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ORIGINAL PAPER

Evaluation of climate change impacts and adaptation measures for maize cultivation in the western Uganda agro-ecological zone

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Abstract In this study, we assessed the probable climate change impacts and the appropriate adaptation strategies for maize cultivation in the western Uganda agro-ecological zone. Detailed assessments were made using climate and crop models. The Statistical Downscaling Model (SDSM) v4.2 was used to downscale low resolution future climate data obtained from general circulation model HadCM3 for two SRES scenarios, A2 and B2. The CERES-Maize crop model of DSSAT v4.0.2.0 was used to simulate maize yield for the assessment of climate change impacts. In the western Uganda agro-ecological zone, the annual average temperature is expected to increase by between 0.69–2.46 and 0.66–1.78 °C under the A2 and B2 SRES scenarios, respectively, in the three future periods of 2020s, 2050s, and 2080s relative to the base period (1961–1990). Monthly average temperatures are expected to increase for most of the months but will slightly decrease for the month of November under both scenarios. The annual average rainfall is expected to decrease by between 4.7–16.4 and 4.7–11.8 % under the A2 and B2 scenarios, respectively, in the three future periods. Monthly average rainfall is expected to decrease for most of the months but will increase for the months of October, November, and December under both scenarios. Crop modeling results show that in the March–May crop season, maize yields will decrease by between 9.6–43.3 and 10.5–28.4 % under the A2 and B2 scenarios, respectively, relative to the base period in the three future periods. However, in the September–November crop season, maize yields are expected to increase by between 8.1–9.6 and 8.6–10.2 % under the A2 and B2 scenarios, respectively. Supplementary irrigation and shifting of planting dates are found to extenuate the impacts of future climate on maize yields. Irrigation application of 80 mm during the growing season in the March–May season is expected to increase maize yields by as high as 42.1 % under future climate, while planting 16 days earlier than the current planting date in the same season is expected to increase maize yields by as high as 17.9 %.

1 Introduction

Climate affects the functioning of many natural and human systems: natural ecosystems, agriculture, water supply, infrastructure, industries, etc.; therefore, change of global climate is certain to create serious consequences on natural and human systems. Climate change is caused by both natural factors (volcanic activity, earth orbital changes, solar variations, etc.) and anthropogenic factors (greenhouse gas and aerosol emission); however, scientific analyses show that recent global warming is mainly due to anthropogenic factors (IPCC 2007). Plausible scientific proof of global climate change is widely elaborated in the Intergovernmental Panel on Climate Change (IPCC) assessment reports III and IV (IPCC 2001, 2007). General Circulation Model (GCM) simulations by the IPCC (2007) show that annual mean precipitation for the East African region (Uganda, Kenya, Tanzania) is projected to increase between 0.5 and 0.6 mm/day, while the annual mean surface air temperature is projected to increase between 2.5 and 3.0 °C for the period 2080–2099 relative to 1980–1999 under the A2 Special Report on Emission Scenario (SRES) (Nakicenovic et al. 2000).

Climate trend analyses in Uganda show that temperatures have been rising since the early 1960s, particularly the

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southwestern part of the country, at an average rate of about 0.3 °C per decade (Mubiru et al. 2009; GoU 2007). Rainfall trend analyses in the country show no change in the annual average rainfall, but the intensity and distribution of the rains throughout the growing seasons are changing (Mubiru et al. 2009; Oxfam 2008). From a national survey conducted by GoU (2007) and a study done by Mubiru et al. (2009), the general consensus is that the onset and cessation of the rains have become erratic and rains for the September–November season have been characterized by heavy downpours and violent storms. Changes in seasonal rainfall patterns have greatly affected the smallholder farmers as they entirely depend on rain-fed agriculture. A study done by Bagamba et al. (2012) shows that between 70 and 97 % of the smallholder farmers in central and southwestern Uganda are highly vulnerable to the impacts of climate change with no ability to cope.

Many production and service sectors in Uganda, particularly agriculture and water, are already being affected by climate change. The southwestern part of the country is increasingly becoming unsuitable for coffee production, a major cash crop and export earner for the country, due to temperature increase (Oxfam 2008). Water levels in Lake Victoria (the biggest lake in the country and East Africa, vital for transport and fish production) have been declining since 1965 with a sharp decline between 2004 and 2007 (Goulden 2006). The drop in lake levels has been attributed partly to climatic factors and partly to human activities. Approximately half of the drop of the lake level between 2000 and 2006 can be explained by excess releases through dams at the outflow of the lake, while the other half appears to be due to climatic factors (Sutcliffe and Petersen 2007).

The negative impacts of climate change on agriculture in Uganda will greatly affect the economy and people's lives because they heavily depend on it. The agricultural sector contributes 30 % of gross domestic product (GDP) and 75 % of the Ugandan labor force derives its livelihood from agriculture (Salami et al. 2010).

This paper assesses the impact of the probable future climate change on the yields of maize (*Zea mays* L), the world's third most important cereal crop after wheat and rice (Uddin et al. 2010). Maize is an important staple food for more than 1.2 billion people in sub-Saharan Africa and Latin America (IITA 2013). Many studies have shown that future climate change will greatly impact maize yields and possibly cause food shortages in many parts of the world. Travasso et al. (2006) show that maize yields could reduce between 5 and 23 % in many parts of Southeastern South America (SESA) under the HadCM3 A2 and B2 SRES scenarios by 2080, while Tao and Zhang (2010), using the super-ensemble-based probabilistic projection system (SuperEPPS), show that maize yields could reduce between 13.2 and 19.1 % in the North China Plain by 2050. Thornton et al. (2008) show that maize production for the East African region could reduce between 11 and 15 % under the HadCM3 and ECHAM4 A1FI scenario by 2050.

Recent increase in the frequency of droughts in Uganda has affected the production of most staple food crops particularly, maize, beans, and banana causing food shortages in the country (WFP 2009; Oxfam 2008). Maize is an important food and secondary cash crop for Uganda; it is grown in almost all districts of the country (Balirwa 1992) and covers the largest acreage among the major food crops grown (UBoS 2007). In the 2008/2009 cropping year, maize acreage was 1.01 million ha (24.5 % of the total cultivatable land) (MAAIF 2011). The adverse impacts of future climate on this important food crop will have greater implications on the food security of the country. Studies assessing climate change impacts on crop yields in Uganda are still sparse. In the past, studies have mainly been carried out either at global level (Cline 2007), continental level (Africa) (Jones and Thornton 2003), or regional level (East Africa) (Thornton et al. 2008).

This paper assesses the probable future climate impacts on maize yields in the western Uganda agro-ecological zone and evaluates various management options to determine the appropriate adaptation measures. According to the IPCC (2001), African countries are the least contributors of anthropogenic greenhouse gases (GHGs) that have triggered global warming and climate change, and yet, they are the most vulnerable due to low adaptive capacity. African countries are particularly vulnerable to the impacts of climate change due to limited skills and equipment for disaster management, limited financial resources, weak institutional capacity, and heavy dependence on rain-fed agriculture (Rockstrom 2000). In this research, detailed assessments have been made by downscaling future climate and modeling crop growth to provide plausible information on the appropriate adaptation strategies to extenuate the impacts of future climate on maize yields.

2 Study area

Uganda is a landlocked country located in East Africa and lies astride the equator between latitudes 4°12′ N and 1°29′ S and longitudes 29°34′ E and 35°0′ E at an average elevation of about 1,100 m above mean sea level. It has a total land area of 241,038 km^2 and a population of 32.4 million (2009 estimate) (CIA 2010). The country has an equatorial type of climate with plenty of sunshine and heavy rainfall in most parts of it.

Parts of the country south of Lake Kyoga and Victoria Nile have two rainy seasons: the March to May season and the September to November season. In the northern part, rains occur between April and October, while the period from November to March is often very dry. Mean annual rainfall near Lake Victoria is about 2,100 mm, while the mountainous regions of the west, southwest, and northeast receive average annual rainfall of about 1,500 mm. The lowest mean annual rainfall occurs in the extreme northeast, about 500 mm (Byrnes 1990).

Mean annual temperatures range from about 16 °C in the southwestern highlands to 25 °C in the northwest, but in the northeast, temperatures exceed 30 °C in the dry season. The maximum temperature ranges between 18 and 35 °C and the minimum temperature between 8 and 23 °C depending on the part of the country (Byrnes 1990).

Uganda is divided into seven broad agro-ecological zones: the banana–coffee system, the banana–millet–cotton system, the montane system, the Teso system, the Northern system, the West Nile system, and the pastoral system as shown in Fig. 1. An agro-ecological zone (AEZ), as defined by the Food and Agriculture Organization (FAO 2010), is a land resource mapping unit, defined in terms of climate, landform, soils, and land cover, fairly homogeneous across the AEZ, and having a specific range of potentials and constraints for land use.

