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Effects of climate change on crop production in Cameroon

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ABSTRACT: This study involves an assessment of the potential effects of greenhouse gas climate change, as well as the direct fertilization effect of CO_2 on crop yields in Cameroon. The methodology involves coupling the transient diagnostics of 2 atmosphere–ocean general circulation models, namely NASA/Goddard Institute GISS and the Hadley Centre's HadCM3, to the CropSyst crop model to simulate current and future (2020, 2080) crop yields (bambara nut, groundnut, maize, sorghum and soybean) in 8 agricultural regions of Cameroon. For the future we estimate substantial yield increases for bambara groundnut, soybean and groundnut, and little or no change and even decreases of maize and sorghum yields, varying according to the climate scenario and the agricultural region. Maize and sorghum (both C4 crops) yields are expected to decrease by 14.6 and 39.9%, respectively, across the whole country under GISS 2080 scenarios. The results also show that the effect of temperature patterns on climate change is much more important than that of precipitation. Findings call for monitoring of climate change/variability and dissemination of information to farmers, to encourage adaptation to climate change.

KEY WORDS: Cameroon · Climate change · CO_2 · Crop yields · Adaptation · CropSyst

1. INTRODUCTION

Agriculture is the mainstay of the Cameroonian economy. About 45% of Cameroon's gross domestic product originates from agriculture, with close to 80% of the labour force employed in this sector (CIA 2007). Most importantly, this sector is also responsible for providing food security to both the rural and urban populations from domestic production. However, this may not be true in the future. With a rapidly expanding population, the pressure on natural resources is mounting. Molua & Utomakili (1998) noted that, due to population growth, low levels of input and equally low levels of government subsidies (e.g. quality seeds, fertilizers, pesticides and herbicides), per capita food production has been declining. This is worrisome and a real challenge for a government with a population of ~17 million people to feed. Worse still is the expected adverse impact of climate change on agriculture in the future, which may pose a further challenge to the country's food security.

Greenhouse gas (GHG)-induced climate change would very likely result in significant damage in the agricultural sector in sub-Saharan Africa, because the region already endures high heat and low precipitation (Slingo et al. 2005, Kurukulasuriya et al. 2006). The Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) (Boko et al. 2007, Christensen et al. 2007) further urge that, even with the predicted climate change scenarios, extreme events (e.g. 1997 & 2005 droughts in Cameroon) may still occur with devastating effects in more vulnerable areas, causing severe socio-economic effects such as shortages of food and other essential basic commodities, as well as long-term food insecurity.

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Though a few studies have been conducted to assess the impact of climate change on agriculture in developing countries (Seo et al. 2005, Adejuwon, 2006, Thornton et al. 2006, Kabubo-Mariara & Karanja 2007), there is a dearth of literature on this impact in Cameroon; thus the adaptation and mitigation measures that are available to policy makers are severely limited.

The present study aims to partially address this research gap. It uses the coupled climate scenario–crop model method, in which coupled atmosphere–ocean general circulation models (A-OGCMs), used to generate future climate scenarios, are integrated into crop models in order to simulate future crop yields (Tubiello et al. 2000, Brassard & Singh 2007). The use of this method allows us to gain an insight not only into how future crop yields may change, but also into the nature of the factors responsible for yield changes, and how they may affect crop production. Understanding the impacts of long-term climate change on agriculture is crucial for future agricultural policies and interventions in Cameroon, as well as aiding practical steps to mitigate potentially adverse impacts of climate change, which is likely to have important implications for future food security.

The general objective of this study is to examine the effects of long-term climate change on Cameroon crop agriculture and identify the adaptation options of agro-ecological systems using a simulation analysis. The specific objectives are to simulate and highlight the expected effects of various long-term climate change scenarios on future agricultural productivity and discuss policy design, research and extension in planning potentially effective adaptation options to mitigate negative climate change impacts.

2. CLIMATE AND AGRICULTURE IN CAMEROON

Cameroon covers an area of about 475 440 km^2 between 2 and 13° N and is among the 52 countries that comprise sub-Saharan Africa. It is ranked 172 out of 229 countries in the world in terms of per capita income, and nearly 40% of the population (6.8 million people) live on <US$2 d^{-1} (World Bank 2007). Most agriculture is practised at the subsistence scale by local farmers using simple tools. The majority of the country's poor live in rural areas and rely on agriculture and other natural resources for their living.

The area is characterized by highly contrasting physical features, including 402 km of coastline and mountain ranges punctuated by peaks of >3000 m. Climate characteristics, reflecting the topography and latitudinal range, roughly follow a north–south gradient, with the humid equatorial region in the south and semi-arid regions to the north. The equatorial zone stretches from 2 to 6°N, covering the southern and the mountainous western part of the country. Its climate corresponds to the classical Guinean region, with the following subtypes: (1) the seaboard, e.g. Kribi and Tiko with abundant rainfall (2634 and 3198 mm yr^{-1}, respectively); (2) inland areas, e.g. Yaounde, with total rainfall <1660 mm yr^{-1} (this climate subtype prevails over the southern part of the southern Cameroon plateau, extending into the east of the country around Batouri); and (3) north of 6° N (the Sudanese–Sahelian subtype differs from the 'inland' with total rainfall decreasing from 1513 to 834 mm yr^{-1}). Annual average temperature across the country varies between 20 and 29°C, and in the extreme north daily temperatures are usually between 25 and 34°C.

The humid equatorial zone in the south favours the cultivation of cash crops such as oil palm, bananas, cocoa, rubber, plantains and coffee, and the key food crops are maize *Zea mays* L., groundnut *Arachis hypogaea* L., sorghum *Sorghum bicolour* (L.), bambara groundnut *Vigna subterranea* L. Verdc and soybean *Glycine max* (L.) Merr. The semi-arid region to the north mostly favours the growth of millet, sorghum, maize and groundnuts. Growing season is related to the rainy season, and planting is fine tuned to very specific times of the year. In the equatorial zone comprising Bamenda, Batouri, Kribi, Tiko and Yaounde, there are 2 rainy seasons: the first is the 'long season', from March to July with planting in March, and the second is the 'short season', from August to November. In the tropical zone (Garoua, Maroua and Ngaoundere) there is only 1 rainy season, from May to October, and planting starts in May (Ndemah 1999). Table 1 shows the geo-location of the study sites, chosen to represent the variety of agricultural landscapes in Cameroon.

