VULNERABILITY ASSESSMENT OF THE MAIZE AND SORGHUM CROPS TO CLIMATE CHANGE IN BOTSWANA

A. C. CHIPANSHI[1], R. CHANDA[2] and O. TOTOLO[2]

[1]*Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration,*
408-1800 Hamilton Street, Regina, SK., S4P 4L2 Canada
E-mail: chipanshia@agr.gc.ca
[2]*Environmental Science, University of Botswana, P/Bag 0022, Gaborone, Botswana*

Abstract. This study examines the sensitivity of maize and sorghum crops to global warming in Botswana, a country with arid climatic conditions and shortfalls in locally produced grain. The vulnerability of the maize and sorghum crops to climate change were studied using crop simulation models while climate change scenarios were generated from Global Circulation Models. Simulated yields indicated that rain-fed crop production under the observed climate was a small fraction of what could be produced under optimal conditions. The gap was attributed to both physical (especially lack of rain) and socio-economic constraints. Using the southern African core climate change scenario, simulated yields declined by 36% in the case of maize and 31% for sorghum in the sand veldt region. Yield reductions from the hard veldt region were in the order of 10% for both maize and sorghum. The growing season became shorter, the average reduction in days in the sand veldt region being 5 and 8 days for maize and sorghum respectively, and correspondingly, 3 and 4 days over the hard veldt region. The food security option currently followed in Botswana was found to be a good adaptive strategy under a changed climate.

1. Introduction

The threat that climate change poses to climate sensitive economic sectors such as agriculture, forestry, wetlands, etc., has necessitated the assessment of the potential impacts of climate at various scales on these sectors in order to reduce their vulnerability and thereby secure the livelihoods of those who depend on them. While recognizing that both the natural and anthropogenetic factors contribute to climate change, the unprecedented rapid increase in green house gases since the industrial revolution implicates human activities to be the major drivers of the projected change in global climatic variables, especially temperature and precipitation. It is feared that ultimately, this might lead to changes in the productive capacity of agricultural soils and perhaps also bring about frequent occurrences of episodic events such as prolonged heat periods, cold snaps, floods and droughts (Schneider, 1992; Houghton et al., 1996). Research on how climate change will affect various ecosystems has progressed as an international effort on many fronts, the results of which have been summarized in the Intergovernmental Panel on Climate Change (IPCC) reports. For agriculture, studies such as those pioneered by the Country Studies Program of the U.S.A. (Smith and Pitts, 1997) have broadened regional understanding of the impacts of climate change in many parts of the world including Africa, Europe, Asia and the Americas (e.g., Hulme et al., 1996; Rosenzweig et al., 1995; Alexandrov and Hoogenboom, 2000; Saseendran et al., 2000). Yet many more case-focussed studies remain to be conducted in order to reduce blanket generalizations and solutions that often characterize the regional and global assessments of the impacts of climate change on crop production. This study is a contribution towards meeting the challenge for more local level studies.

1.1. STUDY AREA AND BACKGROUND

Botswana is landlocked and straddles the Tropic of Capricorn in the centre of the Southern African Plateau (Figure 1). The mean altitude above sea level is approximately 1000 metres and the country's total area is 582 000 km^2. Much of the country is flat, with gentle undulations and occasional rocky outcrops. The eastern region has a relatively less harsh climate and more fertile soils than the rest of the country; and consequently, it is here that most of the people live (one of the study areas is located in this belt, hereafter called the hard veldt). The rest of Botswana (more than two thirds of the total area) is covered by the thick sand layers of the Kgalagadi desert. The sand cover can be as thick as 120 metres. There is an almost complete absence of surface water in the Kgalagadi sand region (the second study area is located in this belt and hereafter called the sand veldt). Due to the scarcity of water for irrigation, nearly all of the crop production is rain fed and under traditional technologies. Analysis of local grain production versus consumption made by the Government of Botswana has indicated that between 70 and 96% of the national annual requirements for staple cereals (mainly sorghum and maize) are imported (MoFDP, 1997).

The scarcity of water for arable agriculture in Botswana is reflected in the low and highly variable annual rainfall received and the high evaporative demands. Rainfall varies from less than 200 mm in the southwest (cv $\sim$45%) to over 650 mm in the northeast (cv $\sim<$35%) and is received during the summer months (October to March) (Bhalotra, 1987). Potential evapotranspiration rates range from 1000–1500 mm yr^{-1} in the northeast to $>$2000 mm yr^{-1} in the southwest (Hulme et al., 1996). Clearly, a large deficit in the available water exists throughout the year and this puts Botswana in an arid climatic zone. Recognising the close link between rainfall and crop production, many of the agroclimatic analyses that have been carried out in the past have related aspects of rainfall characteristics (totals, distribution, and departures from normal) to crop yields. Examples of such analyses include regression studies by Simms (1981) and Vossen et al. (1985). The pentad method, which divides the rainfall season into 5-day periods, has been used as an improvement over regression equations to define the length of the growing season for specific crops (Bhalotra, 1985). A few studies of crop-climate relationships have used parameterized methods to explain crop yield variability. These include the water budget approach and derived stress indices (Frere and Propov, 1979;