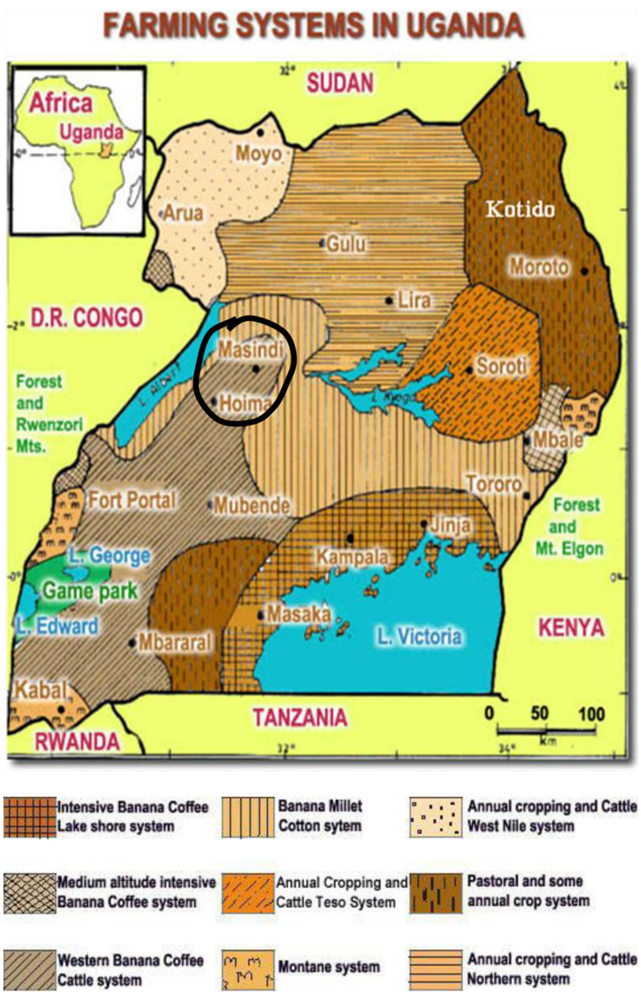


Fig. 1 Map of Uganda showing the agro-ecological zones and the study area (*encircled*). Source: Mwebaze (1999)

The study area covers the districts of Masindi and Hoima in the western Uganda AEZ also referred to as the western banana–coffee–cattle system as shown in Fig. 1. The western Uganda AEZ is a wet zone with rainfall evenly distributed, bimodal and ranging between 1,000 and 1,500 mm/year. The annual average temperature is about 22.6 °C, the soils are of medium to high productivity, and the vegetation is mainly forest-savanna mosaic (Mwebaze 1999). Coffee is the main cash crop, while maize, beans, and banana are the main food crops which also serve as secondary cash crops. Masindi District is the leading producer of maize in western Uganda, while Hoima is the third (IFPRI 2006).

3 Materials and methods

3.1 Climate data

The Uganda Meteorological Department maintains a weather station at Masindi (latitude 1.68° N, longitude 31.72° E, elevation 1,147 masl) from where daily rainfall and temperature data for the study area were collected. The Statistical Downscaling Model (SDSM) version 4.2 used in this study works with climate data for the period 1961–1990 (Wilby and Dawson 2007). Daily rainfall data for Masindi weather station was available for the period 1963–1990, while daily temperature data was available for the period 1962–1979; most of the daily temperature data for the period 1980–1990 was missing due to insecurity during that period in the country. Therefore, analyses for daily temperature data were done for the period 1962–1979. Missing daily rainfall and temperature data were handled or filled using the missing data handling tools of the SDSM v4.2 and DSSAT v4.0.2.0 (Decision Support System for Agrotechnology Transfer) models while downscaling weather parameters and assessing climate change impacts on maize yields. Daily solar radiation data required by the DSSAT crop model was not available at the weather station, and therefore, it was generated from the station co-ordinates and weather parameters using the weather generator tool of the DSSAT crop model.

The National Centre for Environmental Prediction (NCEP) downscaling weather parameters and the Hadley Centre Coupled Model version 3 (HadCM3) general circulation model (Mitchell et al. 1998) A2 and B2 SRES scenarios were downloaded from the Canadian Institute for Climate Studies (CICS) website (CICS 2010). GCM data was only available for the HadCM3 A2 and B2 SRES scenarios; nevertheless, the HadCM3 model has been shown in model comparison studies to simulate precipitation for the East African region better than most models (IPCC 2007; McHugh 2005). The NCEP reanalysis weather parameters were available for the period 1961–

2001, while the HadCM3 A2 and B2 SRES scenario predictor variables were available for the period 1961–2099. Data for most predictor variables was available apart from airflow predictor variables such as vorticity. HadCM3 general circulation model data was available at a resolution of 2.5° latitude by 3.75° longitude. The GCM predictor data was downloaded after identifying the grid box on the globe containing the latitude and longitude of the weather station.

3.1.1 Crop data

The maize variety considered in the study was MH-16, widely grown in East Africa (White and Grace 2001; Smale 1993). The data required for the development of CERES-Maize model for MH-16 was obtained from various secondary sources. Crop data on the number of days to anthesis, physiological maturity (i.e., phenological development stages), and yield were obtained from field experiments done by the Ministry of Agriculture (MOA), United Nations Development Program (UNDP), and the Food and Agriculture Organization (FAO) in Malawi (Heisey and Smale 1995; Smale 1993) as presented in Table 1. The cultivar genetic coefficients were obtained from White and Grace (2001) as provided in Table 2. Management data typical to the study area (i.e., planting date, planting density, planting depth, etc.) and soil characteristics were collected from Bulindi Zonal Agricultural Research and Development Institute (BuZARDI) in Hoima District. Soil data collected includes soil texture, depth, classification, drainage, organic carbon, total nitrogen, and pH.

3.2 GCM and downscaling

The general circulation model used in this study is the Hadley Centre Coupled Model version 3 (HadCM3) (Mitchell et al. 1998). GCMs produce climate data at coarse spatial resolutions; for example, the HadCM3 model has a spatial resolution of 2.5° latitude by 3.75° longitude (CICS 2010). This implies that climate change impact studies based on GCM climate data are less reliable for specific localities or individual sites.

The climate data from HadCM3 A2 and B2 SRES scenarios for the study area were downscaled using the Statistical Downscaling Model (SDSM) version 4.2 (Wilby and Dawson 2007). The SDSM model uses transfer function methodology to develop empirical relationships between the observed local scale predictands (minimum temperature, maximum temperature, precipitation, etc.) and regional scale predictors (mean sea level atmospheric pressure, relative and specific humidity, geopotential height, etc.) for use in the downscaling process. For conditional processes such as precipitation, the model additionally uses stochastic techniques to artificially inflate the variance of the downscaled daily time series to better accord with the observations (Wilby and Dawson 2007).

Table 1 Characteristics of MH-16 maize variety

Variety	50 % anthesis	Physiological maturity	No. of leaves at maturity	Yield		Yield	
				Research station	Management practices	Farmer's field	Management practices
MH-16	70–77 days after planting (DAP)	125–130 days after planting at about 1,000 masl altitude	19–22	4–8 t/ha (from data of six research stations for 2 years)	– Rain-fed – 120 kg/ha N – 60 kg/ha P_2O_5 – Proper tillage, weed, pest, and disease control	2.2–3.1 t/ha (from 5 years aggregate data of farmers' yields national wide)	– Rain-fed – 40–95 kg/ha N – 10–37 kg/ha P_2O_5 – Minimal or no pest and disease control – Associated with poor tillage and weed control

Data obtained from the National Maize Variety Trial field experiments done by the Ministry of Agriculture (MOA), Malawi (1990–1992) and joint Fertilizer Demonstration Trials by the MOA, United Nations Development Program (UNDP), and Food and Agriculture Organization (FAO) in Malawi (1989–1993). Sources: Heisey and Smale (1995), Smale (1993), and White and Grace (2001)

Table 2 Genetic coefficients of MH-16 maize variety

Genetic coefficients (GC)	P1	P2	P5	G2	G3	PHINT
Estimated value of GC	245.3	0.28	843	417.3	7.87	75

Source: White and Grace (2001). P1 = degree days (base 8 °C) from emergence to end of juvenile phase; P2 = photoperiod sensitivity coefficient (0–1.0); P5 = degree days (base 8 °C) from silking to physiological maturity; G2 = potential kernel number; G3 = potential kernel growth rate milligram/(kernel day); PHINT = degree days required for a leaf tip to emerge (phyllochron interval) (degree Celsius day)

The SDSM model performs seven basic functions which are as follows: data quality control and transformation, screening of predictor variables, automatic model calibration, weather generation, statistical analyses, graphing of climate data and model outputs, and scenario generation. The NCEP regional scale predictor variables were screened using the correlation analysis, scatter plots, and seasonal variance tools of the SDSM model to determine the predictors that were strongly correlated with the predictands (daily minimum and maximum temperatures and precipitation). For precipitation, the daily data was first transformed with the fourth root function in order to produce a linear relationship. Additionally, for the strongly correlated predictor variables, it was ensured that the probability value (p value) was less than 0.05 so that the correlation would not be by chance. The screened predictor variables and the observed predictands (daily minimum and maximum temperatures and precipitation) were used to calibrate the SDSM model. The monthly mode of the SDSM model was used in the calibration.

