliser application. We have limited data with which to test the model's performance in simulating the residual effect of fertiliser N carried over from one season to the next (Fig. 3). With these data, performance was reasonable, and we have sufficient confidence to make a first approximation of the impact fertiliser applied in one season might have on the requirement for fertiliser in the next season.

We examined the response to six rates of applied N in the "current" season, in factorial combination with six rates of N applied in the "preceding" season. Seasons were considered in pairs, with both the residual effects of LR management on SR crops and SR management on LR crops being examined. The model was adapted in two ways: firstly, to carry over the appropriate N and water variables across pairs of seasons; and secondly, to modify its planting strategies in situations when a preceding crop was still growing at the opening of the onset/planting window for the current crop. This latter situation is reasonably common in the Kenyan environment because late planted SR crops are often still filling grain when an early onset of LR planting opportunities occurs. This analysis excludes the possibility of longer-term soil fertility changes through decline in soil organic matter or through erosion. It also assumes that any weeds growing during fallow periods were effectively controlled.

The outcome from this study can be looked at in several ways. Firstly, mean gross margins in the current season become progressively less responsive to fertiliser N applied in that season, because of the high N applications in the preceding season (Fig. 16a). Secondly, the response in mean gross margins to current N fertiliser is enhanced if the residual effect of the same rate of fertiliser applied in the previous season is considered (Fig. 16b). In other words, the potential effect of fertiliser N on productivity is underestimated if the

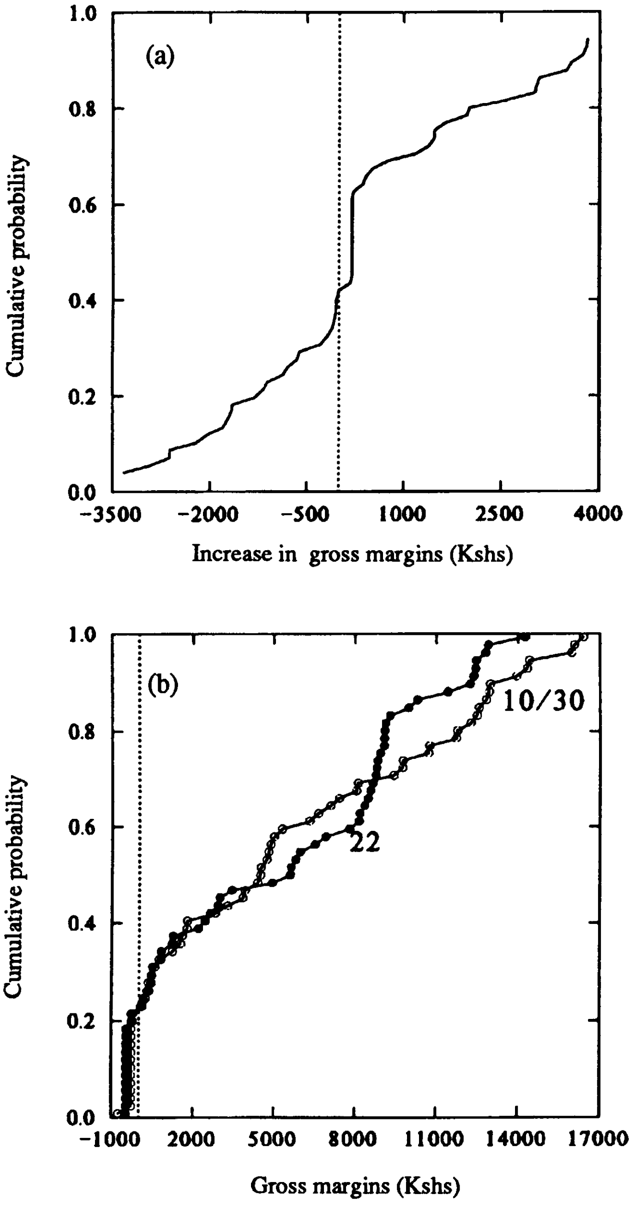

Fig. 15. CDFs for (a) change in gross margin and (b) overall gross margins (solid symbols = single; open symbols = conditional split) associated with a conditional split of N fertiliser (10 g N ha^{-1} at planting + 30kg N ha^{-1} when rain > 150 mm) relative to a single application at planting (22 kg N ha^{-1}).

