Mohammed and Misganaw
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Modeling future climate change impacts on sorghum (*Sorghum bicolor*) production with best management options in Amhara Region, Ethiopia

Adem Mohammed[1*] and Abebe Misganaw[2]

Abstract

Sorghum is one of the most important cereal crops well adapted in arid and semi-arid areas of Ethiopia but yield is low as compared to its potential. The crop has been adversely affected by climate change and climate variability accompanied by low soil fertility, insects and weeds. Thus, assessment of impact of projected climate change is important for developing suitable management strategies. The present study was conducted with the objectives (1) to calibrate and evaluate the CERES-sorghum model in DSSAT (2) to assess impact of projected climate change on sorghum production in 2030s (2020–2049) and 2050s (2040–2069) under RCP4.5 and RCP8.5 scenarios and (3) to identify best crop management strategies that can sustain sorghum production. The CERES-sorghum model was calibrated and evaluated using field experimental data of anthesis, physiological maturity, grain yield and aboveground biomass yield. In the simulation, the initial weather and CO_2 were modified by future climates under the two climatic change scenarios (RCP4.5 and RCP8.5). Historical daily weather data (1981–2010) of rainfall, maximum temperature, minimum temperature, and solar radiation were obtained from the nearest weather stations at Sirinka and Kombolcha while future climate date for 2030s and 2050s were downloaded from the ensemble of 17 CMIP5 GCM outputs run under RCP4.5 and RCP8.5 downscaled to the study sites using MarkSim. Different sowing dates, nitrogen rates, and supplemental irrigation were evaluated for their effectiveness to increase sorghum yield under the present and future climate conditions of the study area. The result of model calibration showed that the RMSE for anthesis, physiological maturity, grain yield, and above-ground biomass yield were 2 days, 2 days, 478 kg ha^{-1}, and 912 kg ha^{-1}, respectively with normalized nRMSE values of 2.74%, 1.6%, 13.42%, and 5.91%, respectively. During the model evaluation the R^2 values were 78% for anthesis, 99% for physiological maturity, 98% for aboveground biomass yield, and 94% for grain yield. The d-statistics values were 0.87, 0.91, 0.67, and 0.98 while the nRMSE values were 2.6%, 2.7%, 23.4%, and 4.1% for the respective parameters. The result of statistical analysis for both model calibration and evaluation revealed that there existed strong fit between the simulated and observed values that indicated the model can be used for different application to improve sorghum productivity in the region. The result of impact analysis showed that sorghum grain yield may decrease by 2030s and 2050s under both RCPs scenarios. However, the result of management scenarios showed that sorghum yield may be substantially increased through use of optimum nitrogen fertilizer, application of supplemental irrigation and by using early sowing dates individually or in combination. In conclusion, projected

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*Correspondence: ademmohammed346@gmail.com
[1] Department of Plant Science, College of Agriculture, Wollo University, P.O.Box 1145, Dessie, Ethiopia
Full list of author information is available at the end of the article

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climate change could adversely affect sorghum production in the semi-arid areas of Ethiopia in the present and future climate conditions but impact could be reduced by using suitable crop management strategies.

Keywords: Climate change, Crop model, DSSAT, RCP, Sorghum, Sowing date

Introduction

In Ethiopia, agriculture is the dominant sector contributing nearly 50% of the Gross Domestic Product (GDP). About 85% of the total employment and livelihoods in the country depend on this sector. The sector is a major source of food for the population and it is the primary contributor to food security (CEEPA 2006). However, the agriculture sector in Ethiopia is highly vulnerable to climate change and climate variability particularly the arid and semi-arid environments. According to the report of Climate Resilient Green Economy (CRGE 2011) climate change has the potential to reverse the economic progress of Ethiopia and could aggravate social and economic problems. The agricultural sector in Ethiopia is highly dependent on rainfall. Irrigation potential of the country is high but irrigation activity is very limited which accounts for less than 1% of the total cultivated land. Crop production is dominated by small-scale subsistence farmers. The subsistence farming accounts for more than 90% of the total agricultural output (CSA 2011). Agricultural output in Ethiopia is highly affected by erratic and unpredictable rainfall with poor distribution (Tefera 2012). Thus, economy of the country is expected to be negatively affected by future climatic conditions. A study conducted by Eshetu et al. (2014) indicated that the GDP of Ethiopia may decrease by about 0.5%–2.5% per year in the near future.

Sorghum (*Sorghum bicolor* (L) Moench) originated in eastern Africa (Lupien 1990). The greatest diversity of sorghum in both cultivated and wild species is found in the eastern part of the African continent (House 1985). In Africa, sorghum is ranked second in terms of production (Belton and Taylor 2003). The crop has the potential to tolerate the effects of water deficit in stressful environments (Haussmann et al. 2007). It is considered an excellent model for drought tolerance among higher plants (Saxena et al. 2002). The crop can also produce reasonable yield in poor soils owing to its nutrient uptake capacity (Dollin et al. 2007). Although sorghum is an important food crop in many of the semi-arid areas of Ethiopia, its yield is still below the expected level because of abiotic and biotic factors. Sorghum production in Ethiopia is highly affected by climate change, climate variability, low soil fertility, water scarcity, lack of improved crop varieties, pests (insect, diseases and weeds) etc. The production in most developing countries in Africa is also highly vulnerable to the impacts of climate change and climate variability (World Bank 2010).

At present, climate change negatively affects the sustainability of agricultural systems in many areas and may continue to challenge communities in developing countries whose livelihoods directly depend on local food production (Wheeler and von Braun 2013). The impacts of climate change may be severe in arid and semi-arid areas where water resources are already low. These areas are very sensitive to climate variability and climate change particularly to high temperature and rainfall variability. Most of the small-scale agricultural systems in many areas are rainfed and may be liable to the direct effect of unpredictable temperature and rainfall variations (Kurukulasuriya et al. 2006). There is a high level of confidence regarding the increase in future temperatures and rainfall over Ethiopia (Hadgu et al. 2015). Thus, Ethiopia may experience further warming by the 2030s and the 2050s in all seasons (Hadgu et al. 2015). A previous study also indicated that annual rainfall may increases in Ethiopia, but there is less certainty regarding spatial and temporal patterns (Conway and Schipper 2011). At present, drought, loss of cattle, reduced harvests, land degradation, and water scarcity occur in Ethiopia (Hadgu et al. 2015). The impacts of future climate change on crop production in Ethiopia are predicted either at the national (Deressa and Hassan 2009) or larger scales such as east Africa (Bryan et al. 2009). There are limited studies at the subnational or local levels in Ethiopia (Alemayehu and Bewket 2016). Therefore, it is necessary to assess impacts of future climate change on crop production at local scale to design appropriate adaptation strategies. The solution to the food crisis in Sub-Saharan Africa (SSA) is improving crops productivity by improving adaptation strategies to both biotic and abiotic stresses (Taylor et al. 2006). This study attempted how future climate will likely affect sorghum production in the semi-arid region of Ethiopia.

The use of adaptive strategies that can reduce impacts on crops is less common in the arid and semi-arid areas of Ethiopia and is often limited to very small groups of farmers. Climate-smart agricultural practices are proven techniques to reverse or reduce the impacts of climate change. Mitigation and adaptation technologies that include the introduction of new crop varieties, the use of water efficient technologies, soil fertility management practices, and the use of optimum inputs (improved seed and fertilizers) are very effective options to cope up the adverse effects of climate change. The negative effects of climatic change and climate variability on sorghum production can be minimized by using proven adaptation technologies (Sandeep et al. 2018). Currently promising adaptation strategies such as changes in sowing dates, application of irrigation and use of optimum fertilizers are used in different areas to minimize yield reduction in wheat crop (Pramod et al. 2017). A study conducted by Adem et al. (2016) also showed that supplemental irrigation, changes in sowing dates, and the use of improved crop cultivar significantly increased yield in chickpea in the semi-arid region of northeastern Ethiopia under the present and future climate conditions. Thus, the present study attempted how suitable adaptation strategies can enhance sorghum production and productivity under the present and future climate conditions of the study region.