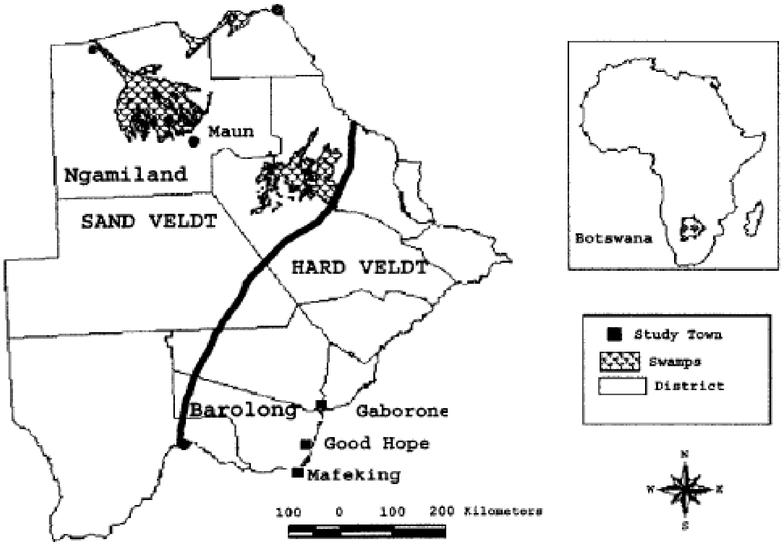


Figure 1. Location of the study areas from the hard and sand veldts.

Vossen, 1990). Yet other studies have been based on simple classifications of soils and/or rainfall to define agro-ecological zones. While these studies affirm that a direct linkage exists between arable agriculture and moisture deficiency in Botswana, the utility of these statistical relationships in climate change studies on their own however is limited. It cannot be ascertained that future climatic conditions will be analogous to climatic conditions for which these models were formulated. In this study, process based approaches, which use fewer site-specific constants, were preferred to statistical models. Besides the physical factors, sociological concerns, many of which are still difficult to represent in biophysical models, contribute immensely to low/high crop production. Food preferences and government policy, for example, may override what is environmentally sound. It is documented that sorghum outperforms maize in most dry climates (e.g., Chipanshi and Ringrose, 2001) but producers accustomed to eating maize would rather grow maize than sorghum, even where there is evidence that sorghum is the ideal crop for the semi-arid conditions. If, therefore, as is widely feared, climate change results in reduced precipitation, rain-fed arable agriculture would become even riskier in Botswana. This study was undertaken in an attempt to anticipate the problem and be able to carry out ameliorative actions ahead of time. It assesses the vulnerability of sorghum and maize crops to climate change scenarios using dynamic crop simulation models and suggests appropriate adaptive measures where necessary. It is often suggested in the climate change literature (e.g., IPCC, 1998) that some effects of climate change are likely to be beneficial for some locations. The extent to which this may be true in the case of grain production in Botswana is also explored by examining the response of maize and sorghum to climate change at two locations.

2. Data

Simulated changes in maize and sorghum yields due to climate change were made for Ngamiland West (northwestern sand veldt) and Barolong (southeastern hard veldt) agricultural districts of Botswana (Figure 1) using biophysical models (discussed under Section 3). These districts were chosen because of the following: both districts receive the same amount of the mean total annual rainfall of about 500 mm but they are pedologically and ecologically different. The latter is in the hard veldt while the former is in the sand veldt and bordering the Okavango Delta. Soils of the sand veldt are predominantly *Arenosols*, and cover more than 60% of the Ngamiland West district (Verbeek, 1989). *Arenosols* are sandy soils which have a low water retention capacity and, consequently, their agricultural potential is relatively low. For this reason, the sand veldt is occupied by agro-pastoralists who often do not produce enough grain for home consumption, let alone for sale (Silitshena, 1998). Sandy soils are interspaced with *Luvisols*, *Fluvisols* and *Phaeozems* which are relatively fertile on account of being in the low lying areas of the Okavango Delta (see location of Delta in Figure 1). The distribution of these fertile soils is however limited, their coverage being about 30 to 40% of the total district. Ngamiland West agricultural district had other advantages over other sites from the sand veldt region in that maize and sorghum yield statistics and the 30-year climate data at Maun airport were available. Climate data included the daily maximum and minimum temperatures, rainfall and sunshine hours from 1961 to 1990. Human settlement is sparse in the sand veldt region but the majority of the country's nature reserves and wildlife are found here.

The hard veldt region in the study is represented by Barolong. The hard veldt has a long history of arable agriculture and both emergent (those who grow enough for themselves and for sale) and commercial farmers are found in this region. The soils of the hard veldt are predominantly *Luvisols*. These soils have a subsurface horizon of clay (an *argillic* B-horizon), and consequently have a very high water retention capacity and nutrient status. *Luvisols* cover more than 60% of the district while the rest are an assortment of sandy soils and rocky outcrops. The 30-year climate data came from two nearby climate stations, Good Hope (rainfall only) and Mafikeng in South Africa (daily maximum and minimum temperature and sunshine). Mafikeng data were used because it was the closest to Good Hope since no temperature data existed for any location in Botswana south of Gaborone prior to 1990. The hard veldt is relatively heavily settled and urbanization has progressed faster than the sand veldt. The two regions as described above capture the dominant agro-ecological divisions of the country. Maize and sorghum crops

Table I

Physical characteristics of the soils used in crop simulations (Sa = Sand, Cl = Clay, Lm = Loam and PAW = Plant Available Water was calculated from the drained upper limit and wilting point of the layer. The texture as shown is the most common in the whole profile)

Soil type	Region	Depth (mm)	PAW (mm)	Texture (%)	Drainage
Calcic luvisol	Hard veldt	0–200	15.8	SaClLm = 53	Medium
		200–300	7.9	SaLm = 32	Medium
		300–400	23.7	LmSa = 15	Medium
		>400	31.6		
Eutric vertisol	Hard veldt	0–270	14.0	SaClLm = 80	Slow
		270–825	30.0	SaCl = 20	Slow
		>825	11.0		Slow
Haplic arenosol	Sand veldt	0–140	6.6	SaClLm = 65	Slow
		140–425	13.4	SaLm = 35	Slow
		425–900	27.0		Slow
Ferric arenosol	Sand veldt	0–200	3.8	SaClLm = 90	Very slow
		>200	15.2	SaLm = 10	Very slow

were chosen for vulnerability assessment because of their widespread use as food crops in Botswana.