Table 1. Geo-references of the 8 agricultural study sites along with annual rainfall data

Site	Latitude (°N)	Longitude (°E)	Elevation (m)	Rainfall (mm)
Bamenda	6.05	10.10	1239	2378
Batouri	4.47	14.37	656	1499
Garoua	9.33	13.38	244	1090
Kribi	2.95	9.89	16	2634
Maroua	10.44	14.25	422	834
Ngaoundere	7.34	13.57	1104	1514
Tiko	4.08	9.37	52	3198
Yaounde	3.83	11.51	760	1655

3. METHODS AND DATA

The study uses the coupled climate scenario–crop model approach in which present and future climate conditions, generated by the selected climate models following 2 GHG emission scenarios, are integrated as inputs into the crop model so as to simulate crop growth, development and production. The 'naive farmer' scenario is used, meaning that all variables other than weather and atmospheric CO_2 concentration, namely soil, cultivar and management characteristics, are held constant between present and future crop yield simulations. Though in reality farmers are able to make management changes to cope with an altered climate, representing the diversity of these adaptations within a modelling project was seen as adding an additional level of complexity to a study primarily aimed at determining the impacts of the climate on crop production.

Present and future crop yields are compared to evaluate the impacts of GHG-induced climate change on agriculture. The A-OGCM climate models used in this study are the coupled NASA/Goddard Institute GISS and HadCM3 of the British Hadley Centre. Both models are forced by the SRES A2 and B2 emission scenarios (Houghton et al. 2001). The selection of A-OGCMs was based on the general quality and reliability of the simulated current climate compared to observed data and data availability to generate baseline (1961 to 1990) and future climate scenarios (2020s, 2080s) (Brassard 2003, Brassard & Singh 2007). The crop model used, CropSyst (Stöckle et al. 2003), was selected for its robustness and relatively easy applicability with commonly available information (Rivington et al. 2007, Moriondo et al. 2007, Tingem et al. 2008).

The study regions were chosen based on the desire to have as complete a representation as possible of the agricultural landscape of Cameroon. Crop yields and changes were evaluated for 5 different crops, namely: maize, sorghum, groundnut, bambara groundnut and soybeans. The choice of these crops is based on the availability of observed yield data for validation purposes, the relative importance of these crops to the subsistence farmer, and the desire to have a diverse and representative view of crop production potential in Cameroon. Representative soil properties (thickness and texture) for each of the simulation points were extracted from the International Soil Reference and Information Center database (www.isric.nl; Batjes 1995). Available agro-data (e.g. yield, phenological parameters) was obtained from the Central Bureau of Statistics' published district reports in the study areas (Agristat 2001).

3.1. Weather data and climate scenarios

Daily observed maximum temperature (T_{max}), minimum temperature (T_{min}) and rainfall data from 1979 to 2003 were obtained from the University Cooperation for Atmospheric Research (UCAR) (http://dss.ucar.edu/datasets) for each of the 8 sites used in the study. For each region, the precipitation, T_{max} and T_{min} data from 1 of the major weather stations was chosen as representative of the climate of that region (1 station per region). Solar radiation (S_o) data was not available. However, S_o is a key input into crop models and can be a major source of error in yield estimates (Rivington et al. 2005). So as to avoid the risk of introducing additional uncertainty between scenarios in estimating S_o, we used functions within the CropSyst crop model, based on air temperature for each scenario, to make estimates. Availability of S_o data remains a problematic issue for crop modelling and climate change impacts, but this approach ensures that any uncertainties in S_o data remain constant between the compared scenarios.

Since we are evaluating long-term effects of climate change and variability on crop yields, it was necessary to expand the temporal range of the weather data for use in the crop model so as to allow a good estimation of the probability of extreme events. We used the ClimGen software (Version 4.1.05; www.bsyse.wsu.edu/climgen/) to produce generated climatic data to supplement the 1979 to 2003 UCAR data. The model requires inputs of daily series of weather variables (precipitation, T_{max} and T_{min}) to calculate parameters used in the generation process for any length of period at a location of interest. Further information on ClimGen is well documented elsewhere (Stöckle et al. 2003).

According to Richardson (2000), long-term data records are needed, at least 10 yr of weather data for estimation of temperature parameters and 20 or more years for estimation of precipitation parameters, to obtain stable representative estimates. Thus, we used the UCAR observed 25 yr historic daily records of temperature and precipitation, to generate a further 25 yr of modelled daily weather data to extend the coverage to 50 yr (baseline scenario) for each location. Statistics using *t*- and *F*-tests (0.05 significance level) to compare the differences between generated and observed weather data indicated that there was no significant difference between generated values and observed data; thus, representative long-term weather data of precipitation and temperatures could, in general, be generated from historical weather data using Clim Gen. Table 2 summarises the outcome of the series of statistical comparisons for all the test sites. Further evidence of model performance was obtained by compar-

Table 2. Comparisons of observed precipitation (mm) and maximum temperature (T_{max}, °C) means and variances with those of 25 yr data generated by ClimGen at 8 sites. Probability levels (p) calculated by *t*- and *F*-tests for monthly means and variance; p >0.05 (5%) indicates that the null hypothesis of equality between observed and simulated data cannot be rejected

Location	Precipitation						T_{max}					
	Observed		Generated		p		Observed		Generated		p	
	Mean	Variance	Mean	Variance	*t*-test	*F*-test	Mean	Variance	Mean	Variance	*t*-test	*F*-test
Bamenda	195.8	25185	176.1	11202.4	0.724	0.097	23.8	2.93	24.7	2.96	0.188	0.493
Batouri	123.2	5375.9	134.7	8506.1	0.74	0.229	29.6	2.5	29.1	3.35	0.457	0.318
Garoua	83.1	8425.6	88.3	7600.7	0.888	0.434	34.9	9.27	34.3	8.89	0.617	0.473
Kribi	219.5	22020	226.6	19342.7	0.838	0.417	30.0	2.05	30	2	0.933	0.484
Maroua	65.9	6842.8	72.3	7646.4	0.854	0.429	34.5	8.81	33.5	8.08	0.447	0.445
Ngaoundere	124.7	12638	126.1	11874.9	0.976	0.46	29.0	4.0	28.1	3.83	0.287	0.472
Tiko	266.5	38782.2	260.3	41799.1	0.94	0.452	30.0	3.25	30.1	3.3	0.937	0.49
Yaounde	135.7	8083	153.6	7593.5	0.624	0.46	28.4	2.47	27.8	2.33	0.329	0.463

ing observed and generated precipitation T_{max} in Ngaoundere, Tiko and Kribi using exceedence probability graphs (Fig. 1). These probabilities of exceedence plots are an important indicator of model performance, in that they show when the model is able to produce estimates that reproduce the probability of event magnitudes occurring, in this case, the mean monthly precipitation and T_{max}. The findings show that ClimGen is capable of producing good quality estimates across the range of spatial scales and climatic zones found within Cameroon. Further information on the assessment of the ClimGen stochastic weather generator at Cameroon sites is well documented in Tingem et al. (2007).