The root mean square error (RMSE) and coefficient of determination (R^2) were computed using Eqs. 1 and 2, respectively, for model calibration and validation to assess the skill of the model in simulating the observed daily average, minimum and maximum temperatures, and precipitation. The lower the value of RMSE and the closer the value of R^2 to 1, the better the model simulates the observed parameters. HadCM3 A2 and B2 SRES scenarios data for the screened predictor variables were input into the scenario generator tool of the calibrated SDSM model to generate the downscaled climate change scenarios for the station.

$$\mathrm{RMSE} = \sqrt{\left(1/n^* \sum_{i=1}^{n} (X_i - Y_i)^2\right)} \tag{1}$$

$$R^2 = \left\{\left(\sum_{i=1}^{n} \left(\left(X_i - \overline{X}\right)^* \left(Y_i - \overline{Y}\right)\right)\right) / \left((n-1)^* S_x S_y\right)\right\}^2 \tag{2}$$

Where:

X_i	Observed (measured) data at time i
Y_i	Computed (simulated) data at time i
n	Number of data points
$\overline{X}$	Mean value of observed data
$\overline{Y}$	Mean value of computed (simulated) data
S_x	Standard deviation of X
S_y	Standard deviation of Y

3.3 Crop modeling

The impacts of future climate on maize yields were analyzed using the CERES-Maize model (Ritchie et al. 1998) of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.0.2.0 The DSSAT software package contains 17 crop models (including CERES-Maize) running on a single soil module, weather module, management module, and soil–plant–atmosphere module (ICASA 2010). The models simulate crop growth (dry weight gain rate, leaf area index, grain filling rate, etc.) on a daily basis, phenological development (germination, seedling emergence, flowering, physiological maturity, etc.), and yield based on plant physiological processes and how they are influenced by the major factors of climate (daily solar radiation, maximum and minimum temperatures, and precipitation), soil characteristics, and management practices (plant density, sowing depth, cultivar characteristics, etc.) (Hoogenboom et al. 2003).

The CERES-Maize model of DSSAT has been widely used in many studies across the globe; examples of these studies include Soler et al. (2007) in Brazil, Mubeen et al. (2013) in Pakistan, Thornton et al. (2008) in East Africa, Mati (2000) in Kenya, and Makadho (1996) in Zimbabwe. Soler et al. (2007) used CERES-Maize to simulate maize yields in Piracicaba, Brazil and obtained results with an error margin of 10–15 %, while Mubeen et al. (2013) used the same model in Punjab, Pakistan and obtained results with an error margin of −8.5–24.5 %. Mati (2000) used CERES-Maize to simulate maize yields in Kenya and obtained results with an error margin of 5–10 %, while Makadho (1996) used the same model in Zimbabwe and obtained results with an error margin of 3–9.5 %. This shows that a properly calibrated CERES-Maize model produces reliable results in various locations across the globe and in the East African region.

The crop model was calibrated by inputting the soil characteristics, weather data, and crop management data and then by adjusting the genetic coefficients to simulate the observed phenological development stages and yield under the farmers' field conditions. The available genetic coefficients of MH-16 were estimated using an earlier version of DSSAT v3.1 from maize field trial datasets of the International Maize and Wheat Improvement Centre or Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) in East Africa (White and Grace 2001). Newer versions, 3.5 and 4.0, have been released since with a lot of improvements in the simulation of crop physiological processes (ICASA 2010); for example, model reviews in White and Grace (2001) showed that the PHINT value had been "hard wired" at 75 in version 3.1 yet it lies between 45 and 50 for tropical maize. Therefore, to simulate the observed cultivar characteristics, it was necessary to adjust the earlier estimated genetic coefficients.

The average cultivar characteristics were determined from the mean of 30 replicates obtained by running the model over 30 different weather years (1961–1990) using the seasonal analysis tool of the DSSAT model. The following factors were considered in the simulation:

1. No chemical applications for pest and disease control.
2. No tillage simulation.
3. Rain fed.
4. Recommended nitrogen fertilizer level of 95 kg/ha was applied; 75 % nitrogen at planting and the remainder 25 % of Nitrogen at 30 days after planting.
5. Simulation for phosphorous was not possible due to limited soil parameters.
6. Planting was done on 1st March in the March–May season and 1st August in the September–November season at densities of 5 plants/m^2 and depth of 5 cm according to prevalent local practices.

The probable impacts of future climate on maize yields were determined by inputting the downscaled HadCM3 A2 and B2 climate change scenarios (daily minimum and maximum temperatures and precipitation) and daily solar radiation (generated by the crop model from the station co-ordinates and weather parameters) for three time periods of 2010–2039, 2040–2069, and 2070–2099 into the calibrated CERES-Maize model. The model was run at the current CO_2 concentration of 330 ppm and then at future CO_2 concentrations under the A2 and B2 SRES scenarios as shown in Table 3 to assess the direct effects (effects on photosynthesis) of increased atmospheric CO_2 concentration on maize yields.

3.4 Assessment of adaptation options

The impacts of various management options (shifting of planting dates, supplementary irrigation, and nitrogen fertilizers) on maize yields under future climate change were analyzed by adjusting the respective management options in the calibrated CERES-Maize model. Simulations were run at different planting dates across the planting window of the March–May and September–November seasons at intervals of about 1 week to assess the impact on the average yields. Supplementary irrigation water was applied using the furrow method in incremental amounts of 10, 20, 30, and 40 mm. Each irrigation level was applied four times at 20 days interval starting 20 days before the flowering date to coincide with the critical stages of maize growth, i.e., flowering and grain filling. Nitrogen fertilizer was applied in incremental amounts of 10 % of the recommended amount of 95 kg/ha to assess its impact on the average yields. All simulations were done at 330 ppm CO_2.

Table 3 Future atmospheric CO_2 concentration (parts per million) under the A2 and B2 SRES scenarios

Period	2010–2039	2040–2069	2070–2099
Median year	2020	2050	2080
A2 scenario	417	532	698
B2 scenario	408	478	559

Source: IPCC (2007) and Travasso et al. (2006)

4 Results and discussion

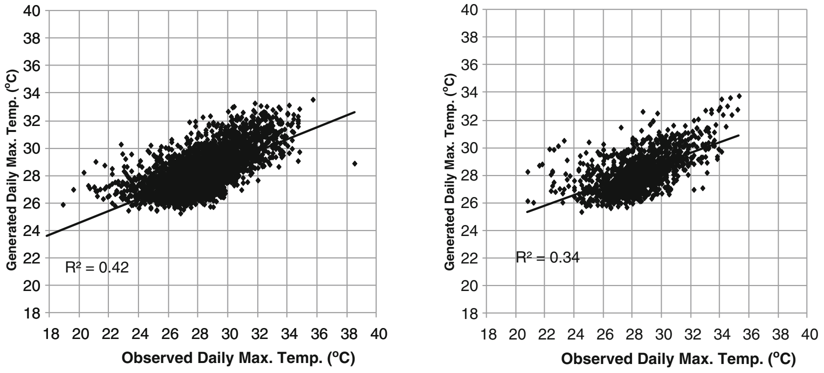
4.1 SDSM model calibration and validation

The SDSM model was calibrated using temperature data for the period 1962–1973 and validated using data for the period 1974–1979, while for rainfall, it was calibrated using data for the period 1963–1980 and validated using data for the period 1981–1990 for the Masindi weather station, depending on data availability. Daily maximum and minimum temperatures and rainfall were downscaled for use in the DSSAT crop model.

The regional predictor variables that were found to have significant correlation with the predictands (daily maximum and minimum temperatures) were as follows: 500 hPa geopotential height (p500), relative humidity at 500 hPa (r500), relative humidity at 850 hPa (r850), surface specific humidity (shum), and mean temperature at 2 m (temp), while the regional predictor variables that were found to have significant correlation with daily rainfall were as follows: mean sea level pressure (mslp), relative humidity at 500 hPa (r500), relative humidity at 850 hPa (r850), and near surface relative humidity (rhum). The results of calibration and validation are shown in Fig. 2.

