Simulation of Plant Density Effects on Maize Yield as Influenced by Water and Nitrogen Limitations

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Summary

Maize is the staple cereal in semi-arid areas of Eastern Kenya. Rainfall is low and unreliable and crop failures are common. Crop models which simulate growth and yield in relation to weather, soil, management and genotype inputs are being investigated as tools to aid research in such areas where rainfall uncertainity dominates agricultural production. Our experience with the CERES Maize Model is considered in this paper and in particular its performance at simulating maize growth and yield under a wide range of plant populations.

The model was tested against an independant data set comprising grain yields and above ground biomass for a short season maize cultivar grown over a population range of 8,000 to 90,000 plants ha^{-1}. The model provided an accurate description of grain yield over this range under both water non-limiting and water limiting situations. Simulation of above ground biomass was less accurate and further work is needed.

The model was used to examine the effects of plant population on the long term returns and risks of maize production at two contrasting sites in eastern Kenya. In the presence of non-limiting soil fertility, high populations were predicted to increase long term average yields with only small increases in the risks of crop failure. When nitrogen was strongly limiting, high populations were predicted to reduce long term yield averages and markedly increase the risks of crop failure.

Introduction

The semi-arid lands of the Machakos and Kitui districts in Kenya, like much of sub-saharan Africa, are home for a rapidly growing population of resource-poor farmers. Population growth of the order of 4 to 5 percent per annum is common (Akong'a & Downing, 1987) and crop yields are generally low, due to climate and soil limitations (Jaetzold & Schmidt, 1983). There is strong cultural preference for maize, and whilst generally well adapted to the temperature regimes of the region, the climate is too dry for reliable production; nevertheless, it remains the staple crop. Total annual rainfall in the region ranges from 500 to 800 mm and the pattern of distribution is bimodal, which results in two distinct seasons for crop production. The term "short rains" (with a peak in Nov.) and "long rains" (with a peak in April) stem from northern and western Kenya, and are less appropriate in the northern and western parts of the Machakos-Kitui districts, where the two seasons are similar in rainfall amount and reliability (see data in Fig. 1 and Table 1 for Katumani) each providing on average, 250-350 mm rain per season. In eastern and southern parts of

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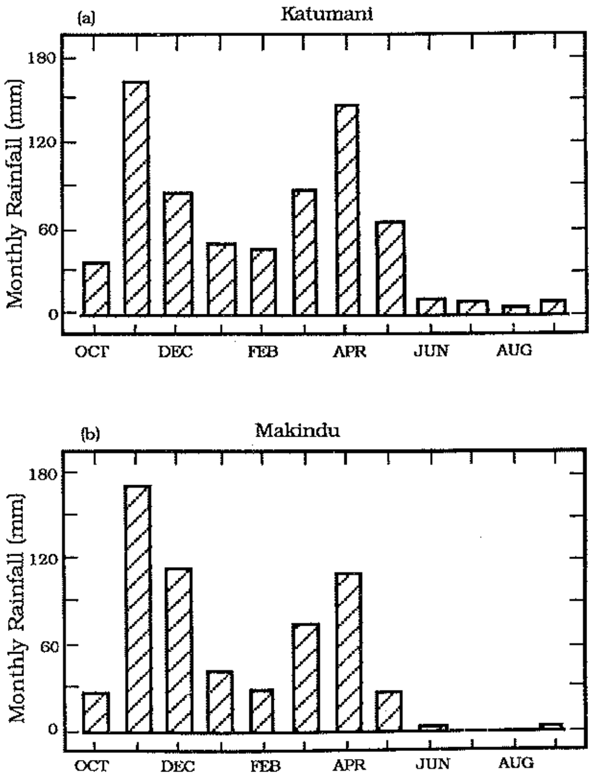

Fig. 1. Mean monthly rainfall totals at (a) Katumani and (b) Makindu.

the district, the " short rains" are wetter and more reliable than the "long rains" (see data from Makindu in Fig. 1 and Table 1).

Rainfall available for any one maize crop is generally low and very unreliable. Coefficients of variation for a growing season range from 45 to 58 percent (Table 1). These compare with 17 to 25 percent for a unimodal rainfall environment in semi-arid northern Australia (Mollah, 1986) and 28 percent for the dominant long rains season in subhumid district of central Kenya (Downing *et al*., 1987).

Whilst rainfall is generally considered the major limitation to crop production, low soil fertility, and in particular low nitrogen levels, limit the ability of crops to benefit from good rainfall seasons when they do occur. Continuous maize cropping and soil erosion have depleted soil nitrogen reserves and the small land-holders have little capacity to purchase inputs such as fertilizers, to maintain or improve productivity (O' Leary, 1984; Ockwell *et al.*, (in prep); Rukandema *et al.*, 1981, 1983a, 1983b). Even when the capital is available, investment in fertilizer is not attractive because of the risky rainfall environment.

