Agricultural Water Management 194 (2017) 68–77

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Identifying best crop management practices for chickpea (*Cicer arietinum L.*) in Northeastern Ethiopia under climate change condition

Adem Mohammed[a,*], Tamado Tana[b], Piara Singh[c], Adamu Molla[d], Ali Seid[e]

[a] College of Agricultural and Environmental Sciences, Haramaya University, P. O. Box 138, Haramaya, Ethiopia
[b] College of Agricultural and Environmental Sciences, Haramaya University, P. O. Box 138, Haramaya, Ethiopia
[c] International Crop Research Institute for Semi-Arid Tropics (ICRISAT), Patancheru, 502 324, Andhra Pradesh, India
[d] International Center for Agricultural Research in Dry Areas (ICARDA), Addis Ababa, Ethiopia
[e] College of Science, Bahir Dar University, Ethiopia

ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 23 August 2017
Accepted 25 August 2017

Keywords:
Chickpea
Climate change
CROPGRO-chickpea model
Drought
DSSAT

ABSTRACT

Chickpea (Cicer arietinum L.) is one of the important cool season food legumes in the semi-arid northeastern Ethiopia; however, its productivity is adversely affected by a number of abiotic and biotic factors. The objectives of this study were to assess impacts of projected climate change on grain yield of chickpea by 2030 s (2020–2049) and 2050 s (2040–2069) and to identify crop management options that increase productivity of the crop. The CROPGRO-chickpea model in DSSAT (Decision Support System for Agrotechnology Transfer) was used to assess impacts of projected climate change on chickpea and to identify adaptation options. The crop model was first calibrated and evaluated in the study area for simulating growth, yield and water balance of the soil. The result of the model calibration and evaluation showed that there were close agreement between the simulated and observed values that showed the performance of the model to simulate growth, phenology and yield of chickpea under semi-arid northeastern Ethiopian condition. The calibrated model was used to assess impacts of projected climate changes on chickpea and identify crop management options. The impact of projected climate change was assessed for 2030 s and 2050 s time periods under all the RCPs with and without CO_2 fertilization. To identify crop management options, different varieties of chickpea, supplemental irrigation and change in planting dates have been evaluated. The result of climate change impact analysis on chickpea showed that grain yield is predicted to significantly increase both by 2030 s and 2050 s under CO_2 fertilization condition across all the RCPs as compared to baseline grain yield (1961–1990). However, simulation without CO_2 showed that grain yield will not significantly increase by 2030 s and 2050 s across all the scenarios. Based on the prediction result it can be generalized that chickpea will be benefited from the projected climate changes in northeastern Ethiopia. According to the simulation result application of two supplemental irrigation (flower initiation and pod setting stages) and early sowing significantly ($P < 0.05$) increase grain yield of chickpea in northeastern Ethiopia under the present and future climate conditions. Selection of appropriate cultivars based on the agroecology of the area has paramount important to increase chickpea productivity under the present and future climate condition.

1. Introduction

The agriculture sector is the key to livelihoods in Ethiopia as it accounts for 52% of national income and 80% of employment (Hanjra et al., 2009). Ethiopia's rapidly growing population relies on a fragile natural resource base for livelihood security conditioned by timely and adequate rainfall. Smallholders produce more than 90% of total agricultural output and cultivate close to 95% of the cropped land. The poverty traps stem mainly from limited access to productive assets such as land and water; high dependence on agriculture; low farm productivity; low levels of human capital; poor infrastructure; and underdeveloped market systems (Hanjra et al., 2009). Land and water resources are highly underdeveloped, as most smallholders lack access to irrigation, and agriculture remains largely rainfed and highly dependent on rainfall (Hanjra

* Corresponding author at: College of Agricultural and Environmental Sciences, Haramaya University, P. O. Box 138, Haramaya, Ethiopia.
E-mail addresses: ademmohammed346@gmail.com, ademmohammed14@yahoo.com (A. Mohammed), tamado63@yahoo.com (T. Tana), p.singh@cgiar.com (P. Singh), adamu_molla@yahoo.com (A. Molla), alinabiot@yahoo.com (A. Seid).

http://dx.doi.org/10.1016/j.agwat.2017.08.022
0378-3774/

et al., 2009). In many parts of northern Ethiopia, agriculture is affected by declining farm size. Coupled with lack of land, variability and unpredictability in rainfall persists, which is a key reason for Ethiopia now ranking as one of the countries at most 'extreme risk' from the effects of climate change. About 50% of Ethiopia's land area is arid or semi-arid, and largely represent the lowland areas of the country. In such areas, the coefficient of inter-annual rainfall variability around the mean is as high as 30% (Bewket, 2007). Current scientific evidence also suggests that global climate change will lead to greater rainfall variability which will further impede the Ethiopian's farming sector (World Bank, 2011). Ferede et al. (2013) in a recent article also discussed the importance of specific agroecological conditions in different parts of Ethiopia in influencing how climate change will impact crop productivity in the country. In recent decades, the Ethiopia's farming systems have been subject to critical rainfall variability leading to fluctuations in production and, in some years, severe food crises in parts of the country (World Bank, 2011).

The ultimate purpose of climate change risk assessment is to identify adaptation strategies for attaining sustainable development in a specific region (Luo et al., 2009). Such adaptation strategies include improved varieties, shifts in recommended planting dates and rates, novel cropping sequences, change in the number of fallow years required for soil-water recharge in rainfed systems, and introduction of alternative or new crops (White et al., 2011). Sowing date is the most frequently varied option (White et al., 2011), which will surely be adjusted to increase temperature. Under warmer future climates, earlier sowing is likely to require cultivars with different phenological development than currently used (Soltani and Sinclair, 2012).

Chickpea (*Cicer arietinum* L.) is the third most important pulse crop in the world after dry beans (*Phaselous vulgaris* L.) and dry peas (*Pisum sativum*) (Parthasarathy et al., 2010). It is cultivated on 11.5 million hectare with a production of 10 million tons with the productivity of 863 kg ha^{-1} (FAOSTAT, 2012). Although chickpea is a crop of temperate region, its cultivation is gradually spreading to sub-tropical and tropical regions of Asia, Africa, North America and Oceania. Chickpea is cultivated on large scale in arid and semiarid environment. About 90% of the world's chickpea is grown under rainfed conditions where the crop grows and matures on a progressively depleting soil moisture profile and experiences terminal drought, a condition in which grain yield of chickpea is low (Kumar and Abbo, 2001). Average chickpea yield remains low in the major chickpea producing countries due mainly to inadequate water supply (Soltani and Sinclair, 2012). Chickpea is a highly nutritious grain legume crop. It is valued for its beneficial effect of increasing productivity of succeeding crops in rotation and, hence, raising sustainability and profitability of production systems (Soltani and Sinclair, 2012).

Despite huge importance of the crop for human diet and land improvement, yield of the crop is still below the expected level in Ethiopia (Kassie et al., 2009). A number of factors which could be abiotic and/or biotic limit the productivity of chickpea. Among abiotic constraints, drought is the most important factor limiting chickpea production (Singh et al., 2008). Occurrence of drought is a common phenomenon in arid and semi-arid areas of north-eastern Ethiopia. Thus, chickpea cultivation is solely dependent on soil moisture reserve where planting is made late during the recession of the main rainy season to escape the water-logging condition. The flowering and pod setting stages of chickpea appear to be the most sensitive stages to water stress (Nayyar et al., 2006). A parallel study of the same authors (Authors et al., 2016 forthcoming) has been carried out to understand the interactions between different aspects of climate change on chickpea in the semi-arid north-eastern Ethiopia. Based on the result, projected climate change will have some positive implication on chickpea productivity. Increase in yield of rainfed chickpea under climate change has also been reported by Gholipoor and Soltani (2009).