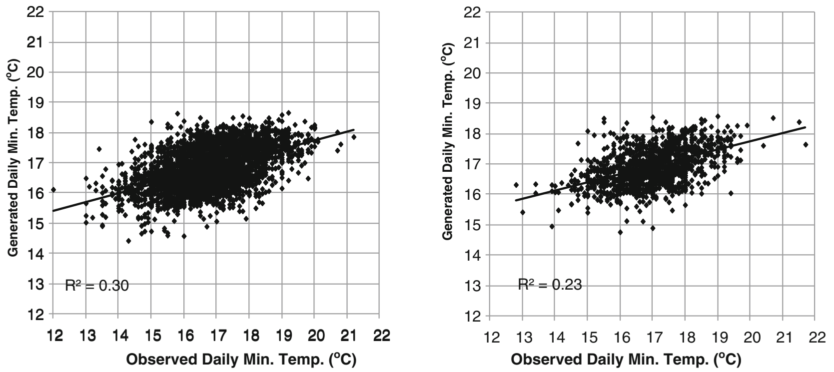
For model calibration of daily maximum temperature, the root mean square error (RMSE)=1.56 °C and coefficient of determination $R^2=0.42$, while for model validation, RMSE=1.64 °C and $R^2=0.34$ were obtained. For model calibration of daily minimum temperature, RMSE=0.96 °C and coefficient of determination $R^2=0.30$, while for model validation, RMSE=0.94 °C and $R^2=0.23$ were obtained. The results show that the SDSM model simulated the observed daily maximum temperature reasonably well, while the model had less skill in downscaling daily minimum temperature. Similar findings were obtained by Coulibaly (2004), Lines et al. (2006), and Yang et al. (2012). The model, however, simulated daily average temperature better than daily maximum and minimum temperatures with the RMSE=0.90 °C

Fig. 2 Observed and generated daily maximum temperature (**a**, **b**), daily minimum temperature (**c**, **d**), and monthly rainfall (**e**, **f**) for SDSM model calibration and validation, respectively



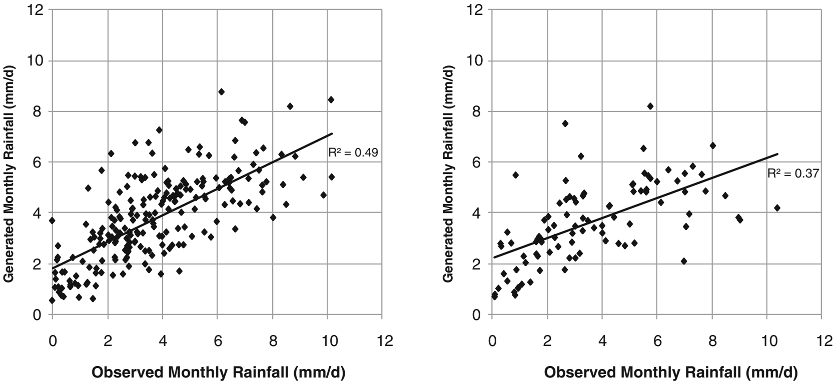
(a) Calibration (1962-1973)

(b) Validation (1974-1979)



(c) Calibration (1962-1973)

(d) Validation (1974-1979)



(e) Calibration (1963-1980)

(f) Validation (1981-1990)

and R^2=0.50 for model calibration and RMSE=0.92 °C and R^2=0.41 for model validation.

The error parameters for SDSM model calibration of monthly rainfall were as follows: RMSE=1.6 mm/day (48 mm/month) and R^2=0.49, while for model validation, RMSE=1.9 mm/day (57 mm/month) and R^2=0.37. Again, these results show that the model simulated the observed monthly rainfall reasonably well. Regression tests could not be applied to the downscaled daily rainfall because of having a non-normal distribution; normal distribution of datasets is a fundamental requirement for regression tests. Downscaling of rainfall is still a subject of ongoing research as it is affected by intermediate occurrence processes (wet/dry day occurrence)

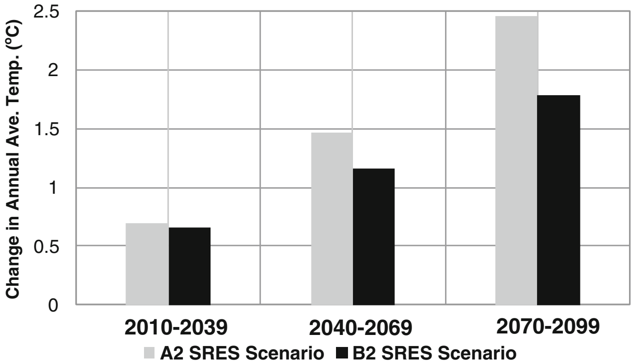
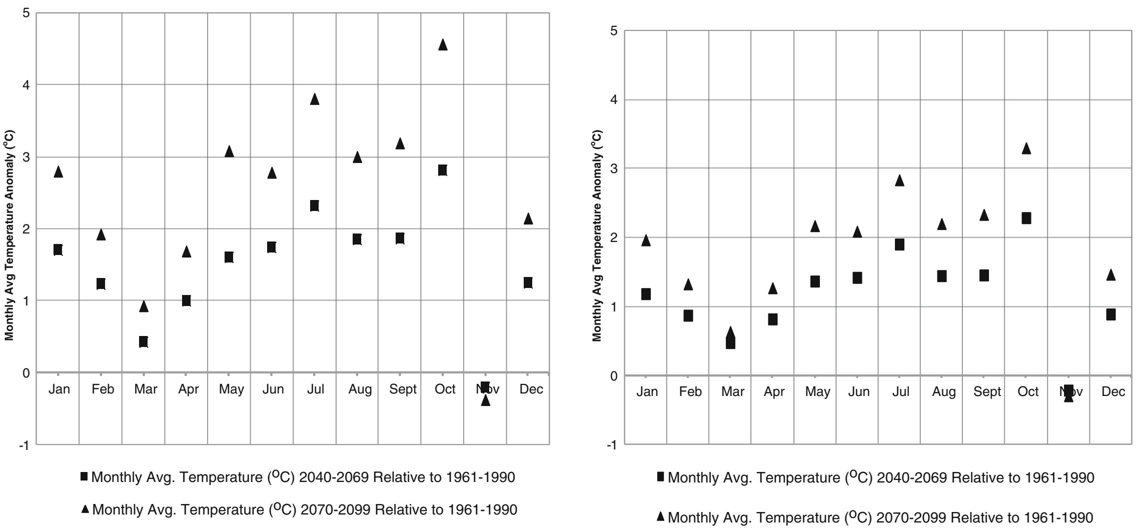


Fig. 3 Projected change in annual average temperature in the study area relative to 1961–1990 annual average of 22.6 °C



(a) A2 SRES Scenario (b) B2 SRES Scenario

Fig. 4 Monthly average temperature anomalies in the study area under the HadCM3 **a** A2 and **b** B2 SRES scenarios in the 2050s and 2080s

in addition to regional forcing factors such as El Nino/Southern Oscillation (ENSO) (Wilby and Dawson 2007; Ojha et al. 2010; Charles et al. 2013).

4.2 Climate change in the western Uganda agro-ecological zone

4.2.1 Change in monthly and annual average temperature

In the western Uganda agro-ecological zone, the annual average temperature is expected to increase by 0.69, 1.47, and 2.46 °C for the periods 2010–2039 (2020s), 2040–2069 (2050s), and 2070–2099 (2080s) relative to 1961–1990 (base period), respectively, under the A2 SRES scenario, while under the B2 SRES scenario, the annual average temperature is expected to increase by 0.66, 1.16, and 1.78 °C in the respective periods (Fig. 3). Monthly average temperatures are expected to increase for most of the months except for the month of November in which a slight decrease is expected under both the A2 and B2 SRES scenarios; the change in the monthly average temperatures ranges between −0.4 and 4.5 °C. The results for the 2050s and 2080s are presented in Fig. 4; in the 2020s, monthly average temperatures show a similar trend and the change ranges between −0.1 and 1.36 °C.

4.2.2 Change in monthly and annual average rainfall

The annual average rainfall in the western Uganda agro-ecological zone is expected to decrease by 4.7, 12.1, and 16.4 % in the 2020s, 2050s, and 2080s relative to the base period, respectively, under the A2 SRES scenario, while under the B2 SRES scenario, the annual average rainfall is expected to decrease by 4.7, 7.9, and 11.8 % in the respective periods (Fig. 5). Monthly average rainfall is expected to decrease for most of the months but will increase for the months of October, November, and December under both the A2 and B2 SRES scenarios; the change in the monthly average rainfall ranges between −49 and 32 mm. The results for the 2050s and 2080s are presented in Fig. 6; in the 2020s, monthly average rainfall shows a similar trend and the change ranges between −15 and 5 mm.