Agricultural systems require systematic approach because of its complexity. Computer science has made it possible to systematically analyze the combined impact of several factors on crops. It becomes possible to accurately predict the crop yield response to the combined effects of soil, plants, and climatic systems. Crop models can predict real crop systems by predicting their growth and development. The Decision Support System for Agrotechnology (DSSAT) technology has been widely used to study soil fertility, water and irrigation management, yield gap analysis, genotype by environment interaction, predicting impact of climate change and climate variability on crops and evaluation of adaptive measures (Bhupinde 2018). At present, the applications of crop modeling techniques has received significant attention and has provided solutions by reducing costs and improving our understanding. The DSSAT technology has been used to simulate crop biomass, yield, and soil nitrogen dynamics under different management practices and climatic conditions (Li et al. 2015). However, there is continuous need to calibrate and evaluate the model under wide ranges of environments and cropping practices (López et al. 2008). The Crop-Environment-Resource-Synthesis (CERES)-sorghum module is one of the crop models in DSSAT technology. The major components of the model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance (Singh and Virmani 1996). The model can simulate sorghum growth and development on daily time step from sowing to maturity and ultimately predicts yield. The model also simulated physiological processes that describe the crop response to major weather factors, including temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are inputs to the model. Therefore, the present study was conducted with the objectives (1) to calibrate and evaluate the CERES-Sorghum model to simulate phenology, growth, and yield of sorghum (2) to predict impact of projected climate change on phenology and yield of sorghum and (3) to evaluate effectiveness of change in sowing date, nitrogen fertilization and supplemental irrigation as adaptation strategies for sustainable sorghum production in the study region.

Materials and methods

Description of the study sites

The study was conducted at two sites (*Sirinka* and *Harbu*) located in the semi-arid areas of Amhara region, northeastern Ethiopia. The Sirinka site is situated at an altitude of 1850 m above sea level (masl) with latitude 11° 45′ 00″ N and longitude of 39° 36′ 36″ E while the Harbu site is located at an altitude of 1450 masl with latitude of 10° 55′ 00″ N and longitude of 39° 47′ 00″ E. The region receives annual total rainfall of 945 mm with mean annual maximum and minimum temperatures of 27.3 °C and 13.6 °C, respectively. Rainfall in the region is low, erratic and uneven in distribution (Adem et al. 2016). The soil type is characterized as Eutric Vertisol (Adem et al. 2016). The study region is dominated by rugged mountains with undulating hills and valley bottoms. Both sites received bimodal rainfall with a small rainfall season that extends from February to April/May (locally known as *Belg*) and the main rainfall season (locally known as *Kiremt*) extends from June to September. Terminal water deficit caused by dry spells is a major constraint for crop production. Major crops grown in the study sites are sorghum, maize, chickpea, haricot bean, field pea, lentil, teff (*Eragrostis teff*). Mixed farming (crops and livestock) is a major production system. Monoculture is dominant whereas crop rotation (cereals with pulse crops) and intercropping are practiced to some extent. The majority of field crops are grown under rainfed conditions during the main rainy season and some crops such as field pea, teff, and mung bean are grown during the short rainy season. Sorghum can be grown in the short as well as during the long rainy seasons based on the nature of the sorghum cultivars (short or long maturing types). There are four distinct seasons in Ethiopia namely Summer (June, July and August), Autumn (September, October and November), Winter (December, January and February) and Spring (March, April and May) as indicated in Fig. 1.

Description of the DSSAT and CERES-sorghum model

The DSSAT technology is the most widely used software across many countries. Currently, it incorporates more than 42 different crops including cereals, grains,

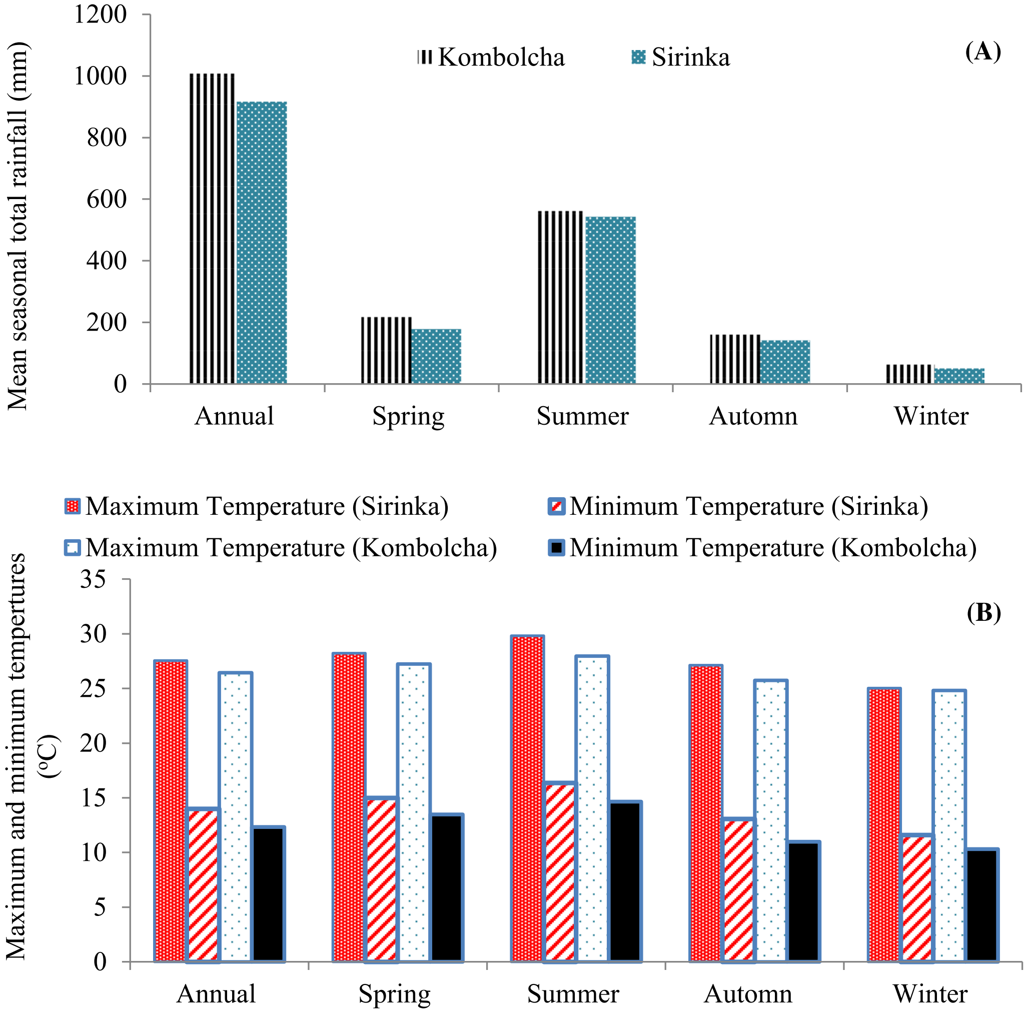

Fig. 1 Mean annual and seasonal total rainfall (**A**) and mean annual and mean seasonal maximum and minimum temperatures (**B**) at Kombolcha and Sirinka weather stations (1988–2018), Ethiopia

grain legumes, and root crops (Hoogenboom 2003). The DSSAT is the first package with weather simulation generators. Its process-oriented and is designed to work independently of location, season, crop cultivar, and management system. It is capable of simulating the effects of weather, soil water, genotype, and soil and crop nitrogen dynamics on crop growth and yields (Jones et al. 2003). DSSAT and its crop simulation models have been used in a wide range of applications in many countries. DSSAT integrates the effects of soil, crop phenotypes, weather, and management options and analyzes the results in minutes. The CERES-sorghum model is one of the models in the DSSAT with major components of vegetative and reproductive development, carbon balance, water balance, and nitrogen balance (Singh and Virmani 1996). The model can simulate the growth, development, and yield using a daily time step from sowing to maturity of the crop. Differences in growth, development, and yield of crop cultivars are affected by genetic coefficients (cultivar-specific parameters) which are inputs to the crop model. The model can simulate physiological processes that describe the crop response to weather factors such as temperature, precipitation, and solar radiation including the effect of soil characteristics on water availability for crop growth.

Model inputs

Field experiments and data collection procedures

For calibrating the crop model, field experiment was conducted at Sirinka in 2019 main crop season in a plot size of 10 m * 10 m replicated three times. In the analysis we considered each individual replicate as a pair data (observed-simulated) to calculate R^2, RMSE, nRMSE and d statistis valuze for each parameters. Sorghum cultivar named *Girana-1* was used as a test crop and was planted in a spacing of 0.75 m * 0.15 m. Recently recommended blended fertilizer (NPSB) with nutrient contents of 18.9% N, 37.7% P_2O_5, 6.95% S and 0.18% B was applied during the sowing time of the crop at a rate of 100 kg ha^{-1}. Nitrogen fertilizer in the form of urea (46%N) was applied during the sowing time a rate of 25 kg ha^{-1} and additional 25 kg ha^{-1} was applied 35 days after the crop emergence.