The impact of climate change on agricultural production was assessed using the observed baseline data and the adjusted A-OGCM-simulated future (2020s, 2080s) climate scenarios from GISS and HadCM3. The GISS model of the NASA/Goddard Institute for Space Studies is described by Hansen et al. (1998). A description of the HadCM3 model is given by Johns et al. (2003). The models differ in how they represent the effects of climate processes. Horizontal grid resolution is 4 × 5° (latitude × longitude) for GISS and 2.5 × 3.75° for HadCM3.

We generated 8 climate change scenarios at each site using the standard scenario generation methodology as discussed in ANL (1994), USCP (1994) and Rosenzweig & Tubiello (1997). Atmospheric CO_2 concentrations were specified for each period according to the 'business as usual' IPCC scenario, the medium-

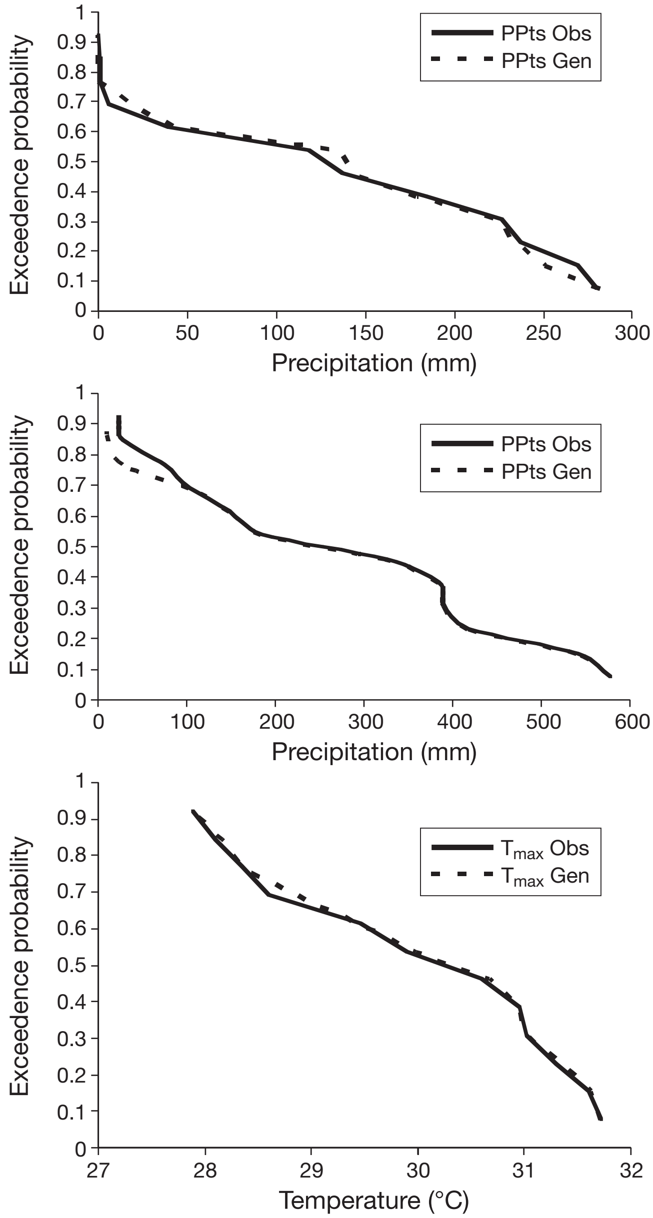

Fig. 1. Exceedence probability functions for the distribution of monthly mean precipitation for the observed (Obs) and generated (Gen) data by ClimGen: (a) monthly mean precipitation in Ngaoundere, (b) monthly mean precipitation in Tiko and (c) exceedence probability functions of monthly T_{max} for observed and synthetically generated data for Kribi

high emission scenario A2, and its more optimistic medium-low counterpart B2 (Houghton et al. 2001).

Scenarios of climate change were created by taking the difference between transient GCM (general circulation model) runs with current climate data from the 30 yr baseline climate period, the baseline temperatures were adjusted by adding the change in temperature and the baseline daily precipitations were adjusted by multiplying ratio changes in precipitation suggested by transient GCM runs (ANL 1994). In this way, new 50 yr long climatological time series were generated for each scenario at each location, providing a broad range of conditions that mirror variability and capture a range of uncertainties as described by the IPCC. Table 3 summarises climate change as projected by the 8 A-OGM scenarios across Cameroon.

3.2. Crop growth model

The CropSyst model is a multi-year, multi-crop, daily time step cropping system simulation model. The model has been applied and used extensively to simulate crop growth and yield for a range of crops such as wheat, maize, soybean, sorghum, groundnut and forage crops in diverse environments. It has been used in detailed studies for tropical crops and has been shown to be robust and accurate for a diverse range of local environments, including those found within Cameroon (Tingem et al. 2008). It is considered a well-balanced crop simulator, simulating different crops from a common set of parameters.

The model simulates the soil water budget, the soil–plant nitrogen budget, the crop canopy and root growth, crop phenology, dry matter production, yield, residue production and decomposition, and erosion. The main weather variable inputs are daily precipitation, T_{max} and T_{min}. S_o is estimated by CropSyst, based on values of air temperature. The model allows the user to specify management parameters such as sowing date, cultivar genetic coefficients (e.g. photoperiodic sensitivity, duration of grain filling, maximum leaf area index [LAI]), soil profile properties (soil texture, thickness, water and initial nitrogen content), fertilizer and irrigation management, tillage, etc. Crop growth is simulated for the whole canopy by calculating unstressed (potential) biomass based on crop potential transpiration and on crop intercepted photosynthetically active radiation. This potential growth is then corrected by any water and nitrogen limitations, to determine actual daily biomass gain. The simulated yield is then obtained as the ratio between actual total biomass accumulated at physiological maturity and crop-specific harvest index (harvestable yield/above-ground biomass).

The simulation of crop development is based on the timing of the important development stages (thermal time) calculated as growing degree days (GDD) accumulated throughout the growing season (starting from planting until harvest). Average air temperature above a base and below a cut-off temperature is considered for GDD calculations. The accumulation of thermal time may be accelerated by water stress.