4.3 Impact of future climate on maize yields

4.3.1 CERES-Maize model calibration

The CERES-Maize model was calibrated by adjusting the available genetic coefficients of MH-16 maize variety (determined using an earlier version of DSSAT v3.1) to simulate the observed yield, days to 50 % anthesis, number of leaves at maturity, and physiological maturity under the farmers' field conditions. The calibrated genetic coefficients are presented in Table 4, while the results of calibration are given in Table 5. It

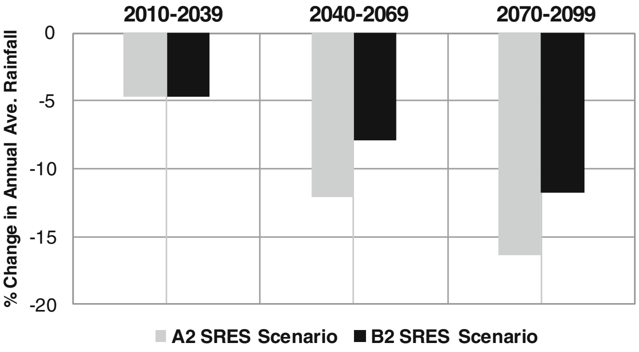
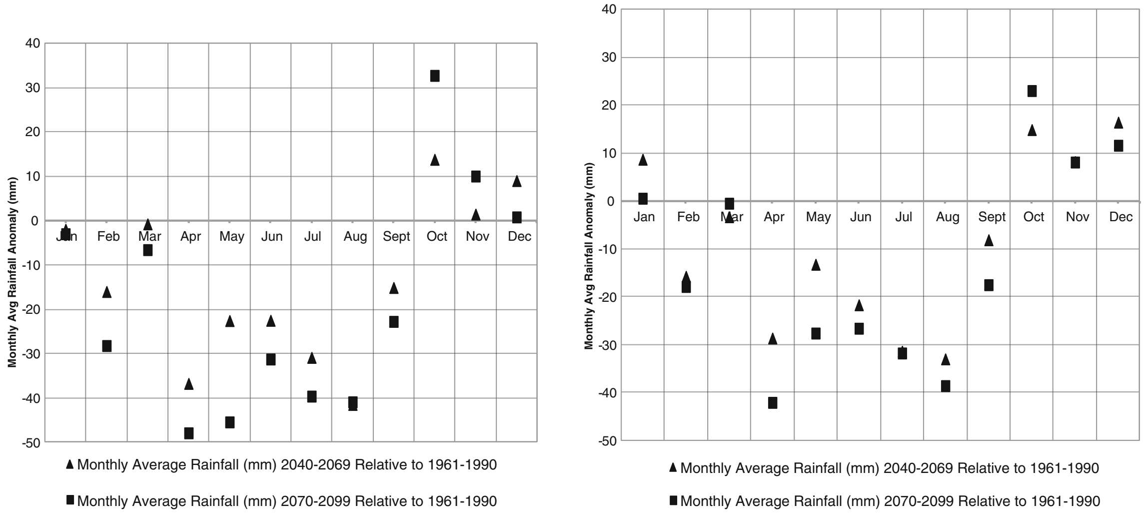


Fig. 5 Projected percentage change in annual average rainfall in the study area relative to 1961–1990 annual average of 1,365 mm



(a) A2 SRES Scenario (b) B2 SRES Scenario

Fig. 6 Monthly average rainfall anomalies in the study area under the HadCM3 **a** A2 and **b** B2 SRES scenarios in the 2050s and 2080s

can be seen that the simulated characteristics of MH-16 are within range of the observed characteristics.

4.3.2 Impacts of future climate on maize yields

Average maize yields were simulated for the 2020s, 2050s, and 2080s under future climate change scenarios, A2 and B2, without considering the direct effects (effects on photosynthesis) of increased atmospheric CO_2 on maize yields and then considering the direct effects. Percentage changes in maize yields relative to the base period average yield were computed for each period and the results are presented in Fig. 7.

Simulation results show that maize yields will decrease by 9.6, 16.4, and 43.3 % for the periods 2020s, 2050s, and 2080s relative to the base period, respectively, under the A2 scenario, while under the B2 scenario, the yields will decrease by 10.5, 14.5, and 28.4 % in the respective periods in the March–May season without considering the direct effects of increased atmospheric CO_2. When the direct effects of CO_2 are considered, the margin of decrease in yields reduces considerably (to between 1.7 and 10.2 %) due to increase in yields as a result of increased atmospheric CO_2. In the September–November season, maize yields will increase by 8.1, 10.2, and 9.6 % for the periods 2020s, 2050s, and 2080s as compared to the base period, respectively, under the A2 scenario, while under the B2 scenario, maize yields will increase by 8.6, 12.1, and 10.2 % in the respective periods without considering the direct effects of increased atmospheric CO_2. When the direct effects of CO_2 are considered, the margin of increase in yields increases slightly (to between 9.5 and 12.6 %).

Table 4 Calibrated genetic coefficients of MH-16 maize variety

Genetic coefficient	P1	P2	P5	G2	G3	PHINT
Calibrated value	270	0.28	800	400	6.5	50

Since maize is a C_4 plant, implying that it operates at saturated CO_2 concentration conditions and hence saturated photosynthesis, the effects of CO_2 on maize yields could be attributed to the effects of CO_2 on stomata resistance. Increased atmospheric CO_2 concentration is well known to increase stomata resistance in all plants (Reddy and Hodges 2000) and hence increases water use efficiency. This implies that when water is a limiting factor to the yields, increased CO_2 increases the yields; however, when water is not a limiting factor, increase in CO_2 may not increase the yields significantly (Travasso et al. 2006). This is clearly demonstrated in the results of the March–May season where rainfall is projected to reduce under future climate conditions (Fig. 6), and increased CO_2 caused significant increases in the yields thereby compensating yield reductions in the season due to the indirect effects of CO_2. In the September–November season where rainfall is projected to increase under future climate conditions (Fig. 6), increased CO_2 caused only slight increases in the yields.

It should be noted, however, that results of direct effects of CO_2 on maize yields are to be interpreted with caution. There are some aspects on the direct effects of CO_2 that are not yet fully understood. For example, current knowledge on the direct effects of CO_2 on crop yields are based on studies carried out in controlled or semicontrolled environments in greenhouses where crop response may differ from when under natural free atmospheric conditions (Reddy and Hodges 2000; Travasso et al. 2006). Additionally, crop response to environments slowly enriched with CO_2 (as it happens under natural

Table 5 Observed and simulated phenological development and yield of MH-16

	Anthesis (50 % silking) (days after planting)	Physiological maturity (days after planting)	Number of leaves at maturity	Average yield at farmers' field (t/ha)
Observed	70–77	125–130	19–22	2.2–3.1
Simulated (average of 30 replicates, 1961–1990)	72	128	20	3.01

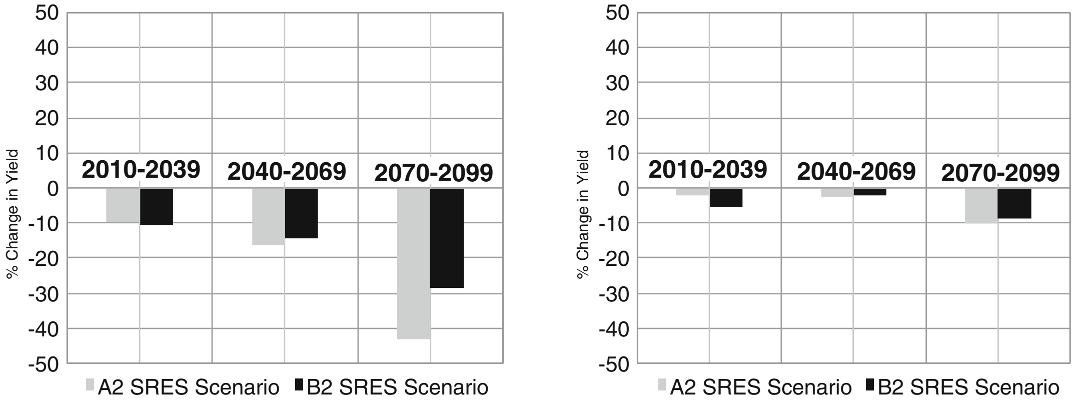
conditions) is not yet fully understood as crops may get acclimatized under such conditions and downregulate the effects (Travasso et al. 2006; Ainsworth and Long 2005).