For observation of anthesis date, physiological maturity date, grain-filling period five plants were randomly selected from each plot and tagged. Days to anthesis was recorded as the number of days from the date of sowing to the date at which 50% of the plants in a plot start heading. Days to physiological maturity was recorded as the number of days from the date of sowing to the date at which 75% of the plants in a plot physiologically matured. Grain-filling period is the numbers of days from 50% flowering to 75% physiological maturity, For those measurements on weight bases a sub-sample (from all plant part) were taken to dry in an oven for 72 h at 60 °C to a constant weight and their weights were determined by using a sensitive balance. Leaf area at 50% anthesis was measured by multiplying leaf length with maximum leaf width and was adjusted by correction factor of 0.75 (i.e. 0.75 * leaf length * maximum leaf width) as suggested by Francis et al. (1969). Thus, the Leaf area index (LAI) was calculated by dividing the leaf area by the sampled ground area. The crop model was evaluated using anthesis date, phenological maturity date and grain yield collected from field trial conducted in 2013, 2014, 2015 and 2017 at Sirinka.

Crop management data

Recommended management practices for sorghum crop are required as input by the model. Thus, information on planting date, planting method, planting distribution, plant population, row spacing, planting depth, cultivar selection, irrigation amount and schedule, fertilizer type and amount, and tillage type were obtained from the nearest Agricultural Research Centre at Sirinka located in the study region.

Soil data

About two weeks before sowing of the crop, soil samples were collected from 1.6 m soil depth near the experimental site for chemical and physical analysis. A total of four distinct soil horizons were identified. Soil samples were collected based on soil horizon and were analyzed for soil texture, pH, organic carbon, total nitrogen, available phosphorous, exchangeable cations, electrical conductivity, bulk density, drained upper limit of soil water content, lower limit soil water content and saturated water content. The soil texture was determined by the modified Bouyoucos hydrometer method (Bouyoucos 1962) using sodium hexametaphosphate as dispersing agent. The soil pH was determined potentiometrically using a digital pH meter in a 1:2.5 soil water suspension (Van Reeuwijk 2002). Organic carbon was determined by wet digestion method whereas total nitrogen was determined through Kjeldahl digestion, distillation and titration procedures of the wet digestion method (Black 1965). Available phosphorus was determined colorimetrically using Olsen's method (Olsen 1954). The Cation exchange capacity was estimated titrimetrically by distillation of ammonium that was displaced by sodium from NaCl solution (Chapman 1965). The soil water dynamics were estimated by inputting soil texture, soil organic matter content and soil bulk density into a soil file creation utility program of the DSSAT software package.

Weather data and RCP scenarios

Daily data of maximum and minimum air temperatures (°C), daily rainfall (mm) and daily total solar radiation (M J M^{-2} day^{-1}) for the period 1981–2020 was obtained from the nearest weather stations at Sirinka and Kombolcha. The Weather Man utility program of DSSAT 4.6 was used to convert the sunshine hours to solar radiation (M J M^{-2} Day^{-1}). Future climate data for the 2030s (2020–2049) and 2050s (2040–2069) were obtained from the 17 CMIP5 GCM outputs run under RCP4.5 and RCP8.5 scenarios downloaded from International Center for Tropical Agriculture (CIAT) climate change portal (http://ccafs-climate.org/) and downscaled to the target site using MarkSim software (Jones and Thornton 2013). WorldClim V1.3 was used to interpolate the climate at the required point. This climate database may be considered representative of the current climatic conditions. It uses historical weather data from several databases. Thus, MarkSim uses the climate records for any given location. In this study, two climate change scenarios (RCP4.5, RCP8.5) were used to predict impact of projected climate change on sorghum production and to explore crop adaptation strategies. The study assumes CO_2 fertilization effect on sorghum Thus, we used 380 ppm of CO_2 for the baseline period whereas 423 ppm and 432 ppm were used for 2030s and 499 and 571 ppm for 2050s for RCP 4.5 and RCP8.5 scenarios, respectively (IPCC 2013). RCP's are greenhouse gas concentration trajectories adopted by the IPCC for its fifth assessment (IPCC 2013). In the RCP4.5 scenario, Greenhouse gas

(GHG) concentrations rise with increasing speed until the forcing is 4.5 W m^{-2} in the year 2100. This is a moderate emission scenario of concentration rise whereas, in RCP8.5, GHG concentrations rise with increasing speed until the forcing is 8 W m^{-2} in the year 2100. This is a high scenario of concentration rise.

Model calibration and evaluation procedures

The CERES-Sorghum model in the DSSAT model was calibrated using field experimental data of 2019 main cropping season conducted at Sirinka site. Calibration is defined as adjustment of model parameters so that the predicted results are very close to the results obtained from the field experiments. The model used genetic coefficients that determine phenology, growth, and yield characteristics of a given crop cultivar. The calibration of the model was performed through a trial and error method by applying small change (+5%) on each parameter and by adjusting the genetic coefficients that determine the phenology of the crop followed by yield and yield components. The adjusted genetic coefficients were used in the subsequent evaluation of the crop model. In the calibration and evaluation phases, the observed dates of anthesis, physiological maturity, and yield were statistically compared to the simulated values using a set of statistical approaches such as the root mean square error (RMSE) (Loague and Green 1991), normalized root mean square error (nRMSE), index of agreement (d) (Willmott et al. 1985), and coefficient of determination (R^2). The RMSE is the standard deviation of the residuals (prediction errors). The residuals measure how far the data points are from the regression line. It tells us how concentrated the data is around the line of best fit. R^2 is a statistical measure of how well the regression predictions approximate the real data points. An R^2 of 1 indicates that the regression predictions perfectly fit the data. The Index of Agreement (d) developed by Willmott (1981) is used as a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott 1981). The nRMSE gives the measure (%) of the relative difference between simulated and observed data. Less value indicates good fit of the model

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$

where n = number of observations, Pi = predicted value for the ith measurement and Oi = observed value for the ith measurement. Thus, lower value indicates good fit of the model.

$$\text{n}RMSE = \frac{RMSE}{N} \times 100$$

where N is the mean of the observed variables. nRMSE gives the measure (%) of the relative difference between simulated and observed data. Less value indicates good fit of the model

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=0}^{n}(|Pi - O|) + (|Oi - O|)^2}\right]$$

The d-statistic was calculated as ($0 \leq d \leq 1$). The more values close to unity are regarded as best agreement between the predicted and observed data (Musongaleli et al. 2014). When d = 1 indicates excellent. Where n: number of observations, Oi and Pi are the observed and predicted values, respectively for the ith data pair; and O is the mean of the observed values.

Analysis of impact of projected climate change on sorghum

The CERES-sorghum model in combination with the seasonal analysis program in DSSAT was used to simulate phenology, growth, and yield of sorghum under the present and future climate conditions of the study area. The sorghum cultivar *(Girana-1)* was used as the test crop. Simulations were carried out for the baseline period (1981–2010) and for the projected climate changes in 2030s (2020–2049) and 2050s (2040–2069) under RCP4.5 and RCP8.5 scenarios. In this study, all the simulations were started on July-2 as it is the average planting date for sorghum in the area most farmers practice. The long rain season usually starts at the end of June to the first week of July. Thus, this study also assumed that the soil profile was at the upper limit of soil water availability in that date and the crop was grown under rainfall conditions in the model. It also assumed that soil condition, crop management practices and crop cultivar characteristics are similar to the present situation. Thus, the response of the sorghum cultivar to future climate was evaluated using typical soil and crop management practices (fertilizers application rates, row spacing, planting date, planting method etc.). In the simulation, the crop was planted in 0.75 m * 0.15 m spacing using blended (NPSB) and Urea fertilizers at rates of 100 kg ha^{-1} and 50 kg ha^{-1}, respectively. This study also assumed no problems of insect, disease and weeds during the simulation periods. The outputs from the crop model like days to anthesis, days to physiological maturity, grain yield and seasonal crop transpiration were computed. The change in phenology and yield were compared as followes.

$$\text{change in antheis or physiological maturity}(\%) = \frac{\text{Xpredicted} - \text{Xbase}}{\text{Xbase}} * 100$$

where, X is anthesis or physiological maturity

$$\text{change in grain yield}(\%) = \frac{\text{YPredicted} - \text{Ybase}}{\text{Ybase}} * 100$$

where, Y is grain yield.