Water balance processes in CropSyst include rainfall, runoff, and interception by the crop canopy and residues, infiltration, redistribution in the soil profile, crop transpiration and soil evaporation. Potential evaporation is estimated by the Priestley-Taylor method (Priestley & Taylor 1972). Water dynamics in the soil is handled by a Richard's equation, which is solved numerically using the finite difference technique.

CropSyst has data requirements that can be reasonably met and provides support utilities to substitute for missing parameters based on well-established procedures (e.g. using pedo-transfer functions to derive soil hydraulic parameters). Hence, it provides a conceptually unified modelling system for many crops, minimizing the dangers of structural uncertainty in making both cross-crop and inter-spatial comparisons (Rivington et al. 2007). As such, it is able to represent well the variation in yield determined by weather-driven environmental conditions and respond to specific management regimen.

Values were assigned to crop parameters based on typical values from the CropSyst user manual and from the authors' own experience. A number of parameters accounting for cultivar-specific differences were calibrated based on outputs of development and growth characteristics. Further parameterization was achieved by minimization of differences between actual and simulated yields for a limited num-

Table 3. Changes in the climate variables between baseline and future climate as predicted by the 8 general circulation model scenarios. A2 and B2: medium-high and medium-low emission scenario, respectively

Scenario		Δ CO_2 (ppm)	Δ Precipitation (%)	Δ Mean temperature (°C)
GISS	A2 2020	415	−3.7	1.6
	2080	677	1.1	4.4
	B2 2020	411	−2.2	1.4
	2080	548	−1.5	3.1
HadCM3	A2 2020	415	0.8	0.7
	2080	677	4.5	3.5
	B2 2020	411	4.1	0.8
	2080	548	5.2	2.5

ber of simulation trials using available field-reported data (Agristat 2001). Remaining parameters were adjusted within a reasonable range as provided by the manual. The calibration of the phenological parameters (e.g. GDD) was made using data provided by the Institute of Agricultural Research (IRA-Cameroon).

Simulations were run with sowing dates set to 15 March, corresponding to Day 74 of the year (DOY), in Bamenda, Batouri, Kribi, Tiko and Yaounde. In Garoua, Maroua and Ngaoundere, the sowing date was set to 15 May (DOY 135), which agrees with traditional crop management in the zones (Ndemah 1999) for all crops. A 1 m soil depth was considered to simulate the soil water balance, because it corresponds to the observed maximum crop root length (Farre 1998). The finite difference soil water balance function, by which water moves up and down depending on the soil water potential of vertically adjacent layers, was used for the redistribution of water in the soil under non-limiting soil fertility. An implementation of the Priestley-Taylor equation (Priestley & Taylor 1972), based on air temperature and S_o inputs, was used to compute the reference evapotranspiration. Of the crop residue, 40% was assumed to remain in the field after harvest for recycling purposes (Abraha & Savage 2006). No irrigation was used as this is not a common practice.

Table 4. Relative difference (RD, %) between observed yields and yields simulated with baseline climate data for 5 crops; RD = [(observed – simulated) / observed] × 100, average over 50 yr. n.a.: no data available

Location	Bambara	Groundnut	Maize	Sorghum	Soybean
Bamenda	–5.4	–0.5	0.1	n.a.	–2.1
Batouri	n.a.	–0.1	–1.6	n.a.	n.a.
Garoua	–0.1	–0.03	–0.1	0.2	n.a.
Kribi	n.a.	–0.7	–0.9	n.a.	n.a.
Maroua	–0.8	–9.3	0.4	–6.0	n.a.
Ngaoundere	–4.6	–13.0	–0.7	–1.7	2.2
Tiko	–5.5	0.6	–1.9	n.a.	–10.5
Yaounde	–2.1	–4.7	–1.5	n.a.	n.a.

3.3. Crop model and ClimGen validation

Validation of the simulated crop yields was limited by the availability of observed yield data. Basic tests were conducted in order to verify the applicability of the CropSyst crop model to the selected agricultural regions, and to evaluate the reliability of its results. This was done by comparing, for the different crops and agricultural regions, the averages of the simulated and observed (Agristat 2001) yields for each crop at each region across Cameroon. The results, presented in Table 4, are expressed as the percentage difference between average simulated and observed yields. According to Ritchie et al. (1998) and Brassard (2003), a difference between observed and simulated yields of up to ±15% is judged acceptable. As seen in Table 4, for all crops and regions, the validation results are within this range; hence, the model can be seen as robust under the diverse range of environmental conditions found within Cameroon. More detailed evaluation of maize estimates by the model are available in Tingem et al. (2008).

Statistical tests (t- and F-tests) to compare the differences between generated and observed weather data indicated there was no significant difference between generated values and observed data (significance level <0.05); thus, representative long-term weather data on precipitation and temperature could, in general, be generated from historical weather data using Clim Gen (Tingem et al. 2007). This finding has particular relevance for agricultural modelling applications in Cameroon where there are limited observational records, making it difficult to evaluate long-term effects of weather on crop yield.

3.4. Projection analyses

The effects of a CO_2-induced climate change on crop production, expressed as the relative changes in yields between baseline and future (2020s/2080s) climate are presented as percentage changes in average yields from the baseline. In order to assess the strength of CO_2 effects on crop yield, as indicated by Tubiello et al. (2000), simulations were also run without incorporating the change in atmospheric CO_2 levels.

The yields and phenological maturity dates simulated under the alternative climate scenarios were compared using exceedence probability (P_e, %) distributions, following Weibull (1961):

$$P_e = \frac{m}{n+1}$$

where m is the rank order of each yield estimate, with $m = 1$ as the largest and $m = n$ as the lowest, with n being the number of observations. The coefficient of variation (CV) values of yield, defined as the ratio of standard deviation to the mean, were computed over the entire time series available at each site. The %CV represents a measure of the farmer's risk, low CVs indicate stable year-to-year production, while high CVs denote high inter-annual variability (Rosenzweig & Tubiello 2007).

4. RESULTS

4.1. Climate change analyses

The GCM runs were for 2 time periods: the 2020s, representing the period from 2010 to 2039, and the 2080s, representing the period from 2070 to 2099. According to these runs, annual temperatures in the selected regions across the country are expected to rise by 0.7 to 0.8°C, according to HadCM3, with respect to the baseline, in the 2020s. Alternatively, the GISS projects a 1.4 to 1.6°C increase in the same time period. Annual temperatures in the 2080s are projected to increase relative to the baseline by 2.5 to 3.5°C and 3.1 to 4.4°C according to the HadCM3 and GISS GCMs, respectively.