In view of the increasing population and anticipated climate change, production must continue to increase to meet the current and future demand for food in the country. This may be possible through improved crop management options that to suite to the target region. However, there is no published work on impact of supplemental irrigation chickpea productivity especially in the semi-arid areas of north-eastern Ethiopia. Therefore, we evaluated the impact of supplemental irrigation and sowing dates on productivity of different maturity duration of chickpea cultivars using CROPGRO—Chickpea model in semi-arid areas of north-eastern Ethiopia where chickpea is an important crop.

2. Materials and methods

2.1. Description of the study area

The crop model was calibrated at two locations (Sirinka and Chefa) and evaluated at four locations (Sirinka, Chefa, Jarri and Kobo) found in Northeastern Ethiopia. However, both impacts and adaptation options to climate change were conducted for the two locations (Sirinka and Chefa) only. Sirinka is located at an altitude of 1850 m above sea level with geographic coordinates of 11.45.00 N latitude and 39. 36. 00 E longitude. The mean maximum air temperature at Sirinka is 25 °C and mean annual rainfall is 741 mm. Chefa is located at an altitude of 1450 m above sea level with geographic coordinates of 10. 43. 12. N latitude and 39. 49. 48 E longitudes. The mean maximum air temperature is 26.4 °C and mean annual rainfall is 793 mm. The soil texture at the sites except Kobo is clay whereas soil at Kobo is clay loam. The northeastern part of Ethiopia is generally characterized by rugged topography with undulating hills and valley bottoms. The region receives bimodal rainfalls that include: the small rainfall season from February to April/May (locally known as *Belg*) and the main rainfall season from June to September (locally known as *Kiremt*). Rainfall in the region is highly variable and erratic. As a result, terminal drought or stress is a major constraint for most crops. Major Field crops are sorghum, chickpea, haricot bean, field pea and lentil. Mixed cropping (crops and livestock) is the major production system in the area. Mono cropping and sole cropping are dominant in the area; however, crop rotation (cereals with pulse crops) and intercropping are also practiced at some extent. Almost all field crops are grown under rainfed condition in the main rainy season (June to September); however, some crops are grown in the small rainy season (February to April/May). Chickpea is mainly grown in the post rainy season of the main season as sole crop on residual soil moisture.

2.2. Experimental procedures

Experimental data for the calibration of the model was generated from sowing date experiment conducted in 2014 main season at two sites (Sirinka and Chefa) found in northeastern Ethiopia. Three sowing dates (1 September, 10 September and 20 September) were designed to calibrate the crop model in the study region. The model was evaluated using phenological and yield experimental data of 2005, 2006 and 2007) obtained from Sirinka Agricultural Research Center for Sirinka, Chefa, Kobo and Jarri locations in the study region. The sowing dates at Sirinka for 2005, 2006 and 2007 seasons were 6 September, 30 August and 3 September, respectively and the respective harvesting dates were 22 December, 12 December and 19 December. The sowing dates at Chefa for 2005, 2006 and 2007 seasons were 4 September, 1 September and 6 September, respectively whereas the respective harvesting dates were 23 December, 20 December and 10 December. Similarly, the sowing dates at Jarri for 2005, 2006 and 2007 seasons were 1 September, 4 September and 6 September, respectively and the respective harvesting dates were 14 January, 8 January and 22 December. The sowing dates at Kobo for 2005, 2006 and 2007 seasons were 26 August, 30 August and 28 August, respectively and the respective harvesting dates were 2 December, 16 November and 20 November. An improved and well adapted *desi*-type chickpea variety named '*Kutaye*' was used as a test crop.

2.3. Description of the DSSAT model

DSSAT model (Decision Support System for Agrotechnology Transfer) is one of the most widely used modeling systems across the world. It was initially developed under the auspices of the International Benchmark Sites Network for Agrotechnology Transfer (Hoogenboom,

2003).Currently, the DSSAT shell is able to incorporate models of 27 different crops, including several cereal grains, grain legumes, and root crops (Hoogenboom, 2003). The models are process-oriented and are designed to work independent of location, season, crop cultivar, and management system. The models simulate the effects of weather, soil water, genotype, and soil and crop nitrogen dynamics on crop growth and yield (Jones et al., 2003). DSSAT and its crop simulation models have been used for a wide range of applications, including on-farm and precision management to regional impact assessments of the impact of climate change and variability. As a software package integrating the effects of soil, crop phenotype, weather and management options, DSSAT allows users to ask "what if" questions and simulate results by conducting, in minutes on a desktop computer, experiments which would consume a significant part of an agronomist's career.

2.4. Description of the CROPGRO-Model

The CROPGRO-Chickpea model is part of the suite of crop models available in DSSAT software (Hoogenboom et al., 2010). The major components of the model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance (Singh and Virmani, 1996). It simulates chickpea growth and development using a daily time step from sowing to maturity and ultimately predicts yield. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are inputs to the model. The physiological processes that are simulated 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. Soil water balance is a function of rainfall, irrigation, transpiration, soil evaporation, runoff from the soil surface and drainage from the bottom of the soil profile. The soil water balance submodel used in CROPGRO-chickpea model found in the DSSAT program is described in detail by Ritchie (1998).The volumetric soil water content varies among each soil layer between a lower limit (LL- corresponding to the permanent wilting point) and a saturated upper limit (SAT- corresponding to the saturation point). If the water content is above the drained upper limit (DUL- corresponding to field capacity), then the water drains to the next soil layer. Daily surface runoff of water was calculated using the USDA Soil Conservation Service (SCS) curve number technique. The runoff curve number (CN) was supplied as input, which ranges from 0 (no runoff) to 100 (all runoff) based on soil type, land cover and surface residue applied. In the model, high temperature influences growth and development and reduces allocation of assimilates to the reproductive organs through decreased pod set and seed growth rate. Increased CO_2 concentration in the atmosphere increases crop growth through increased leaf-level photosynthesis. Increased CO_2 concentration also reduces transpiration from the crop canopy via an empirical relationship between canopy conductance and CO_2 concentration. Thus the model has the potential to simulate crop growth and development of chickpea cultivars under climate change conditions, such as high air temperatures, variability in rainfall and increased CO_2 concentrations in the atmosphere that ultimately result in final crop yields at maturity. The CROPGRO-chickpea model was updated and modified mostly the crop parameters in the species file of the model. These changes were based on the research findings of Wang et al. (2006) and Devasirvatham et al. (2012).

