

Development of a Modelling Capability for Maize in Semi-arid Eastern Kenya

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THE place for models in the conduct of agricultural research under variable climates is discussed by Keating et al. elsewhere in these proceedings. Models that relate crop growth to climate, soil, genotype and management factors can assist in the evaluation of strategies for enhancing crop productivity under variable climates. To be a useful tool, a model needs to provide acceptably accurate estimates of crop growth and yield in relation to the major factors which determine productivity. In this paper, we report on research carried out in semi-arid eastern Kenya over the period 1985–89, aimed at developing a capability to model maize growth and yield in relation to the major soil, management and climatic constraints.

Choice of Model

Maize is the preferred cereal in the region (Rukandema 1984) and it dominates the farming system. Hence, we chose to examine the prospects for modelling maize growth and yield. While intercropping of maize with grain legumes is common, lack of suitable intercropping models precluded examination of such systems. Crop production is almost entirely rainfed and the rainfall regime is highly variable and often limiting (Downing et al. 1987). When not constrained by water deficits, the most common constraint appears to be nitrogen supply. It was thus essential that the chosen model be capable of dealing with both water and nitrogen constraints and their interaction with management in the most effective way. The analysis of previous research in the region (Keating et al., these proceedings) highlights the importance of the within-season distribution of rainfall in relation to the timing of crop development. Hence, it was also clear that a dynamic model was required and a daily time step was the most appropriate, given that the majority of climate data is available on this basis. CERES–Maize was the only model that met these selection criteria.

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Model Description

CERES–Maize was originally developed by the Agricultural Research Service of the United States Department of Agriculture at Temple, Texas. The model and its components have been documented elsewhere (Godwin et al. 1984; Jones et al. 1984; Ritchie 1984; Jones and Kiniry 1986). Briefly, CERES–Maize is a model that simulates maize growth and yield in relation to climate, soil, genotype and management inputs. 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 growth under sub-optimal conditions. Major inputs and outputs to the model are summarised in Table 1.

Model Testing — Development of the Database

Whilst research on maize had been conducted in the eastern Kenya region for more than 30 years, the data available were not generally suitable for testing CERES–Maize. Incomplete reporting of management or location data, combined with difficulties in obtaining weather data and the general absence of any detailed soil characterisation, were frequent problems. We therefore embarked on an experimental program in 1985 to build up the necessary datasets.

Experiment 1 was conducted in the 'short rains' of 1985–86 at Katumani Research Station (lat. 1°35' S, long. 37°14' E, altitude 1601 m) on a Chromic Luvisol (Gicheru and Ita 1987). The composite maize cultivar, Katumani Composite B (KCB), was sown at the times shown in Table 2. Plant population, N fertiliser and irrigation treatments imposed are also shown. Replicates are modelled separately in this experiment since they differed slightly in the established plant population, the depth of soil (a stone layer that varied in depth from 110 to 190 cm restricted rooting depth) and, in the case of irrigated treatments, the timing and quantity of applied water. The degree of water limitation experienced by the

Table 1. The CERES-Maize model

<i>(a) Major inputs</i>		<i>(b) Some outputs</i>		
Factor	Inputs	Factor	Output	
Climate	Maximum temp. (daily)	Phenology	Emergence date	
	Minimum temp. (daily)		Tassel initiation date	
	Rainfall (daily)		Silking date	
	Solar radiation (daily)		Physiological maturity date	
	Mean annual air temperature	Growth	Leaf number*	
Difference between the highest and lowest mean monthly air temperature	Grain number per unit area			
Irrigation	Amount (mm) applied on any day		Ear number per unit area	
	Soil		Leaf area index*	
			Saturated soil water content	Leaf, stem, grain, root dry weight per plant*
		Drained upper limit soil water content	Biomass production*	
		Lower limit of plant extractable water	Grain yield per unit area*	
Layer thickness and bulk density		Root length extension*		
Runoff curve number	Water	Soil water content*		
Root distribution weighing factors for each layer		Soil evaporation*		
Whole profile drainage rate coefficient		Plant transpiration*		
Stage 1 soil evaporation coefficient		Potential evapotranspiration*		
Soil albedo		Actual evapotranspiration*		
Organic carbon concentration (%)	Nitrogen	Runoff*		
Soil water at start of simulation		Drainage out of profile*		
Mineral NO ₃ -N and NH ₄ -N concentrations at start of simulation		Water stress indices		
Genotype		Heat units from emergence to end of juvenile phase	Grain nitrogen (%)	
		Photoperiod sensitivity coefficient	Total plant nitrogen content	
	Heat units from silking to physiological maturity	Nitrogen stress indices		
	Potential kernel number	Soil NO ₃ -N and NH ₄ -N concentrations*		
	Potential kernel growth rate	Immobilisation		
Management	Sowing date	Location	Latitude	
	Plant population		Residues	Surface residue weight and C:N ratio
	Sowing depth			Depth of incorporation of surface residues
Location	Latitude			Root dry weight of previous crop
	Longitude			Root C:N ratio
	Altitude	Fertilisers	Fertilisation dates	
	Soil type		Fertiliser type, amount and depth	
	Soil water at start of simulation			

