Journal of Arid Environments (2000) **46:** 333–344
doi:10.1006/jare.2000.0699, available online at http://www.idealibrary.com on IDEAL®

The influence of climate change on maize production in the semi-humid–semi-arid areas of Kenya

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(Received 15 July 1999, accepted 15 August 2000)

The effect of climate change on maize production in the semi-humid and semi-arid, agro-climatic zones III-IV of Kenya was evaluated using two General Circulation Models (GCMs): the Canadian Climate Center Model (CCCM) and the Geophysical Fluid Dynamics Laboratory (GFDL), as well as the CERES-Maize model. Long-term climate data was obtained from three meteorological stations situated in eastern, central and western regions of Kenya, while maize data was obtained from six sites within the regions. The climate scenarios were projected to the year 2030. Temperature increases of 2·29 and 2·89°C are predicted by the CCCM and GFDL, respectively. Rainfall levels are predicted to remain unchanged, but there are thought to be shifts in distribution. It is predicted that the short-rains season (October–January) will experience some increased rainfall, while the long-rains season (April–July) will show a decrease. Maize yields are predicted to decrease in zone III areas, while an increase is predicted in zone IV areas. However, the predicted changes in yields are low since they all fall below 500 kg ha^{-1}, except the Homa Bay site. Thus, to counter the adverse effects of climate change on maize production, it may be necessary to use early maturing cultivars, practice early planting, and in eastern Kenya, shift to growing maize during the short-rains season.

Keywords: climate change; maize; semi-arid areas; Kenya; GCMs; CERES-Maize

Introduction

Maize is the staple food for over 90% of Kenya's population and provides about 42% of the dietary energy intake (Karanja & Oketch, 1990). Maize occupies a much larger area than any other crop with over 1 million ha of the crop being grown (Republic of Kenya, 1994). About 70% of the maize in Kenya is produced by small-scale farmers for subsistence. However, rising population pressure and variation of weather patterns have caused insufficient domestic production, thereby undermining the national food policy. In the 1960s and early 1970s Kenya produced sufficient food, but since the mid-1970s there has been periodic imbalances between food production and demand. To meet future food demand, projections indicate that maize supplies from domestic production and/or imports will have to double in the next 15–20 years (Karanja & Oketch, 1990). As most of the available arable land is already being utilized, future increases in maize production will have to rely on improvements in yields rather than areal expansion. Since maize production in Kenya is usually rainfed, a well-informed

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approach to the management of climatic factors influencing maize production is just as important as other inputs such as fertilizer, seed quality, and cultural management activities.

Maize production in Kenya

The major climatic factors affecting maize in Kenya include temperature, rainfall, day length, solar radiation, and humidity (Allan, 1971). Due to Kenya's position on the Equator, the variations in mean monthly temperature are 5°C a year. The maximum and minimum temperatures are closely correlated with altitude. Most of the maize in Kenya is rain-fed. Maize does not grow in areas with less than 500 mm rainfall, and is best suited to areas with over 750 mm, although it grows well in areas receiving up to 2200 mm per annum. In Kenya, maize grows well in climatic zones II, III and IV (Fig. 1, Table 1), with different varieties best suited to each zone. In recent years, population expansion in marginal areas has forced maize production to spread to zone V, but good yields are hampered by frequent droughts and poor soils. Rising population pressure and eccentricities of weather patterns have caused insufficient domestic food production, thereby undermining the national food policy. In the 1960s and early 1970s Kenya produced sufficient food, but since the mid-1970s, there has been periodic imbalances between food production and demand. To meet future food demand, projections indicate that maize supplies from domestic production and/or imports will have to double in the next 15–20 years (Karanja & Oketch, 1995; Mills *et al.*, 1995), and, as mentioned earlier, most of the arable land in Kenya is already being utilized so future increases in maize production will have to rely on improvements in yield rather than areal expansion.