2.5. Calibration and evaluation of the CROPGRO-Chickpea model

The CROPGRO-Chickpea model requires genetic coefficients that describe the growth and development characteristics for each individual cultivar. A stepwise calibration procedure was followed to calibrate the genetic coefficients in the model. First, the genetic coefficients were selected from a given genotype from those in the same maturity group or similarly adapted and the model was run for location, cultivar or treatment and the values were assigned to specific genetic coefficients for growth, beginning with the parameters for phenology (flowering and physiological maturity dates) and followed by the growth and yield parameters of the crop. This procedure was performed by a trial-and-error process, *i.e.* a process in which values were assigned to each factor by determining whether the model generated results close to those measured under field conditions. The coefficients were then adjusted until there was a match between observed and simulated dates of flowering, physiological maturity, leaf area index, grain and biomass yield. Accordingly, the genetic coefficients describing the growth and yield of the test variety were determined. The model validation stage involves the confirmation that the calibrated model closely represents the real situation. The procedure consists of a comparison of simulated and observed data. To evaluate model performance and accuracy in prediction, root mean square Error (RMSE) (Wallach and Goffinet, 1987), Willmot's Index of agreement (d), mean absolute error (MAE), coefficient of determination (R^2) and mean deviation (MD) were computed from observed and simulated variables (leaf area index, total above ground biomass, seed biomass, days to flowering, days to physiological maturity, and grain yield).The detail result of model calibration and evaluation is reported in other paper by the same authors ((Authors et al., 2016 forthcoming)

2.6. Climate data for the target locations

Simulation of climate change adaptation required projected climate data to modify the observed weather data of the study sites. In order to investigate the sensitivity of chickpea production under future climate (2020–2049) and (2040–2069), daily weather variables such as rainfall, maximum temperature, minimum temperature and solar radiation were obtained from the WorldClim baseline climate data (1980–2009), and the 17 CMIP5 GCM outputs run under RCP 4.5 and RCP 8.5 for 2030 s and 2050 s time slice were downloaded for the target sites from CIAT's climate change portal (http://ccafs-climate.org/) and downscaled to the target sites using MarkismGCM. The following global circulation models were used to assess crop management options for chickpea. BCC-CSM 1.1 (Wu, 2012), BCC-CSM 1.1(m) (Wu, 2012), CSIRO-Mk3.6.0 (Collier, 2011), FIO-ESM (Song et al., 2012), GFDL-CM3 (Donner, 2011), GFDL-ESM2G (Dunne, 2012), GFDL-ESM2 M (Dunne, 2012), GISS-E2-H (Schmidt, 2006), GISS-E2-R (Schmidt et al., 2006), HadGEM2-ES(Collins, 2011), IPSL-CM5A-LR (Dufresne et al., 2013), IPSL-CM5A-MR (Dufresne, 2013), MIROC-ESM (Watanabe, 2011), MIROC-ESM-CHEM (Watanabe, 2011), MIROC5 (Watanabe, 2010), MRI-CGCM3 (Yukimoto, 2012) and NorESM1-M (Kirkevag et al., 2008).

For any location, MarkSim makes use of a climate record. A climate record contains the latitude, longitude and elevation of the location, and monthly values of rainfall, daily average temperature and daily average diurnal temperature variation. It also includes the temporal phase angle, that is, the degree by which the climate record is "rotated" in date. This rotation is done to eliminate timing differences in climate events, such as the seasons in the northern and southern hemispheres, so that analysis can be done on standardized climate data. The climate record is rotated to a standard date, using the 12 point Fast Fourier transform, on the basis of the first phase angle calculated using both rainfall and temperature (Jones et al., 2003). In MarkSim, almost all operations are done in rotated date space. The climate database WorldClim V1.3 is used to interpolate the climate at the required point. WorldClim may be taken to be representative of current climatic conditions (most of the data cover the period 1980–2009). It uses historical weather data from a number of databases. WorldClim uses thin plate smoothing with a fixed lapse rate employing the program ANUSPLIN. Bicubic interpolation is used over a kernel of the nearest sixteen GCM cells on a $1 \times 1^{\circ}$ grid of GCM differentials. These are calculated from polynomials fitted to each GCM result which are used to return the values for any year or RCP regime. The ensemble (of 17 GCMs in this case) is calculated directly from the polynomial coefficients for each GCM. The estimated GCM differential values are added to the rotated record. This is an example of unintelligent downscaling (Wilby et al., 2009) to the monthly climate values. MarkSim then uses stochastic downscaling to simulate the daily weather sequences.

2.7. Climate scenarios for the simulation study

The four climate scenarios (RCP2.6, RCP4.5, RCP6 and RCP8.5) were used to assess impact s of climate change on phenology and yield of chickpea for the near term (2020–2049) and mid- term (2040–2069) whereas only two scenarios (RCP4.5 and RCP8.5) were used to identify crop management options. The baseline scenario (1961–1990) was used for comparison. Regarding CO_2 concentration, 360 ppm was used for the baseline scenario whereas 423 and 432 ppm were used for RCP 4.5 and RCP 8.5, respectively for 2030s. Similarly, 499 and 571 ppm of CO_2 were used for RCP 4.5 and RCP 8.5, respectively for the 2050s.

RCP's are greenhouse gas concentration trajectories adopted by the IPCC for its fifth assessment (IPCC, 2013). These scenarios are briefly described as follows. In RCP2.6 (also known as RCP3PD) Greenhouse Gases (GHGs) concentrations rise in the first half of the century and then decline so that the forcing (extra energy trapped in entire atmosphere) is 2.6 Wm^{-2} in the year 2100. Peak forcing is 3 $W m^{-2}$ of the 21st century. This is a rapid mitigation scenario of concentration rise. In RCP4.5 scenario, GHGs 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. In RCP6, GHGs concentrations rise with increasing speed until the forcing (extra energy trapped in entire atmosphere) is 6 $W m^{-2}$ in the year 2100. This is a moderately-high scenario of concentration rise. In RCP8.5 GHGs 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.

2.8. Crop management scenarios

The possibilities for achieving more benefit of chickpea grain yield were tested by supplemental irrigation, different sowing dates and cultivars of different maturity groups in order to find the most suitable strategies with the changing future climates. The supplemental irrigation here after designated as (SI) was applied two times at the critical growth stages of the crop (flowering and pod initiation). At Sirinka, for the first and second application equal amount of 65 mm of water each was applied during the flowering and pod initiation stage of the crop whereas at Chefa, 75 mm of water for the first and second application was applied. It was assumed that the supplemental irrigation water was applied when the available soil moisture in the crop rooting depth reaches 60% of its field capacity. Hence, the amount of water applied was the amount that replenishes the soil water content in the rooting depth back to its field capacity level. To evaluate crop response to supplemental irrigation, virtual cultivars incorporating various plant traits were developed from the baseline cultivar (*Kutaye*) calibrated for the northeastern Ethiopian conditions which represents farmers' preference for the *Desi* type of chickpea cultivars grown at both sites. Three maturity durations of chickpea cultivars were considered – baseline (no change), 10% shorter maturity and 10% longer maturity. To make the crop maturity short, genetic coefficients determining emergence to 50% flowering (EM-FL), flowering to beginning seed growth (FL-SD) and beginning seed growth to physiological maturity (SD-PM) were decreased by 10% each. To make the crop maturity long, these coefficients were increased by 10% each.

In this study, three sowing conditions were considered. The standard sowing date here after designated as SSD was arbitrarily set as the median sowing date for chickpea in the sowing window of the crop which is 10 September each year. The early sowing dates then were set as (SSD-10 days) and (SSD-20 days) whereas the delayed sowing dates were set as (SSD + 10 days) and (SSD + 20 days). For both site, the simulation was initiated one month before the actual planting date in order to correctly simulate the soil water balance and this was applied for each sowing date treatment in the experiment. Under normal sowing conditions, the sowing window for chickpea in the study area is from 1 September to 20 September. At the time of sowing phosphorus (P) at a rate of 23 $kg ha^{-1}$ was applied as Di-ammonium phosphate. A plant population of 33 plants m^{-2} and row spacing of 30 cm was considered for simulating chickpea growth. Simulation of management and genetic options were carried out for the temperature, rainfall, solar radiation and carbon dioxide changes of the 2030 s (2020–2049) and 2050 s (2040–2069) time slices a long with the baseline climate (1980–2009). The crop was considered free from pests and diseases. To simulate crop response to the changes in genetic traits, virtual cultivars incorporating various plant traits were developed from the baseline cultivar (*Kutaye*) calibrated for the north-eastern Ethiopian conditions which represents farmers' preference for the *desi* type of chickpea cultivars grown at both sites (Authors et al., 2016 forthcoming). For developing these virtual cultivars, three maturity durations of chickpea crop were considered – baseline (no change), 10% shorter maturity and 10% longer maturity. To make the crop maturity short, genetic coefficients determining emergence to 50% flowering (EM-FL), flowering to beginning seed growth (FL-SD) and beginning seed growth to physiological maturity (SD-PM) were decreased by 10% each. For the longer maturity cultivar, these coefficients were increased by 10% each.