4.4 Assessment of agro-adaptation measures

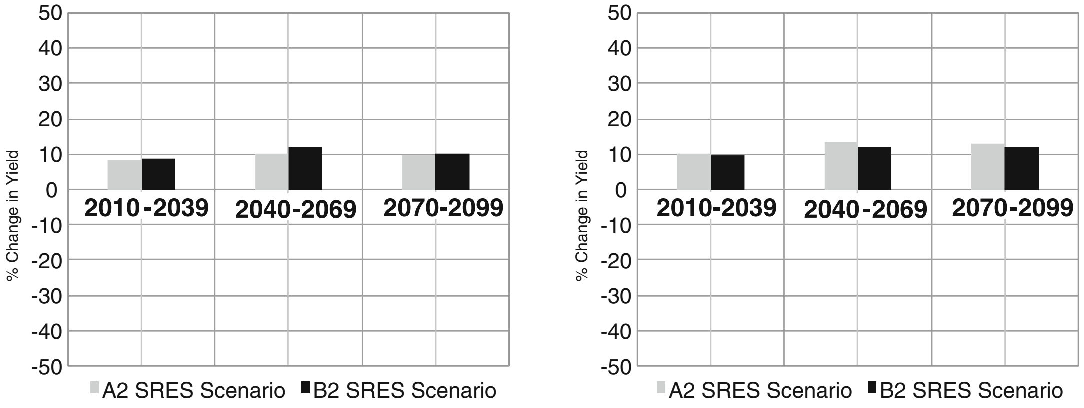
The study evaluated various possible adaptation measures to alleviate the adverse impacts of future climate on maize yields using the developed CERES-Maize model. These include provision of supplementary irrigation, application of nitrogen fertilizer, and changing planting dates. The results are presented and discussed below.

4.4.1 Supplementary irrigation

Supplementary irrigation water was applied using the furrow method in incremental amounts of 10, 20, 30, and 40 mm to determine the optimum level of supplementary irrigation. Each irrigation level was applied four times at 20 days interval starting 20 days before flowering. Simulations were done for the periods 2020s, 2050s, and 2080s under the A2 and B2 SRES scenarios. Results for the A2 scenario are presented in Fig. 8; results for the B2 scenario were similar to those of the A2 scenario. Similarly, results for 2020s were similar to those of the 2050s and 2080s, and hence, only the results for the 2050s and 2080s are presented. The results show that for all

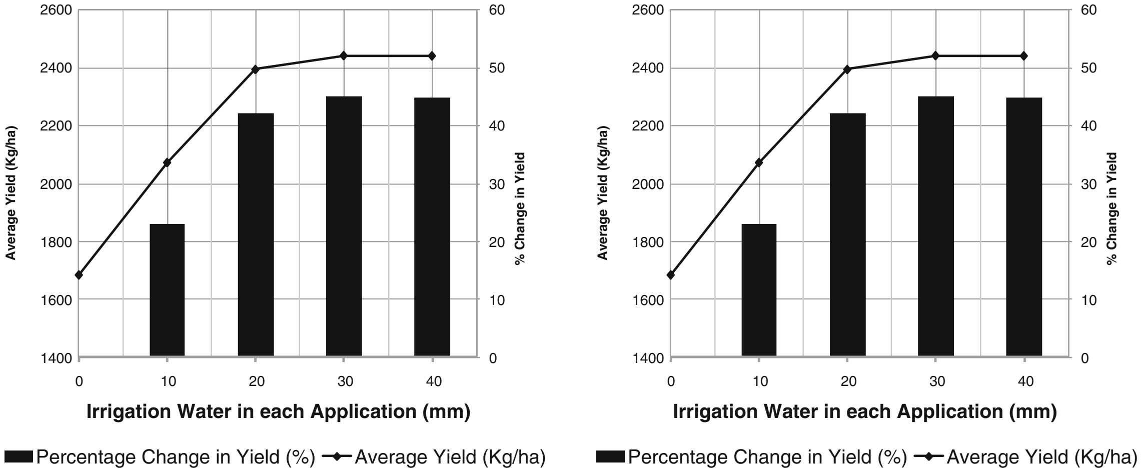


(a) At 330ppm CO_2 – March-May Season (b) At increased CO_2 – March-May Season



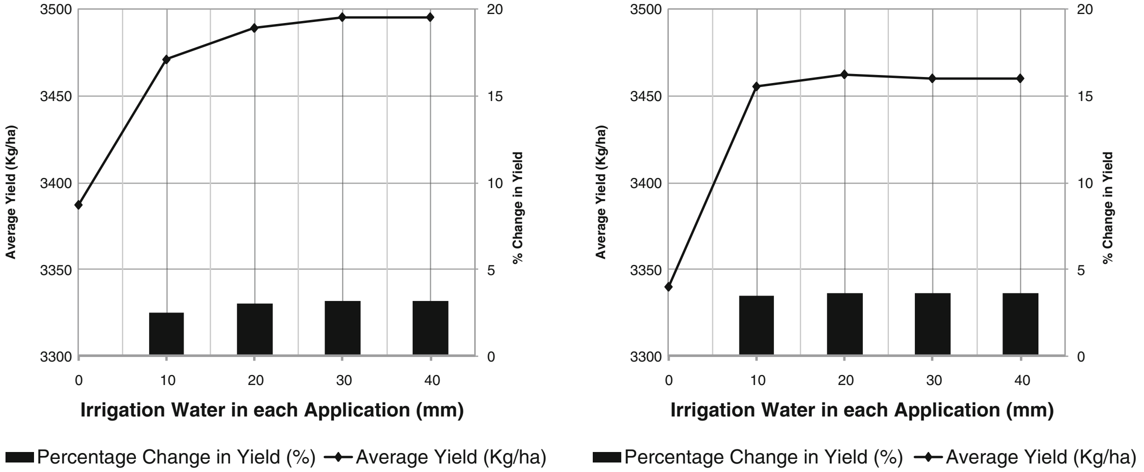
(c) At 330ppm CO_2 – Sept-Nov Season (d) At increased CO_2 – Sept-Nov Season

Fig. 7 Percentage change in maize yields under the A2 and B2 scenarios relative to 1961–1990 average yield without (**a**, **c**) and with (**b**, **d**) considering the direct effects of increased atmospheric CO2



(a) 2040-2069 –March-May Season

(b) 2070-2099 –March-May Season



(c) 2040-2069 –Sept-Nov Season

(d) 2070-2099 –Sept-Nov Season

Fig. 8 Impact of supplementary irrigation on the 2050s and 2080s maize yields under the A2 SRES scenario in the March–May season (**a**, **b**) and the September–November season (**c**, **d**)

the three future periods under both the A2 and B2 scenarios, in the March–May season, the optimum amount of supplementary irrigation is about 80 mm in four applications (i.e., 20 mm per application), while in the September–November season, the optimum amount of supplementary irrigation is about 40 mm in four applications (i.e., 10 mm per application).

Simulation results indicate that the supplementary irrigation in the March–May season would improve the 2020s, 2050s, and 2080s yields by 14.2, 28.6, and 42.1 %, respectively, under the A2 scenario, while under the B2 scenario, the yields would improve by 14.0, 22.8, and 28 % in the respective periods. In the September–November season, supplementary irrigation would improve the 2020s, 2050s, and 2080s yields by 2.0, 2.5, and 3.5 %, respectively, under the A2 scenario, while under the B2 scenario, the yields would improve by 0.3, 2.3, and 1.7 % in the respective periods. Since application of supplementary irrigation water in the September–November season does not improve the yields significantly, it implies that the season rainfall is generally enough to meet the crop water requirements.

Application of supplementary irrigation significantly mitigates the impacts of future climate on maize yields in the March–May season. Application of 80 mm of supplementary irrigation during the growing season in the March–May season under future climate increases maize yields by 3.3 and 7.5 % in the 2020s and 2050s, respectively, while maize yields reduce by only 19.4 % in the 2080s relative to 1961–1990 average yield under the A2 scenario. Without application of supplementary irrigation, maize yields reduce by 9.6, 16.4, and 43.3 % during the respective periods under the same scenario. Similar results were obtained under the B2 scenario. In the September–November season, application of supplementary irrigation does not improve maize yields significantly. The results are presented in Fig. 9.