Precipitation is expected to increase or decrease depending on the GCM used. For the GISS and HadCM3 average percent changes in precipitation ranged from –3.7 to 1.1% and from 0.8 to 5.2%, respectively. However, the GISS model projected a decreasing trend of precipitation in the 2020s and 2080s for most of the study sites (Table 3). The HadCM3 model simulated an increasing trend in precipitation across all scenarios.

4.2. Crop yield changes under alternative climate scenarios

Relative changes in the average yields of maize, sorghum, bambara groundnut, groundnut and soybean predicted between present (baseline) and future (2020s/2080s) climates are presented in Table 5.

4.2.1. Maize

Nearly all future climate scenarios show a general tendency towards diminishing future maize yields in all agricultural regions; ranging between +27.1 and –69.6% (Table 5). At Bamenda both scenarios predict grain yield to decrease by 5.9 to 24.7% in the 2020s and by 20.6 to 69.6% in the 2080s. The CV of yield (Table 6) consistently increased in the early and latter parts of the 21st century at Bamenda, Batouri and Garoua, suggesting increased risk to farmers.

The exceptions for both GISS and HadCM3 simulations were Ngaoundere and Kribi agricultural regions, where yield increased by 6.2 to 27.1% and 9.6 to 25.9%, respectively, with decreased year-to-year variation. This was due to a relatively low projected increase in air temperatures during the grain-filling periods in Ngaoundere (July) and Kribi (May). The decrease in the duration for the regular crop-growing season for maize in the near future was simulated at between 2 and 11 d for A2 and B2 scenarios, respectively, and at approximately 5 to 26 d in the last 3 decades of the century, compared to growing season length under current climatic conditions (Fig. 2). The greatest decrease across all the scenarios was recorded in Bamenda (69.6% decrease) under GISS A2 2080, and the highest yield was at Ngaoundere (27.1% increase) under HadCM3 A2 2020s (Table 5). Taking the mean overall regions, yield oscillated between –14.6 and 8.1% for GISS and between –8.2 and 15.7% for the HadCM3 model.

4.2.2. Sorghum

The sorghum results appear to indicate that, with the exception of the HadCM3 A2 & B2 2020s data, CO_2-induced climate change will result in either a substantial decrease or no change on sorghum crop yield, variable with location and scenario. Changes in yield (Table 5) follow 2 patterns. Firstly, continuous decreases in yield are projected under A2 and B2 emission scenarios for both GISS and HadCM3, in the latter part of this century. This is the pattern expected at Garoua, Maroua and Ngaoundere, which represent the Sahelian eco-climatological zones in which these crops are grown. Secondly, a slight reduction in yields is recorded for both GCMs and emission scenarios in the 2020s period. Sizable gains occur in Maroua (+17.1 and 14.6%) under HadCM3 A2 & B2 2020, respectively. The 2080 simulations exhibit a 9.3 to 63.8% drop in yields, with the larger reduction occurring in Ngaoundere under GISS A2 2080 (–63.8%) and increased CVs across all scenarios. The smallest effects on yields were simulated under HadCM3 A2 2020 at all locations. Change in number of days from emergence to crop maturity ranged from 2 to 29 d, with the greatest reduction recorded at Ngaoundere.

4.2.3. Groundnut

Projections indicate substantial increases in the yield of groundnut by 21.5 to 109% from the baseline, across all scenarios in Batouri, Kribi, Maroua, Ngaoundere and Tiko, with reduced CVs. Simulated production in Bamenda decreased across all scenarios by 11.9 to 41.6%, except for HadCM3 A2 & B2 2020, where yields increased by 1.9%. Scenario A2 2080s for both GCMs produced a drop in yields at Garoua and Yaounde by 1.2 to 12.4%. The growing season was shortened by 2 to 6 d.

Table 5. Relative change (%) in yields (kg ha^{-1}) between baseline and future climate, as predicted by the 8 climate scenarios for 5 crops studied

/Location	Baseline	GISS				HadCM3			
		A2 2020	A2 2080	B2 2020	B2 2080	A2 2020	A2 2080	B2 2020	B2 2080
Maize									
Bamenda	1294	–24.7	–69.6	–22.9	–51.2	–6.7	–56.2	–5.9	–20.6
Batouri	1488	0.9	–33	0.2	–17.8	13.6	–22.5	14.2	–8.2
Garoua	1945	3.1	–16.1	4.1	–11	9.1	–12.1	11.2	–6.4
Kribi	1835	18.9	9.6	19.4	13.1	25.4	12.3	25.9	15.3
Maroua	2171	5.3	–10.5	6.9	–6.6	13.3	–8.1	10.6	–2.91
Ngaoundere	2318	24.6	6.2	25	17.3	27.1	13.8	26.9	22
Tiko	2447	12.6	–0.6	12.5	3.5	18.3	3.4	18.4	7.6
Yaounde	2158	18.4	–2.7	20	7.8	24.1	3.5	24.1	12.3
Mean	1957	7.4	–14.6	8.2	–5.6	15.5	–8.2	15.7	2.4
Groundnut									
Bamenda	1017	–13.5	–41.6	–11.9	–30.1	1.9	–33.4	1.9	–22.7
Batouri	996	38.4	21.9	30.4	30.0	51.3	47.1	57.8	50.6
Garoua	995	15.7	–7.4	16.9	0.6	19.8	–1.2	23.2	6.6
Kribi	557	109.0	113.0	109.0	108.7	110.0	108.7	109.2	108.9
Maroua	1172	45.3	34.5	46	38.2	48.9	36.6	48	40.7
Ngaoundere	1197	50.3	37.2	51	41.7	57.2	40.1	57.1	44.5
Tiko	948	19	–1.8	25.6	12.1	35.2	16.8	32.3	21.5
Yaounde	1106	8.1	–12.4	11.1	–2.8	18.6	–6.3	18.6	1.8
Mean	998	34.0	17.9	34.8	24.8	42.9	26.1	43.5	31.5
Bambara									
Bamenda	1160	31.2	1.2	32.9	17.3	42.5	13.2	43.3	23.5
Garoua	1402	24.3	4.9	25.2	11.9	31	10.2	30.1	16.8
Maroua	1310	37.2	25.9	37.8	29.5	41.3	28.2	40.4	32.1
Ngaoundere	1571	52.5	46.8	53.4	49.1	58.3	48.7	57.1	50.5
Tiko	1184	9.3	–5.1	2	6.4	20.5	12.5	28.2	11.2
Yaounde	1193	21.5	3.9	24.6	12.8	31.6	9.6	31.6	16.8
Mean	1303	29.3	12.9	29.3	21.2	37.5	20.4	38.5	25.2
Sorghum									
Garoua	1311	–8.2	–35.7	–6.1	–28.5	1.3	–32	4.4	–21.9
Maroua	1484	3.2	–20.1	6.3	–14.2	17.1	–16.2	14.6	–9.3
Ngaoundere	1280	–16.6	–63.8	–12.3	–47.8	3.8	–53.5	3.4	–40.7
Mean	1358	–7.2	–39.9	–4.0	–30.2	7.4	–33.9	7.5	–24.0
Soybean									
Bamenda	572	57.6	27.9	58.5	38.8	68.7	34.2	78.9	45.5
Ngaoundere	1169	27.9	5.5	29.6	12.6	39.5	10.9	39.5	18.8
Tiko	110	126.9	130.4	127.7	134	153.6	148.2	145.5	162.4
Mean	617	70.8	54.6	71.9	61.8	87.3	64.4	88.0	75.6