The Maize and Sorghum yield models used in this study require a minimum set of inputs of weather, soil and crop management data. Required climate data are daily values of maximum and minimum temperature, daily solar radiation and rainfall. Solar radiation data at both study sites were not available but these were calculated using an Angstrom type of equation using observed sunshine hours (Adringa, 1986). Required soil data include the physical soil properties such as particle size distribution, moisture holding capacity and bulk density. These were obtained from the Department of Soil Survey (Government of Botswana). A sample of the physical characteristics of the soils used in the study is shown in Table I. Management data which include the planting dates, fertilizer application and seeding rates were obtained from the database managed by the Sebele Agricultural Research Station in Gaborone (Maphanyane, 1999, pers. comm.).

Besides the above data, the CERES group of models require a set of parameters describing the crop environment interactions, termed genetic coefficients. To use the CERES maize and sorghum models in Botswana, it was necessary to obtain genetic coefficients of the widely grown varieties. Results of field trial plots at

Table II

Genetic coefficients of Botswana maize and sorghum cultivars

MAIZE cultivar	P1	P2	P5	G2	G3	PHINT
Kalahari Early Pearl (KEP)	200	0.3	800	700	8.5	38.9

P1: Length of the juvenile period (degree days above 8 °C)
P2: Factor to account for delay in development when day length is less than the optimum
P5: Time in degree-days from silking to maturity
G2: Maximum kernels per plant
G3: Kernel filling rate (mg/day) during grain filling under optimum conditions
PHINT: Phylochron interval (time in degree days between successive leaf tip appearance)

SORGHUM cultivar	P1	P20	P2R	P5	G1	G2	PHINT
Segaolane	460	12.5	90	600	5	6	49.0

P1: Length of the juvenile period (degree days above 8 °C)
P20: Longest day in hours for maximum development
P2R: Delay in development (degree days) if hours are less than P20
P5: Period from grain filling to maturity in degree-days
G1: Scaler for leaf size
G2: Scaler for partitioning of assimilates to the head
PHINT: Phylochron interval (time in degree days between successive leaf tip appearance)

Sebele Agricultural Research station (∼15 km north of Gaborone) were used to derive the genetic coefficients. Field trial plots data included planting date, plant population, fertilizer application rates, plant stand density, crop stages, number of ears per plant and grain weight at harvest. Model calibration coincided with the 1997/98 growing season. To establish appropriate coefficients, the Genetic Coefficient Calculator (Hunt et al. (1993) of DSSAT (see Tsuji, 1994) was used. The method uses an iterative procedure which compares simulated and observed values and genetic coefficients are modified until the agreement between observed and modelled values is as close as possible. The calibration experiment was conducted for medium maturing maize and sorghum, that is Kgalagadi Early Pearl (KEP) and Segaolane crop cultivars, respectively. These varieties are widely grown in Botswana (Maphanyane, 1999, pers. comm.). The calculated genetic coefficients are shown in Table II.

Table III

Selected characteristics of the GCMs used in this study

Model	CCC	OSU	UKTR
Resolution	Atmospheric: 3.7 × 3.7°, 10 layers Ocean: 1.8 × 1.8°, 29 levels	4 × 5°, 9 levels 4 × 5°, 13 layers	2.5 × 3.75°, 11 layers 2.5 × 3.75°, 20 layers
Major processes	• Has thermodynamic ice model • Uses modified bucket model for water budget analysis • Has flux correction for heat, water and ocean temperature	• Has thermodynamic ice model • Land surface model includes canopy processes • No flux correction for heat and water	• Previous model outputs are used to initialize the atmospheric and ocean modules • Land surface scheme includes stomatal control by plants • Has flux correction for heat and water

CCC – Canadian Climate Centre.
OSU – Oregon State University.
UKTR – United Kingdom Transient.

3. Methodology

Guidelines that have been suggested for creating climate change scenarios for Country Study Programs (Smith and Pitts, 1997; IPCC, 1992) were used. These were Global Circulation Models (GCMs) and transient scenarios. More than one GCM was used because results of climate change experiments are not always the same between two or more models. In this study, the GCM that has been used to study the climatic change pattern of southern Africa, the United Kingdom Transient GCM (UKTR), was chosen since it has been tested in the study area, and is hereafter referred to as the 'core scenario'. It is one of the leading models that has less noise in simulating the climatology of southern Africa (Hulme et al., 1996). In addition, the UKTR is known to capture ENSO-like events that bring about rainfall variability across Southern Africa (Joubert, 1995). In order to represent the range of extremes that may take place in rainfall, two other models, which simulate extreme drying, on one hand, and extreme rainfall, on the other, are included in this discussion. These are the Canadian Climate Centre (CCC) GCM (McFarlene et al., 1992) and the Oregon State University (OSU) GCM (Schlesinger and Zhao, 1989), respectively. The approach of using a variety of GCMs that span a range of precipitation values has been used elsewhere to estimate the unknown variability in precipitation (Carter et al., 1996). While it is not the intention of this study to discuss the underlying assumptions of the GCMs, relevant characteristics of the GCMs used in this study are shown in Table III. Detailed discussions of GCM characteristics can be found in Gates et al. (1992) and Boer et al. (1992).