Development of agronomic packages that improve and stabilize crop production in the semi-arid areas is a national priority. An important component is plant density. However, the origin of the current recommendation of 40,000 plants ha^{-1} (Bakhtri *et al.*, 1984) is obscure and not based on published experimental work. The plant population studies that have been pub-

Table 1. Characteristics of the two rainfall seasons in semi-arid eastern Kenya

Site	Years of Record	Season*	Median Rainfall (mm)	Range		CV[3] %
				lowest	Highest	
Katumani[1]	1956-82	Short rains	270	155	925	51
		Long rains	297	133	660	45
Makindu[2]	1951-80	Short rains	261	38	830	58
		Long rains	175	18	510	52

* Oct-Dec/Jan for short rains, Mar - May/June for long rains

[1] Katumani Experiment Station, near Machakos, data from Stewart & Faught (1984).

[2] Makindu Met. Station, data from Downing *et al.*, (1987) and Musembi (1985).

[3] Coefficient of variation = Standard Deviation/Mean * 100 (untransformed data).

lished (Nadar, 1984; Table 2) produced different answers in different seasons. In good seasons, high optimum populations were indicated (i.e. 7 to 15 plants m^{-2}) whilst low plant populations gave best results in poor seasons (i.e. 1 to 3 plants m^{-2}). The site and season specificity of results of trials like those shown in Table 2, makes it difficult to develop soundly-based plant population recommendations. The risks associated with any recommended agronomic practice are also of great importance to the subsistence farmers of the region, who appear to rate food security as the most important objective of their farming practice (Ockwell *et al.*, in press).

This paper examines the potential role of a crop simulation model in developing plant population recommendations which take account of the considerable environmental variation that occurs within the region and which quantify the associated risks.

Review of Literature

The Relationship Between Maize Yield and Population Density

The general shape of the relationship between maize yield and plant population is well known. Yields generally increase up to some maximum with increasing population and then decline. Numerous authors have presented results which show this type of "parabolic" relationship for maize and it has been observed to a greater or lesser extent for many other crops (see review by Willey & Heath, 1969). Some authors have presented yield data at different plant populations and attempted no further analysis (see, Beech & Basinski, 1975; Choudhary, 1981; Kamprath *et al.*, 1973; Kayode *et al.*, 1981; Lucas, 1986). Other authors have used regression techniques to fit curves to their yield data and estimate populations at which yields are likely to be maximized.

Various regression models have been used. Some give better fits than others and some have been argued to have greater biological validity than others. Polynomial equations ($y = a + bp + cp^2$ where y = grain yield per unit area and p = plant population and a, b and c are constants) are simple and can give good fits to the data but are usually rejected on grounds of biological validity. The exponential equation of Duncan (1958) ($y = pK_{10}bp$, where b is a negative constant and K is a constant) has been shown to fit maize data well and an attempt has been made to develop the theory that would give this relationship some biological basis (Duncan, 1984). The reciprocal equations of Shinozaki & Kira (1958), Holliday (1960), de Wit (1960) and Bleasdale & Nelder (1960) (of the general form $y = p/(a + bp)$ but with many variations) received the most attention in Willey & Heath's (1969) review and they concluded that limited biological meaning could be ascribed to the constants in these equations. However, these reviewers also concluded that the interaction of the genetic and environmental components of the yield/density relationship was a far more complex situation than was likely to be successfully described by a "few simple constants".

Little new light has been thrown on this

Table 2 Summary of past plant population studies in semi-arid eastern Kenya for Katumani Composite B (KCB) Maize (from Nadar, 1984)

Season/Year*	Optimum population (plants m^{-2})	Seasonal Rainfall (mm)	Site
LR 1978, SR 1978/79	7 to 9	>500	Katumani
LR 1982	1 to 3	245	Kampi ya Mawe Katumani
SR 1982/83	7 to 15	>500	Katumani
LR 1981	6 to 7	>700	Muguga

* (LR = Long rains, March - June; SR = Short rains, Oct - Jan)

subject since the time of Willey and Heath's review. While these regression equations have been useful in exploring and describing experimental results. (see Nunez & Kamprath, 1969; Ologunde & Ogunlela, 1984; Rees, 1986), they have not proven to be very useful tools that allow extrapolation away from the experimental trials.

Effects of Water and Nitrogen Limitations — The yield - density relationship in maize has generally been studied under favourable conditions of water and nitrogen supply, where competition for light exerts the major influence on the shape of the population response. Hence, the preoccupation with spatial arrangement (plants per hill, row spacings etc.) which often have only minor effects within certain limits (e.g. the 3 to 8 percent differences in yield associated with manipulating plants per hill analysed by Duncan, 1984). Analysis of the major effects of plant population when resources such as water or nitrogen are limiting, has received little attention. Duncan (1958) showed that the slope of the log (plant yield) versus plant population relationship was reduced when nitrogen levels were reduced. This led to a substantial reduction in yield at populations above the optimum. Ogungbile & Ologunde (1986) developed multiple regression models based on polynomial equations relating yield to plant density and nitrogen fertilizer applications. Probert (1987) achieved a more satisfying result by combining a reciprocal equation, which described the plant density response, with a Mitscherlich function which described the phosphorus fertilizer response.