The actual and potential maize production capabilities of the various maize-growing areas of Kenya depend on the agro-ecological zones. Usually, the wetter areas have higher yields than the drier regions because the most limiting factor in maize production is rainfall amount and distribution. Figure 1 shows the distribution of maize-potential areas of Kenya. Table 2 quantifies the maize production potentials according to agro-ecological zones. This study set out to determine the impacts on maize yields due to climate change scenarios in the semi-humid–semi-arid agro-climatic zones III and IV of Kenya and to evaluate the possible adjustment strategies necessary.

Table 1. *Description of the agro-climatic zones*

Agro-climatic zone	Annual rainfall (mm)	Rainfall/potential evapotranspiration (%)	Temperature zone	Mean annual temperature (°C)	Altitude (feet)
I	1100–2700	> 80	9	< 10°C	> 10,000
II	1000–1600	65–80	8	10–12	9000–10,000
III	800–1400	50–65	7	12–14	8000–9000
IV	600–1100	40–50	6	14–16	7000–8000
V	450–900	25–40	5	16–18	6000–7000
VI	300–550	15–25	4	18–20	5000–6000
VII	150–350	< 15	3	20–22	4000–5000
			2	22–24	3000–4000
			1	24–30	< 3000

Source: Sombroek *et al.* (1982).

Figure 1. Major agro-climatic zones and the maize growing areas of Kenya. Source: Sombroek *et al.* (1982) and CIMMYT (1999).

Data collection

Selection of study sites

Six study sites were selected in the transitional agro-climatic zones III and IV of Kenya at Katumani, Kampi ya Mawe, Kichaka Simba, Mtwapa, Paponditi and Homa Bay

Table 2. *Area under maize production in Kenya for various zones*

Attribute	Agro-ecological zone						
	Low	Dry mid	Moist mid	Dry transitional	Moist transitional	High transitional	Total
Rainfall (mm)	0–800	400–1400	1000–1400	1400–1800	1400–2000	1800–2500	
Current area (1000 ha)	42·3	260·8	277·4	80·4	557·7	348·9	1568
Percent total potential area	4·8	37·4	10·5	11·9	19·9	15·6	100
Production (1000 MT)	69·5	313·8	494·3	140·7	1366	972·1	3356
Yields (MT ha^{-1})	1·64	1·20	1·78	1·75	2·45	2·79	2·14

Source: Mills *et al.* (1995).