Analysis of management scenarios for sorghum

The effect of changes in sowing date, nitrogen rates, and supplemental irrigation were evaluated as sorghum adaptation strategies for their effectiveness to sustain production in the study region. The sowing window for sorghum in the study region is between mid-June and mid-July. Accordingly, the sowing window was categorized as early sowing date, standard (normal) sowing date and late sowing date. Based on this category three sowing dates (15th June, 30th June, and 15th July) were selected. In this regard, sowing on 15th June was considered as early sowing while sowing on 30th June was the normal sowing date as it was practiced by most farmers whereas sowing on July 15 was considered as late sowing for sorghum. Effect of nitrogen was evaluated at three levels (0, 46, and 92 kg N ha^{-1}) and was applied in the form of Urea fertilizer (46%). Regarding irrigated treatments, 100 mm water was applied as supplemental irrigation in ten days interval starting the anthesis period of the crop to reduce the effect of terminal water deficit. Thus, two levels of irrigation treatments (rainfed and supplementaly irrigated) were evaluated. The simulation analysis was performed individually and in combination for all the factors indicated above (change in sowing date, nitrogen rates, and supplemental irrigation) to find the most promising adaptation strategies. Finally, simulated output data were analyzed using analysis of variance (ANOVA) techniques using a statistical analysis system (SAS 2009). Means were compared using the least significant difference (LSD) at 5% probability level. The simulation years were considered as replications as yield in one year under a given treatment was not affected by another year (prior year carryover of soil water was not simulated). Simulation years were unpredictable weather characteristics and therefore formal randomization of the simulation years was not needed.

Results and discussion

Results of model calibration evaluation

The CERES-Sorghum model was calibrated using experimental data of anthesis, physiological maturity, grain yield and aboveground biomass yield collected at Sirinka during the 2019 main crop season. The CERES-sorghum model consists of eleven eco-physiological coefficients that are used to simulate phenology, growth, and yield of sorghum (Table 1). The calibrated genetic coefficients in the model are also indicated in Table 1. After the calibration, the value of the thermal time from the beginning of grain filling to physiological maturity (P5) was set to 490 degree days while the thermal time from seedling emergence to the end of the juvenile phase was set to 420 degree days (Table 1). The RMSE for anthesis,

Table 1 Calibrated genetic coefficients of *Girana-1* cultivar within the model

Parameters	Definition	Genetic coefficients
P1	Thermal time from seedling emergence to the end of the juvenile phase (°C.d)	420
P2	Thermal time from the end of the juvenile stage to tassel initiation (°C.d)	102
P2O	Critical photoperiod or the longest day length (in hours)	13
P2R	Phasic development leading to panicle initiation (°C.d)	90
PANTH	Thermal time from the end of tassel initiation to anthesis (°C.d)	400.5
P3	Thermal time from to end of flag leaf expansion to anthesis (°C.d)	152.5
P4	Thermal time from anthesis to beginning grain filling (°C.d)	81.5
P5	Thermal time from beginning of grain filling to physiological maturity (°C.d)	490
PHINT	The interval in thermal time between successive leaf tip appearances (°C.d)	49
G1	Scaler for relative leaf size	10
G2	Scaler for partitioning of assimilates to the panicle (head)	4

physiological maturity, grain yield, and above-ground biomass yield were 2 days, 2 days, 478 kg ha^{-1}, and 912 kg ha^{-1}, respectively while the nRMSE for the respective parameters were 2.74%, 1.6%, 13.42%, and 5.91% (Table 2). The results showed that there were an acceptable agreement between the simulated and measured anthesis, physiological maturity, and yield of sorghum which indicated that the cultivar specific parameters (genetic coefficients) within the crop model were reasonably adjusted. However, the performance of the model should be further evaluated with independent set of data for simulation of real situation in the study areas.

Thus, for evaluating the performance of the model for simulating phenology and yield of sorghum four years of experimental data (2013, 2014, 2015 and 2017) were obtained from Sirinka site conducted by Sirinka Agricultural Research Center located in the study region. The crop parameters used for the evaluation were anthesis date, physiological maturity date, grain yield and aboveground biomass yield. The result showed that the goodness of fit (R^2) was 78% for anthesis, 99% for physiological maturity, 98% for aboveground biomass yield, and 94% for grain yield while the d statistics values were 0.87 for anthesis, 0.91 for physiological

Table 2 Comparison between simulated and observed anthesis date, physiological maturity (days), grain yield and aboveground biomass yield of *Girana*-1 sorghum cultivar (number of pair data (n) = 3) using R^2, RMSE and nRMSE during model calibration at Sirinka

Parameters	Observed	Simulated	R^2	d	RMSE	nRMSE (%)
Days to Anthesis (days)	73	75	0.78	0.87	2	2.74
Days to maturity (days)	125	127	0.94	0.92	2	1.6
Grain yield (kg ha^{-1})	3562	3084	0.89	0.90	478	13.42
Aboveground Biomass yield (kg ha^{-1})	15,420	14,508	0.87	0.88	912	5.91

Table 3 Comparison between simulated and observed anthesis date, physiological maturity date, grain and biomass yields using R^2, d, RMSE and nRMSE during model evaluation (number of comparison = 4)

Parameters	Observed	Simulated	R^2	d	RMSE	nRMSE (%)
Anthesis (days)	71 (3.3)	73 (3.25)	0.78	0.87	1.83	2.6
Physiological maturity (days)	122 (6.34)	125 (7.54)	0.99	0.91	3.3	2.7
Grain yield (kg ha^{-1})	2932 (515)	2351 (543)	0.94	0.67	685.6	23.4
Biomass yield (kg ha^{-1})	11,656 (1296)	11,365 (1025)	0.98	0.98	477.8	4.1

Numbers in the parenthesis indicate the standard deviation

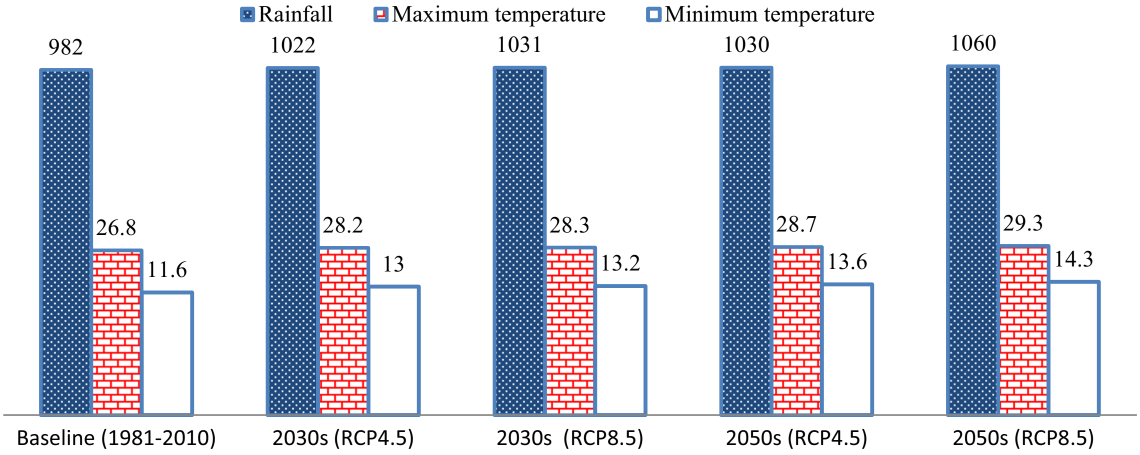

Fig. 2 Projected mean annual total rainfall (mm), mean annual maximum and mean annual minimum temperature (°C) of the baseline period, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios in the study region

maturity, 0.67 for grain yield and 0.98 for aboveground biomass yield (Table 3). The nRMSE values were 2.6% for anthesis, 2.7% for physiological maturity, 23.4% for grain yield, and 4.1% for aboveground biomass yield (Table 3). Results of model evaluation showed that there were an excellent fit between the simulated and observed values indicating the performance of the model to simulate phenology (anthesis and flowering), growth, and yield under the semi-arid environments of northeastern Ethiopia. The results also indicated that the model can be used for different applications such as to study the effect of climate change on sorghum production and to select best crop adaptation strategies for sorghum production under the present and future climate conditions of the study region.