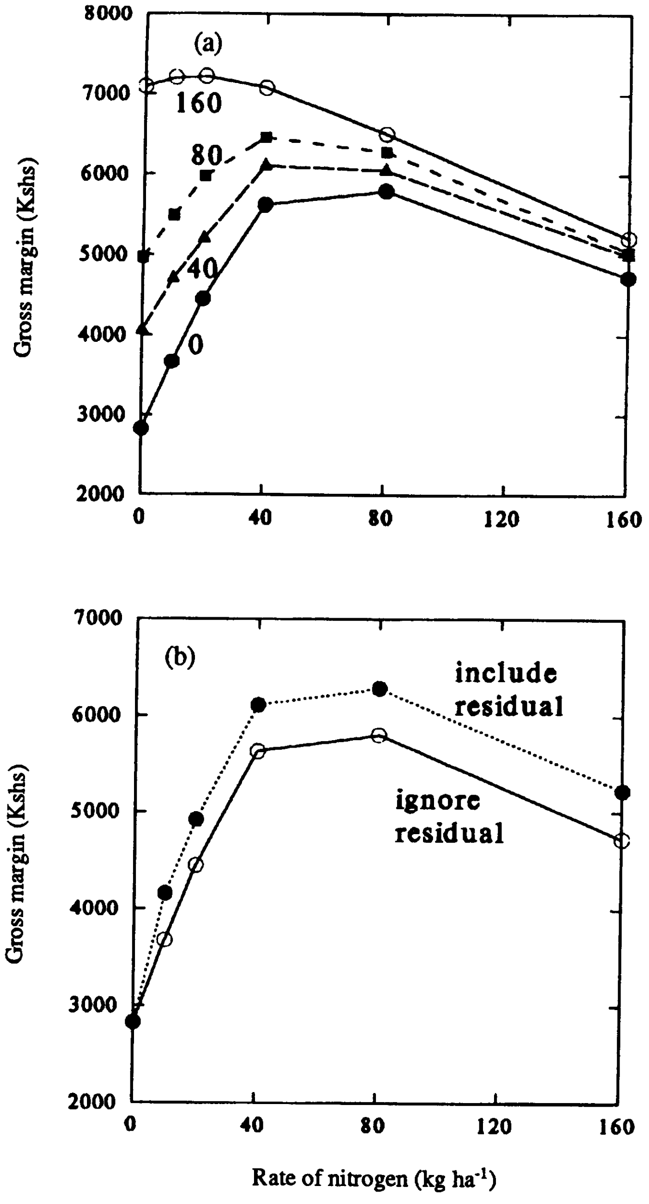

Fig. 16. Effects of residual N on response to current N: (a) response to fresh N as influenced by 4 levels of N (in kg N ha $^{-1}$ as indicated) applied in the previous season; and (b) response to fresh N ignoring residual effects (open symbols, solid lines) compared to response to fresh N assuming the same rate of N was applied the previous season (closed symbols, broken lines).