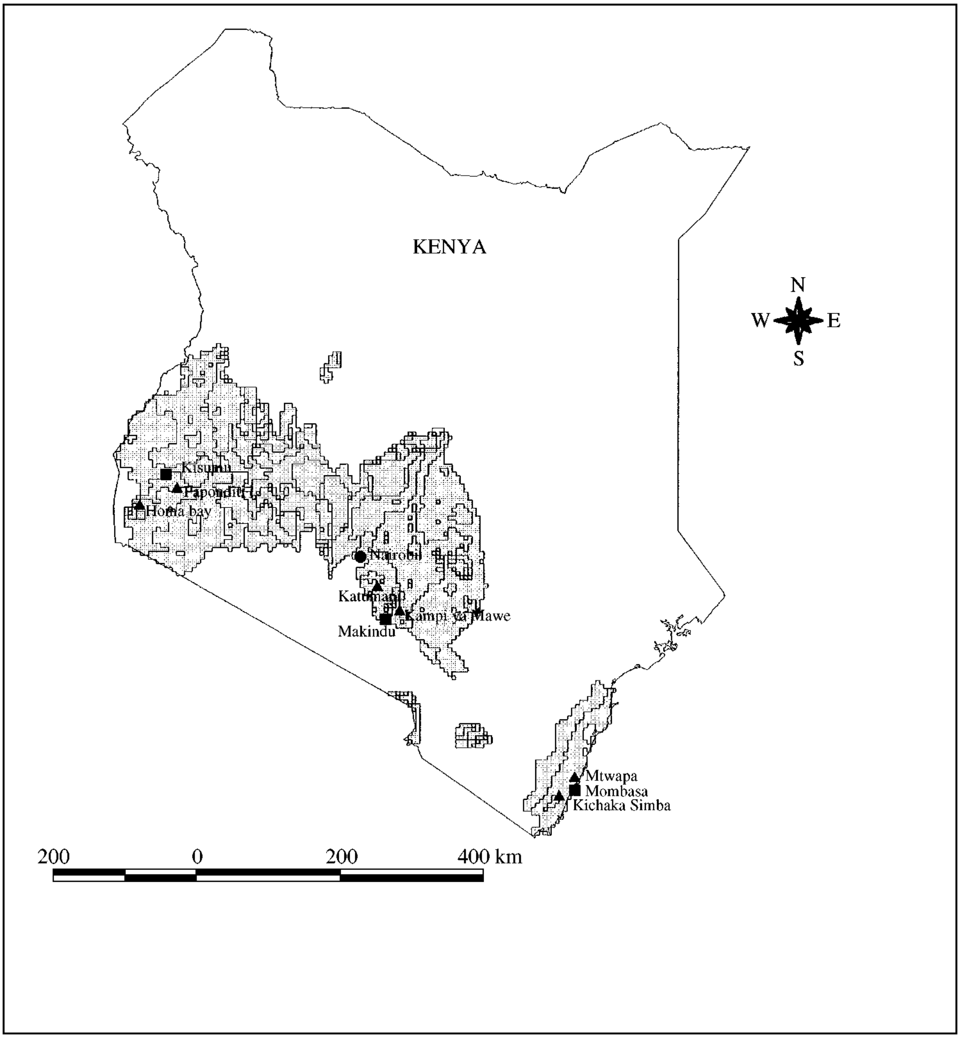

Figure 2. Location of the study sites in Kenya: □ maize growing zones; ■ meteorological station; ▲ maize experimental site.

(Fig. 2), where reliable climate and maize phenology data were available (Onyango *et al.*, 1994). Long-term weather data were obtained from the Kenya Meteorological Department stations situated close to the study sites, i.e. at Makindu, Mombasa and Kisumu (Table 3), while crop and soils data were obtained from the Kenya Agricultural Research Institute (KARI), Ministry of Agriculture and other institutions (Mati & Karanja, 1998).

Climate data

For baseline simulations and the creation of climate change scenarios, climate data was collected at two levels of detail as follows:

(1) Climate data for a 35-year period (1960–1994) was obtained from Mombasa, Kisumu and Makindu meteorological stations, for use in the GCMs. It included

Table 3. *Site characteristics for maize data*

Meteorological station	Site	Altitude (m)	Zone	Maize variety
Makindu	Katumani Research Center	1580	IV	Katumani composite
Makindu	Kampi ya Mawe	1160	IV	Makueni composite
Mombasa	Kichaka Simba	25	III	Coast composite
Mombasa	Mtwapa Research Center	130	III	Coast Composite
Kisumu	Paponditi	1160	III	Katumani B,C, 512
Kisumu	Homa Bay	1150	IV	Katumani B,C, 511

daily precipitation, maximum and minimum daily temperatures, and mean daily solar radiation.

(2) From the six crop-growing sites additional climatic data were collected for running the crop models, for the period 1988–1992, when controlled experiments on maize were conducted. These data included daily rainfall amounts, daily maximum and minimum temperatures, and daily solar radiation. The mean values of annual precipitation, and actual and potential evapotranspiration are shown in Table 4.

Soils data

Soil characteristics for each research site included soil depth, particle size classification, initial amounts of nitrogen in the form of nitrate and ammonium, pH, organic matter, fertilizer application dates and amounts, and type of fertilizer (Table 5). Also, data on soil albedo, moist bulk density, saturated water content, lower limit of plant water extraction, drained upper limit, horizon thickness, and C/N ratio. It was found necessary to classify each site by assigning it a generic soil type associated with the DSSAT soil characteristics in order to run the model.