The impact of water deficits on the plant population response appears to have received less attention than has nitrogen. Work in Botswana (Anon., 1985) led to the formulation of multiple regression equations which related grain yield of sorghum and maize to seasonal rainfall and plant population. Although recognised as a very empirical approach with many limitations, the vast quantity of trial results over a period of almost 40 years led to relationships which allowed development of useful recommendations. A similar relationship between maize yield and seasonal evapotranspiration at different plant populations has been proposed by Stewart & Faught (1984) for semi-arid Kenya.

The general lack of attempts to describe the water effect on the yield/density relationship may indicate a general realization that it is too complex an issue for the regression based techniques that have been available.

A Simulation Approach

We have been investigating the possibility of using a crop simulation model, CERES-Maize (Jones & Kiniry, 1986), to assist in the development of physiologically-sound plant population recommendations. The dynamic character of this model should enable it to deal with the complexities of nitrogen and water limitations, better than the static regression models discussed above. The model would firstly aid in the interpretation of results from different sites and seasons, such as those shown in Table 2. Secondly, in conjunction with historical weather data, the model would be used to develop recommendations which can be tailored to suit better the range of agroclimatic variation in the region of interest and to quantify the risks and returns of different strategies.

Features of CERES Maize

CERES Maize is a simulation model which estimates maize phenology, dry matter production, dry matter partitioning and yield in daily time steps from inputs of soil, genotype, management and climate information. The routines used to estimate phenology and growth under non-limiting moisture and soil fertility regimes form the central core of the model. The model estimates soil water and nitrogen status and this information is used to modify phenology and growth.

Important processes simulated include; leaf initiation and growth, stem growth, root growth, light interception, net photosynthesis, timing of reproductive development, grain initiation and growth, soil water extraction, plant transpiration, soil evaporation, nitrogen transformations in the soil, and nitrogen uptake by the plant. CERES-Maize growth and phenology routines simulate the growth of a single plant and the variable "PLANTS" (plants m^{-2}) is used largely as a multiplicative factor to convert to or from a per unit area basis. Hence, while plant population response has received only limited attention in the development of the model, there is scope for the model to simulate these responses through simulation of the magnitude and pattern of use of the water, nitrogen and radiation resources.

The model was developed by the Agricultural Research Service of the United States Department of Agriculture at Temple, Texas. The model and its components have been well documented (Godwin *et al* 1984; Jones *et al* 1984; Ritchie 1984;

Table 3 (a). Major inputs to CERES-Maize (nitrogen version)

Factor	Inputs
Climate	Max. temp. (daily) Min. temp. (daily) Rainfall (daily) Solar radiation (daily) Mean annual air temperature Difference between the highest and lowest mean monthly air temperature.
Irrigation	Julian day number and amount (mm)
Soil	Saturated soil water content Drained upper limit soil water content Lower limit of plant extractable water Layer thickness and bulk density. Runoff curve number Root distribution weighing factors for each layer Whole profile drainage rate coefficient Stage 1 soil evaporation coefficient Soil albedo Organic carbon concentration (%) Initial soilwater at start of simulation Initial mineral NO_3-N and NH_4-N at start of simulation
Genotype	Heat units from emergence to end of juvenile phase Photoperiod sensitivity coefficient Heat units from silking to physiological maturity Potential kernel number Potential kernel growth rate
Management	Sowing date Plant population Sowing depth
Location	Latitude
Residues	Surface residue weight Depth of incorporation of surface residues Surface residue C:N ratio Root dry weight of previous crop Root C:N ratio
Fertilizers	Fertilization dates Fertilization amounts and depths Fertilizer type

Table 3 (b). Some outputs from CERES-Maize (nitrogen version)

Factor	Output
Phenology	Emergence date Tassel initiation date Silking date Physiological maturity date
Growth	Leaf number* Grain number per unit area Ear number per unit area Leaf area index* Leaf stem, grain, root dry wt. per plant* Biomass production* Grain yield per unit area* Root length extension*
Water	Soil water content* Soil evaporation* Plant transpiration* Potential evapotranspiration* Actual evapotranspiration* Runoff* Drainage out of profile* Water stress indices
Nitrogen	Grain nitrogen % Total plant nitrogen content Nitrogen stress indices Soil NO_3-N and NH_4-N status* Immobilization, mineralization amounts*

Outputs marked with an * are available on a daily basis.

Table 4. Genetic coefficients for the Maize cultivar Katumani Composite B (KCB) used in the calibration and testing of CERES-Maize

Code	Description	Value
P1	GDD_8 from emergence to end of juvenile phase	115
P2	Photoperiod sensitivity coefficient (dh^{-1})	0.5
P5	GDD_8 from silking to physiological maturity	660
G2	Potential kernel number (kernels/plants)	450
G3	Potential kernel growth rate (mg/kernel/d)	10.5

* GDD_8 is the heat sum, in growing day degrees above a base temperature of 8°C with adjustments for temperatures exceeding 34°C.