4.4.2 Nitrogen fertilizer

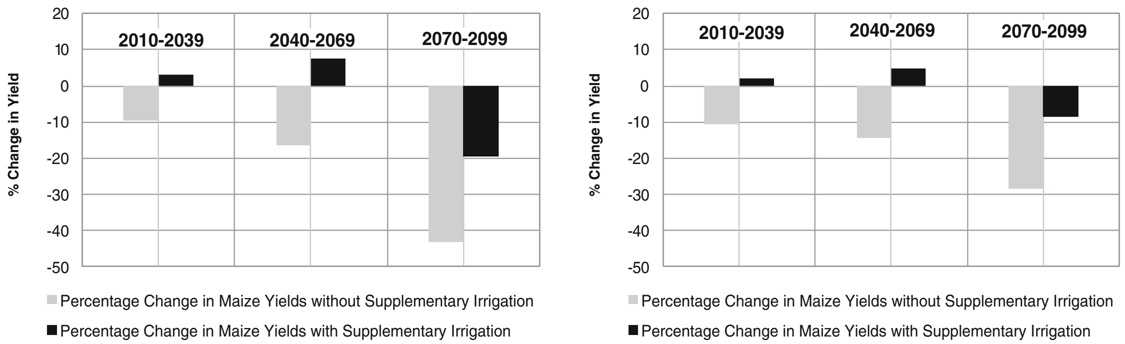
Nitrogen fertilizer was applied in incremental amounts of 10 % of the recommended amount of 95 kg/ha to assess the impact on the average maize yields for the period 1980–2001 under the current GHG forcing and for the periods 2020s, 2050s, and 2080s under future climate change scenarios, A2 and B2. The simulation results show that about 40 % of the recommended nitrogen fertilizer (38 kg/ha) is required to obtain optimum yields under current and future climate change conditions and this would improve the yields by between 1 and 4 %. Results are presented in Figs. 10 and 11 for the 1980–2001 and 2070–2099 periods, respectively.

The low response of the yields to nitrogen fertilizer is attributed to the high organic nitrogen content of the soils in the study area (2.73 %C and 0.25 %N). The soil nitrogen balance file from the DSSAT model runs showed that nitrogen from soil humus contributes over 75 % of the total nitrogen requirement for the growing season, implying that most of the inorganic nitrogen applied was simply fixed as nitrate in the soil. However, it should be noted that under continuous cultivation, soil fertility may deteriorate with time, and therefore, nitrogen fertilizer will be vital in improving maize yields under future climate conditions.

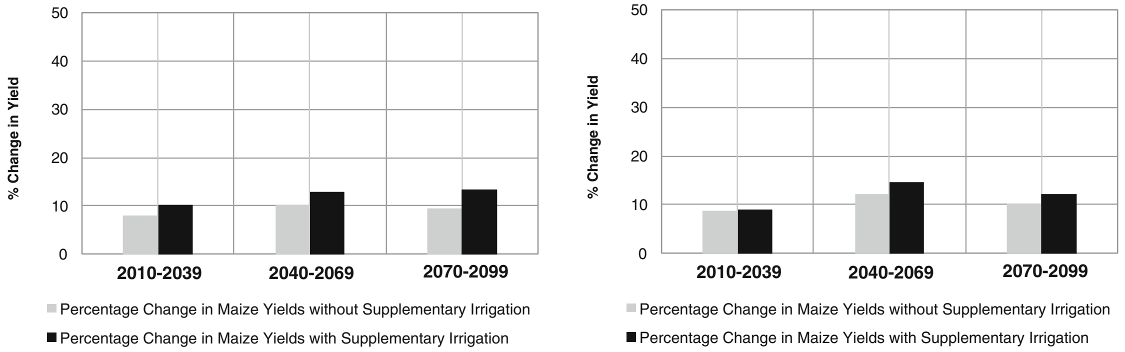
4.4.3 Planting dates

Simulations were run at different planting dates (at intervals of about 1 week) across the planting window of the March–May and September–November seasons for the periods 2020s, 2050s, and 2080s under both the A2 and B2 SRES scenarios to determine the optimum planting dates. The results show that maximum yields can be obtained by planting between 9th and 16th February (on average 16 days earlier than 1st March, the current prevalent planting date) in the March–May season for all the three future periods under both scenarios. In the September–November season, the highest yields are obtained by planting between 1st and 8th August which is generally in the range of the current prevalent planting period. Results for the 2050s and 2080s under the A2 scenario are presented in Fig. 12.

Changing of planting dates significantly mitigates the negative impacts of future climate on maize yields in the March–May season. Planting 16 days earlier than 1st March, in the March–May season, results in maize yield reductions of 4.9,

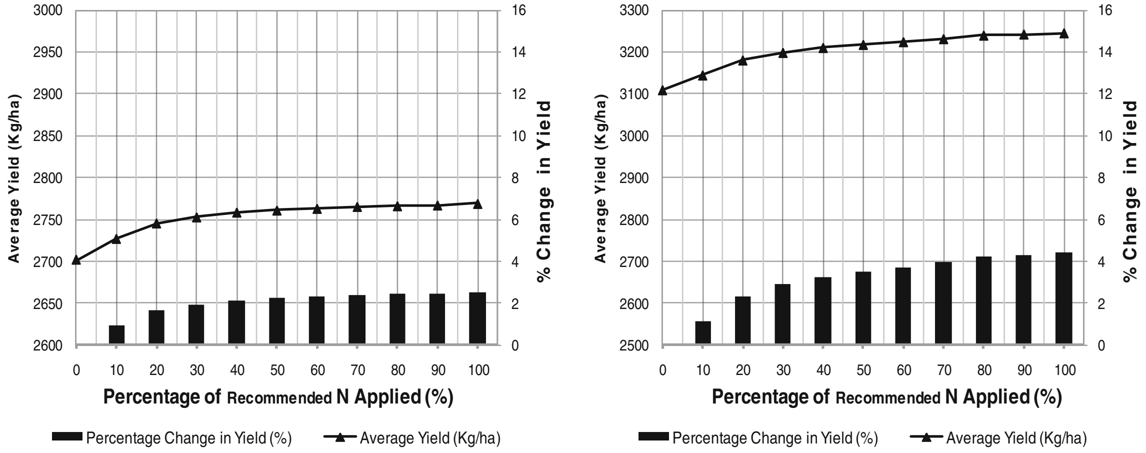


(a) A2 SRES Scenario – March-May Season (b) B2 SRES Scenario – March-May Season



(c) A2 SRES Scenario – Sept-Nov Season (d) B2 SRES Scenario – Sept-Nov Season

Fig. 9 Impact of supplementary irrigation on maize yields in the 2020s, 2050s, and 2080s relative 1961–1990 average yield in the March–May season (**a**, **b**) and the September–November season (**c**, **d**)



(a) (b)

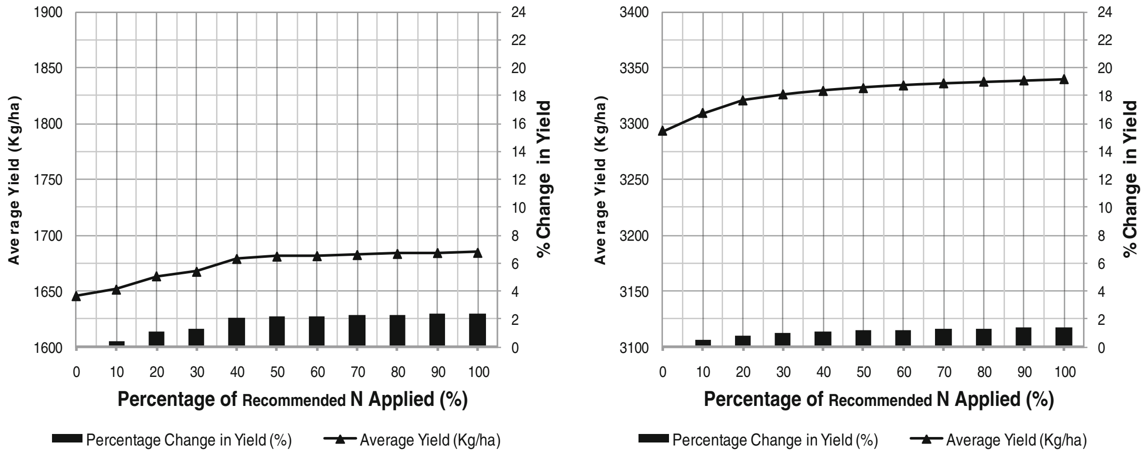
Fig. 10 Impact of nitrogen fertilizer on average maize yields for the period 1980–2001: **a** March–May season and **b** September–November season

13.5, and 33.1 % in the 2020s, 2050s, and 2080s, respectively, under the A2 scenario as compared to reductions of 9.6, 16.4, and 43.3 % in the respective periods under the same scenario by planting on 1st March. Under the B2 scenario, planting 16 days earlier than 1st March, in the March–May season, results in maize yield reductions of 5.5, 13.8, and 22.1 % in the respective periods as compared to yield reductions of 10.5, 14.5, and 28.4 % in the respective periods under the same scenario by planting on 1st March. These results indicate that the gain in the yield due to changed planting date is 4.7, 2.9, and 10.2 % (A2 scenario) and 5.0, 0.7, and 6.3 % (B2 scenario) for the three future periods. Changing of planting dates from the current planting date (1st August) in the 2020s, 2050s, and 2080s in the September–November season does not cause a significant improvement in the maize yields. The results for the March–May season are presented in Fig. 13.