Crop management data

Crop phenology data for the six study sites was obtained from controlled experiments covering 5 years (1988–1992), whereby two fertilizer application levels (0 and 25 kgN ha^{-1}) had been used. Maize varieties, planting dates, plant populations, dates of emergence, tasseling, silking, maturity, physiological maturity, and maize yields were recorded. In addition, the altitude, latitude and longitude of each site were recorded.

Table 4. *Climatic attributes of the study sites*

Climatic attribute	Homa Bay	Paponditi	Kampi Mawe	Katumani	Mtwapa	Kichaka Simba
Annual ET (mm)	1524	1500	1554	1388	1755	1575
Potential evaporation	1882	1882	1973	1647	2114	2073
Precipitation (mm)	1222	1176	708	673	1273	1301

Table 5. *Soil characteristics*

Attribute	Katumani	Kampi Mawe	Kichaka Simba	Mtwapa	Paponditi	Homa Bay
pH	6·3	6·2	6·2	7·0	6·8	6·0
Organic C (%)	0·57	1·10	0·66	0·66	1·01	1·97
Water content (mm 10 cm^{-1})	19·3	10·5	9·6	4·2	17·3	14·9
Bulk density (g cc^{-1})	1·32	1·25	1·50	1·49	1·57	0·99
Soil albedo	0·1	0·1	0·1	0·1	0·1	0·1
Saturated water content (cm)	120–160		80–120	80–120	80–120	120–160
Lower limit	125	153	138	115	100	110
Nitrogen (%)	0·12	0·13	0·08	0·07	8·1	0·2
Layer thickness (cm)	180	180	180	180	120	120
C/N	4·8	8·1	8·3	9·4	8·1	0·9

Table 6. *Calibration of the CERES-Maize model*

Station	Growing period (days)		Grain yields (kg ha $^{-1}$)		
	Simulated	Actual	Simulated	Actual	Percent
Homa Bay	118	123	4635	5120	90·5
Paponditi	130	126	1067	1120	95·3

Data analysis

Choice of models

Two General Circulation Models (GCMs), the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe & Wetherald, 1987) and the Canadian Climate Centre Model (CCCM) (Boer et al., 1992), were used for simulating climate change. The CERES-Maize simulation model (Jones & Kiniry, 1986) of DSSAT was used to simulate crop responses to changes in climate, management variables, soils, and different CO_2 atmospheric levels. The Decision Support System Transfer (DSSAT) is a comprehensive software system that integrates crop growth models with crop, weather, and soil data, and various application programs (IBSNAT, 1994). The DSSAT was used in this study to integrate databases and a crop model (CERES-Maize) in the climate change studies. In using the CERES-Maize model, some assumptions were made regarding the future maize growing conditions, such as the assumptions that there would be no soil problems such as salinity, no pest problems, and that both cultivar and management technology would remain the same.

Calibration of the CERES-Maize model

The CERES-Maize model was calibrated using the data from two stations, Paponditi and Homa Bay, for 1990 long rains, against the normal climate scenarios. The results are given in Table 6.

From the calibration results, the model was found to simulate yields well within acceptable limits, having an error margin of about 5–10%. It was also found that yields were generally underestimated, while the growing periods were slightly longer. Since the climate data used to simulate the weather scenarios had been adopted from the nearest meteorological station, and also that some of the climate data had to be generated, then the limitations of the sources of the climate data must be taken into consideration when using these results.

Selection of scenarios

The selection and construction of scenarios used in the climate impact assessment were made to estimate the effects of climate change. Data from the current standard WMO normal baseline climatological period of 30 years (1961–1990) were used. In selecting the six study sites mentioned earlier, these factors were taken into account. The climatological data from the baseline period were used as inputs for impact modelling. The GCMs were used to modify observed climate data and then create scenarios for each of the six crop sites.