The above GCMs were run assuming the doubling of CO_2 concentration in the atmosphere ($2 \times CO_2$) over mid 20th century conditions. Average monthly rainfall and temperature anomalies simulated by the GCMs were added to baseline climate data (observed daily weather values at sites in each of the two crop districts). For temperature, the difference in temperature between $2 \times CO_2$ and $1 \times CO_2$ simulations was added to the observed daily temperature data for the period 1961 to 1990. For rainfall, the ratios in precipitation ($2 \times CO_2/1 \times CO_2$) were multiplied by observed precipitation values. Incremental scenarios, also known as arbitrary changes in climate, were used to create another set of scenarios so that a wide range of the likely temperature changes could be examined. Changes in temperature for incremental scenarios were +2 and +3 °C over the base period of 1961–90 but assuming that the current rainfall variability will remain the same.

Based on results of GCM experiments, climatic change patterns for the study areas were arrived at by comparing the long term observed temperature and rainfall (1961–1990 climate normals) with those simulated from the UKTR, CCC and OSU GCMs. GCM experiments were made using the Model for Assessment of Green house-Gas Induced Climate Change SCENario GENarator (MAGGIC SCENGEN) software (Hulme et al., 2000). The observed values are data points at Maun or Good Hope/Mafeking while simulated values relate to gridded data over a large area of approximately 5° square enclosing the study areas. We therefore place more weight on trends more than the absolute values when comparing the simulated with the observed climate. Temperature is shown as mean monthly values while precipitation is represented as percentage departures from the normal (climate of 1961–1990).

Maize and sorghum yields under the present and future climate scenarios were simulated using the Crop Estimation Through Resource and Environment Synthesis (CERES) models packaged in the DSSAT (Decision Support for Agrotechnology Transfer) software (Tsuji et al., 1994). The CERES family of models for cereals simulate crop growth, development and yield. The processes that are simulated on a daily basis include the water balance, nitrogen dynamics, phenology and plant growth. In order to investigate the effect of climate on these processes and crop yields, the following assumptions were made: pests and natural disasters such as floods and droughts have no effect on crop yields. In addition, it was assumed that technology and management practices including the tolerance of cultivars will remain the same under conditions of climate change. Given these assumptions, simulated yields were intended to bring out effects of climate change on crop performance. Due to the strong response that elevated CO_2 may have on crop yields in the version of the CERES models used in this study, the 1961–1990 background CO_2 was used. This approach was taken in view of the fact that several unknowns exist regarding the physiological and biochemical responses of crops at elevated CO_2 levels (Archambault, 2001). Where the combined effects of CO_2 concentration and climate change have been simulated (e.g., Jansen, 1990; Adams et al., 1990; Toure et al., 1995) only the effects of CO_2 on radiation use efficiency have been addressed. Other physiological processes such as stomatal resistance and transpiration are difficult to explain.

In order to compare changes in yields following a climate change experiment, the difference between the experiment and the potential was expressed as a percentage of the potential. The potential represents yields under the observed climate without stresses. Mean values were used in the comparisons.