Projected climate changes and its implication

Projected climate changes in the study region

Future climate projection in the study region showed that both mean annual maximum and mean annual minimum temperatures may increase by 2030s and 2050s under both RCP4.5 and RCP8.5 scenarios (Fig. 2). The projection result showed that mean annual maximum temperature may increase by 1.4 °C and 1.5 °C by 2030s under RCP4.5 and RCP8.5 scenarios, respectively as compared to the baseline period. Projection for 2050s period also showed that mean annual maximum temperature may increase by 1.9 °C and 2.5 °C for the respective RCP scenarios. Likewise, mean annual minimum temperature may increase by about 1.4 °C and 1.6 °C by 2030s whereas it is projected to increase by 2 °C and 2.5 °C by 2050s under the respective RCP scenarios (Fig. 2). The projection result revealed that mean annual total rainfall may increase by about 4% and 5% by 2030s under RCP4.5 and RCP8.5, respectively whereas it may increase by 5% and 8% by 2050s under the respective scenarios (Fig. 2). The result of the projected climate changes in this study is in line with that of Conway and Schipper (2011), Setegn et al. (2011), and Dereje et al. (2012) who reported an increase in future temperature in the coming decades in Ethiopia. It can be concluded that the variations in these climate parameters could negatively affect crop production in the semiarid environments of northeastern Ethiopia (Table 4).

Projected climate change impact on phenology of sorghum

Effect of future climate (rainfall and temperature) on anthesis and physiological maturity dates of sorghum at the two sites (Harbu and Sirinka) is depicted in Figs. 3 and 4. The Simulated values at both sites showed that anthesis and physiological maturity dates of the cultivar *Girana-1* may significantly ($P < 0.05$) decrease by 2030s and 2050s under both RCP4.5 and RCP8.5 scenarios as compared to the simulated value for the baseline period (1981–2010). The reduction of anthesis date at *Harbu* site may be 3.4% and 3.9% by 2030s for RCP4.5 and RCP8.5 climate scenarios, respectively whereas the reduction by 2050s may be 4.8% and 7.2%, for the respective RCP scenarios (Fig. 3). The prediction results for 2030s and 2050s periods also showed that physiological maturity date may decrease under both RCP4.5 and RCP8.5 scenarios with reduction of 3.4% and 3.7% by 2030s and 4.5% and 5.8% reduction by 2050s for the respective RCP4.5 and RCP8.5 scenarios. In the same way, the reduction of anthesis date at Sirinka site may be 10.5% and 12.5% by 2030s whereas by 2050s the reduction may be 6% and 20% for the respective RCP scenarios (Fig. 4). Similarly, physiological maturity date at the Sirinka site may be reduced by 13%

Table 4 Physico-chemical characteristics of soil at Sirinka in 2019 main season where PWP, permanent wilting point; FC, field capacity; SAT, saturation; RGF, root growth factor; SKS, saturated hydraulic conductivity; BD, bulk density and CEC, cation exchange capacity

Soil depth (cm)	PWP ($Cm^3\ Cm^{-3}$)	FC ($Cm^3\ Cm^{-3}$)	SAT ($Cm^3\ Cm^{-3}$)	RGF (0–1)	SKS ($cm\ h^{-1}$)	BD ($g\ cm^{-3}$)	Soil Texture (%)		
							Sand	Silt	Clay
0–30	0.11	0.227	0.450	1.0	0.09	1.24	31	40	40
30–60	0.099	0.193	0.452	0.35	0.43	1.29	55	15	30
60–120	0.079	0.165	0.452	0.122	1.32	1.36	41	39	20
120–160	0.179	0.316	0.475	0.061	2.59	1.31	63	19	18

Soil depth (cm)	Soil pH	Organic Carbon (%)	Total Nitrogen (%)	Available Phosphorus (mg/kg)	Electrical conductivity (us/cm)	CEC (Meq/100gm soil
0–30	7.2	2.73	0.02	8.031	0.165	58.3
30–60	7.4	1.62	0.13	6.752	0.123	53.7
60–120	7.8	1.26	0.07	4.450	0.087	57.5
120–160	8.0	2.32	0.03	4.297	0.052	60.2

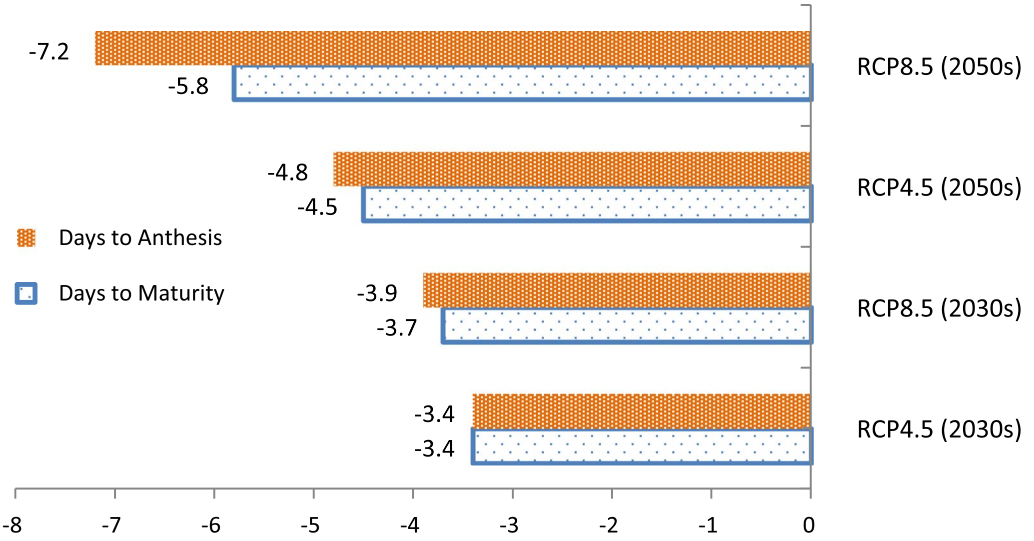

Fig. 3 Change in anthesis and maturity dates (%) of *Girana-1* cultivar at Harbu in 2030s and 2050s) under RCP4.5 and RCP8.5 scenarios as compared to simulated values for the baseline period (1981–2010)

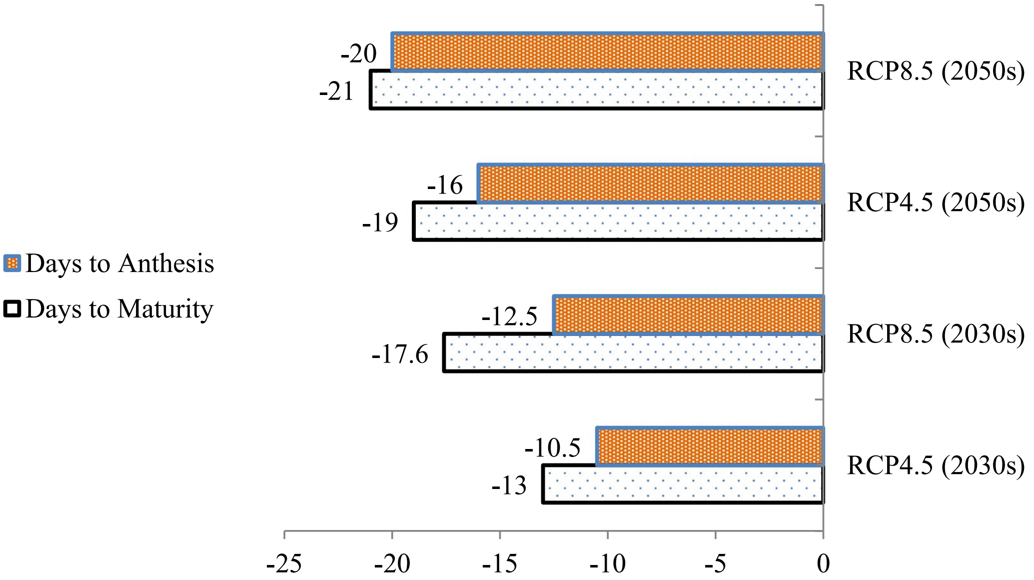

Fig. 4 Change in anthesis and maturity dates (%) of *Girana-1* sorghum cultivar at Sirinka in 2030s and 2050s under RCP4.5 and RCP8.5 scenarios as compared to simulated values for the baseline period (1981–2010)

and 17.6% by 2030s whereas maturity date may decrease by19% and 21% by 2050s for the respective RCPs scenarios (Fig. 4). The decrease in maturity date was higher than the anthesis date at Sirinka site due to greater terminal water deficit at Sirinka site as compared to Harbu site. There is also variation in soil texture and related soil characteristics among the two sites that could contribute variation in soil moisture availability for the crop. These conditions could affect the response of crop to terminal water deficit. At both sites, the highest reduction in anthesis and physiological maturity dates were predicted by 2050s time period as compared to the prediction result for 2030s and the baseline periods. This could be due to the highest increase in temperature by 2050s