2.9. Statistical analysis

All the multi-year simulation output data of crop grain yields were analyzed using analysis of variance (ANOVA). The study used the Randomized Complete Block Design (RCBD) in factorial arrangement. Accordingly, simulation years were considered as replications (blocks), as the chickpea yield in one year under a given treatment was not affected by another year (prior year carry-over of soil water was not simulated). Also, the simulation years had unpredictable weather characteristics; therefore, a formal randomization

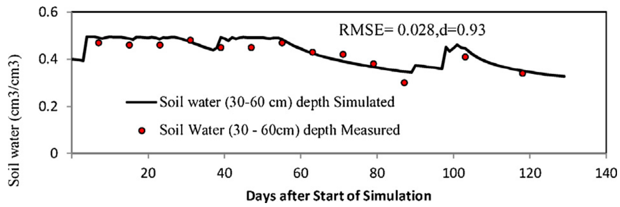

Fig. 1. Comparison of simulated and observed soil moisture content for the 30–60 cm soil depth at Sirinka.

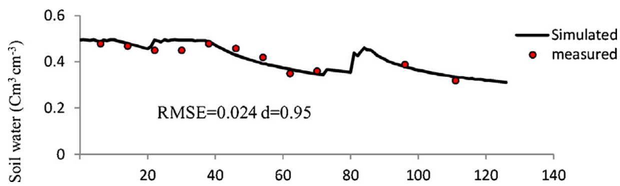

Fig. 2. Comparison of simulated and observed soil moisture content for 30–60 cm soil depth at Chefa.

of simulation years (blocks) was not needed. The analysis was done using SAS v 9.1.2 (SAS, 2003) software and means were separated using least significance test (LSD). In addition, descriptive statistics such as percentile characteristics were used for comparison.

3. Results and discussion

3.1. Model calibration for soil water content measurement

Before attempting to calibrate the crop genetic coefficients, the soil parameters that most determine the simulation of soil moisture were calibrated. Soil moisture was measured up to 60 cm depth, hence the volumetric soil water was calibrated for the conditions of soil layers of 0 – 30 cm and 30–60 cm by adjusting two of the water holding characteristics (lower limit and drainage upper limit) in order to match the simulated values to the observed values for the purpose of making the simulations more specific to the conditions of the field. The soil parameters selected for calibration were those that minimized the root mean square error (RMSE) between simulated and observed volumetric soil water content for the two soil layers. The result showed that considerable agreement was evident between the observed and simulated values of the soil moisture content. The RMSE and d values were 0.06 and 0.91 for 0–30 cm soil depth and 0.028 and 0.93 for 30–60 cm soil depths, respectively, indicating a good agreement of observed and simulated values. Hence, the model was reasonably well in predicting moisture content of the soil profiles at both sites. The calibrated soil moisture content for the 30–60 cm of the soil profile is presented in Fig. 1.

3.2. Model evaluation for soil moisture content

To evaluate the model performance for simulation of the soil water balance under rainfed condition, the model was evaluated for soil moisture changes for 0–30 cm and 30–60 cm soil depths using observed soil moisture data. The RMSE and d values for soil moisture content change for 30–60 cm soil depth were 0.024 and 0.95, respectively (Fig. 2) indicating a good agreement among the observed and simulated values. The result in general showed that the model was able to predict soil moisture changes reasonably well. This indicated that the model performance to predict growth, phenology and yield of chickpea correctly.

Table 1
Results of calibration from the sowing date experiment in 2014 at Sirinka and Chefa sites.

Parameters	Simulated	Measured	RMSE	CV (%)
Days to first flowering (dap)	51	48	3	6.3
Days to first pod (dap)	63	59	4	6.8
Days to first seed (dap)	72	67	5	7.5
Days to physiological maturity (dap)	111	116	1	0.9
Grain yield (kg ha^{-1})	3830	3590	240	6.7
Pod weight (kg ha^{-1})	4778	4675	103	2.2
Unit grain weight (g)	0.19	0.22	0.025	11.4
Number of seeds per pod	2	2	0	0.0
Total biomass yied (kg ha^{-1})	7681	9623	1342	13.9
Straw yield (kg ha^{-1})	3850	5345	1495	27.9
Leaf Area Index (maximum)	4.83	4.89	0.06	12.3
Harvest Index	0.42	0.34	0.08	23.5
Threshing percent (%)	80.2	79	1.20	14.7
Days to harvest maturity (dap)	122	121	1.0	0.8

3.3. Calibration of chickpea genetic coefficients

The CROPGRO-Chickpea model uses eco-physiological coefficients for simulation of development, growth, and yield. The calibration of the model was carried out using sowing date experimental data sets of both sites.

The comparison between observed and simulated days to flowering, physiological maturity, grain yield, total above ground biomass, pod weight, leaf area index, unit grain weight for the *Kutaye* cultivar (Table 1) showed that the cultivar specific parameters within the model were reasonably adjusted.

3.4. Model evaluation for days to flowering and physiological maturity

Model evaluation against measured values showed that the model was able to predict the number of days to flowering very close to the observed results (Fig. 3). However, the model over estimated the number of days to flowering as compared with the observed number of days to flowering for most of the treatments with mean deviation (MD) of 5.7 days. The average RMSE for all the treatments between the observed and the predicted results was 6 days. The normalized root mean square error or CV (coefficient of variation) of the model for all the treatments was 13.4% that is within the moderate range of model performance assessment as reported by Jamieson et al., 1991. The errors in prediction of days to flowering were in the range of −3 to + 13 days of observed dates. The model prediction for days to physiological maturity was ranged from −8 to + 7 days for all treatments. The average predicted days to flowering and days to physiological maturity in these experiments were 51 and 105 days, respectively whereas the respective observed values were 46 and 103. The respective values of RMSE for days to flowering and days to physiological maturity were 6 and 1.8 days whereas the corresponding coefficient of variation (CV) values were 13.4 and 3.8 indicating a good agreement between the simulated and observed values. The R^2 values for predicted and observed days to flowering and days to maturity were 0.69 and 0.95 respectively. The result showed that model was also able to reasonably predict days to flowering and days to physiological maturity of the chickpea across locations and seasons (Figs. 3 and 4).

3.5. Model evaluation for grain and above ground biomass yields

The crop model was evaluated for simulating grain and above ground biomass yields across seasons and locations. The result indicated that the model was able to predict both the grain and above ground biomass yields reasonably well. The observed and simu-

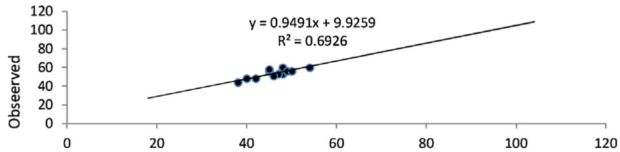

Fig. 3. Comparison of observed and simulated days to flowering of chickpea for the data sets of 2005, 2006 and 2007 at Sirinka, Chefa, Jarri and Kobo sites.

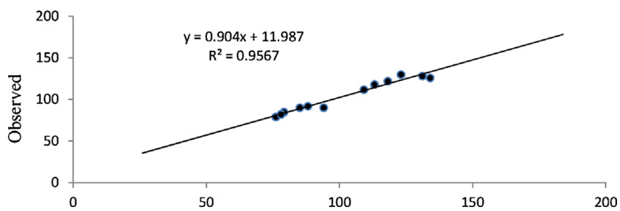

Fig. 4. Comparison of observed and simulated days to physiological maturity of chickpea for the data sets of 2005, 2006 and 2007 at Sirinka, Chefa, Jarri and Kobo sites.