Jones and Kiniry 1986). We use what is known as the "nitrogen version" but with some enhancements to the input/output and operational features (Hargreaves and McCown 1988). The model is written in FORTRAN and will run on a IBM-compatable microcomputer. Model inputs and outputs are summarized in Table 3a and b. The genetic inputs for the maize variety used in this paper, Katumani Composite B, (KCB) were measured in a separate experiment and are presented in Table 4.

Under the configuration we use, a 120-day maize crop can be simulated in approximately 40 seconds (20 seconds where nitrogen is known not to be limiting) so it is feasible to conduct multiple runs for risk analysis using historical weather data.

Methods

Model Testing

A calibration of the non-nitrogen version had previously been done using data from an experiment conducted at Katumani during the short rains of 1985/86 (Wafula & Keating, 1987). Briefly, changes were needed in the functions which determine leaf size, specific leaf area and stem growth during grain filling to give an acceptable fit.

Subsequently an experiment was conducted at Katumani (short rains of 1986/87) with the objective of testing the ability of CERES-Maize to simulate the population response under different levels of water limitation. The experiment consisted of two replicates of a systematic response surface with plant density ranging from 0.88 to 8.88 plants m^{-2}. Plant density increased along the row over this range at the rate of 10% from one plant to the next. Row spacing was held constant at 75 cm. Two cultivars were studied, but the results reported here will be limited to the currently recommended cultivar, KCB. Two water regimes were studied. In the wetter treatment, the crop was planted at the onset of the rains (3/11/86) and irrigation supplied. This treatment received a total precipation of 408 mm, of which 104 was from irrigation during the grain filling period. In the drier treatment, the crop was planted 17 days after onset (20/11/86) with no irrigation. This treatment received a total rainfall of 266 mm and experienced water deficits, particularly during grain filling. All treatments received a complete fertilizer application which included split nitrogen applications totalling 75kg N ha^{-1}. Measured yield data presented in this paper are the means of two replicates and 3 "steps" in the population response surface, with 10 plants per step (i.e. 60 plants). Grain yield data are in kg ha^{-1} at 15.5% moisture.

Risk/Return Analysis — Daily rainfall data records were assembled for two sites, Katumani & Makindu, for the time periods indicated in Table 5. The temperature and radiation data used were the monthly means for the two sites. Dry planting was assumed to occur on October 15 and March 15 at both sites in the short and long rains, respectively. The hypothetical crops were "grown" under two soil fertility regimes. In one case, fertility was set to be

Table 5. Details of sites used for risk analysis

Sites	Rainfall[1] years used	Altitude (m)	Annual mean temp (°C)	Annual mean daily radiation ($MJ\ m^{-2}\ d^{-1}$)	Annual rainfall (mm)	Annual evaporation (mm)	AEZ[2]
Katumani	1961-1983	1601	19.2	19.5	711	1807	UM4
Makindu	1961-1983	1000	22.6	18.9	612	2112	LM5

[1] At Katumani, 43 seasons were studied. 1975 SR. and 1980 SR were excluded because of missing rainfall data.
At Makindu, 42 seasons were studied. 1978 SR, 1980 LR. and 1980 SR were excluded because of missing rainfall data.

[2] AEZ refers to agroecological zone as outlined by Jaetzold & Schmidt (1983).
UM4 is the upper midlands, zone 4, best suited to cultivation of maize and sunflowers.
LM5 is the lower midlands, zone 5, best suited to livestock herding and cultivation of drought tolerant crops like millet.

non-limiting, while in the other, the crops received no nitrogen fertilizer and soil organic carbon and mineral N levels were set to average levels recorded for the major soil of the region (Semb & Robinson, 1969; R.F. Isbell, unpub. data, 1985). The important soil characteristics used are summarized in Table 6. The genotype coefficients for KCB, the cultivar simulated, were those determined during the course of the calibration studies (see Table 4). Curves relating grain yield to plant population were generated for each season at each site by running the model at populations of 1,2,3,4,5,6,7,8 plants m^{-2}. These response surfaces were used to identify the plant

Table 6. Characteristics of soil used in risk/return analysis

General Information
Classification: Chromic Luvisol or Oxic Paleustalf
Soil Albedo = 0.13 (unitless)
Upper limit of 1st stage soil evaporation = 9mm
Whole profile drainage coefficient = 0.50 (d^{-1})
Runoff curve number = 74 (unitless)
Layer Information