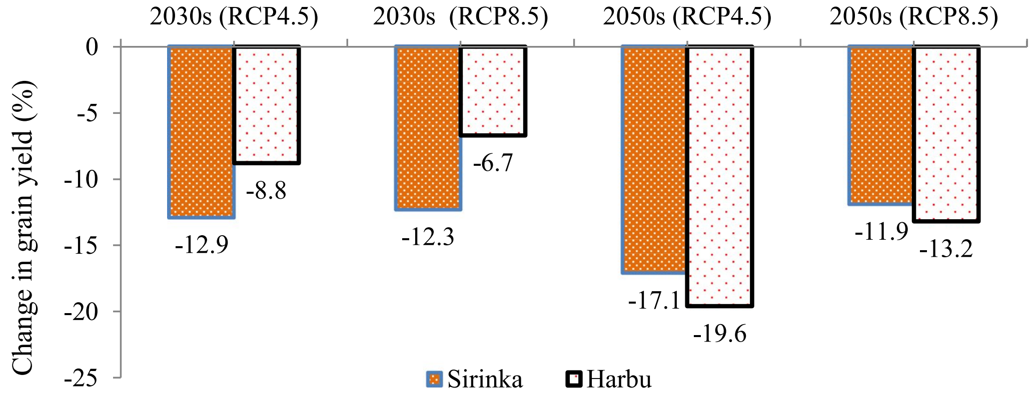

Fig. 5 Change in grain yield (%) of *Girana-1* sorghum cultivar at Sirinka and Harbu sites in 2030s and 2050s as compared to the baseline period (1981–2010)

that may cause water deficit on crop as high temperature can aggravate evaporation and evapotranspiration rates. Under very high temperature condition the crop may be forced to complete its life cycle before the occurrence of water deficit. Very high temperature may accelerate the growth and development stages of the sorghum crop and reduce the crop life cycle. Crop physiological process such as respiration and photosynthesis rates may increase as temperature increase and may result in shortening of growth and development stages of the crop. A previous study by Turner and Rao (2013) also showed that anthesis and maturity days of sorghum were significantly reduced when the temperature was increased by about 1%. A study by Baviskar et al. (2017) also showed that increased temperature resulted in quick accumulation of heat units from sowing to flowering making the crop flower and mature earlier.

Projected climate change impact on sorghum grain yield

The change in sorghum grain yield at Harbu and Sirinka sites under the projected climate conditions are depicted in Fig. 5. The simulated grain yield for the baseline period was 2699 kg ha^{-1} whereas the simulated yields by 2030s were 2462.9 kg ha^{-1} and 2519.3 kg ha^{-1} for RCP4.5 and RCP8.5 scenarios whereas the simulated grain yields by 2050s for the respective RCP scenarios were 2171 kg ha^{-1} and 2343 kg ha^{-1}. The simulated values showed that grain yield may decrease at both sites by 2030s and 2050s time periods as compared to the baseline yield. Based on the prediction result at Harbu site, sorghum grain yield may decrease by 8.8% and 6.7% by 2030s and it may decrease by 19.6% and 13.2% by 2050 under RCP4.5 and RCP8.5 scenarios, respectively (Fig. 5). Simulated results for the Sirinka site also showed similar trend in that grain yield may decrease by 12.9% and 12.3% by 2030s and by 17.1% and 11.9% by 2050s for the respective RCP

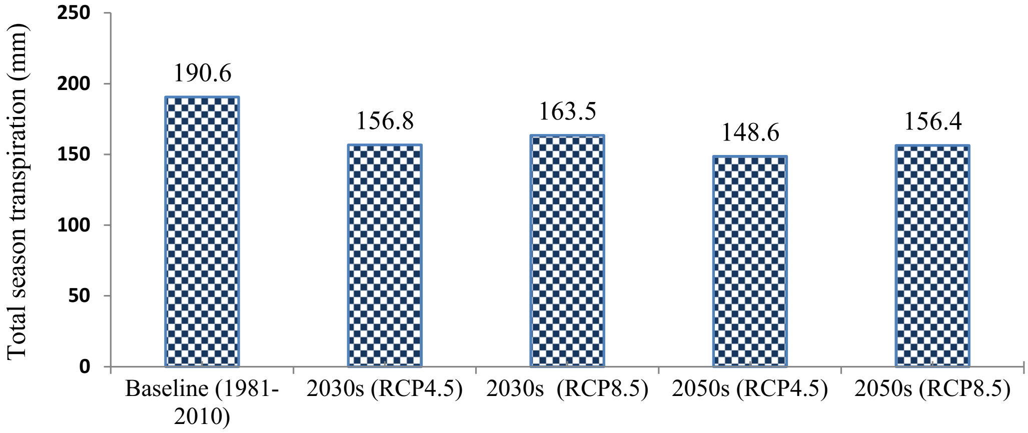

Fig. 6 Mean simulated seasonal sorghum transpiration (mm) in the baseline period, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios at Sirinka

scenarios (Fig. 5). The relatively lower reduction in grain yield by 2050s as compared to grain yield reduction by 2030s could be associated to highest increase in rainfall by 2050s which may increase soil moisture availability for the crop by reducing problem of terminal water deficit.

The reduction of sorghum grain yield under future climate conditions could be attributed more to the increase in future temperature which may affect the crop by accelerating the growth and developmental stages and ultimately reduce yield. The increase in future temperature may aggravate evaporation and evapotranspiration rates and may cause water shortage required for the normal growth and development of the crop. Results showed that total seasonal transpiration by the crop was reduced under future climate conditions due to increase in temperature (Fig. 6). The reduction in crop transpiration could lead to yield reduction. Water shortage due to high temperature can affects nutrients absorption by the crop, photosynthesis rate translocation of photosynthesis products from the source (leaves) to sink (grain) and also affect other physiological processes of the crop. The decrease in grain yield of sorghum may be also associated to the adverse effect of future climate on soil physical and chemical properties. For instance, climate can affect soil texture, structure, bulk density, porosity, nutrient retention capacity, etc. In addition, change in climate could affect soil fertility due to increase in soil salinity (Schofield and Kirkb 2003; De Paz et al. 2012) and reduced nutrients and water availability for crops. Climate change can also affect the chemical properties of soil such as soil pH (Reth et al. 2005), soil salinity, cation exchange capacity, nutrient cycle, nutrients acquisition and biodiversity. Studies showed that soil physical and chemical properties are highly correlated with soil biological properties which can affect the soil fertility (Haynes 2008). Most soil functions such as pH, cation exchange capacity, water and nutrient retention, and soil structure are dependent on soil organic matter. Thus, the variation in decomposition rate of soil organic matter could adversely affects soil fertility (Golovchenko et al. 2007). This fact can indicate that the increase in future temperature associated with the change in rainfall pattern may adversely affect sorghum yield. Thus, these conditions may require changes in crop management practices that can sustain soil fertility in the study area. The study by Seo et al. (2005) also showed that global warming is expected to affect many crops negatively but the increase in future rainfall will have a beneficial effect. In contrast to this result, Chipanshi et al. (2003) and Msongaleli (2015) reported that the grain yield of sorghum will increase under future climate changes. The study by Wortmann et al. (2009) also showed that sorghum production could increase in eastern Africa considering slight temperature increases. Such variations could be attributed to differences in the global climate models (GCMs) used in the simulation and/or the downscaling methods employed on the GCMs in the studies. Another possible reason could be regional variations among the study areas as climate change impact is highly location-specific.