Note: Different letters under each scenario indicates statistically significant difference. SI and RF stand for supplemental Irrigation and rainfed, respectively

Table 2
Comparison between observed and simulated grain yield of chickpea at harvest (kg ha^{-1}) for the data sets of 2005, 2006 and 2007 at Sirinka, Chefa, Jarri and Kobo sites.

Locations	Treatments	Obs	Sim	MD	RMSE	CV (%)
Sirinka	2005 data set	3450	3544	94	94	2.7
	2006 data set	2413	2546	133	133	5.5
	2007 data set	3297	3756	459	459	13.9
Chefa	2005 data set	3297	3356	59	59	1.8
	2006 data set	2905	3125	220	220	7.6
	2007 data set	2300	2456	156	156	6.8
Jarri	2005 data set	2717	2897	180	180	7
	2006 data set	3170	3245	75	75	2.4
	2007 data set	4023	4120	97	97	2.4
Kobo	2005 data set	2813	2908	95	95	3.3
	2006 data set	1564	1767	203	203	13
	2007 data set	1390	1679	289	289	20.8
Mean		2778	2950	171.7	171.7	7.3

Note: Obs, Sim, MD, RMSE and CV (%) stands for observed, simulated, mean deviation, root mean square error and coefficient of variations, respectively.

Table 3
Comparison between observed and simulated above ground biomass yield (kg ha^{-1}) of chickpea for the data sets of 2005, 2006 and 2007 at Sirinka, Chefa, Jarri and Kobo sites.

Locations	Treatments	Obs	Sim	MD	RMSE	CV (%)
Sirinka	2005 data set	4900	5167	267	267	5.4
	2006 data set	2953	3245	292	292	9.8
	2007 data set	4867	5023	156	156	3.2
Chefa	2005 data set	4400	4678	278	278	6.3
	2006 data set	3828	3980	152	152	4
	2007 data set	3232	3456	224	224	6.9
Jarri	2005 data set	3267	3245	−22	−22	1
	2006 data set	5633	6000	367	367	6.5
	2007 data set	4213	5000	787	787	18.7
Kobo	2005 data set	4033	5234	1201	1201	29.8
	2006 data set	4560	5600	1040	1040	22.8
	2007 data set	4567	6230	1663	1663	36
Mean		4204	4738	533.7	533.7	12.5

lated grain and above ground biomass yields across locations and seasons are presented in Tables 2 and 3.

The result of the linear regression analysis among the observed and simulated grain and aboveground biomass yields also indicated that there were close agreement between the values. The RMSE values for grain yield (kg ha^{-1}) and above ground biomass yield (kg ha^{-1}) were 171.7 and 533.7. The respective CV (%) values were 7.3 and 12.5, respectively that are in the excellent ranges of model performance. The close agreement between the simulated and observed values indicated the performance of the model to simulate yield parameters across locations and seasons.

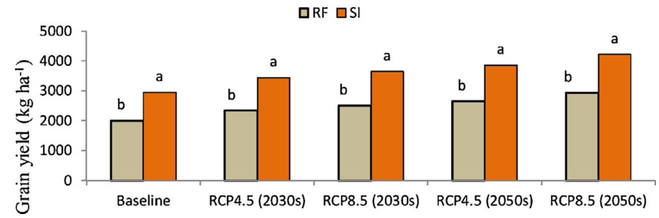

Fig. 5. Effect of supplemental irrigation on mean grain yield of chickpea under different climate scenarios at Sirinka.

3.6. Effect of projected temperature and rainfall on chickpea phenology and yield

Days to flowering and days to maturity of chickpea are predicted to significantly decrease by 2030 s and 2050 s under all climate scenarios (RCPs) as compared to the simulated value for the baseline climate. The highest significant reduction is predicted for scenario RCP8.5 both by 2030 s and 2050s. This could be associated more to the highest increase in temperature for scenario RCP8.5. The reduction in days to flowering and maturity under projected climate change condition could be attributed more to the increase in temperature. High temperature can shorten crop life cycle by speeding up the crop growth and development stages. The reduction in life cycle of the crop could reduce yield. However, the increase in temperature by 2030 s and 2050 s could not significantly affect chickpea grain yield. However, under CO_2 fertilization condition, chickpea grain yield is predicted to significantly increase both by 2030 s and 2050 s as compared to the grain yield for the baseline period (1960–1990). In general, it can be concluded that chickpea will be benefited from the projected climate change both by 2030 s and 2050 s mainly due to the increase in precipitation and/or increase in CO_2 concentration. In agreement with this result, Hong et al., 2011 reported that among the three climate scenarios (A1B, A2 and B1) the scenario that reduced days to plant maturity the most was scenario A2, which is associated with its higher temperature. As the crop growth cycle is strongly related to temperature, the duration of a crop life cycle is conditioned by the daily temperatures absorbed by the plant. Therefore, an increase in future temperature could lead to speed up growth and development of crops that ultimately reduce the duration between sowing and harvesting. As a result, grain yield accumulation could fall with the shortening of a crop life cycle (IFPRI, 2011).

3.7. Effect of supplemental irrigation on grain yield of chickpea under projected climate changes

The impact of supplemental irrigation on mean chickpea grain yield was evaluated for the baseline, 2030 s and 2050 s under RCP4.5 and RCP8.5 scenarios. Supplemental irrigation is found to significantly increase grain yield of chickpea across different scenarios (Fig. 5). According to the result, mean grain yield of chickpea is predicted to increase by about 47% under the baseline scenario and by about 46% and 45% for 2030 s and 2050s; respectively under both scenarios where as the increase at Chefa is predicted to be 17% for the baseline period and 16% and 19% for 2030 s and 2050s, respectively. The impact of supplemental irrigation on mean chickpea grain yield was evaluated at Sirinka under the individual climate scenarios (baseline, RCP4.5 and RCP8.5). Supplemental irrigation is predicted to significantly ($P< 0.05$) increase mean chickpea

Table 4
Mean simulated days to flowering (DF) and days to maturity (DM) of chickpea at Sirinka and Chefa sites in the baseline, 2030 s and 2050s.

Time periods	Climate scenarios	DF		DM	
		Sirinka	Chefa	Sirinka	Chefa
1961–1990	baseline	52.7a	54.2a	109a	124a
2030	RCP2.6	51.2b	52.3b	104.6b	117.5b
	RCP4.5	50.9b	52.3b	104.2b	117.6b
	RCP6	51.2b	52.3b	104.8b	117.5b
	RCP8.5	50.7c	52c	103.6c	115.1c
2050	RCP2.6	50.9b	52.3b	103.9bc	117.b
	RCP4.5	50.5c	52.c	103d	115.2c
	RCP6	50.5c	51.9c	103.3 cd	115.3c
	RCP8.5	50d	51d	101.8e	113d

Note: Means followed with the same letter (s) in each column are not significantly different at 5% probability level.

grain yield across all the scenarios. Based on the result, supplemental irrigation is predicted to increase mean grain yield by about 47% under the baseline scenario, by about 47% and 45% by 2030 s and by about 46% and 44% by 2050 s under RCP4.5 and RCP8.5 scenarios, respectively.