Depth (cm)	LL	DUL	SAT	WR	NH_4	NO_3	C	BD
0-10	0.14	0.25	0.30	1.00	5.0	10.0	0.8	1.35
10-20	0.14	0.25	0.30	0.86	2.5	5.0	0.6	1.35
20-30	0.14	0.29	0.32	0.64	0.5	3.0	0.5	1.35
30-50	0.15	0.30	0.33	0.47	0.5	3.0	0.3	1.40
50-70	0.17	0.30	0.34	0.35	0.5	3.0	0.3	1.40
70-90	0.17	0.30	0.35	0.25	0.5	3.0	0.3	1.40
90-110	0.18	0.31	0.36	0.15	0.5	1.0	0.3	1.40
110-130	0.18	0.32	0.37	0.08	0.5	1.0	0.3	1.40

where LL = Lower Limit of plant extractable volumetric water (cm cm^{-1})
DUL = Drained upper limit of volumetric soil water (cm cm^{-1})
SAT = Saturated volumetric soil water (cm cm^{-1})
WR = Root distribution weighting factor (unitless)
NH_4 = Mineral NH_4 at planting (mg NH_4 -N per kg soil)
NO_3 = Mineral NO_3 -N at planting (mg NO_3 -N per kg soil)
C = Organic carbon (%)
BD = Moist Bulk Density (g dry soil cm^{-3} moist soil volume,

population which maximized yield over the 23 year period considered. The probabilities of crop failure (yields < 300 kg/ha^{-1}) and of achieving different yield levels under the various management regimes were also estimated.

Results and Discussion

Testing Response to Plant Population

Apart from some evidence of overestimating grain yield in the wet treatment at populations above 8 plants m^{-2} the model simulated grain yields accurately (Fig. 2a). Biomass simulations (Fig. 2b) were not as accurate as those for grain yield. There was a small (approximately 20%) but consistent underestimation of biomass at low plant populations - a problem earlier identified (Wafula & Keating, 1987) but as yet unsolved. The detailed dry matter partitioning data collected in this experiment will provide an opportunity to address this problem. It is also necessary to correct the overestimation (30%) of biomass at populations above 5 plants m^{-2} under water stress, presumably due to an underestimation of the degree of water stress in these plots during vegetative growth.

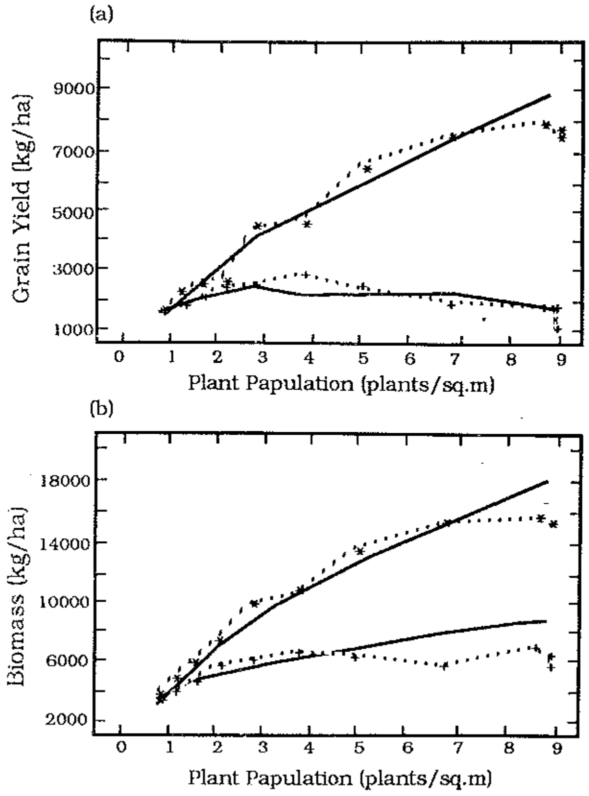

Fig. 2. Response of KCB maize to plant population in the 1986/87 short rains season.
(a) Grain Yield: broken lines are observed grain yields for irrigated (*) and non-irrigated (+) crops. Solid lines are yields estimated by CERES-Maize.
(b) Biomass: broken lines are observed above ground biomass yields for irrigated (*) and non-irrigated (+) crops. Solids lines are yields estimated by CERES-Maize.

The Risk/Return Analysis — The above test of the model's ability to simulate the response of maize grain yield to plant population under different water regimes was sufficiently encouraging to justify running the model using 23 years of weather records as outlined previously in section 4.2. Crops were simulated to germinate in all seasons considered, with the exception of the 1983 long rains at Makindu, where germination failure was predicted due to insufficient rainfall within 40 days of planting. Simulated grain yields (15.5% moisture) ranged from 21 to 9315 kg ha^{-1} at Katumani and 0 to 8278 kg ha^{-1} at Makindu. The maximum yields simulated in the wettest seasons in the absence of soil fertility limitations (in the range 8000 - 9000 kg ha^{-1}) were similar to those recorded for well fertilized, irrigated plots on research stations [Stewart, 1983; B.M. Wafula & B.A. Keating (unpublished data, 1986)] and may be close to the yield ceiling for the open pollinated maize cultivar under study. The maximum yields simulated in the presence of nitrogen limitation (2600 - 3000 ka ha^{-1}) were similar to yields recorded on well-managed farmers crops in a wet season (A.P. Ockwell, S. Nguluu & L. Muhammed, unpublished data).