Table 5 Effects of sowing dates and supplemental irrigation on sorghum grain yield (kg ha^{-1}) in the baseline, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios at Harbu

Treatments	Baseline	2030 s		2050s	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
15 June + RF	3038B	2566B	2453B	2445AB	2508AB
30June + RF	2562C	2328BC	2392BC	2085BC	2260B
15 July + RF	1986D	1994C	1983C	1670C	2159B
15 June + SI	3672A	3145A	2937A	2799A	2908A
30 June + SI	3172B	3005A	2984A	2644A	2697A
15 July + SI	2539B	2750AB	2757AB	2565A	2766A
LSD (0.05)	397	435	445	477	409

RF and SI indicates rainfed and supplemental irrigation, respectively

Crop management scenarios for sorghum production

At Harbu site, both the main and the interaction of sowing dates and supplemental irrigation significantly ($P < 0.05$) affected sorghum grain yield in the baseline period, in 2030s, and 2050s under both RCP scenarios (Table 5). Simulation for the baseline period showed that the highest significant simulated grain yield (3672 kg ha^{-1}) was from early sowing (15th June) under irrigated conditions whereas the lowest grain yield (1986 kg ha^{-1}) was from late sowing (15th July) under non-irrigated condition. The normal sowing date (30 June) and the late sowing dates under irrigation conditions did not show any significant yield variation with early sowing treatment under non-irrigated condition. Simulation under the baseline climate showed that late sowing under rainfed condition significantly decreased grain yield. Simulation for 2030s under RCP4.5 scenario showed that early sowing, the normal sowing date and late sowing date all under irrigated condition did not show significant grain yield variations among them. Under this scenario, the lowest simulated grain yield (1994 kg ha^{-1}) was from late sowing under non-irrigated condition and it was statistically similar to yield from the normal sowing date under non-irrigated condition but it was significantly lower than simulated yield from early sowing under non-irrigated condition (Table 5). Simulation for 2030s period under RCP8.5 also showed similar trend. Simulation for 2050s under RCP4.5 showed that the highest simulated grain yield (2799 kg ha^{-1}) was from early sowing under irrigated condition but it was statistically similar to yield from the normal sowing date and the late sowing date treatments under irrigation condition. The lowest simulated grain yield (1983 kg ha^{-1}) was from late sowing under non-irrigated condition and it was statistically similar to yield from the normal sowing date but statistically lower than yield simulated under early sowing and non-irrigated condition. Simulation for 2050s under RCP8.5 scenario showed similar trend. The overall results showed that change in sowing date has not significant effect on sorghum yield under this scenario that could be due to the highest increase in temperature. Rather the use of irrigation or a change in cultivar type may result in improved sorghum yield by 2050s under RCP8.5 scenario..

Most of the simulated results showed that supplemental irrigation was an important water management practice that can increase sorghum yield across different time periods and climate scenarios. In similar manner, early sowing can be an important practice to increase sorghum production under the semi-arid environments of the study area particularly under non-irrigated condition. In most of the simulation, early sowing (15 June) resulted in the highest yield under non-irrigated conditions (Table 5). Early sowing is preferable as it helps for the crop to match the peak water demand with the main rainy period whereas late planting will push the peak water demand period of the crop after the main rainy season passed. Results also showed that there were limited synergetic effects of sowing dates and supplemental irrigation on increasing sorghum productivity. All the sowing dates under irrigated conditions did not show any significant yield variations across time periods and climate scenarios. The semi-arid environment of northeastern Ethiopia is characterized by low and variable rainfall and terminal water deficit is the key problem for crop production. Thus, sorghum yield in these environments can be maximized through early sowing of the crop and by using supplemental irrigation.

Table 6 Effect of sowing dates and supplemental irrigation on grain yield in the baseline period, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios at Sirinka

Treatments	Baseline	2030s		2050s	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
15 June + RF	2866B	2549B	2424B	2432AB	2490AB
30June + RF	1931C	2314BC	2366BC	2061BC	2245B
15 July + RF	1270D	1976C	1974C	1659C	2145B
15 June + SI	3616A	3119A	2937A	2789A	2892A
30 June + SI	2716B	2991A	2917A	2632A	2685A
15 July + SI	1781C	2732AB	2736AB	2548A	2752A
LSD (0.05)	314	432	445	477	406

RF and SI indicates rainfed and supplemental irrigation, respectively

At Sirinka site, both the main and the interaction of sowing dates and supplemental irrigation significantly ($P < 0.05$) affected simulated grain yield in the baseline, by 2030s, and 2050s under both RCP4.5 and RCP8.5 scenarios (Table 6). Simulation for the baseline period showed that the highest significant simulated grain yield (3616 kg ha^{-1}) was from the early sowing date under irrigated condition. Simulated yield from early sowing date under rainfed conditions was statistically similar to yield from the normal sowing date under irrigated condition (Table 6). The lowest simulated grain yield (1270 kg ha^{-1}) was from the late sowing date under non-irrigated condition (Table 6) followed by yield from the normal sowing date under non-irrigated condition. Simulation result under the baseline scenario showed a decreasing trend in yield under non-irrigated conditions when sowing date was delayed (Table 6). Simulation for 2030s under RCP4.5 showed that the highest simulated grain yield (3119 kg ha^{-1}) was from early sowing date under irrigation conditions but it was statistically similar to yield from the normal and late sowing dates under irrigated conditions. The lowest simulated grain yield (1976 kg ha^{-1}) was from late sowing under non-irrigated conditions and it was statistically similar to the normal sowing date under non-irrigated conditions but statistically lower than yield from the early sowing date under non-irrigated condition (Table 6). Simulation for 2030s under RCP8.5 scenario showed similar trend to simulated yield by the 2030s time period. Simulation for 2050s under RCP4.5 scenario also showed that all the sowing dates under irrigated conditions did not showed any significant yield variations The lowest simulated grain yield was from the late sowing date under non-irrigated condition and it was statistically lower than yield from the early sowing date under non-irrigated condition but statistically similar to yield from the nomal sowing date under non-irrigated condition. Simulation for 2050s under RCP8.5 showed similar trend in that all the sowing dates under irrigation conditions and the early sowing date under non-irrigated condition did not showed any yield variations (Table 6). All the sowing dates under rainfed conditions also did not show any significant grain yield variation that could be attributed to extreme increase in temperature under RCP8.5 scenario by 20050 s. Thus, change in cultivars and supplemental irrigation could be suggested as management options for sorghum under this scenario. However, the simulated values showed that delayed sowing date under non-irrigated conditions significantly reduced sorghum grain yield in the present and future climate conditions of the study area. Change in planting dates did not show any significant effect on grain yield of sorghum under irrigated condition. The reduction in grain yield under late sowing in rainfed conditions could be attributed to terminal water deficit that may occur during the critical growth stage of the crop particularly at the anthesis and grain filling stages. The semi-arid areas in Ethiopia are characterized by low and uneven distribution of rainfall. The occurrence of frequent dry spells during the growing season of sorghum is common in the area. Terminal water deficit may affect the sorghum crop and there may be complete crop failure as well. The results of the present study at both sites showed that early sown of sorghum may successfully increase yield in rainfed condition under the present as well as future climates of the study areas. Crops under early sowing condition can utilize soil moisture required for their growth and development. Under early sowing the sorghum crop may complete its growth and development stages before the occurrence of terminal water deficit. In contrary, late sowing under rainfed condition significantly affected grain yield that could be associated to the late-season water deficit. The effect of terminal water deficit on crop can be minimized by using supplemental irrigation which can substantially increase yield under all sowing date conditions. Supplemental irrigation is the addition of limited amount of water to rainfed crops to improve and stabilized yield when the rainfall is unable to provide sufficient moisture for the crop. Supplemental irrigation is an effective adaptation strategy to climate change that can reduce the adverse effect of water deficit which mostly occurs during the critical crop growth stages of crop. Thus, it can be concluded that early sowing under rainfed condition and application of supplemental irrigation can be considered as potential adaptation strategy to increase sorghum yield in the present and future climate conditions of the semi-arid environments of Ethiopia where water deficit is major constraints for crop production. The study by Cunha et al. (2015) also revealed that change in sowing date is an adaptive strategy to climate change which can prevent crops from terminal water deficit.