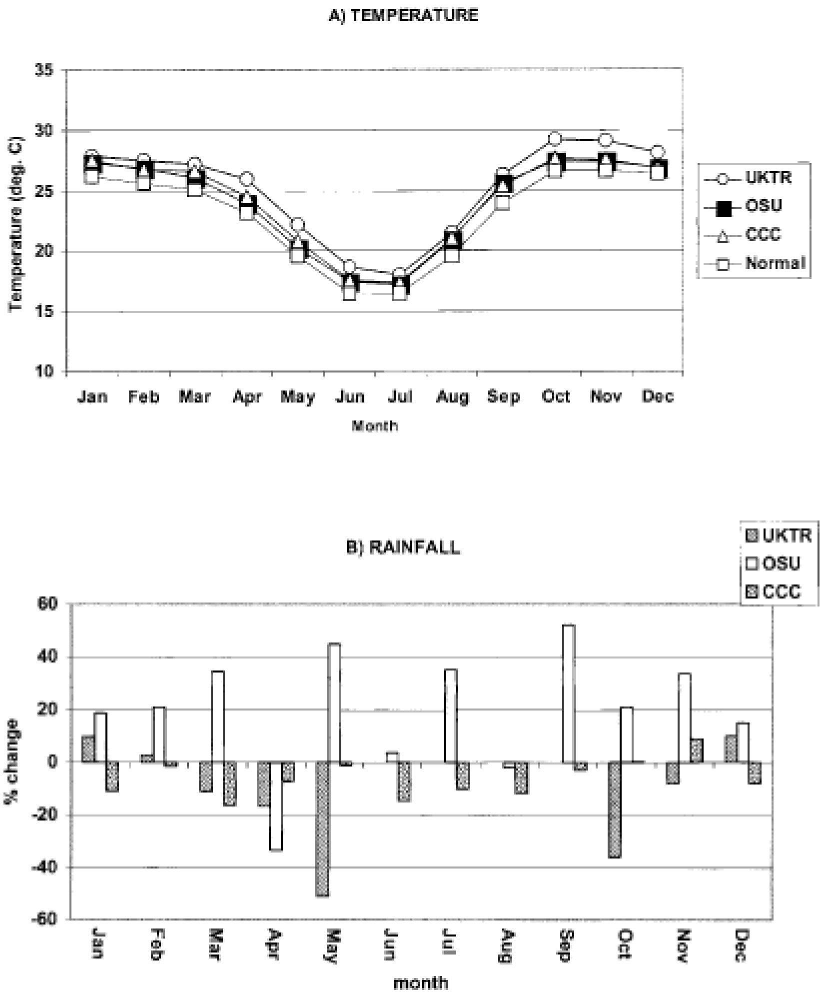
4. Results

4.1. SIMULATED TEMPERATURE AND PRECIPITATION

Over the sand veldt region, the core scenario simulated an annual average temperature increase of 2.2 °C with respect to the normal (1961–1990), (Figure 2a). This was followed by the CCC, which was also warmer, by 1.1 °C while the OSU was warmer by 1 °C. With respect to rainfall (Figure 2b), both the core scenario and the CCC showed the largest deficits during the summer rainfall months of January through May. Summer months span two adjacent years in Botswana (October to March). Moisture deficits and rising temperature could result in increased evapotranspiration rates, changes in the relative humidity and radiation. Under rain fed agriculture, increased moisture losses to the atmosphere can lead to increased moisture stress as anticipated by the two drying scenarios represented by the UKTR and CCC. From the hard veldt region and using long-term climate data at Good Hope/Mafeking, the change in the mean monthly temperature (Figure 3a) was around 1 to 2 °C and this was less than what was projected for the sand veldt region. Of the three models, only the UKTR model showed a seasonal difference in temperature between the observed and simulated values, being highest during the winter dry months. The changes in the simulated precipitation (Figure 3b) were comparable to those from the sand veldt region in terms of the timing of high deficits, i.e., towards the end of summer months of March to May. On a relative basis, the differences in temperature and precipitation between the observed and simulated climate indicated that the hard veldt may be less vulnerable to warming and drying than the sand veldt.

4.2. CROP SIMULATIONS

The potential yields simulated by the crop models and observed yields were compared at crop district level (only 11 years are shown in the results due to the non availability of crop yield data prior to 1979). Potential yields are weighted averages of model-simulated values for different soil types found in the study areas. The comparison of observed and simulated yields showed difference by a wide margin at both study sites (see Tables IV and V). For those years when data were available, yields as officially reported were below what could be expected under the prevailing climatic conditions. For the hard veldt region (Table IV), observed maize


A) TEMPERATURE

B) RAINFALL

Figure 2. Simulated changes in (a) temperature and (b) precipitation for the sand veldt region and using climate values at Maun airport.

yields in 11 years were 8% of what was potentially achievable. Observed sorghum yields were 21% of the potential yields for the same period. The gap between the potential and actual yields was even wider for the sand veldt region where the observed maize and sorghum yields in 11 years accounted for only 5% and 8% of the potential yields, respectively (Table V). The effect of the harsh environment at both locations on grain yields is further illustrated by years when no observed

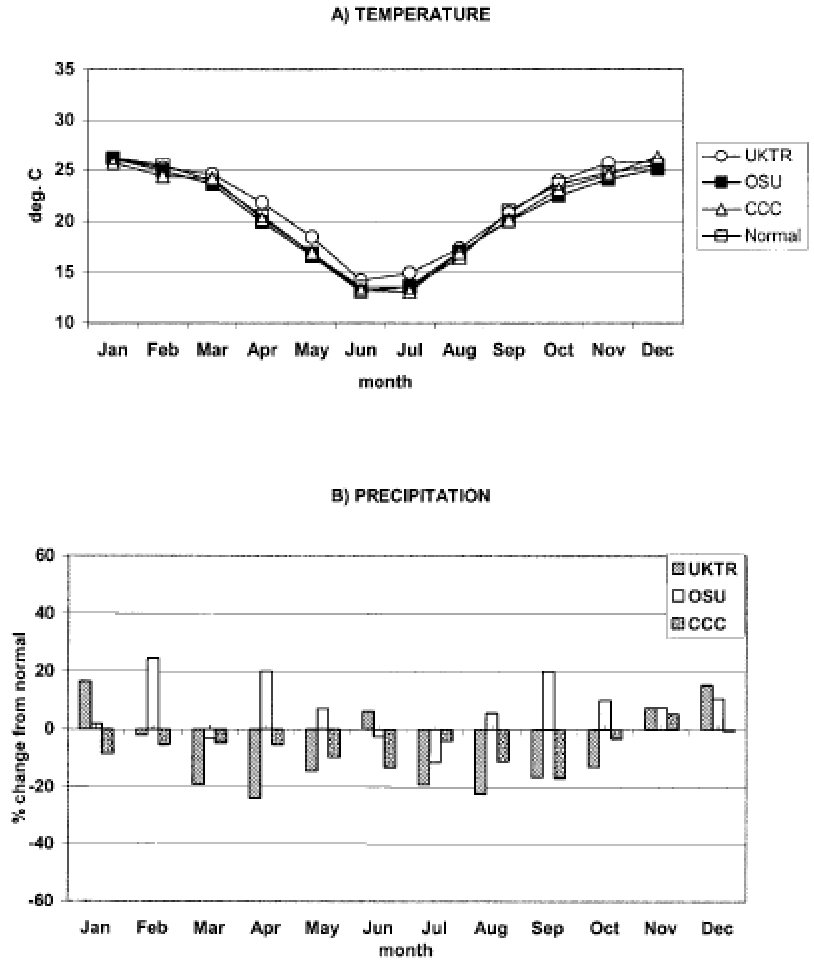


Figure 3. Simulated changes in (a) temperature and (b) precipitation for the hard veldt region and using climate values at Good Hope/Mafeking.