The population response, averaged over all seasons is shown in Fig. 3 for both sites and both soil fertility levels. In the presence of adequate nitrogen, the model predicts that maximum production in the long term would be achieved with populations of the order of 8 plants m^{-1}. In such a situation, long term average yields of 2700 kg

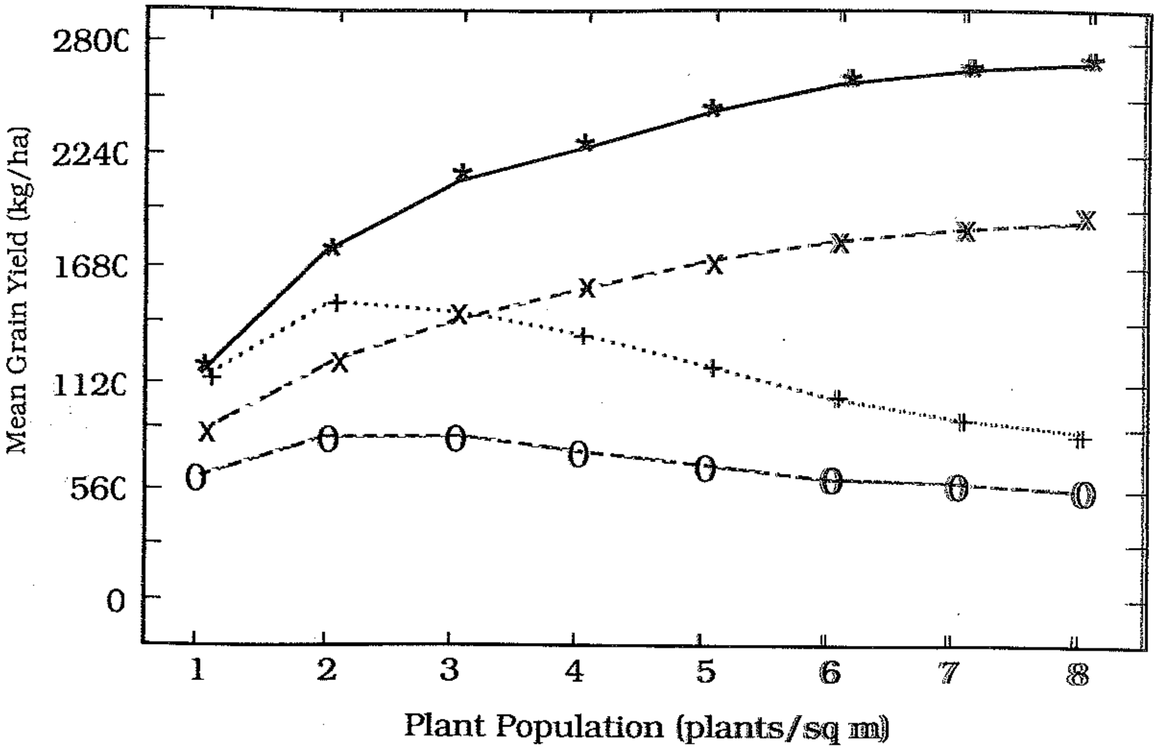

Fig. 3. CERES-Maize estimates of grain yield in response to plant population, averaged over the 1961-1983 period.
* ———— * Katumani with nitrogen non-limiting
x- - - - - - - - x Makindu with nitrogen non-limiting
+ ....+ Katumani with nitrogen limiting
o —·—·— o Makindu with nitrogen limiting

ha^{-1} and 2000 kg ha^{-1} could be expected for Katumani and Makindu respectively. The presence of a strong nitrogen limitation, which is common within the region, shifts the average response to plant population. Grain yield is predicted to be much less responsive to plant population in such circumstances. Estimated population optima are reduced to 2 plants m^{-2} for Katumani and 2 to 3 plants m^{-2} for Makindu. At these population optima, nitrogen deficits are estimated to limit long-term average yields to approximately 1500 and 800 kg ha^{-1} for Katumani and Makindu respectively. These latter yield levels are still probably in excess of the district averages. Jaetzold & Schmidt (1984) suggest that yields without fertilizer additions average between 750 and 900 kg ha^{-1} in this region, but other factors such as delays in planting, poor weed and pest control and non-nitrogen fertility limitations will all contribute to lower district average yields.

The foregoing discussion has considered only long term production averages and is in itself, inadequate for the needs of risk-averse subsistence farmers. In the farmers mind, the need to produce sufficient food for his family in all or as many seasons as possible appears to be a more important consideration than is maximization of production in the long term. The probability of crop failure at the two sites is presented in Fig. 4 in relation to soil fertility and plant population. We have defined as "crop failures" crops which gave yields less than 300 kg grain ha^{-1}. Rukandema (1984) reports that an average of 1.95 ha are cultivated per household in Machakos district and that each household averages 8.7 persons. Hence yields less than 300 kg grain ha^{-1} will translate to less than 0.4 kg maize per person per day (based on 2 seasons per year), which is insufficient for dietary needs.