4.2.4. Bambara groundnut

Bambara groundnut showed gains across all scenarios, except for Tiko, where a decrease by 5.1% was registered under GISS A2 2080s. Yield across all locations oscillated between 12.9 and 38.5%. Projected increased CVs occurred at Bamenda, Tiko and Yaounde, with growing season becoming shorter by 2 to 5 d.

4.2.5. Soybean

A substantial increase in soybean yields was generally estimated for the future. GISS and HadCM3 projected yield increases in the range from 27.9 to 153.6% in the 2020s and from 5.5 to 162.4% in the 2080s, with decreasing year-to-year variance. In Bamenda, average yield gain across all scenarios was 51.3%, whereas at Ngaoundere and Tiko it was 23.0 and 141.1%. HadCM3 projections resulted in more yield gains. The change in maturity dates across the areas of cultivation ranged between 5 and 23 d shorter.

5. DISCUSSION AND IMPLICATIONS FOR POLICY

The study shows that most crop yields will likely be different in the future under the effects of increased atmospheric CO_2 and the resulting climatic changes, as expressed by the 8 future climate scenarios. For the future climates, maize yields are projected to decrease

Table 6. Variation in crop yields under projected climates across agricultural regions (percent changes from base climate). Coefficient of variation = 100 × standard deviation / mean

Location	GISS				HadCM3			
	A2 2020	A2 2080	B2 2020	B2 2080	A2 2020	A2 2080	B2 2020	B2 2080
Maize								
Bamenda	19.7	21.1	19.8	22.9	17.9	21.9	17.2	22.1
Batouri	10.4	18.8	16.8	12.3	12.4	14.8	12.7	9.3
Garoua	7.9	9.5	7.8	9.2	13.4	9.3	7.7	8.9
Kribi	7.9	8.6	8.2	7.5	7.1	7.2	7.6	7.7
Maroua	8.5	6.4	8.9	7.3	8.0	6.9	8.3	8.3
Ngaoundere	4.3	3.5	5.0	4.3	4.3	3.8	4.3	4.3
Tiko	5.2	5.6	4.9	5.1	4.7	5.6	4.7	5.1
Yaounde	6.2	7.0	6.2	7.5	7.0	8.2	7.0	7.4
Mean	8.8	10.1	9.7	9.5	9.4	9.7	8.7	9.1
Groundnut								
Bamenda	9.5	6.1	9.6	6.2	9.8	7.5	9.7	7.7
Batouri	51.1	51.7	49.6	48.3	46.7	47.9	42.0	47.7
Garoua	8.7	7.7	8.7	8.2	11.0	8.1	8.7	8.4
Kribi	14.0	17.1	14.0	14.0	13.9	14.0	14.0	14.0
Maroua	10.5	10.3	10.5	10.4	10.5	10.4	10.5	10.4
Ngaoundere	8.4	10.1	8.5	9.6	8.3	9.6	8.2	9.4
Tiko	28.0	27.8	27.3	29.3	26.3	25.9	25.9	26.1
Yaounde	12.5	12.4	12.8	12.4	12.7	12.4	12.7	12.5
Mean	17.8	17.9	17.6	17.3	17.4	17.0	16.5	17.0
Bambara								
Bamenda	7.3	21.9	6.9	7.4	7	7.7	7.3	6.9
Garoua	4.3	4	4.3	4	4.6	4	4.8	4.1
Maroua	7.5	7.6	7.5	7.5	7.7	7.5	7.7	7.5
Ngaoundere	7	7.6	6.8	7.3	6.3	7.4	6.2	7.1
Tiko	29.1	26.5	39.8	25.3	25.7	17.9	23.4	28.5
Yaounde	8.3	8.5	8.2	8.5	8.9	8.5	9	8.4
Mean	10.6	12.7	12.3	10.0	10.0	8.8	9.7	10.4
Sorghum								
Garoua	16.4	12.7	16.9	13.9	23.0	13.5	18.8	15.4
Maroua	17.8	14.6	16.2	16.9	15.5	15.9	17.1	17.5
Ngaoundere	18.7	19.5	17.9	20.4	16.6	18.4	16.7	31.2
Mean	17.6	15.6	17.0	17.1	18.4	15.9	17.5	21.4
Soybean								
Bamenda	9.9	10.8	10.2	11.1	10.9	11.2	18.3	10.1
Ngaoundere	3.8	5.6	3.5	4.6	3.5	4.4	3.5	4.5
Tiko	33.3	27.5	32.2	30.3	23.4	22.1	28.1	20.4
Mean	15.7	14.7	15.3	15.3	12.6	12.6	16.6	11.7

or stay relatively unchanged; sorghum yields are projected to decrease, especially according to the GISS A2 2080 scenario; bambara groundnut, groundnut and soybean yields are projected to be substantially higher in all of the agricultural regions of Cameroon. Overall there is a clear A-OGCM model-linked pattern emerging from these results. For all crops, the more positive changes (highest increase or smallest decrease) are found when using the HadCM3 scenarios and the more negative changes are found with GISS scenarios. Of the 2 GCMs used, the GISS links increasing temperatures with decreasing rainfall, whilst the HadCM3 model forecasts an increase in temperature accompanied by increased precipitation. The differences in crop yield under each of the scenarios at each location reflect a complex interplay between temperature increase, projected changes in precipitation and increase in atmospheric CO_2 concentrations. The transient GCM scenarios created in the present study provide a plausible indication of the Cameroon climate over the coming decades of the 21st century, depending on emissions of GHG and trends in energy demands.