Assessment of impacts

The GCM results needed to create the climate change scenarios are changes in minimum and maximum temperature, precipitation, and incident solar radiation. Crop growth and water use benefit from increases in carbon dioxide (CO_2). The CERES-Maize model simulates the changes in photosynthesis and evapotranspiration caused by increases in atmospheric CO_2. The model then produces results for climate change and the direct effects of CO_2 on crop growth and water use.

The CERES-Maize model was simulated for crop yield response, water balance, phenology, and growth throughout the season on a daily basis in relation to the major climatic factors, including daily solar radiation, maximum and minimum daily temperature, soils, precipitation, and management (maize varieties, sowing dates, potential fertilizer type, application rates, row spacing, and the potential yield per ha for the present variety). This data was run on baseline climate change scenarios to give present and projected maize yields in the region. The CERES-Maize model was simulated for multi-year scenarios using the CCCM and GFDL climate generators, for rainfed maize growing conditions, for both normal climate as well as projected climate scenarios. Future scenarios were projected to the year 2030, when CO_2 levels are predicted to double ($2 \times CO_2$) (Carter *et al.*, 1994). Assessments of changes in the modelled yields (t ha^{-1}) were also carried out to evaluate the implications of climate change on maize production.

Results and discussion

Climate change

The basic climatic attributes of the study areas are presented in Table 4. Although relatively high rainfall amounts have been recorded for Mtwapa, Kichaka Simba, Paponditi and Homa Bay, poor rainfall distribution and high evaporation rates have adverse effects on the performance of maize in these regions.

Results of climate change simulations by the two GCMs predicted temperature increases in the semi-arid zones III-IV of Kenya. In the absence of other environmental and social-economic factors, the magnitude of this warming varies with each zone. The GFDL model predicted higher temperature increases, averaging about 2·89°C, as compared to the 2·29°C temperature gradient predicted using the CCCM model. This compares well with the findings of Kariuki & Omenda (1998) who, using the same GCMs, predicted a temperature rise of 2 to 40°C for the main forest areas of Kenya. On a seasonal basis, both models predicted higher temperature gradients in the period from September to December, which is usually the hot or warm season. An increase in temperature at this time of the year would cause higher evapotranspiration rates, reducing available soil moisture.

The effects of climate change on rainfall showed higher totals for the short-rains season, from October to January, for all the study areas. The GFDL model simulated higher rainfall levels than the CCCM. Conversely, low rainfall levels were predicted for the months of May to July, which coincides with the grain-filling stage for maize in eastern and coastal areas of Kenya. Therefore, it appears that shifts in the seasonal growing stages of maize during the short-rains period (October–February) would be preferable to those for the long-rains period (March–July).

Prediction of long-term maize yields

The results of the climate change simulations for five planting dates within the planting season, beginning 15 February to 15 April, with both the CCCM and the GFDL models, are shown in Table 7. These scenarios were run for zero fertilizer application, so

Table 7. *Predicted seasonal maize yields*

	Yields for different planting dates ($kg\,ha^{-1}$)				
	15 February	1 March	15 March	1 April	15 April
Homa Bay					
Normal climate	5813	4740	1500	0	77
CCCM ($2 \times CO_2$)	6684	5652	3534	296	0
GFD3 ($2 \times CO_2$)	6609	5538	3724	474	0
Paponditi					
Normal climate	1559	1407	1149	821	158
CCCM ($2 \times CO_2$)	1337	633	1416	1692	396
GFD3 ($2 \times CO_2$)	1112	558	949	1644	554
Kichaka Simba					
Normal climate	2056	2399	2393	2166	2190
CCCM ($2 \times CO_2$)	1988	2402	2566	1923	1861
GFD3 ($2 \times CO_2$)	1820	2185	1800	1848	1717
Mtwapa					
Normal climate	1582	1068	549	29	17
CCCM ($2 \times CO_2$)	1921	1025	626	33	16
GFD3 ($2 \times CO_2$)	1723	1107	692	46	19
Kampi Mawe					
Normal climate	1153	343	123	0	0
CCCM ($2 \times CO_2$)	1881	1293	608	7	216
GFD3 ($2 \times CO_2$)	1440	1306	420	0	322

as to maintain uniform crop phenology data in all the study areas. In addition, fertilizers are rarely used for maize production by small-hold farmers in the semi-arid areas. Problems existed with the data from the Katumani site so they were not included in the final analysis.