* These outputs are available on a daily basis.

crops grown in this experiment ranged from none in the irrigated plots to strong water stress during grain filling for the late planted dryland crops. The corresponding grain yields ranged from 1600 to 8000 kg/ha.

Experiment 2 was conducted at Katumani during the short dry season (December to March) in 1985-86. This experiment consisted of two plant density levels grown

at a range of water regimes achieved with a line-source irrigation installation. Crops in this experiment generally experienced strong water stress around the silking period and grain yields ranged from 0 to 3300 kg/ha depending on the severity of this stress.

Experiment 3 was conducted at Kiboko Research Station, Kenya (lat. 2°13' S, long. 37°43' E, alt. 915 m)

on a Ferric Luvisol (Siderius and Muchena 1977) during the short rains of 1986–87. Kiboko (997 m) is lower in altitude than Katumani (1601 m) and therefore warmer (mean annual air temperature of 23.5°C compared with 19.5°C at Katumani). This experiment was similar in design to experiment 1 except that a second cultivar, Dryland Composite (DLC), was included (Table 2). Grain yield ranged from 1370 to 6160 kg/ha.

Experiment 4 was conducted at Katumani during the short rains of 1986–87. The experiment explored the interaction between plant population (varied over the range 0.88 to 8.88 plants per m² in a systematic design) and water regime (early-planted, irrigated compared to late-planted, non-irrigated). Two cultivars were studied (Table 2) and grain yields ranged from approximately 1500 to 8000 kg/ha in the wet treatment and 1200 to 3000 kg/ha in the dry treatment.

Experiment 5 was initially designed to investigate the plant density by nitrogen interaction, with variation in water regime being achieved by early and late planting (Table 2). It was conducted on a Chromic Luvisol at Katumani during the 1987 short rains. Poor early season

rainfall meant that all plants from both planting dates were dead or close to death by the end of December 1987. Rain in January 1988 did not lead to significant recovery. Grain yield was zero for all treatments and biomass yield ranged from 10 to 150 kg/ha.

Experiment 6 was a repeat of experiment 5 (plant population and nitrogen supply interaction) in the long rains of 1988, at two sites, Katumani and Kiboko. Treatments consisted of factorial combinations of 2 nitrogen fertiliser rates (0 and 120 kg N per ha) and 5 plant populations over the 1.1 to 7.4 plants per m² range. The trial was rainfed at Katumani and fully irrigated at Kiboko. Yields increased from 2000 to 5400 kg grain per ha and 1000 to 6000 kg grain per ha at Katumani and Kiboko, respectively. In both cases, strong N × plant population interactions were observed.

Experiment 7 commenced in the short rains of 1988–89 (expt. 7a) at both Katumani and Kiboko. Response to rate of N fertiliser (over the range 0 to 160 kg N per ha) was examined. In the long rains of 1989 (expt 7b) the residual value of fertiliser applied in expt 7a was compared with fresh applications.

Table 2. The range of cultural treatments for maize crops grown to evaluate the CERES–Maize model.