Higher plant populations and nitrogen

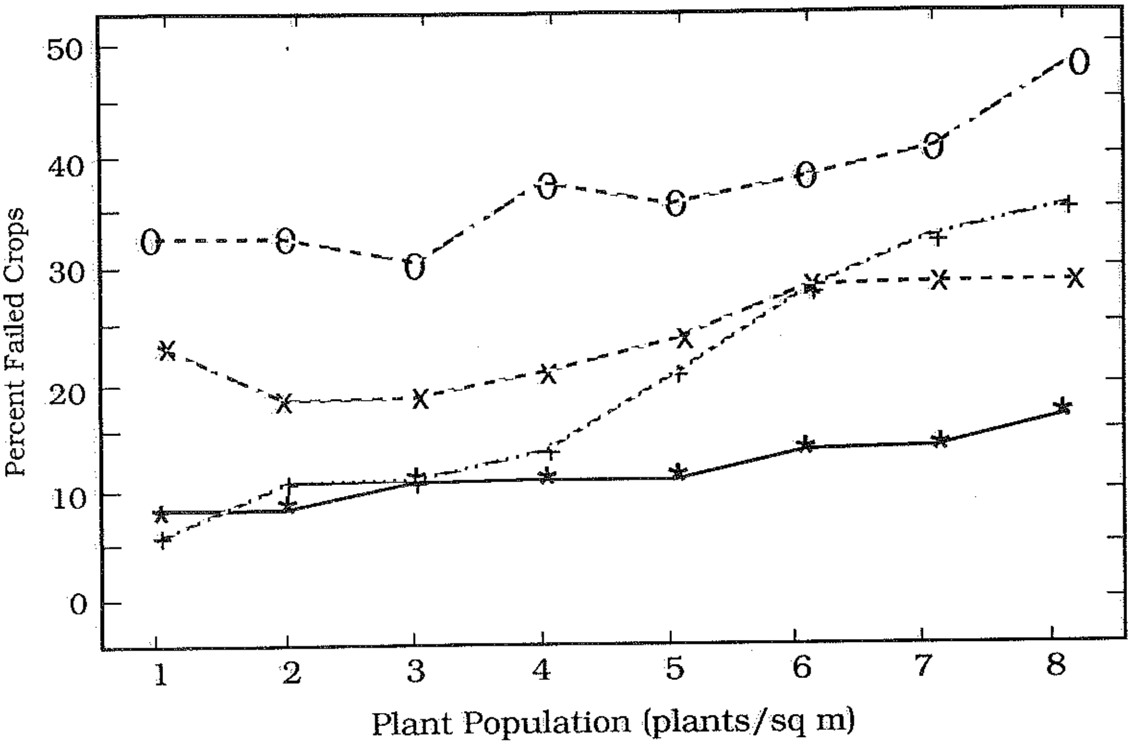

Fig. 4. CERES-Maize estimates of percentage of failed crops (i.e. grain yield < 300 kg ha^{-1}) over the 1961-1983 period, in response to plant population.

* ———— * Katumani with nitrogen non-limiting
* ------------* Makindu with nitrogen non-limiting
\+ ....+ Katumani with nitrogen limiting
o —·—·—·— o Makindu with nitrogen limiting

deficits were both predicted to increase the risk of crop failure (Fig. 4). These factors also interacted strongly, particularly at Katumani, where the riskness of high plant populations was estimated to increase in the absence of adequate nitrogen. As would be expected, the incidence of crop failure was estimated to be higher at the drier Makindu site (range: 19-47% of seasons) than at Katumani (range: 9-35% of seasons).

In Fig. 5, the probabilities, based on the simulated frequencies, of yields exceeding any given level, are shown for the two soil fertility levels and four of the eight plant populations evaluated. The remaining populations were omitted to simplify the figure, but were intermediate to the populations shown.

In the presence of adequate nitrogen, high populations provide a chance of high yields with only a small increase in the probability of lower yields in poor seasons. In a nitrogen limiting situation, plant populations above 3 to 4 plants m^{-2} do not appear to increase the probability of higher yields during good seasons and are predicted to substantially increase the probability of lower yields during poor seasons.

General Discussion

The generally good agreement between yield estimates of CERES-Maize under widely differing water and plant population regimes provides confidence in its use for long term risk analysis. Elsewhere in the world, CERES-Maize has performed satisfactorily, (e.g. Hodges *et al.*, (1987) used CERES-Maize to forecast yields and estimate total production for the US cornbelt; de Vos and Mallett (1987) in South Africa),