Higher temperatures translate into faster crop development and earlier maturation, which results in lower crop yields because the plant intercepts less cumulative S_o before it reaches maturity and harvest (Brassard & Singh 2007). This relationship appears to be confirmed by the results presented, although changes in cloud patterns that may alter the atmospheric radiative transfer are not assessed here. Growing periods are shorter under GISS scenarios than under HadCM3.

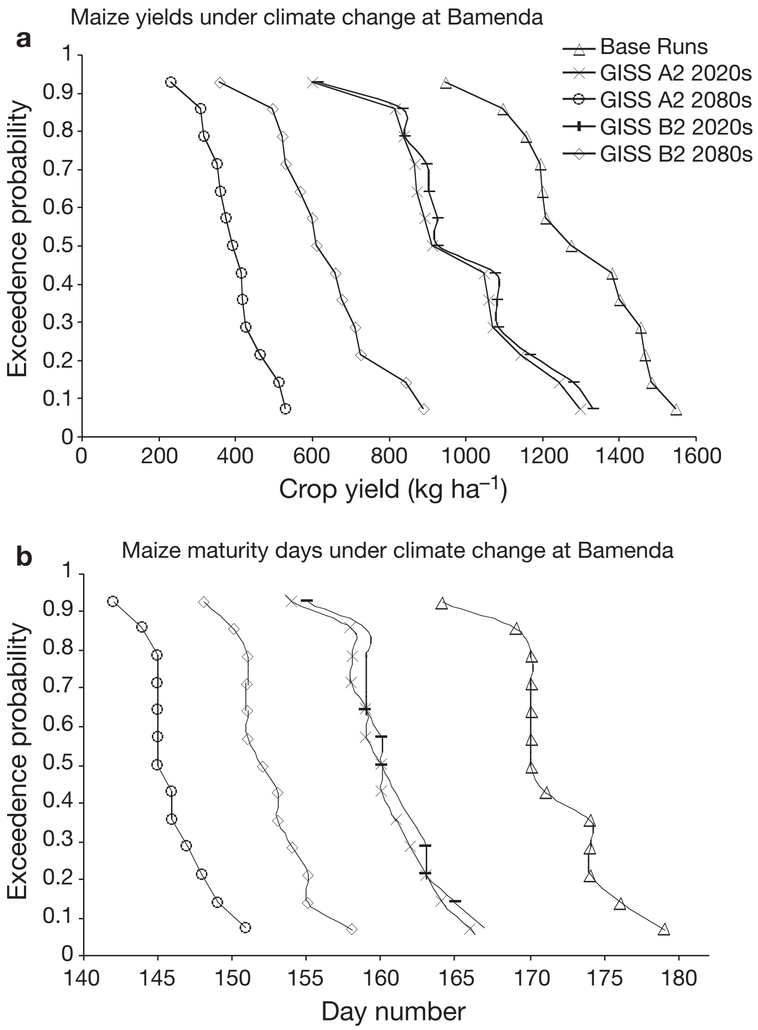

Fig. 2. Exceedence probability distribution of (a) maize grain yields under baseline and climate change scenarios and (b) maize maturity days under climate change scenarios at Bamenda

This is because the projected temperatures under HadCM3 scenarios were moderate, so little change in development period occurred as the climate changed. Under GISS climate change scenarios, high temperatures and decreased precipitation worked in unison to decrease growth period in the future projections. In addition, the increased rainfall in the HadCM3 scenarios was able to accommodate the increased growth due to enhanced photosynthesis that occurred under elevated CO_2 conditions.

Using regression analysis, Rosenzweig & Hillel (1993) found that daily T_{max} >30°C during the growing season were negatively correlated with maize yield in the US Maize Belt. The future Cameroonian climate scenarios used had maximum daily temperatures >30°C on several days during the growing season (Table 7). Results in this table closely match the yield changes of maize and sorghum, with an increased number of days with temperatures >30°C within a given scenario resulting in decreased yields. These findings are similar to those of Chipanshi et al. (2003) and Adejuwon (2006).

The positive effects of elevated CO_2 concentrations on biomass production and grain yield are higher at increased temperatures for C3 carbon-fixation plants (Wheeler et al. 1996). For Cameroon, our results indicate that the negative effect of increased temperatures will, in almost all cases for bambara groundnut, groundnut and soybean, be compensated by the positive effects of higher CO_2 concentrations. The drops in the yield of groundnut and bambara at Bamenda and Tiko under the GISS and HadCM3 scenarios A2/B2 2080, respectively, may at least in part be explained by changes in nodule activity and nitrogen supply as a result of the higher temperatures and/or precipitation changes (Haskett et al. 2000).

Overall, a strong increase is projected in bambara, groundnut and soybean (C3 crops) yields and little or no change and even decreases for maize and sorghum (C4 crops). These are consistent with other simulations and experimental results reported by Downing et al. (2000) and Thomson et al. (2005). They show the greater importance of the direct CO_2 fertilization effect for C3 species where it is responsible for most of the anticipated increases in future yields. The direct CO_2 effects have less of an impact on C4 crop yields because these crops are already near their maximum photosynthesis rate at current CO_2 levels (Chartzoulakis & Psarras 2005).

Although the magnitude and direction of climate change effects on crop yields are dependent on the simulated strength of the CO_2 response (Fig. 3), Long et al. (2006) and Morgan et al. (2005) are critical of the way in which CO_2 effects on crop production are simulated, pointing out the possible exaggeration of an increased CO_2 effect under controlled conditions. This is particularly relevant to C3 crops, in which the photosynthetic efficiency was assumed to be >30%. Long et al. (2007) argue that the actual effect of CO_2 concentration is about half of that suggested by experiments used to develop climate models. In the same way, Leakey et al. (2006) showed that maize crops growing under ample water and nutrients showed a lack of response to increased CO_2. Following Leakey et al. (2006) and Long et al. (2007), then, the pattern of modelled agricultural yields in Cameroon shown here may

Table 7. Average number of days in the growing season with maximum daily temperature >30°C under current climate (baseline) and climate change scenarios projected by 2 climate change models (GISS and HadCM3) for 2 future decades (2020 and 2080)

Location	Baseline	GISS				HadCM3			
		A2 2020	A2 2080	B2 2020	B2 2080	A2 2020	A2 2080	B2 2020	B2 2080
Bamenda	5	15	52	14	30	9	35	8	22
Batouri	60	89	133	87	113	75	123	75	107
Garoua	110	134	154	132	147	120	147	121	140
Kribi	83	113	147	111	135	98	139	97	127
Maroua	109	131	150	129	145	117	144	118	137
Ngaoundere	17	37	92	35	64	24	69	25	50
Tiko	81	109	142	107	128	95	134	95	120
Yaounde	36	62	113	60	87	48	101	48	80

be incorrectly biased towards a positive response. Such uncertainty about the response of crops to atmospheric CO_2 concentrations raises doubts on the ability to model future yields. Locations with modelled increases might see no change, and those with no change or reductions might in reality experience crop failure. On the other hand, Ewert et al. (2007) and Tubiello et al. (2007) showed that crop yield responses to elevated CO_2 are similar across FACE (free air carbon enrichment) and non-FACE experimental data.