Expt no.	Site	Sowing date(s)	Cultivars	Nitrogen treatments (kg N/ha)	Plant population (plants/m ²)	Seasonal rain (mm)	Irrigation (mm)
1	Katumani (Field C)	29-10-85	KCB	0 and 80	2.0–6.5	255	6–176
		21-11-85	KCB	–	2.0–6.5	227	0
2	Katumani (Field C)	18-12-85	KCB	–	2.1–6.8	127	11–222
3	Kiboko Kiboko	12-11-86	KCB, DLC	–	2.1–6.7	219	50–200
		26-11-86	KCB, DLC	–	2.1–6.7	167	50
4	Katumani	3-11-86	KCB, DLC	–	0.88–8.88	337	104
		20-11-86	KCB, DLC	–	0.88–8.88	303	0
5	Katumani Katumani (both Field E)	9-11-87	KCB	–	1.1–6.3	79	0
		27-11-87	KCB	–	1.1–6.3	12	0
6	Katumani Kiboko	25-3-88	KCB	0 and 120	1.1–7.4	310	0
		8-4-88	KCB	0 and 120	1.1–7.4	124	375
7a	Katumani Kiboko	27-10-88	KCB	0, 20, 40, 80, 160	4.4	427	0
		11-11-88	KCB	0, 20, 40, 80, 160	4.4	332	0
7b*	Katumani Kiboko	1-4-89	KCB	0, 20, 40, 80, 160	4.4	227	0
		31-3-89	KCB	0, 20, 40, 80, 160	4.4	319	52
8	Wamnyu (Kyengo farm)	1-11-88	KCB	0, 20, 40, 80, 160	2.9 to 3.7	491	0

* Fertiliser treatments include a comparison of fresh and residual sources.

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Experiment 8 examined the response to fertiliser N (5 rates from 0 to 160 kg N per ha) under farmer management. The experiment was conducted in the short rains of 1988 on the farm of Mama Kyengo, near Wamunyu (lat. 1°25' S, long 37°34'E, altitude 1190 m). The soil was a Haplic Alisol (Aore and Gatabi 1990). The terrace was planted by the farmer and subsequently managed by him. Fertiliser treatments were applied as 30 m long strips, banded beside the young maize plants, randomised across a terrace and replicate three times. Rainfall was recorded on the farm and soil mineral nitrogen monitored.

A total of 159 datasets was available from these eight experiments. One hundred and seventeen came from the cooler Katumani location, 37 from the warmer Kiboko site and 5 from the Kyengo farm site which is at an intermediate altitude. Forty-two relate to maize grown at low plant densities (2.2 plants per m² or lower), 46 were grown at high plant densities (above 6.6 plants per m²) and the remainder at intermediate plant populations. The majority (129) of the data are from the cultivar KCB, while 30 feature the cultivar DLC. Forty-eight of the crops were grown under favourable water regimes using supplementary irrigation, whilst the remaining crops experienced a degree of water stress ranging from mild to severe. Zero yield was recorded in eight of the data sets when the crops died due to extreme water stress prior to silking. Fertiliser was supplied such that nitrogen was not a constraint in 114 of the datasets and no or low rates of fertiliser-N were used to achieve nitrogen deficits in the remainder of the database.

All grain yields reported in this paper are expressed at 15.5% moisture content. Times to silking and physiological maturity (blacklayer formation) were measured from emergence.

Model Adaptation

We commenced this work with a visual-interactive version of CERES-Maize v.1 (Hargreaves and McCown 1988). This version is compatible with both the original standard and nitrogen versions (Jones and Kiniry 1986), but which features operational enhancements which facilitate interactive use of the model.

While performance of the original model was reasonable, a number of revisions were made to deal with problems encountered during its application in Kenya. In addition, problems identified and enhancements made in the maize modelling program in northern Australia (Curberry et al., these proceedings) were applied in Kenya. The scope of the model in use in Kenya was also broadened to allow more realistic simulation of both fixed and tactical management options.

Modifications

The severity of the water deficits encountered in the region under study were so great that crops actually died (e.g. expt 5). The original model would not simulate crop death, but allowed severely stressed crops to remain in 'suspended animation'. If rain was received later in the vegetative growth period, the simulated crops recommenced growth, and low, but significant, yields could be achieved. In reality, such crops were dead and the farmer would have considered re-sowing on the late rain. Routines were introduced which killed crops in response to an accumulated index of water deficit during the early- to mid-vegetative growth period.