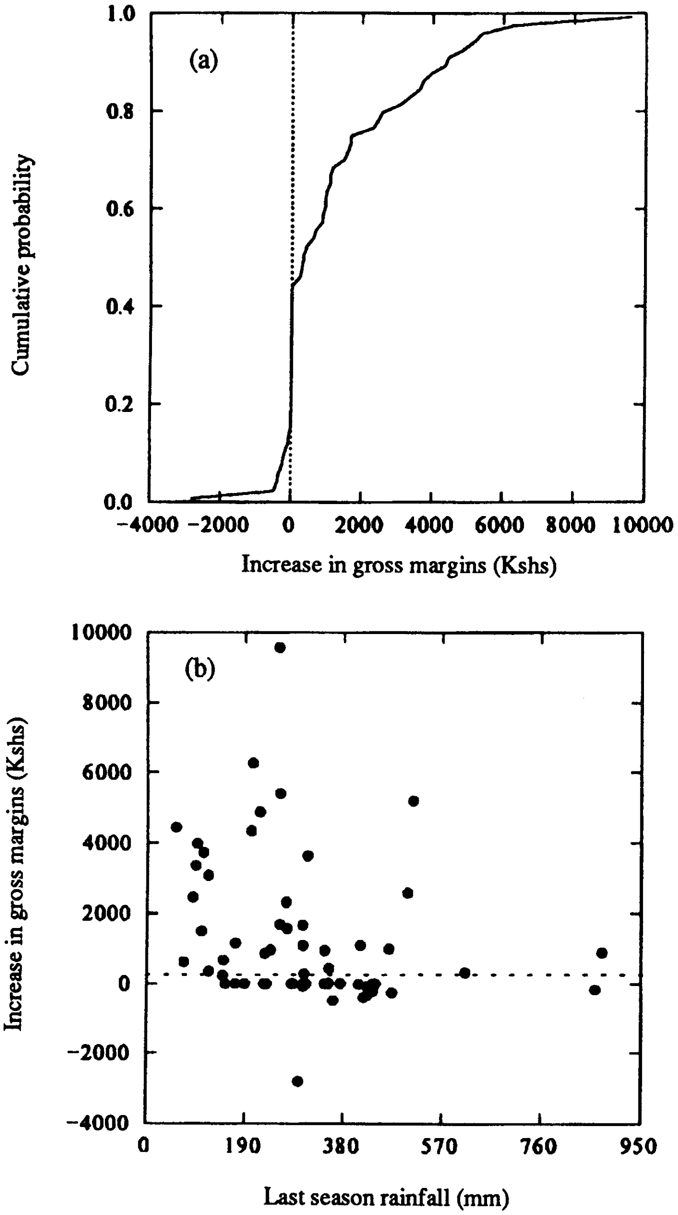

Fig. 17. Residual value of 40 kg N ha^{-1}: (a) CDFs for additional gross margin with the application of 40 kg N ha^{-1} in the previous season and no fertiliser in the current season; and (b) relationship between residual value of 40 kg N ha^{-1} and rainfall in the previous season.

residual effect is ignored. Thirdly, assuming a farmer was using 40 kg N ha^{-1}, he could expect this application to provide some "residual value" in his next season's crop on 50% of occasions (Fig. 17a). In this case, "residual value" is assessed as the difference in gross margin for an unfertilised crop in the current season associated with or without 40 kg N ha^{-1} applied in the previous season. The residual value of last season's fertiliser is low when rainfall was high in season, but it is potentially high when the previous season was dry (Fig. 17b). Whether or not this potential residual value is realised depends on the rainfall regime in the current season.

Fertiliser Use and Risk Aversion

The foregoing analysis has highlighted large potential benefits from use of fertiliser N, yet minimal fertiliser is used in the region. The reason frequently proposed to explain this contradiction is farmers' unwillingness to take risks. We examined the CDFs of gross margin for various combinations of plant population and nitrogen fertiliser (shown in Fig. 13) in terms of stochastic dominance (SDWRF) to evaluate the possible impact of risk aversion on fertiliser use.

Moderate plant populations (3.3 to 4.4 plants m^{-2}) and moderate fertiliser rates (20 to 40 kg N ha^{-1}) are risk efficient for farmers with r values in the 0.00005 to 0.0002 range (Table 2). We do not yet have information on the risk aversion characteristics of farmers in semiarid Kenya, but this range probably corresponds to the intermediate and moderately risk averse group of Indian subsistence farmers surveyed by Binswanger (1978) and reinterpreted by Bailey and Boisvert (1989) in terms of value (in rupees) of groundnut production ha^{-1}. In that work, 75% of farmers could be classified as having r values in the range 0.00005 to 0.00037 which approximates 0.00003 to 0.00025 in Kshs. Low plant populations without fertiliser were revealed as stochastically efficient for farmers whose risk aversion coefficient exceeded 0.0003; i.e. whose marginal utility drops 3% for every 100 Ksh ha^{-1} of maize grain produced (Table 2). This group could probably be equated with the 8% of Indian subsistence farmers identified by Binswanger (1978) as severe and extreme risk averting classes.