The effect of supplemental irrigation on cultivars grain yield was evaluated. Supplemental irrigation is predicted to increase grain yield of the standard, the short duration and the long duration cultivars by about 54%, 33% and 58%, respectively under the baseline scenario, by about 52%, 44% and 48% under RCP4.5 scenario by 2030 s and by about 52%, 42% and 46% under RCP8.5 by 2030s. Similarly, supplemental irrigation is predicted to increase grain yield of the respective cultivars by about 50%, 43% and 46% under RCP4.5 by 2050 s and by about 48%, 39% and 43% under RCP8.5 by 2050s. Supplemental irrigation is also found to significantly ($P< 0.05$) increase mean grain yields of chickpea at Chefa site across the respective time periods and scenarios. Based on the result, grain yield is predicted to increase by about 17% under the baseline scenario, by about 15% and 17% by 2030 s and by about 19% and 18% by 2050 s for RCP4.5 and RCP8.5 scenarios, respectively. The effect of supplemental irrigation on each cultivar was evaluated and the result showed that grain yield of the standard, the short duration and the long duration cultivars are predicted to increase by about 16%, 4% and 20%, respectively under the baseline scenario, by about 16%, 4% and 22% under RCP4.5 scenario by 2030 s and by about 15%, 10% and 23% under RCP8.5 scenarios by 2030s. It is also predicted to increase grain yields of the respective cultivars by about 18%, 12% and 23% under RCP4.5 by 2050 s and by about 15%, 8% and 17% under RCP8.5 scenario by 2050s (Table 4).

3.8. Combined effect of cultivars and sowing dates on grain yield of chickpea under projected climate changes

The combined effect of cultivars and sowing dates on grain yield of chickpea was evaluated for the baseline climate and the projected climate changes by 2030 s and 2050 s under RCP4.5 and RCP8.5 scenarios. The result showed that early sowing (SSD-20 days) at Sirinka is predicted to significantly increase mean grain yield of chickpea by about 43%, 42% and 48% for the baseline, 2030 s and 2050 s where as yield is predicted to increase at Chefa by about 33%, 40% and 12% for the respective time periods. On the other hand, mean grain yield of cultivars is predicted to decrease under delayed sowing conditions across time periods and locations. In all the simulation, it was observed that early sowing significantly increased grain yield of all the chickpea cultivars across the different time periods and scenarios (Table 5). The highest increase in grain yield at Sirinka is predicted for the short duration cultivar under the early sowing (SSD-20 days) condition across the present and future climate conditions whereas the highest increase in grain yield at Chefa is predicted for the long duration cultivar under the early sowing (SSD-20 days).

3.9. Combined effect of cultivars, sowing dates and supplemental irrigation on grain yield of chickpea under projected climate changes

The combined effect of cultivars, sowing date and supplemental irrigation on grain yield of chickpea was evaluated across climate scenarios (baseline, RCP4.5 and RCP8.5) by 2030 s and 2050 s. The combination of early sowing (SSD-20 days), supplemental irrigation and cultivars are found to significantly increase grain yield in the present and future climate conditions. Based on the simulation result it can be generalized that in areas where terminal drought is a major constraint for crop production, applications of one or two supplemental irrigation at the critical growth stages of the crop (flowering and pod setting stages) is very important to increase soil moisture condition that is required for the normal growth and development of the crop. Terminal drought or stress that occurs at critical growth stages of the crop is a major problem at both sites. Therefore, rainfed chickpea production system in the semi-arid environments of northeastern Ethiopia can be improved

Table 5
Combined effect of cultivars and sowing dates on chickpea grain yield at Sirinka in the baseline, 2030 s and 2050 s under RCP4.5 and RCP8.5 scenarios.

Treatments	Baseline yield	% change	2030 s yield				2050 s yield			
			RCP 4.5	% change	RCP8.5	% change	RCP 4.5	% change	RCP8.5	% change
SC + SSD (control)	1961	–	2315	–	2478	–	2638	–	2941	–
SC + SSD-20 days	2810	43	3290	42	3503	41	3858	46	4390	49
SC + SSD-10 days	2267	15	2735	18	2969	20	3197	21	3595	22
SC + SSD +10 days	1861	−5	2023	−13	2187	−12	2321	−12	2574	−12
SC + SSD +20 days	1874	−4	2014	−13	2125	−14	2184	−17	2447	−17
SDC + SSD	2183	11	2547	10	2704	9	2947	12	3223	10
SDC + SSD-20 days	2916	48	3444	49	3636	47	4036	53	4531	54
SDC + SSD-10 days	2378	21	2878	24	3092	25	3349	27	3727	27
SDC + SSD + 10 days	1931	−2	2080	−10	2309	−7	2486	−6	2710	−8
SDC + SSD + 20 days	1913	−2	2068	−11	2200	−11	2292	−13	2498	−15
LDC + SSD	1851	−6	2132	−8	2324	−6	2351	−11	2631	−11
LDC +SSD-20 days	2569	31	3069	33	3268	32	3614	37	4112	40
LDC + SSD −10 days	2068	5	2535	10	2755	11	2864	9	3245	10
LDC + SSD +10 days	1760	−10	1922	−17	2077	−16	2152	−18	2402	−18
LDC + SSD +20 days	1820	−7	1912	−17	2033	−18	2047	−22	2339	−20
LSD (p = 0.05)	470	–	569	–	623	–	632	–	767	–

LSD: Least significant difference at 5% probability level: % Change: Percent change in grain yield with reference to the grain yield of the standard cultivar under the standard sowing date. SC, SDC and LDC stand for standard, short and long duration cultivar, respectively.

Table 6
Combined effects of cultivars, sowing dates and supplemental irrigation on chickpea grain yield at Sirinka in the baseline, 2030 s and 2050 s time slice under RCP4.5 and RCP8.5 scenarios.

Treatments	Baseline yield	% change	2030 s yield (kg ha^{-1})				2050 s yield (kg ha^{-1})			
			RCP 4.5	% change	RCP 8.5	% change	RCP 4.5	% change	RCP 8.5	% change
SC+ SSD (control) +RF	1961	–	2320	–	2476	–	2632	–	2935	–
SC+ SSD +SI	3018	54	3525	52	3766	52	3972	51	4339	48
SC+ SSD–20 days +SI	3521	80	4043	74	4224	71	4629	76	5249	79
SC+ SSD–10 days +SI	3228	65	3703	60	3940	59	4191	59	4614	57
SC+ SSD + 10 days +SI	2790	42	3145	36	3331	35	3656	39	3979	36
SC + SSD + 20 days +SI	2605	33	2865	23	3054	23	3226	23	3620	23
SDC + SSD + SI	2919	49	3352	44	3525	42	3774	43	4106	40
SDC + SSD–20 days + SI	3460	76	4067	75	4216	70	4679	78	5173	76
SDC + SSD–10 days + SI	3033	55	3556	53	3769	52	4050	54	4502	53
SDC + SSD + 10 days + SI	2807	43	3126	35	3373	36	3715	41	3984	36
SDC + SSD + 20 days + SI	2645	35	2988	29	3180	28	3434	30	3778	29
LDC + SSD + SI	2918	49	3433	48	3623	46	3840	46	4173	42
LDC + SSD–20 days + SI	3579	83	4055	75	4251	72	4632	76	5188	77
LDC + SSD–10 days + SI	3284	67	3854	66	4139	67	4317	64	4717	61
LDC + SSD + 10 days +SI	2559	30	2876	24	3060	24	3340	27	3727	27
LDC + SSD + 20 days + SI	1957	0	2722	17	2915	18	3226	23	3436	17
LSD (p = 0.05)	535	–	638	–	681	–	677	–	789	–

LSD: Least significant difference at 5% probability level: % Change: Percent change in grain yield with reference to the grain yield of the standard cultivar under standard sowing date. SC, SDC and LDC stand for standard, short and long duration cultivar, respectively. RF and SI stands for rainfed and supplemental irrigation, respectively.

using supplemental irrigation. The simulation result also showed that although chickpea can be grown under limited moisture conditions in many areas, the crop requires adequate supply of moisture particularly at its critical growth stages for its proper growth and development. It was also observed that the grain yield response to the supplemental irrigation varied with cultivars (Table 6). Hence, the scheduling of supplemental irrigation at the right time and in the right quantity is the most important factors for realizing high grain yields of chickpea. In can also be concluded that supplemental irrigation is water optimizing strategy by which crops are deliberately allowed to sustain some degree of water deficit and yield reduction in order to maximize the productivity per unit of water used.