yields were recorded in 1985 and 1988. These years were characterized by drought conditions that covered most of the country (Nicholson, 1994; Van Regenmortel, 1995). Besides the hostile climate, several other factors affect agricultural production in Botswana. Many of the subsistence farmers blame their low production on lack of technology (especially with respect to land preparation), inadequate labour, lack of inputs and low capital (SMEC, 1987; van der Maas, 1994; Makhwaje et al., 1995). If we anticipate that the current trend of these constraints to grain production will continue in the 21st century, the actual yields could drop even further since stresses arising from pest occurrence, cost of inputs, and economic downturns may become worse under a changed climate for most subsistence farmers (Hume et al., 1996).

The projected changes in grain yields due to climate change as predicted by the GCM scenarios are shown in Tables IV and V and results of each scenario are distinguished by name. For the hard veldt region, the UKTR scenario shows the largest decrease in both maize and sorghum yields followed by the CCC. The wet scenario represented by the OSU shows slight increases in both maize and sorghum yields. The drop in yields of maize and sorghum using the UKTR experiment results is nearly the same at around 10%. The reduction in time from seeding to maturity for both crops is similar, dropping by 3 and 4 days. The CCC and OSU experiments indicate slight increases of 1 or 3 days at the hard veldt location. Yield reduction between maize and sorghum differs by 1.6% using the UKTR and by less than 1% using the CCC experiment. Based on yield potential alone, this may suggest that growing maize may be advantageous over sorghum in the hard veldt. Growing maize, however, requires more management than sorghum (Maphanyane, 1999, pers. comm.).

Maize and sorghum yield reductions of around 29.5% and 22.5% were projected by the core scenario experiment in the sand veldt region (Table V). Except for the wet scenario (OSU) which showed an increase in grain yields, the dry scenarios (UKTR and CCC) indicated that both maize and sorghum yields could decline over the potential yields. Yield reductions as projected by the core experiment were accompanied by a shorter growing time of between 5 and 8 days for maize and sorghum respectively. All the three climate change scenarios indicated a reduced length of growing time for the sand veldt region.

Overall, this analysis shows that the adverse effects of a warmer and drier climate may exhibit different impacts depending on location and crop type. The drop in yields for the hard veldt region following a climatic shift is relatively smaller compared with results from the sand veldt region (see Tables IV and V). The relatively higher yield reductions in the sand veldt region point to the myriad of problems that currently haunt this region in light of the poor sandy soils and high evaporative losses. As a result, growing a water-demanding crop in the sand veldt region such as maize under a drier climate may become even more difficult.

4.3. CROP SIMULATIONS USING INCREMENTAL TEMPERATURE CHANGES

Arbitrary changes in temperature were selected to investigate the variations that could occur in crop yields in response to climate change. Temperature changes of 2 and 3 °C were assumed and these rates are within the range of estimates suggested by the IPCC for a changed climate (Leggett et al., 1992). At both locations, the incremental changes in temperature led to reduced maize and sorghum yields in comparison to the observed yields under the observed climate. For the

Table IV

Sensitivity of the simulated maize and sorghum crops to climate change over the hard veldt region (ferric luvisol)

Base year	Observed	Yield (kg/ha)				Harvest dates (Julian)			
		Potential	UKTR	CCC	OSU	Potential	UKTR	CCC	OSU
MAIZE									
1980	90	1595	1265	1449	1923	61	60	65	66
1881	1670	2413	1729	2154	2442	68	61	67	68
1982	4175	2366	2609	2520	2030	57	55	58	59
1983	2870	2001	2399	2101	1860	57	53	57	56
1984	1050	1019	881	804	831	53	52	55	56
1985	0	2737	1890	2157	2747	55	52	53	54
1986	20	2628	2315	2669	3259	58	55	59	60
1987	20	2085	1501	1738	2976	55	51	53	54
1988	10	2860	2534	2856	3241	57	54	58	59
1989	120	2807	2958	2949	2500	67	63	69	67
1990	3390	2673	2518	2601	3015	62	59	64	62
Average	180	2289	2054	2182	2439	59	56	60	60
	% Change		–10.3	–4.7	6.5		–5.4	1.2	1.7
SORGHUM									
1980	105	3771	2853	3302	4784	98	94	99	104
1881	1195	8264	7850	8464	8643	104	97	105	109
1982	2295	6007	5483	5745	6432	88	85	91	93
1983	360	1990	1884	1900	2435	85	80	86	86
1984	815	755	574	645	1058	80	77	80	83
1985	40	3726	2353	3151	5027	82	79	83	85
1986	670	3464	3096	2837	4289	84	80	87	88
1987	600	2126	1357	1795	3002	80	77	82	82
1988	1070	6294	5756	6347	6849	88	84	89	91
1989	3585	7581	7355	7682	7793	103	97	106	107
1990	120	5670	5172	5482	6175	95	91	96	99
Average	1000	4513	3976	4305	5135	90	86	91	93
	% Change		–11.9	–4.6	13.8		–4.7	1.7	4.1

Table V

Sensitivity of the simulated maize and sorghum crops to climate change for the sand veldt region (haplic arenosols)