While further study is needed, it would appear that risk aversion alone can not explain the behaviour of the majority of farmers who do not use fertiliser

Table 2. Stochastically efficient combinations of N fertiliser and plant population at varying degrees of risk aversion (r, in Kshs from maize production ha^{-1}). CDFs are shown in Fig. 14.

Qualitative risk aversion	r lower bound	r upper bound	Population (plants m^{-2})	Fertiliser (kg N ha^{-1})
Neutral	0.00000	0.00005	4.4	40, 80
Slight	0.00005	0.00010	3.3, 4.4	20, 80
Moderate	0.00100	0.00020	3.3	20
Strong	0.00020	0.00030	2.2, 3.3	0, 20
Extreme	0.00030	0.00040	2.2	0

in this region. Future studies need to confirm that the model has not overestimated the response to fertiliser N or that this response is not unduly limited by factors not considered in the model (e.g. pests and diseases). Socioeconomic research needs to assess farmer attitudes toward risk and examine other constraints to fertiliser use (e.g. access to capital, distribution problems, incorrect perceptions as to the value of fertiliser N).

A Guide to Planning Research Relevant to Development

The analysis presented above, has focused on the way in which various soil and management factors can influence the response to applied N in relation to rainfall variability. The general shape of the response functions and the nature of the interactions contain few surprises. In this section we use the model to provide a credible basis for a quantitative hypothesis as to how farmers in the region might develop more productive systems.

Fig. 18 shows the probabilities for gross margins from the following four steps in a hypothetical development pathway:

(i) Step 1 is a scenario that approximates the current system. Runoff is high (mean 62 mm per season, CN = 80) and organic carbon is low (0.9% in the surface). The strategy employs a low plant population (1.6 plants m^{-2}) typical of many farmers' crops, no N fertiliser, and no return of crop residues to the field. Mean grain yield of 970 kg ha^{-1} is on the upper side of the average reported in the region (700 to 900 kg ha^{-1}, Jaetzold and Schmidt 1983), but in our case we have not considered losses due to poor management such as delayed planting, weeds, or pests.

(ii) Step 2 represents a first step towards a better system. It involves adding 10 kg N ha^{-1}, increasing plant population to 2.2 plants m^{-2} and returning the "extra" stover produced to the field as surface mulch. Crop residues are in high demand as animal feed (Tessema and Emajong 1984) and we feel there is only potential to consider returning stover produced over and above that normally produced by conventional low input systems (i.e. step 1 in this analysis). We assume that this stover will reduce runoff (mean 40 mm per season, CN = 70) and surface evaporation (1st stage evaporation coefficient, U, of 7 mm instead of the standard 9 mm), and over time will marginally increase soil carbon levels (1.0% at the surface). Mean grain yield of 1830 kg ha^{-1} was predicted for this scenario.

(iii) Step 3 involves further increases in plant population (3.3 plants m^{-2}) and N fertiliser (20 kg N ha^{-1}) and the assumed benefits of returning the extra stover (mean of 23 mm runoff with a CN = 60 and U = 5 mm; C% of 1.1 at the surface). Mean grain yield of 2300 kg ha^{-1} was simulated.

(iv) Step 4 combines 40 kg N ha^{-1} with a plant population of 4.4 plants m^{-2}. The extra stover produced is assumed to be returned and this is assumed to have increased soil fertility (surface C% of 1.2 %) and reduced both runoff (mean 12 mm, CN = 50) and soil evaporation (U = 4 mm). The mean grain yield of 2740 kg ha^{-1} simulated in this scenario can be viewed as a production potential for excellent management.