Silking was found to be delayed by severe water or nitrogen stress, and changes were made to the model to simulate such delays. A number of other changes were made which we felt improved model integrity or had conceptual advantages. For example, the method used to simulate leaf area was modified to better account for the relationships between total leaf number and leaf area (Keating and Wafula 1991), and the capacity to simulate multiple cobs per plant was added. The temperature optimum used in the thermal time calculation (34°C) was found to be too high, leading to an overprediction of development rates when the model was tested under warmer temperatures (Lenga and Keating 1992). This was corrected by invoking a plateau in the development rate versus temperature curve between 28 and 34°C.

Problems were encountered when simulation was extended from one rainy season, over a long dry season, and into a second rainy season (e.g. when simulating the residual fertiliser effects in expt 7). Mineral-N during the early weeks of the second rainy season was underestimated. While the precise reasons for this remain uncertain, changes were made to the nitrogen mineralisation routines to better reflect the flush of mineral nitrogen that appears in soils of the region after prolonged dry periods.

Enhancements

Planting date was an input in the original model, fixed for any particular crop being simulated. This was unrealistic in this region where farmers plant in response to what they perceive as the onset of the rainy season. Routines were introduced which allow the user to define criteria for season onset in terms of the length, pattern and quantity of rain needed to initiate a planting opportunity. Related routines allow for replant options should a crop emerge but fail to survive during an onset window.

Management information such as plant population and fertiliser rate were also fixed inputs for a particular crop being simulated in the original model. Enhancements

were made which allowed these inputs to be conditional on the timing of onset of the season. For instance, if the rains started and sowing took place before a nominated date, high plant populations and fertiliser N could be set. If the rains started late, the simulation could be set up to use low plant populations and not apply fertiliser. Opportunities were also made for within-season management (fertiliser side-dressings, thinning) to be conditional on the timing and quantity of early-season rain. This capability to deal with conditional management strategies meant that strategies such as response farming (Stewart and Faught 1984; see also Wafula et al., these proceedings) could be simulated.

The adapted model is referred to as CM-KEN.

Model Performance

All Data

The model validation dataset contained information from 159 crop/treatment combinations, with yields ranging from 0 to 8000 kg/ha in response to variation in sowing date, water, nitrogen, plant population and climatic conditions (Table 2). The line of best fit between predicted and observed grain yield (Fig. 1) was close to the 1:1 line (slope (s.e.) = 0.94 (0.03) and intercept (s.e.) = 249 (103)) and coefficient of determination (r^2) was 0.88, with a root mean squared deviation (RMSD) of 689 kg/ha.

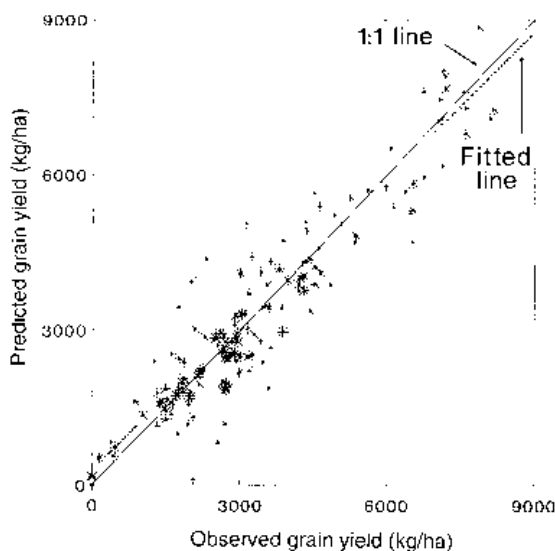


Fig. 1. Comparison of observed maize grain yield with that predicted by CM-KEN. Solid line is 1:1; the fitted (broken) line has slope (s.e.) = 0.94 (0.03); intercept (s.e.) = 249 (103), $r^2 = 0.88$, $n = 159$.