Base year	Observed	Yield (kg/ha)				Harvest dates (Julian)			
		Potential	UKTR	CCC	OSU	Potential	UKTR	CCC	OSU
MAIZE									
1980	50	1489	1467	1167	1608	40	42	37	37
1881	120	3032	2145	2464	2895	44	37	39	39
1982	225	1187	827	1014	1211	36	32	33	34
1983	15	1717	1182	1325	1911	36	32	33	33
1984	15	1787	1727	1839	2186	51	45	49	49
1985	25	1711	915	1336	1827	39	32	37	38
1986	40	2597	1931	2154	2838	41	33	39	39
1987	30	1259	750	978	1671	35	31	34	34
1988	0	1968	1619	1559	2445	38	32	37	35
1989	125	4023	2316	2839	2721	45	36	40	38
1990	650	1786	1015	1229	1947	39	34	35	35
Average	110	2051	1445	1628	2114	40	35	38	37
	% Change		–29.5	–20.6	3.1		–13.1	–7.0	–7.4
SORGHUM									
1980	60	5153	3837	4373	5043	85	73	78	78
1881	145	7085	5733	6490	6478	92	76	83	83
1982	160	821	610	688	984	76	67	70	71
1983	35	2057	1706	1828	2714	76	68	72	72
1984	285	194	270	175	213	60	82	56	56
1985	55	2364	2119	2063	3272	79	69	74	74
1986	35	3774	3133	3418	4818	84	71	77	78
1987	200	1902	1184	1532	2397	69	67	64	70
1988	0	2897	1523	2123	2570	80	68	75	76
1989	570	5868	5215	5700	5648	93	78	86	86
1990	20	5174	3561	4562	5826	83	72	76	76
Average	280	3390	2626	2996	3633	80	72	74	75
	% Change		–22.5	–11.6	7.2		–9.8	–7.5	–6.5

sand veldt (Table VI) the reduction in maize yield given a 2 °C rise was 21.6% but this increased to 35.8% for a 3 °C rise in temperature. The drop in sorghum yield given the same temperature change in the same region was lower in comparison to maize, being 16.1 and 25.6% for a 2 and 3 °C rise in temperature, respectively. The simulation showed that the length of growing time decreased by 5 and 7 days for maize and 10 and 14 days for sorghum. Maize had a shorter growing time than sorghum. This result indicates that sorghum could do better under a changed climate than maize in the sand veldt region.

We found a similar pattern in yield reductions in the hard veldt region as previously found in the sand veldt for the same incremental temperature values (Table VII); that is, yields decreased as temperature was increased by 2 or 3 °C above the observed climate. The length of the growing time became shorter for maize than sorghum. Both maize and sorghum yield and growing time reductions were much lower in this region compared to the sand veldt and this further reinforced the earlier finding that the hard veldt location is more favourable to arable farming than the sand veldt region on account of their good soils.

5. Discussion

Results of this study indicate that grain farming in Botswana is constrained by the poor soils and inadequate precipitation. These conditions are likely to worsen during the 21st century due to low precipitation and high temperature that are projected by GCM scenarios over the next several decades. Simulated maize and sorghum yields in the two contrasting regions of Botswana have shown that yields and the length of the growing time decrease because of temperature increase.

Both maize and sorghum are C4 plants, which have optimum photosynthetic response at higher temperatures (30 to 35 °C) and insolation, than most C3 plants. However the high temperatures and insolation will be accompanied by elevated CO_2 levels and there is evidence that there are fewer benefits of growing C4 plants under elevated CO_2 levels (Salisbury and Ross, 1985). Instead, C3 plants outperform C4 plants at higher CO_2 levels (Ringius et al., 1996) and most weeds for maize and sorghum are C3 plants. Weed competition with maize and sorghum is therefore more likely to increase. Also, it is expected that problems of the sandy environment such as degraded fertility and erosion will increase. *Arenosol* soils, which cover more than half of the country, are most liable to wind erosion and a drier and warmer climate can only worsen soil erodibility and nutrient loss. Since the 1990s, evidence from satellite imageries and field work indicates that soil exposure around settlements/ boreholes and encroachment of woody weeds on bare soil areas, have been taking place in Botswana (Ringrose and Matheson, 1990). These findings may be indicative of a warming trend taking place already, although it is currently attributed to overgrazing.

Table VI

Simulated changes in maize and sorghum over the sand veldt region (Haplic arenosol) given incremental temperature rises of 2 and 3 °C

Base year	Yield (kg/ha)			Harvest dates (Julian)		
	Climatology	2 °C rise	3 °C rise	Climatology	2 °C rise	3 °C rise
MAIZE						
1980	1489	–	972	40	–	33
1981	3032	2254	1888	44	37	34
1982	1187	917	724	36	33	31
1983	1717	1353	923	36	33	29
1984	1787	1981	1904	51	43	42
1985	1711	1031	886	39	32	32
1986	2597	2149	1998	41	34	33
1987	1259	902	771	35	32	29
1988	1968	1837	1530	38	33	32
1989	4023	2456	2007	45	37	33
1990	1786	1202	868	39	34	30
Average	2051	1608	1316	40	35	33
% Change		–21.6	–35.8		–13.8	–19.4
SORGHUM						
1980	5153	4168	3483	85	74	68
1981	7085	5949	5311	92	77	72
1982	821	671	583	76	67	64
1983	2057	1929	1854	76	68	64
1984	194	191	349	60	53	54
1985	2364	2358	2329	79	69	66
1986	3774	3462	3116	84	73	69
1987	1902	1378	1151	69	67	63
1988	2897	1726	1356	80	68	65
1989	5868	5380	4991	93	80	76
1990	5174	4090	3214	83	72	67
Average	3390	2846	2522	80	70	66
% Change		–16.1	–25.6		–12.4	–17.0