Effect of nitrogen and supplemental irrigation on sorghum grain yield

At Harbu site, both the main and interaction of nitrogen and supplemental irrigation significantly ($P < 0.05$ affected grain yield in the baseline, by 2030s and 2050s under both RCP4.5 and RCP8.5 scenarios (Table 7). Simulation in the baseline period showed that the highest simulated grain yield (3768 kg ha^{-1}) was from the application of 92 kg N ha^{-1} under supplemental irrigation (SI) condition but it was not significantly different from simulated yield due to the application of 46 kg N ha^{-1} under supplemental irrigation condition (Table 7). Simulated yield from unfertilized and non-irrigated conditions was the lowest with simulated yield of 2376 kg ha^{-1} (Table 7). Results also showed that simulated yield under fertilized and non-irrigated conditions were significantly lower as compared to yield from fertilized and irrigated conditions (Table 7). The simulated grain yield from non-fertilized and irrigated conditions was statistically similar to the grain yield from the fertilized but non-irrigated conditions in the baseline period as well as in future climate periods (Table 7). The simulation result by 2030s under RCP4.5 also indicated that the highest simulated yield (3145 kg ha^{-1}) was due to the application of 46 kg N ha^{-1} under irrigation conditions but it statistically similar to simulated yield due to the application of 92 kg N ha^{-1} under irrigated conditions. The lowest simulated grain yield (2279 kg ha^{-1}) was due to the unfertilized and non-irrigated treatment but it was statistically similar to the simulated yield due to the applications of 46 kg N ha^{-1} and 92 kg N ha^{-1} applications under non-irrigated conditions. In general, application of nitrogen fertilizer under irrigated condition significantly increased sorghum grain yield as compared to simulated grain yield under

Table 7 Effect of nitrogen fertilization (kg ha^{-1}) and supplemental irrigation on sorghum grain yield in the baseline, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios at Harbu

Treatments	Baseline	2030s		2050s	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
0 kg N + RF	2376C	2279C	2185D	2036C	2161C
46 kg N + RF	3038B	2566BC	2453CD	2445B	2508B
92 kg N + RF	3116B	2494BC	2403CD	2321B	2419BC
0 kg N + SI	2831B	2752B	2633BC	2269BC	2478B
46 kg N + SI	3672A	3145A	2937A	2798A	2908A
92 kg N + SI	3768A	3072A	2860AB	2710A	2836A
LSD (0.05)	310	303	302	256	263

RF and SI indicates rainfed and supplemental irrigation, respectively

Table 8 Effect of nitrogen fertilization (kg ha^{-1}) and supplemental irrigation on grain yield in the baseline, 2030s and 2050s under RCP4.5 and RCP8.5 scenarios at Sirinka

Treatments	Baseline	2030s		2050s	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
0 kg N + RF	1734F	2239C	2155D	2002C	2139C
46 kg N + RF	2866D	2549B	2424CD	2432B	2498B
92 kg N + RF	4036B	2475BC	2392CD	2317B	2418B
0 kg N + SI	2098E	2703B	2589BC	2230BC	2452B
46 kg N + SI	3616C	3119A	2917A	2787A	2893A
92 kg N + SI	5265A	3061A	2845A	2697A	2830A
LSD (0.05)	343	302	303	258	267

RF and SI indicates rainfed and supplemental irrigation, respectively nitrogen application only across all time periods and climate scenarios. This result indicated there existed strong synergetic effect of nitrogen and irrigation application on sorghum productivity. Availability of soil moisture is very important for the crop to maintain the water requirement of the criop. In addition, water is very important for nutrient absorption, translocation of photosynthesis products from leaves to grain, maintain internal temperature etc. All these conditions leads to increase in crop yield.

At the Sirinka site, results revealed that both the main and the interaction of nitrogen and supplemental irrigation significantly ($P<0.05$) affected grain yield in the baseline, by 2030s and 2050s under both RCP4.5 and RCP8.5 scenarios (Table 7). Simulation for the baseline period showed that the highest simulated grain yield (5265 kg ha^{-1}) was due to the application of 92 kg N ha^{-1} under irrigated conditions (Table 8). The mean simulated grain yield from the non-fertilized and non-irrigated treatments was significantly inferior as compared to the mean simulated grain yield from fertilized and irrigated treatments. Simulation by 2030s under RCP4.5 scenario showed that the highest grain yield (3119 kg ha^{-1}) was due to the application of 46 kg N ha^{-1} under irrigated conditions but it was statistically similar to simulated yield due to the application of 92 kg N $ha^{-1`}$ under irrigated condition. In all the simulations, the lowest simulated grain yields were due to unfertilized and non-irrigated treatment across the climate periods and scenarios (RCPs). Results revealed that yield response of sorghum to nitrogen fertilizer application was much lower under non-irrigated conditions, even when the nitrogen application rate was increased as compared to grain yield response to increase nitrogen rates under irrigated conditions. This clearly indicated that nutrient absorption by plant is greatly facilitated by moisture availability in the soil. Plants can easily absorb nitrogen from the soil when there is available soil moisture in the soil. Nitrogen is one of the essential nutrients reuired by crops for the normal growth and development. Water deficit in the soil can limit nutrients availability by the crop and finally affect yield. Previous studies by Gonzalez et al. (2005); Garwood and Williams (1967) showed that the uptake of nitrogen by crop roots requires soil water, as water is the main agent that transports solutes from the soil system to the plant system. Water deficit in the soil affect nitrogen uptake by the crop. Nitrogen deficiency in associated with low soil moisture could significantly reduce the concentration of nitrogen in the crop tissue and affect yield of the crop. A study by Sadras et al. (2016) also showed that the interaction effect of water and nitrogen could modulate the geochemical cycling of nitrogen, regulate functional diversity of crops, regulate crop yield, grain size, root growth, leaf stoichiometry, and photosynthesis. Sinclair and Rufty (2012) also reported that availability of nitrogen and water can increase yield in many crops. Thus, it can be concluded that the use of optimum nitrogen fertilizer and supplemental irrigation can sustain sorghum production in the semi-arid areas of Ethiopia under the present as well as future climate conditions.

Conclusion

Agriculture is the main economic sector in Ethiopia and it is the major contributor to the GDP and Foreign Exchange. At present, productivity of major crops in Ethiopia is declining due to climate variability, climate change, low soil fertility, low yielding crop varieties, lack of suitable crop management practices, diseases, insects and weeds. At present, sorghum production is mainly affected by the increasing temperatures, changes in rainfall patterns and extreme weather events. The consequence of climate change is mainly severe in semi-arid areas of Ethiopia as the country is among the most vulnerable countries in the Sub-Saharan. Due to the frequent occurrence of drought and rainfall variability, the farming system in the country is exposed to seasonal shocks that lead to seasonal food insecurity. The early offset of rainfall in association with the low water retention capacity of the soil exposes crops to terminal drought As the result, the crop production system in arid and semi-arid areas does not support the food requirement of the households throughout the year.

Crop models have been used to study the effects of climate change on crops and to identify sustainable crop management practices. However, models must be calibrated and evaluated before they are used for different applications. Thus, a field experiment was conducted in *Sirinka* and *Harbu* sites located in the northeastern Ethiopia. The CERES-sorghum model in DSSAT technology was used in this study. The model was first calibrated and evaluated with phenology, growth and yield data obtained from field experiments conducted in the study region. Historical daily climate data (1981–2010) was obtained from Ethiopian national meteorological agency whereas future climate data of temperature, rainfall and solar radiation for 2030s (2020–2049) and 2050s (2040–2069)) were obtained from ensembles of the 17 GCMs (CMIP5) models outputs. The seasonal analysis program in DSSAT coupled with the CERESS-sorghum model were used to simulate impact of future climate and to identify suitable management scenarios for sorghum crop. The effect of different sowing dates, nitrogen fertilizer and supplemental irrigation were evaluated as management scenarios individually and in combination for their effectiveness to increase sorghum productivity under the present and future climate conditions of northeastern Ethiopia.

The results of model calibration and evaluation showed that the simulated growth, development, and yield were in good agreement with the observed values. The crop model successfully simulated the growth, development, and yield of the sorghum cultivar *Girana-1*. We concluded that if the model is properly calibrated, it could be used for decision support to improve sorghum production under the present and future climate conditions of the study area. The result of future climate change impact on sorghum production showed that future climate may have a profound negative effect on sorghum production under both RCP4.5 and RCP8.5 scenarios. Sorghum yield could be substantially increased through early sowing, application of optimum nitrogen fertilizer, and by using supplemental irrigation individually and in combination. However, the adoption of early sowing and the use of supplemental irrigation could be limited due to shortage of irrigation water, high fertilizer cost, dryspells and insect pests. The agriculture extension system in the region should focus on developing small scale irrigation in the study areas. In addition, farmers may be advised to apply integrated nutrient management and integrated pest management practices to reduce challenges related to fertilizers and pests and increase sorghum yield. Thus, future studies should focus on identification of sound climate adaptative strategies for sorghum production in the semi-arid areas of Ethiopia and similar agroecologies.

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Author contributions

AMo was involved in analyzing and interpreting the data regarding the crop modeling and calibration process. Ami has been involved in the field work and analysis of the data and also in the write of the manuscript. Both authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent for publication

The authors are agreed to publication the article in the journal.

Competing interests

"The authors declare that they have no any competing interests" in this section. Availability of data and materials: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author details

[1]Department of Plant Science, College of Agriculture, Wollo University, P.O.Box 1145, Dessie, Ethiopia. [2]Departmet of Plant Sciences, College of Agriculture and Natural Resource Management , Tulu Awulia University , P.O.box 32, Tulu Awulia, Ethiopia.

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