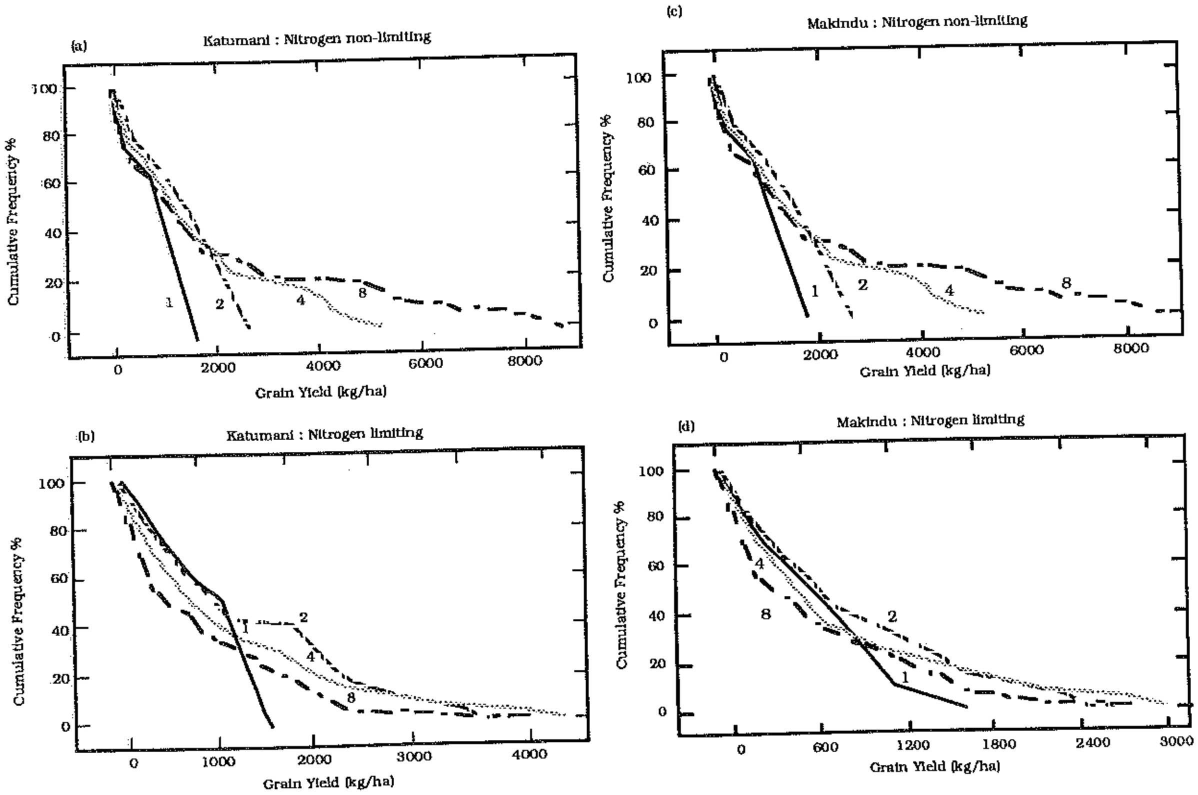

Fig. 5. CERES-Maize estimates of the cumulative frequency of obtaining at least the specified grain yield over the 1961-1983 period. Numbers on the curves are plant populations (in plants m^{-2}).

or has been satisfactory after calibration, (Carberry *et al.*, (in prep.) in northern Australia).

While validation of the nitrogen submodel is incomplete for Kenya, the interaction between plant population and nitrogen limitation predicted by the model is consistent with reports in the literature. Also there is similarity between the shape of the responses to population and nitrogen reported by Duncan (1958) and the average responses simulated by CERES-Maize (Fig. 3). While Duncan's analysis provides a static quantification of some experimental data, our simulation approach provides estimates of long term yield averages in response to management options that could not feasibly be derived in any other way. In addition, this approach allows the risks of cropping in different regions and under different management options to be quantified.

The long term yield advantages of higher plant populations (i.e. 6 to 8 plants m^{-1}) have been suggested previously from work conducted on research stations. (e.g. Nadar, 1984). We suggest that these advantages can be obtained in situations where soil fertility is not limiting, with only small increases in the risks of crop failure. In contrast, in situations where nitrogen is limiting, maximum long term production is predicted to be greatest with lower plant populations (2-4 plants m^{-2}). Further increases in plant population are predicted to reduce long term yield averages and markedly increase risk of crop failure.

The limited surveys that have been conducted of plant populations on farms show that farmers generally achieve populations in the 2 to 4 plants m^{-2} range. Average mono-crop maize populations reported include, 20,000 plants ha^{-1} (Nadar, 1984); 34,700 plants ha^{-1}(Stewart & Kashasha, 1984); 31,100 plants ha^{-1} (Ockwell *et al.*, in prep) and 31,000 plants ha^{-1} (Figueiredo, 1986). Our results suggest that current farmer practice may be an appropriate strategy for the generally low soil fertility on farms in this region.

Research now underway on research stations and on farmers fields will provide the necessary data to validate, or if necessary modify, the nitrogen aspects of the model. If the model is simulating N supply adequately, it is clear that no major improvements in the productivity of the cereal cropping system can be achieved without improvements in nitrogen supply. Research towards low-capital-cost sources of nitrogen, such as legumes and farm yard manures, is thus a priority area. Research which improves the efficiency of utilization and reduces the riskiness of fertilizer application (e.g. the " response" farming concept of Stewart & Faught (1984) is also needed.

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