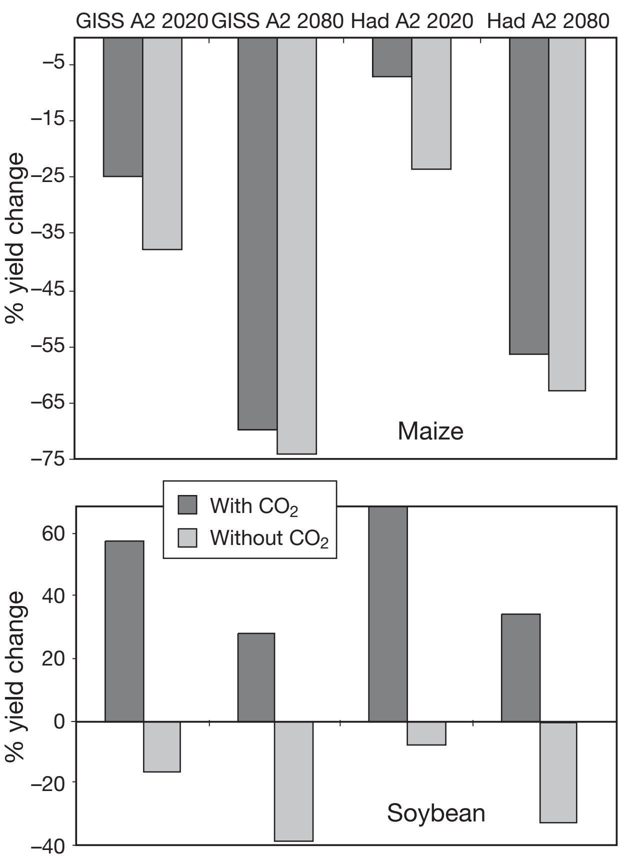

Fig. 3. Changes in simulated yields of maize and soybean (Bamenda station) in response to climate change with/without accounting for the direct effect of atmospheric CO_2

Their results conflict with those of Long et al. (2007), and they urge greater co-operation between experimentalists and modellers across all disciplines, so that key questions of importance to crop yield and crop production under future climate, environmental and socio-economic change can be framed within comprehensive and mutually beneficial research programmes.

Uncertainties in the response of crops to elevated CO_2 also have to be related to the uncertainty associated with limitations of the climate change projections and how they manifest themselves in crop model estimates. In the present study, coarse-scale GCM data have been used and S_o has been estimated by CropSyst. It was beyond the scope of this study (and the capabilities of the data used) to investigate what the changing relationships between altered precipitation and temperature magnitudes and S_o might be in the future. Using CropSyst to estimate S_o for all scenarios partially resolves the issue of the relationship between temperature and S_o, but not precipitation and S_o. The future projection data are based on magnitude adjustments of the current climate; hence, in reality, future correlations between variables will change, but this is not encompassed within the data. Further downscaling sophistication is required in order to supply more reliable, site representative data that include relative changes between temperature, cloud cover, precipitation and S_o.

Clearly, climate change will also have complex interaction with the timing and severity of disease, pest and weed interactions (Fuhrer 2003), but their combined effects on the yields presented here were assumed to be controlled. This sends a cautious signal to Cameroon where poor and vulnerable people are dependent on agriculture and failure in crop production under climate change will exacerbate poverty and food-insecurity challenges already faced by an impoverished rural and urban society.

Also, the projected climate had mixed effects on variation of yields as shown in Table 6. The construction of GCM scenarios assumes that the climate variability of the future is the same as the observed; therefore, any changes in the CV of yields were as a result of a complex mix of temperature, rainfall, CO_2 fertilization effect and plant physiology, interacting with soil properties and affecting crop growth over time (Thomson et al. 2005, Alcamo et al. 2007). In reality the projected climate change will result in higher yield variability, posing significant consequences for farming businesses and future management decisions (Mearns et al. 1997, Tingem et al. 2008). Thus, predicting seasonal rainfall and yield will become more important than for the current climate, and farmers will need to make more dynamic and tactical decisions about crop choices. On the side of public authorities, more effective extension programs are needed to bring about or increase farmers' awareness of climate change. More effective farm planning, crop insurance and economic diversification offer the potential of increasing farmers' resilience to adverse changes in the future.

The simulations showed, especially for maize and sorghum, a different type of adaptation to climate change is needed. One of the effects of higher temperature in Cameroon is reduced growth and grain filling periods. Developing different cultivars, which are better adapted to future climates is one option, especially varieties with a longer season. Other potential adaptations include changes in sowing date, the implications of which the authors are currently researching. Some locations may be suitable for development of water storage and irrigation capabilities, but these will require substantial infrastructural and educational investments. Increased incidence of supra-optimal temperatures will make larger areas of Cameroon unsuitable for maize and sorghum cultivation, perhaps necessitating a return to bambara groundnut, groundnut and soybean, which may be critical in ensuring food security in an uncertain future. Indeed, this will have important social implications because maize and sorghum have become cultural symbols for people in this region. This will require a lot of interdisciplinary research work in order to find acceptable substitute food crops.

However, the conclusions and recommendations presented here must not be seen as accurate predictions of future crop yields, but more as indicators of the possible impacts of climate change on Cameroon's agriculture, which may be useful in designing appropriate adaptation options. It is the responsibility of the government and the scientific community to provide farmers with the adequate and necessary expertise and guidance for undertaking proactive, well-informed adaptation measures. Also, more improvement in the amount of available data and rigorous field experimentation, which could enhance our ability to assess the impacts of future climate scenarios on cropping systems dynamics, are needed.

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