One important merit of supplemental irrigation is the greater potential for benefiting from unexpected rainfall during the growing season owing to the availability of larger storage space in the crop root zone. However, in the semi-arid tropical environments of northeastern Ethiopia, the amount of water available for irrigation could be generally limited. In such situations, an efficient application of water is very critical as it can contribute significantly to reducing water losses and increasing water use efficiency.

Given that, in this particular study, supplemental irrigation has been done at flowering, pod formation and grain-filling stages, moisture shortage has been resolved fairly. As a result, period of grain-filling has been lengthened and more photosynthetic products accumulated in grains. The result of this study showed that for many semi-arid areas where low moisture is a major crop production constraint, application of supplemental irrigation particularly at the critical crop growth stages (flowering and grain filling) could lead to a significant improvement on chickpea grain yield. Nayyar et al. (2006) reported that water defect at chickpea generative stages prevents yield potential attainment through flowers and pods shedding. In agreement with this result, excellent responses to supplemental irrigation have been reported by Rockström et al. (2007). According to the report of Leport et al. (1999) terminal drought stress, which occurs during the pod-filling phase, is a common yield reduction problem in many chickpea growing areas. The result of the current study also showed that better responses from supplemental irrigation could be obtained when irrigation water is applied at the critical time of the crop growth stages (flowering, grain and pod setting). In conclusion, supplemental irrigation can be used to overcome the changes in soil-water-plant relations, especially in alleviating soil water stress resulting from changes in crop evapotranspiration (ET).As rainfall is erratic and highly unpredictable in many semi-arid environments of the north-eastern Ethiopia, supplemental irrigation will be the most reliable option to alleviate problem of terminal drought on crops.

However, the best response from the supplemental irrigation can be achieved through water responsive cultivars that can manifest a strong response to limited water applications, which means that cultivars should have a relatively high yield potential. In addition, cultivars should maintain some degree of drought resistance, and hence express a good plasticity. Therefore, for the present as well as future climate conditions, new varieties should be developed using both traditional breeding techniques as well as modern genetic engineering techniques. Such varieties are predicted to increase the water use efficiency while maintaining or even increasing the yield levels.

According to the prediction result, early sowing of short duration cultivar is significantly important to increase chickpea productivity in the present and future climate conditions in areas where low soil moisture is a major crop production constraint. Short duration cultivars and early sowing are very helpful for the crop to escape terminal drought condition that usually occurs at flowering and grain filling stages of the crop. On the other hand, early sowing of long duration and standard (medium) types of cultivars are important in areas where high temperature is a major crop production constraint in the present and future climate conditions. High temperature could affect chickpea productivity by altering its development and growth stages. High temperature can speed up crop growth and development stages and shorten the life cycle of the crop. As the result, grain yield of the crop could be decreased. Long duration can maintain the adverse effect of high temperature on growth and development stages. On the other hand, the reduction in grain yield of chickpea under the delayed sowing conditions might be attributed more to the failure of some pods and seeds to develop due to severe water stress condition during the reproductive period of the crop. Leport et al. (1999) reported that the number of seeds of chickpea plants was significantly reduced as a result of terminal drought. Saini and Westgate (2000) also reported that water stress during the flowering and pod setting stage of the crop could delay or completely inhibit flowering and pod setting through an inhibition of floral induction. As sowing time for chickpea is delayed, the residual soil moisture available to support the crop growth could be depleted on wards which could expose the crop for terminal drought and finally reduce the grain yield.

Based on the result of the present study, sowing date in the study region should be advanced for at least 20 days as compared to the present chickpea sowing date and also should be combined with suitable cultivars. In agreement with this finding, Soltani and Sinclair (2012) reported that under warmer future climate, earlier sowing is likely to require cultivars with different phenological development than currently used. The study also concluded that the combined applications of appropriate cultivars, early sowing and supplemental irrigation are the most promising crop management strategies to increase chickpea productivity in the semi-arid environments of northeast Ethiopia. Early sowing could help the crop to escape terminal drought or stress that often occurs at flowering and grain filling stages of the crop. Supplemental irrigation is also an important crop management option to reduce the problem of terminal stress/drought. In agreement with this result, Geerts and Raes (2009) reported that supplemental irrigation provides a means of reducing water consumption while minimizing adverse effects on grain yield. A recent review by Sinclair and Vadez (2012) has quantified this relationship and results have shown that by doubling the available soil water from 150 mm to 300 mm will double grain yield. This shows the great potential for enhancing chickpea grain yields through providing irrigations. Studies have also showed that in chickpea and lentil supplemental irrigation can significantly increase seed yields and water use efficiency (Oweis et al., 2004). The results also showed that in both chickpea and lentil, grain yields increased linearly with the amount of water applied. Therefore, supplemental irrigation with a limited amount of water, if applied to rainfed crops during critical stages in combination with early sowing and suitable cultivars can result in substantial improvement in chickpea yield.

4. Conclusion

The results of model calibration and evaluation in semi-arid environments of north-eastern Ethiopia showed that simulated growth, development and yield of chickpea were in good agreement with their corresponding observed values. The result showed that the CROPGRO-Chickpea model was able to successfully simulate growth, development and yield of chickpea. Therefore, if properly calibrated, the model can be used to quantify the possible benefits and prioritization of various crop management options individually or in combinations. The possibilities for increasing rainfed chickpea grain yield was tested by changing the normal chickpea sowing date and using supplemental irrigation applied at flowering and grain filling stages of the crop. Based on the simulation result, supplemental irrigation and early sowing dates are predicted to significantly increase chickpea grain yield at both sites in the present and future climate conditions. However, the highest chickpea grain yield at both sites could be achieved through the combination of early sowing and supplemental irrigation. Therefore, all the tested management options were found to be effective to increase chickpea productivity in semi-arid areas of north-eastern Ethiopia in the present and future climate conditions.

References

Bewket, W., 2007. Rainfall variability and the need for water security in Ethiopia. In: In the Nile Waters and Ethiopia: Mainstreaming the Nile Issue into the Media, Academia and Research Institutions. Workshop Proceedings, Addis Ababa : Flamingo Printing Press PLC.

Collier, M.A., 2011. The CSIROMk3.6.0 Atmosphere-Ocean GCM. participation in CMIP5 and data publication, Perth, pp. 12–16 (MODSIM December 2011).

Collins, W.J., 2011. Development and evaluation of an Earth-System model-HadGEM2. GMD 4 (4), 1051–1075.

Devasirvatham, V., Gaur, P.M., Mallikarjuna, N., Tokachichu, R.N., Trethowan, R.M., Tan, D.K.Y., 2012. Effect of high temperature on the reproductive development of chickpea genotypes under controlled environments. Funct. Plant Biol. 39 (12), 1009–1018.

Donner, L.J., 2011. The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. J. Clim. 24 (13).

Dufresne, J.L., 2013. Climate change projections using the IPSL-CM5 earth system model: from CMIP3 to CMIP5. Clim. Dyn., 1–43.