It is not difficult to find some weak points in the detail of this hypothetical pathway. We have used curve number to simulate the effects of surface mulch

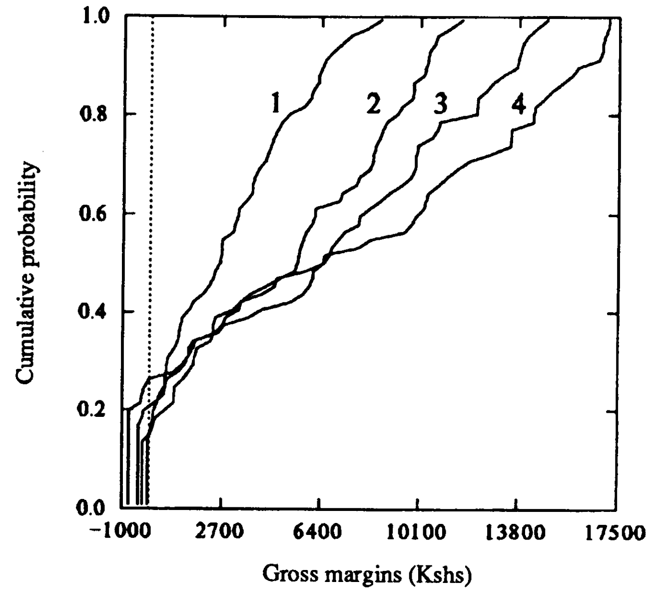

Fig. 18. CDFs for gross margin associated with four steps in a proposed development pathway (see text for detail of steps 1 to 4).

on runoff, and while the relationship between the average amount of stover available and average runoff simulated in the four steps is of the right general shape (data not shown), we have no other reason to believe them. Other studies in Kenya have shown that mulch is very effective at reducing runoff (Liniger 1988) and research on these issues is now a major activity at Katumani.

This hypothesis suggests that useful gains can be made by modest inputs (e.g. compare step 2 with step 1). Experimentation now needs to focus on this point. Are the benefits of using rates as low as 10 kg N ha^{-1} as large as suggested here? Do the models underestimate losses of the small amounts of N (e.g. to weeds)? Placement of this N in relation to the planting row may be critical and the model may need modification to deal with such effects, if they are proven important.

This analysis has incorporated the effect of fertiliser residues remaining from the previous crop but has considered no other long-term effect on soil fertility. The current zero input system (step 1) can be expected to degrade further, while fertilised crops with return of residues should have positive effects on soil structure and fertility. Factors such as soil and nutrient loss associated with runoff and erosion have not been considered in the model applied here, but they will be critical to determining the long-term implication of differing crop production strategies on soil productivity. Research is now underway to incorporate such phenomena into the models in use in Kenya.