Plant Population Responses

Experiment 4 provided a large dataset to test the model's capacity to simulate the response of maize yield to plant population, under both favourable and limiting water regimes. The experimental data show that when water was freely available (441 mm over the season), yields increased from approximately 1500 to 7000 kg/ha as plant population was raised from 0.88 to 8.88 plants per m^2 . When water was limiting (303 mm over the season), yields peaked at approximately 2800 kg/ha and stayed steady (DLC) or declined (KCB) as plant populations were raised above 3.7 plants per m^2 . This strong water \times plant population interaction was accurately simulated (RMSD = 549 kg/ha) by CM-KEN for both the KCB and DLC cultivars (Fig. 2).

Experiment 6 investigated the interaction between plant population and nitrogen supply. As was the case for water, the interaction was strong. Grain yields increased in response to increased plant population in the presence of adequate nitrogen. Yields reached a plateau or declined as plant population was increased in the presence of a nitrogen constraint (Fig. 3). While the absolute precision of the predicted grain yields was not always good, the model was clearly capable of predicting the general nature of the plant population by nitrogen supply interaction (RMSD = 582 kg/ha).

N Rate Trials

The model slightly overestimated yields in the SR of 1988 at Katumani (Fig. 4). Yields were lower in the 1989-LR crops because of water stress and were well simulated. At Kiboko, the model underestimated the response to N in 1988-SR. Responses to freshly applied N fertiliser up to 80 kg N per ha were recorded at both sites in 1989-LR and these were accurately simulated (Fig. 4).

Fertiliser applied in 1988-SR at rates above 40 and 80 kg N per ha at Katumani and Kiboko, respectively, provided a residual benefit to 1989-LR crops. The model simulated residual effects although the predictions were not as accurate as was the case for fresh fertiliser applications in the same season.

RMSD for yield prediction within the 30 datasets collected in the N rate experiments (7a and 7b) was 665 kg/ha while observed yields ranged from 1500 to 7000 kg/ha ($r^2 = 0.85$, Slope (s.e.) = 1.2 (0.1), Intercept = 739 (362)).

N Response under Farmer Management

A strong response to nitrogen fertiliser was recorded in the trial that was located on Kyengo's farm (expt 8). CM-KEN overestimated the overall yield level in this trial, but accurately simulated the general magnitude of

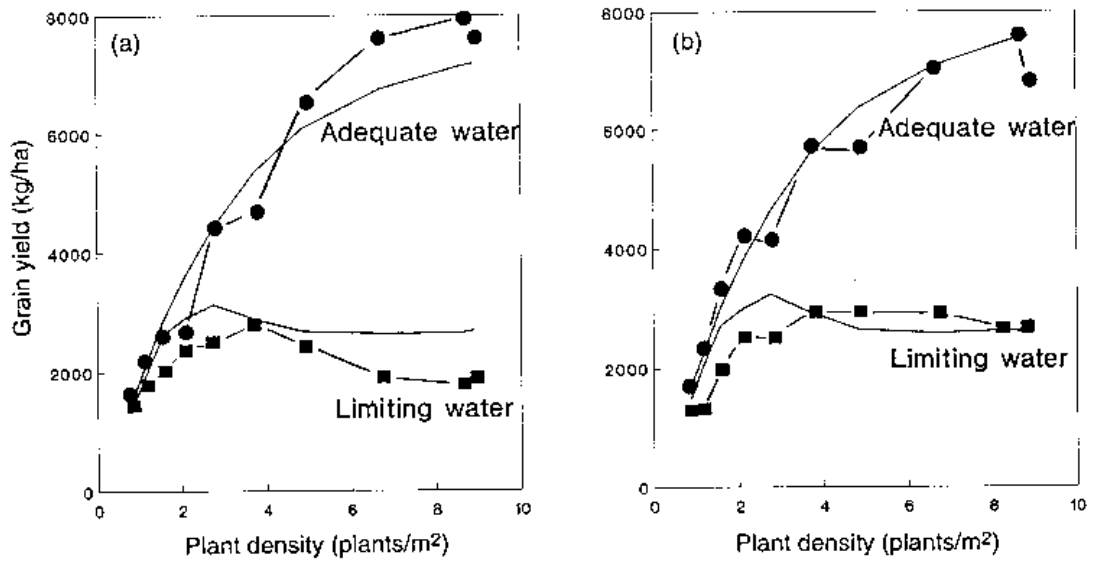


Fig. 2. Observed (symbols, broken lines) yields for maize under two water regimes (wet = circles, dry = squares) at a range of plant populations (Experiment 4). Yield predicted by CM-KEN is also shown (solid lines). Details of water regimes are given in Table 2.