These results indicate that planting date has a profound influence on maize yields. On average, the models predicted higher yields for crops planted early than those planted late due to the benefit of higher moisture levels in the soil early in the year during the grain-filling stage of the crop. This is because in the semi-humid and semi-arid areas of Kenya, rainfall tends to fall in a few heavy and poorly distributed storms within the growing season (Kilewe & Thomas, 1992). The results of the model simulation indicated that the highest yields would be obtained by planting the crop in mid-February. This would ensure optimum utilization of soil moisture from the onset of the rains. Depending on planting dates, both GCMs predicted on average an increase in grain yield by the year 2030. This can be linked to the beneficial effects of increased carbon dioxide and higher temperatures. From the weather scenarios, positive shifts in rainfall are expected to occur in the months of January, March, May, and September. The negative shifts in rainfall in the months of June and July would imply that earlier maturing maize varieties would be preferred.

The CCCM model predicted slightly higher yields than the GFDL model. Although both GCMs predicted higher grain yields compared to baseline normal climate simulations, it was noted that, with the exception of Homa Bay, the other areas would produce less than 2000 kg ha^{-1} of maize. Thus, despite these increases, maize yields would still be poor in these zones. The maize varieties most affected are the Makueni Composite and the Coast Composite. Thus, improvements in these varieties may be necessary, such as making them mature earlier in order to counter the expected adverse effects of climate change.

Conclusions

Climate change was predicted, by both CCCM and GFDL models, to affect temperature and rainfall characteristics in the semi-arid zones III-IV of Kenya. Temperature is expected to increase by 2·29 to 2·89°C by the year 2030. Seasonally, temperature is expected to increase in the months of September to December. Precipitation is expected to remain nearly the same quantitatively, but shifts in the seasonality are expected. However, the increases in temperature would result in increased evapotranspiration rates. This would theoretically cause a decrease in maize production in zones III of Kichaka Simba, Mtwapa and Paponditi, while an increase would be expected in zone IV areas, assuming no adverse effects from pests, diseases, and weeds. However, the predicted change in yields would be low, falling below 500 kg ha^{-1} in most cases.

Shifts in the planting dates would become necessary, particularly early planting of the crop in mid-February. The shifts in rainfall seasonality would therefore cause a reduction in maize yield by affecting the grain-filling period for long-maturing varieties. The increase in temperature in the short-rains period, and the reduction of rainfall in the long-rains period would necessitate a shift to a preference of growing maize in the short–rains season rather than during the long rains. As both the Makueni Composite and the Coast Composite varieties are likely to suffer most adversely from changes in climate, improvements on these maize varieties will be required in the future to provide more drought resistant crops with shorter growing periods.

Recommendations

This study obtained that, due to the predicted climate change, it would be necessary to prepare mitigation strategies for sustainable maize production in the semi-arid areas of Kenya. This should include: (1) research into the development of maize varieties that produce higher yields, are more drought resistant, and mature earlier; (2) the encouragement of early planting; (3) increasing awareness of farmers and local leaders to the possibility and effects of climate change, including the vulnerability of the crop and the necessary mitigation strategies; (4) searching for alternatives to rain-fed maize production in these dry zones, including the introduction of irrigation, runoff harvesting, use of soil conditioners and other such techniques of dryland farming; (5) the study of methods to improve maize culture, including use of fertilizers and manures, changes in planting dates, or shifts in the crop growing season such as growing maize mostly in the short-rains season in Eastern Kenya as opposed to the long-rains season; and (6) the support of further research on the adaptation of mitigation strategies against adverse climate change in the food sector in Kenya, including its effects on crops other than maize.

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