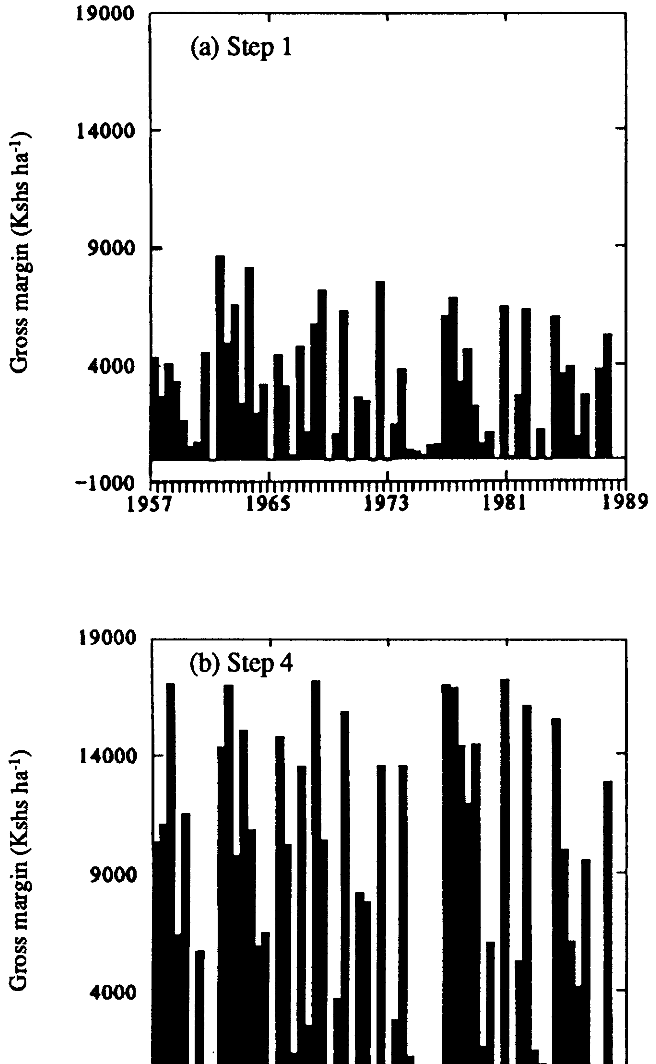

Fig. 19. Gross margins for maize simulated at Katumani from 1957 to 1988: (a) step 1; 1.6 plants m^{-2}, CN=80, U=9mm, C=0.9%, no fertiliser; and (b) step 4; 4.4 plants m^{-2}, CN=50, U=4mm, C=1.2%, 40 kg N ha^{-1}.

The extreme variability in this climatic environment can be appreciated in terms of the long-term yield sequences simulated (Fig. 19). The combination of better soil water and fertility management does help to raise productivity, but periods of catastrophic drought such as that seen in 1975 and 1983-84 are still bound to result in food shortfalls. Here, "coping strategies" (O'Leary 1984) must be invoked (e.g. grain storage, reserves of wealth).

CONCLUSIONS

The simulation study presented here has essentially considered management strategies (i.e. fertiliser rate, plant population) for a number of scenarios (i.e. soil fertility levels, recent fertiliser history, soil water characteristics) within one domain (chromic luvisol at Katumani). Having fixed on a general strategy, a number of tactical options may exist to vary management in response to seasonal conditions (e.g. McCown *et al.* 1991). Similar studies are soon to be undertaken for other domains; i.e. drier and hotter agroclimates of the region and for different soil types.

Past warnings concerning the use of simulation models in agronomy (Passioura 1973; Monteith 1981) are still relevant today. However, the relevance of the technique to applied agronomic research is no longer in doubt. While the available models of crop growth and yield in relation to climate, soil and management are by no means perfect, they have reached the stage where they can provide useful insight into complex cropping systems. This is particularly so in regions of high climatic risk, where the issues get more complicated and our ability to investigate them experimentally is diminished. Models can assist both in the identification of efficient management strategies in the long-term and in short-term tactical decisions in response to soil, climate or crop conditions. This study has shown that they can be powerful tools to focus research on key issues in the production system.

Future work would appear to need to progress on a number of fronts. Firstly, there is still an obvious need for better models, with the requirement for data generation and testing that accompanies such model development. In this regard, models, are needed with improved capacity to deal with longer-term changes in soil properties in relation to crop and soil management. Secondly, the understanding of the system generated through a simulation study, such as that presented here, needs to be translated into information that decision makers can more readily use. In this paper, we have focused on the information needs of researchers wishing to better focus their research. However, farmers, extension personnel and government policy makers need to make decisions every day at a range of spatial and temporal scales. The quantitative understanding of how the system operates as generated by the simulation studies, is relevant to the problems being considered by all these decision makers. However, direct extrapolation of simulation results to the decision problems facing a particular farmer or a policy maker will be limited by information constraints associated with differences in scale. Research needs to address these questions, and progress in the emerging fields of decision support, expert systems, and geographic information systems will no doubt be relevant.

ACKNOWLEDGEMENTS

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