- (a) The cultivar Katumani Composite B (KCB).
- (b) The cultivar Dryland Composite (DLC).

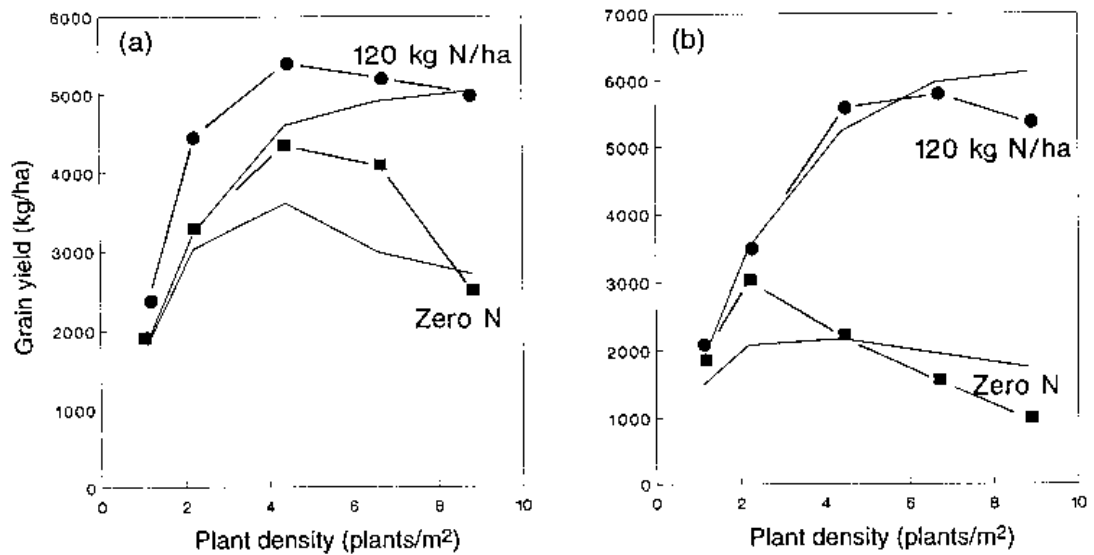


Fig. 3. Observed (symbols, broken lines) yields for maize under two nitrogen regimes (high N = circles, low N = squares) at a range of plant populations (Experiment 6). Yield predicted by CM-KEN is also shown (solid lines). Other details are given in Table 2.

- (a) At Katumani - rainfed.
- (b) At Kiboko under irrigation.