Table VII

Simulated changes in maize and sorghum over the hard veldt region (vertic luvisols) given incremental temperature rises of 2 and 3 °C

Base	Yield (kg/ha)			Harvest dates (Julian)		
year	Climatology	2 °C rise	3 °C rise	Climatology	2 °C rise	3 °C rise
MAIZE						
1980	1476	1027	892	63	54	52
1981	4996	3949	4238	68	56	52
1982	7116	5947	5332	57	49	46
1983	3026	2555	2020	57	50	47
1984	1296	1021	856	53	48	48
1985	2389	1384	1169	55	47	47
1986	4032	2486	2145	58	49	48
1987	1559	1277	1093	55	48	44
1988	4442	3299	2793	57	51	47
1989	9126	7090	5724	67	56	52
1990	2753	2333	2200	62	53	49
Average	3837	2943	2587	59	51	48
SORGHUM						
1980	3305	1959	1516	97	85	79
1981	7164	7183	6202	104	85	80
1982	4106	7414	7133	81	87	80
1983	1203	1519	1577	65	74	70
1984	642	512	469	80	69	66
1985	3486	2202	1813	82	72	68
1986	2872	3130	4430	68	67	69
1987	1960	1435	2143	80	72	69
1988	5127	3759	3332	88	76	72
1989	7072	6888	6608	103	86	80
1990	4265	3258	2883	95	82	76
Average	3746	3569	3464	86	78	74
% Change		–4.7	–7.5		–9.3	–14.2

Based on our vulnerability assessment, it would appear that maize and sorghum in the hard veldt are less vulnerable to warming and drying than is the case in the sand veldt. This conclusion is probably due to the contrasting soil water retention capabilities of the major soils found in the two study areas. The majority of the soils in the hard veldt (Rhergen, 1985, 1986) have good water retention capacities even under reduced soil moisture conditions. The Barolong area (the sample for the hard veldt region) however is not representative of what is typically indigenous. It is here that commercial farming by relatively richer farmers are found while subsistence farmers that typify much of the wider countryside are marginalized on relatively poor soils such as the *Regosols* and *Arenosols*. Therefore, grain farming in Barolong and much of the hard veldt if examined from the point of view of subsistence farming may be just as vulnerable as the sand veldt.

This study has shown that the gap between current and potential cereal yields under rain fed conditions and potential yield is tremendous. For the period examined, the actual yields are sometimes only 5 or 8% of what is potentially achievable. Recognizing that Botswana's climate and soils are too unfavorable to sustained crop farming, the government of Botswana changed the food policy from 'food self sufficiency' to 'food security' in the early 1990s (Sigwele, 1993). While the food self-sufficiency strategy attempted to promote the production of adequate food to meet national needs, the food security policy aims at helping families diversify their income bases so that they could have access to food and other basic needs. Sigwele (1993) has convincingly illustrated that despite Government subsidies to the arable agricultural sector worth millions of dollars over many years, the attainment of the food self-sufficiency objective appeared ever distant. The food security strategy aims at promoting sustainable agricultural and non-agricultural income and employment generating opportunities. Under this strategy, farmers are encouraged to grow crops according to ecological suitability and market competitiveness. This is clearly a very realistic strategy, as it is based on full recognition of the severe environmental constraints to arable agriculture that affect close to 95% of the country. The strategy would become an even more appropriate adaptive mechanism under a drier and warmer climate. This conclusion is based on this study's finding that climate change in Botswana could entail desiccation, shortening of the crop growing period, and reductions in crop yields. The prognosis is particularly true for the sand veldt where yield reductions are expected to be significantly higher than the hard veldt.

For agriculture to contribute meaningfully to food security in some rural areas of Botswana under a changed climate, additional mitigation and/or adaptive strategies are required. Many of the dry-land technologies such as zero till have not been thoroughly researched in Botswana. As a way of adapting to a drier climate, these technologies, that have proved to be useful in places with a similar arid climate as that of Botswana, should be examined by researchers as to their applicability. Due to its low water use efficiency compared to sorghum, it may not be economical to continue growing maize at the same scale and intensity in the middle part of the 21st century. Maize is grown chiefly for human consumption and proposing a change from growing a food crop that has become a cultural symbol has a lot of social implications. This will require a lot of interdisciplinary research work in order to find acceptable substitute food crops.

6. Conclusion

Due to the adverse agro-climatic conditions and various socio-economic constraints, the productivity of arable agriculture in Botswana is low and vulnerable to climatic change. This study revealed that the effects of climate change on the major food crops (maize and sorghum) would push grain production to meaningless lows in the sand veldt region. The Barolong area found in the hard veldt region represents a tiny fraction of the country with productive soils where grain farming may be sustainable under a changed climate. Grain production over most of the country remains vulnerable to climate change. The beneficial effects of CO_2 enrichment on the improved water use efficiency and crop yields are not likely to be realized in Botswana. Most of the grain crops in Botswana are C4 species and these are bound to face fierce competition from the abundant C3 weedy grasses and the woody shrubs, which could outperform the food crops. Faced with this challenge, the strategy of food security, which focuses on increasing the capacity of households to buy food irrespective of the prevailing climatic conditions, is a useful approach. This strategy, in combination with agroclimatic management programmes, is a valuable and a robust adaptive strategy now and under a more adverse climate.

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