Dunne, J.P., 2012. GFDL's ESM2 global coupled Climate–Carbon earth system models. part I: physical formulation and baseline simulation characteristics. J. Clim. 25, 6646–6665.

FAOSTAT, 2012. Food and agriculture organization of the united nations 2012. In: FAO Production Year Book. FAO, Rome, Available at http://apps.fao.org. (Accessed 15:01:13).

Ferede, T., Ayenew, A.B., Hanjra, M.A., 2013. Agroecology matters: impacts of climate change on agriculture and its implications for food security in Ethiopia. In: Munir Hanjra, A. (Ed.), Global Food Security: Emerging Issues and Economic Implications. Nova Science Publishers, New York, USA, pp. 71–112 (Chapter 3).

Geerts, S., Raes, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96 (No. 9), 1275–1284.

Gholipoor, M., Soltani, A., 2009. Future climate impacts on chickpea in Iran and ICARDA. Res. J. Environ. Sci. 3 (1), 16–28.

Hanjra, M.A., Ferede, Tadele, Gemechu Gutta, Debel, 2009. Pathways to breaking the poverty trap in Ethiopia: investments in agricultural water, education, and markets. Agric. Water Manage. 96, 1596–1604.

Hong, W., Yong, H., Budong, Q., Brian, M., Herb, C., Tom, M., Grant, M., Robert, Z., Con, C., Ron, D., Reynald, L., Kelsey, B., Tingting, L., Xiaobo, Q., Gerrit, H., Jeffrey, W., Tony, H., 2011. Impact of Climate Change on Wheat Production for Ethanol in Southern Saskatchewan, Canada. World Renewable Energy Congress, Sweden, pp. 8–13.

Hoogenboom, G., Jones, J.W., Wilkens, P., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.L., White, J.W., Uryasev, O., Royce, F.S., Ogoshi, R., Gijsman, A.J., Tsuji, G.Y., 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

Hoogenboom, G., 2003. Crop growth and development. In: Bendi, D.K., Nieder, R. (Eds.), Handbook of Processes and Modeling in the Soil-Plant System. The Haworth Press, Binghamton New York, pp. 655–691.

IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, M., Allen, J., Boschung, A., Nauels, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jamieson, P.D., Porter, J.R., Wilson, D.R., 1991. A test of the computer simulation model ARC-Wheat1 on wheat crops grown in New Zealand. Field Crops Research 27, 337–350.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Kassie, Menale, Shiferaw, Bekele, Asfaw, Solomon, Abate, Tsedeke, Muricho, Geoffrey, Ferede, Setotaw, Eshete, Million, Assefa, Kebebew, 2009. Current Situation and Future Outlooks of the Chickpea Sub-sector in Ethiopia ICRISAT (Nairobi) and EIAR (Debre Zeit).

Kirkevag, A., Iversen, T., Seland, O., Debernard, J.B., Storelvmo, T., Kristjansson, J.E., 2008. Aerosol-cloud-climate Interactions Climate Model CAM-Oslo Tellus A 60 (3), 492–512.

Kumar, J., Abbo, S., 2001. Genetics of flowering time in chickpea and its bearing on productivity in semiarid environments. Adv. Agron. 72, 107–138.

Leport, L., Turner, N.C., French, R.J., Barr, M.D., Duda, R., Davies, S.L., Tennant, D., Siddique, K.H.M., 1999. Physiological responses of chickpea genotypes to terminal drought in a Mediterranean-type environment. Eur. J. Agron. 11 (3–4), 279–291.

Luo, Q., Bellotti, W., Williams, M., Wang, E., 2009. Adaptation to climate change of wheat growing in South Australia: analysis of management and breeding strategies. Agricu. Ecosyst. Environ. 129 (1–3), 261–267.

Mohammed, Adem, Tana, Tamado, Singh, Piara, Molla, Adamu, 2016a. Calibration and Evaluation of the CROPGRO-Chickpea of DSSAT Model to Simulate Development. Growth and Yield under Semi-Arid Environments (forthcoming.

Mohammed, Adem, Tana Singh, Tamado, Driba Korecha, P., Molla, Adamu, 2016b. Impact of Projected Climate Changes on Rainfed Chickpea Productivity in the Semi-arid Areas of North-eastern Ethiopia (forthcoming.).

Nayyar, H., Singh, S., Kaur, S., Kumar, S., Upadhyaya, H.D., 2006. Differential sensetivity of macrocarpa and macrocarpa types of chickpea (cicer arietinum) to water stress accociation of contrasting stress response with oxidative injujry. J. Integr. Plant Biol. 48, 1318–1329.

Oweis, T., Hachum, A., Pala, M., 2004. Water use efficiency of winter sown chickpea under supplemental irrigation in a Mediterranean environment. Agric. Water Manage. 66, 163–179.

Parthasarathy, P., Birthal, P.S., Bhagvatula, S., Bantilan, M.C.S., 2010. Chickpea and Pigeonpea Economies in Asia: Facts, Trends and Outlook. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India, pp. 76 (502 324).

Rockström, J., Hatibu, N., Oweis, T.Y., Wani, S.P., 2007. Managing water in agriculture. In: Molden, D. (Ed.), Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–352.

SAS, 2003. SAS Version 9. 1.2 © 2002-2003. SAS Institute, Inc, Cary, NC.
Saini, H.S., Westgate, M.E., 2000. Reproductive development in grain crops during drought. In: Sparks, D.L. (Ed.), Advances in Agronomy, Vol. 68. Acadamic press, London, p. 609.
Schmidt, G.A., 2006. Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. J. Climate 19, 153–192.
Singh, P., Virmani, S.M., 1996. Modelling growth and yield of chickpea (*Cicer arietinum L.*). Field Crop Res. 46, 41–59.
Singh, R., Sharma, P., Varshney, R.K., Sharma, S.K., Singh, N.K., 2008. Chickpea improvement: role of wild species and genetic markers. Biotechnol. Genet. Eng. Rev. 25, 267–314.
Soltani, A., Sinclair, T.R., 2012. Optimizing chickpea phenology to available water under current and future climates. Eur. J. Agron. 38 (0), 22–31.
Song, Z., Qiao, F., Song, Y., 2012. Response of the equatorial basin-wide SST to wave mixing in a climate model: an amendment to tropical bias. J. Geophys. Res. 117, C00J26.
Wallach, D., Goffinet, B., 1987. Mean squared error of prediction in models for studying ecological and agronomic systems. Biometrics 43, 561–573.
Wang, J., Gan, Y.T., Clarke, F., McDonald, C.L., 2006. Response of chickpea yield to high temperature stress during reproductive development. Crop Sci. 46, 2171–2178.
Watanabe, M., 2010. Improved climate simulation by MIROC5: mean states variability, and climate sensitivity. J. Climate 23, 6312–6335.
Watanabe, S., 2011. MIROC-ESM2010: model description and basic results of CMIP5-20c3 m experiments. Geosci. Model Dev. 4 (4), 845–872.
White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crops Res. 124 (3), 357–368.
Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.M., Sutton, R.T., 2009. A review of climate risk information for adaptation and development planning. Int. J. Climatol. 29, 1193–1215.
World Bank, 2011. Climate-Smart Agriculture: Increased Productivity and Food Security, Enhanced Resilience and Reduced Carbon Emissions for Sustainable Development, Opportunities and Challenges for a Converging Agenda: Country Examples. World Bank, Washington D.C.
Wu, T., 2012. A mass-Flux cumulus parameterization scheme for largescale models: description and test with observations. Clim. Dynam. 38, 725–744.
Yukimoto, S., 2012. A new global climate model of Meteorological Research Institute: MRI-CGCM3–Model description and basic performance. J. Meteorol. Soc. Jpn. 90a, 23–64.