5 Conclusions and recommendations

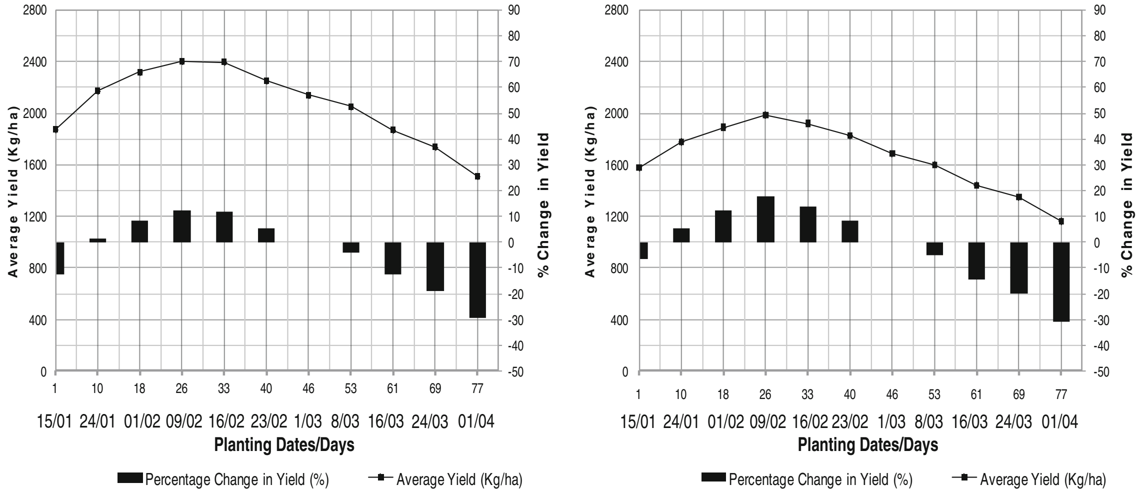
The present simulation study analyzed the possible impacts of climate change and evaluated several adaptation options to mitigate the negative impacts on maize yields in the western Uganda agro-ecological zone. The results have shown that the SDSM v4.2 model can simulate the daily average and maximum temperatures with good skill, while daily minimum temperature and monthly rainfall are simulated with less skill but reasonably well. The CERES-Maize crop model of DSSAT v4.0.2.0 has shown good skill at simulating the observed phenological development stages and the yield of the maize crop. Therefore, these models are reliable tools for climate change impact studies.

The results have shown that the annual average temperature is expected to increase by as high as 2.46 and 1.78 °C under the A2 and B2 SRES scenarios, respectively, by 2080s

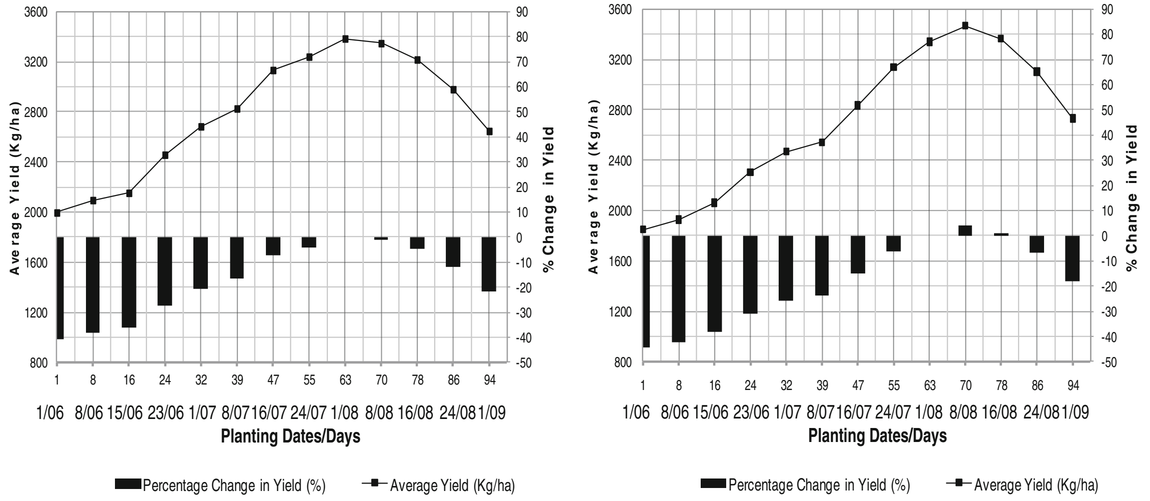


(a) (b)

Fig. 11 Impact of nitrogen fertilizer on average maize yields for the period 2070–2099 under the A2 scenario: **a** March–May season and **b** September–November season

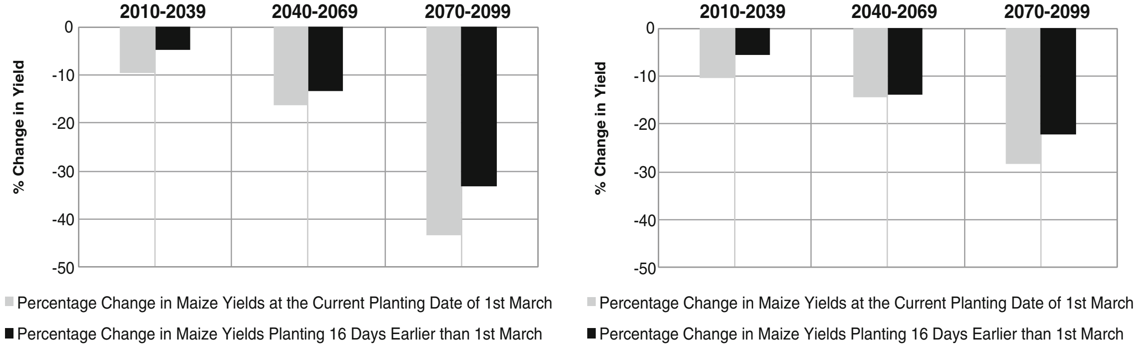


(a) 2040-2069 –March-May Season (b) 2070-2099 –March-May Season



(c) 2040-2069 –Sept-Nov Season (d) 2070-2099 –Sept-Nov-May Season

Fig. 12 **a**–**d** Variation and percentage change of average maize yields with planting dates for the periods 2040–2069 and 2070–2099 under the A2 SRES scenario (1st March and 1st August are current planting dates)



(a) A2 SRES Scenario –March-MaySeason (b) B2 SRES Scenario –March-MaySeason

Fig. 13 **a**, **b** Impact of planting 16 days earlier than 1st March (the current prevalent planting date) on maize yields in the 2020s, 2050s, and 2080s relative 1961–1990 average yield in the March–May season relative to the base period (1961–1990), while the annual average rainfall is expected to decrease by 16.4 and 11.8 % under the respective scenarios. However, seasonal rainfall is expected to increase for the September–November crop season and to decrease for the March–May crop season. Crop modeling results have shown that in the March–May crop season, maize yields will decrease by as high as 43.3 and 28.4 % under the respective scenarios relative to the base period. Therefore, research organizations such as the National Agriculture Research Organization (NARO) should focus on developing heat- and drought-resistant cultivars that will cope with future climate change conditions. Heat resistant cultivars will be vital in taking advantage of the increased precipitation in the September–November crop season under future climate change.

Supplementary irrigation of 80 mm applied during the March–May growing season has shown increased maize yields of about 42.1 % under future climate change. At this level of supplementary irrigation, a moderate amount of about 800 m^3 per hectare will be required; therefore, intervention measures such as rainwater harvesting through construction of valley tanks and valley dams fitted with community pumps powered by either electricity or solar power and harnessing streams and rivers flowing from high mountains where water could flow by gravity could meet the future supplementary irrigation water demands. Planting 16 days earlier than the current planting date (1st March) in the same season is expected to increase maize yields by as high as 17.9 % implying that shifting of planting dates will be a useful adaptation strategy against the probable impacts of future climate change.

Due to the high organic nitrogen content of the soils in the study area, it was found that only about 38 kg/ha (40 % of the recommended nitrogen fertilizer of 95 kg/ha) is required to attain optimum yields under current and future climate conditions. Therefore, it is recommended that area-specific fertilizer specifications be developed for the country for effective and economical use of nitrogen fertilizers. However, it should be noted that under continuous cultivation, soil fertility may deteriorate with time, and therefore, nitrogen fertilizer will be vital in improving maize yields under future climate conditions.

Currently, there is limited data on the genetic coefficients of the local maize varieties developed by the National Agriculture Research Organization (NARO). It is therefore recommended that future research should focus on the determination of the genetic coefficients of the local cultivars and assessment of their resilience to future climate change.

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