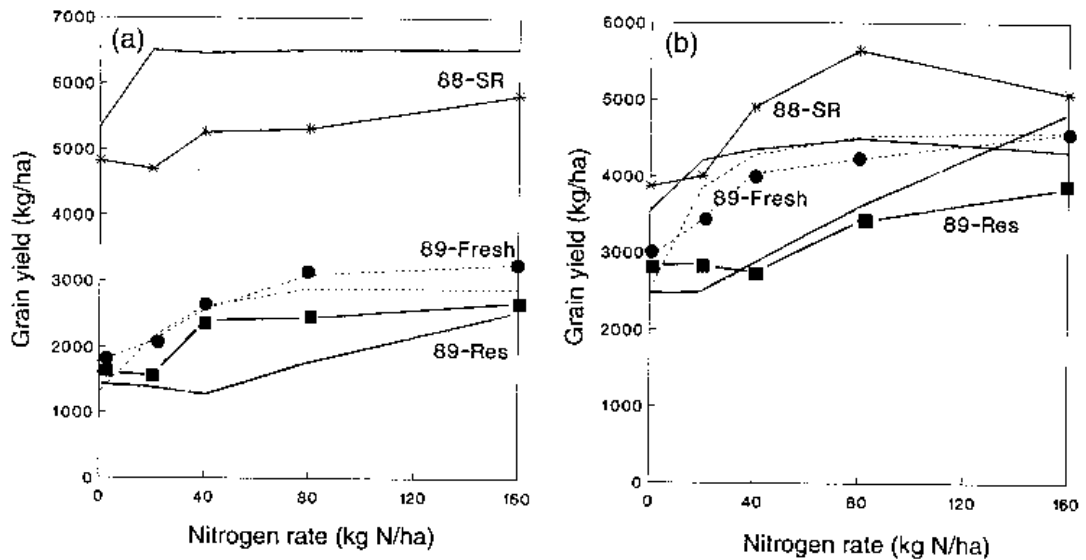


Fig. 4. Observed (symbols) yields for maize in relation to rate of nitrogen fertiliser (Experiment 7). Upper heavy solid line and * (fresh application in 1988-SR - expt 7a). Middle dashed line and round symbols (fresh application in 1989-LR). Lower solid line and square symbols (residual value of fertiliser in 1989-LR - expt 7b). Yield predicted by CM-KEN is also shown (corresponding lines without symbols).

- (a) At Katumaru - rainfed.
 (b) At Kiboko.

the N response (Fig. 5). This trial was planted and managed by the farmer and the yield overestimation is

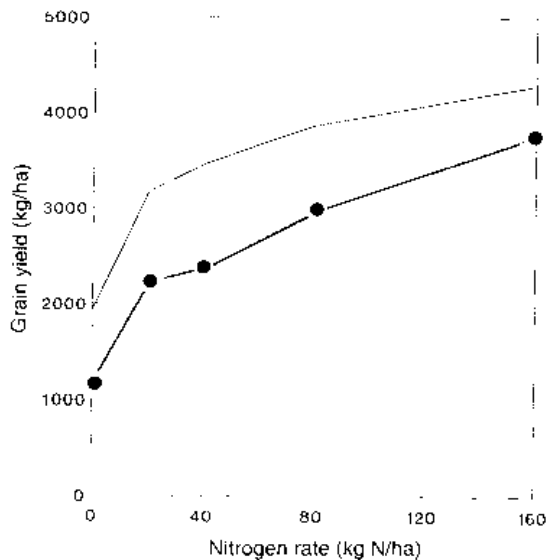


Fig. 5. Observed yields (symbols, lower line) for maize in response to nitrogen fertilisation on Kyengo's farm under farmer management (Experiment 8). Yield predicted by CM-KEN is also shown (upper line).

thought to be the result of some constraint or management limitation not simulated within the model. The uniformity of the plant stand was much poorer on the farm than in other experimental situations. Gaps and multiple plants from the same planting position existed in this crop and may represent a yield limitation not considered within CM-KEN. While weeds were not a major problem in this crop, they were more frequent than in experimental crops and may have also constrained yields.

Discussion

This work has shown that CERES-Maize is capable of simulating maize growth and yield in relation to water, nitrogen and management controls in this environment. The modifications and enhancements made within CM-KEN build on the basic validity of CERES-Maize and make it a more useful tool for application in semi-arid Kenya. It is acknowledged that the changes made were based on limited data and may not have wider validity, but our objective in this work was to develop the best possible simulation within a defined region.

The general level of precision with which responses were simulated was better under water constraint than under nitrogen constraint. We believe this reflects, at least in part, the sensitivity of the model to initial soil N status and errors inherent in estimation of mineral-nitrogen in

the soil profile under variable field conditions. Shortcomings in predicting nitrogen mineralisation will also contribute to errors in simulation.

The present model deals inadequately with longer-term changes in soil organic matter content, and does not simulate how soil properties change as a result of tillage and soil erosion. Neither does it attempt to deal with limitations imposed by weeds, pests, diseases or nutritional limitations other than nitrogen.

These limitations mean that the model is not suitable for the regional estimation of farm production, as many of these constraints will be operational, and suitable input data are unavailable on a regional scale. We believe it is best suited to the evaluation of alternative strategies to improve productivity or reduce risk. Under such circumstances, the assumption can be made that these other constraints (weeds, pests, diseases, etc.) must be overcome, prior to invoking the technical innovation under evaluation. The model is used in such a context in the final paper in these proceedings.

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