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Full Length Research Paper

Assessing impacts of climate change on tef (*Eragrostis tef*) productivity in Debrezeit area, Ethiopia

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Tef is one of the major staple food crops in Ethiopia. Tef productivity in semi arid areas has been limited by climate variability. Drought and other extreme climatic events are expected to increase under the future climate. However, the impact of climate change on tef yield has not been adequately documented. The objective of this study was thus to assess the impacts of climate change on tef productivity. Climate outputs from five General Circulation Models (GCMs) ("ACCESS1-0", "bcc-csm1-1", "CCSM4", "GFDL-ESM2M", and "HadGEM2-ES") with two Representative Concentration Pathway (RCP4.5 and RCP8.5) scenarios over three time periods: near (2010 – 2039), mid (2040 – 2069) and end term (2070 – 2099) periods were used as data input in a calibrated AquaCrop model for simulating future tef yield under three sowing dates: early (July 18), normal (July 28) and late (August 19). Results of the model simulation showed that tef yield under climate change varied substantially with sowing date, time period, RCPs and GCMs. Median yields increased and decreased by up to 10% and 39% for early and late sowing, respectively during the end term period whereas it reduced by up to 4% and 50% for early and late sowing, respectively during the near term period. The main reason for the slight increase in yield with early sowing was due to efficient use of rainwater over the growing period; relatively conducive early seedling establishment and better synchronization of the crop growing cycle with the rainy period. Contrarily, late sowing showed an overall significant yield reduction which could be attributed to poor synchronization of the rainy period with the growing cycle of the crop (especially exposure to long dry period after the reproductive period). Simulated yield for the end term period was also relatively higher compared to the mid and near term period. This could be due to the increased positive impacts of CO_2 as a result of increased CO_2 concentration towards the end term period. Among the climatic factors, rainfall distribution and amount will have the greatest impact on tef yield under future time period. Early sowing should be considered as an adaptation strategy for tef under future climate.

Key words: Climate change, tef, Debrezeit, sowing date.

INTRODUCTION

Climate change is a major threat especially to economic sectors sensitive to climate such as agriculture (Downing, 1993; Stern, 2007). Many climate models suggest that future climate will be expected to have higher temperature and higher levels of atmospheric carbon dioxide compared to the mean historical climatic condition (IPCC, 2007; IPCC, 2009). Consequently, low income countries that fully depend on agriculture or that have less diversified incomes are expected to suffer most

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from climate change as their coping capacity is low (Boko et al., 2007; Stern, 2007; Cline, 2007; Challinor et al., 2007; Thornton et al., 2011; Swaminathan and Kesavan, 2012).

Ethiopia is one of the sub-Saharan Africa countries, which have been suffering from frequent drought over the past decades (Araya and Stroosnijder, 2011; Araya et al., 2012). Tef, one of the major food crops in Ethiopia, has been grown by most farmers in Ethiopia. Due to its '*Enjera'* quality, majority of the Ethiopian people prefer tef as food source to other cereals types (Ketema, 1997; CSA, 2011). '*Enjera*' is a traditional food type made mainly from fermented flour of tef. Tef has high demand not only for its grain as source of food but also for its straw as source of feed for livestock. In addition, growing tef has several advantages such as its resistance to waterlogging and drought stresses and adaptation to wider growing environment with limited pest factors (Ketema, 1997). Furthermore, the crop has been proved to have health benefits (gluten free) (Spaenij-Dekking et al., 2005). Because of the above reasons the crop has wider area coverage compared to other crops (CSA, 2011).

Like for other crops, climate change is expected to affect this important staple food crop. Thus, quantitative scientific evidence on tef yield and its future productivity and availability is vital for policy makers, farmers and planners in order to understand the food gaps with the growing population under the changing future climate. However, such quantitative information together with various possible scenarios has not been well documented to date.

The recently released famous, commonly grown and dominant tef improved variety, *Quncho,* (Kebebew et al., 2011) has been selected for this research. The selection of this tef variety was based on its dominance in terms of area coverage, possibilities of its future expansion and intensification and availability of calibrated model for simulating yield under future climate scenarios.

Calibration data sets in Araya et al. (2010a) have been updated for the famous improved variety, *Quncho* – tef, by Hailay (2012) and Araya et al. (submitted). In this study, the *Quncho* – tef calibration data sets were applied in a crop model to assess the impact of future climate on tef yield. The future climate was generated based on procedure of the phase Five Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2009; Moss et al., 2010; AgMIP, 2013a, b). The objective of this research is to assess and quantify the impact of climate change on tef productivity in Debrezeit area.

MATERIALS AND METHODS

Site description

This research was conducted in the Oromya regional state, Debrezeit (latitude 8°42'21" and longitude 39°01'58") which is found in the semi-arid zone of central Ethiopia. It is one of the major tef (*Quncho)* growing areas in Ethiopia. In addition, observation data was obtained from Axum (latitude 14°07'50" and longitude 38°47'24"), located in the northern Ethiopia.

Climate

Climate data for Debrezeit that includes the long-term (1980 – 2009) daily rainfall, daily maximum and minimum temperature (Tmax and Tmin) was obtained from the Ethiopian National Meteorological Agency (NMA). Due to limited availability of climate data, the reference evapotranspiration was derived using Hargreaves equation (Allen et al., 1998).

The study area has bimodal rainfall with 73% of the rainfall received during the main growing season (June to September) locally called '*Kiremt*' and about 21% of the total is received during the short rain season that occurs between February and May locally called '*Belg*'. The other 6% of the total mean annual rainfall is received during the dry season called '*Bega*'. The total long term mean annual rainfall for the study site is about 830 mm. The annual mean daily minimum and maximum temperature are approximately 13.02°C and 24.6°C, respectively.

Field survey and data collection

Field survey was conducted at Axum observational sites during the cropping season in 2012 and 2013. Tef grain yield and aboveground biomass were sampled from farmer's field using a 1m × 1m quadrant. The sampling was conducted using standard sampling methods based on the bureau of statistics in the region. In addition, more than 30 farmers were interviewed regarding the overall tef management practices in the area (including fertilizer, irrigation, and weeding). Costs of inputs used were also noted. Furthermore, four years (2007 – 2010) *Quncho*-tef grain and biomass data together with sowing dates and other management information was collected from Debrezeit Research Center (Tsedale, 2014). The observational data collected from both Axum and Debrezeit were used only to conduct simple model simulation performance test.

Soils

The soil physical characteristics information for both Axum and Debrezeit was obtained from site-specific observation. Considering the homogenous nature of the soils, one set of dominant soil data was used for each site. The soil type described in Table 1 shows the physical characteristics of the dominant soils at Debrezeit and Axum sites.

Management

Tef – "*Quncho"*, which is a high yielding improved variety,

Table 1. Soil physical characteristics of observational sites.

Site	Depth	PWP	FC	SAT	TAW	KSAT	CN	tau
	M	Vol%	Vol%	Vol%	mm/m	mm/day		
Axum	0.15	15	30	50	150	15	90	0.22
	0.15	16	30	50	140	15		0.22
	0.15	16	28	50	120	15		0.22
	0.15	18	27	50	90	15		0.22
Debrezeit	1.2	19.3	37.7	54	184	100	90	0.43

FC, field capacity; PWP, permanent wilting point; TAW, total available water; CN, curve number; tau, drainage coefficient; KSAT, saturated hydraulic conductivity; and SAT, water content at saturation.

was released and disseminated to farmers some years ago (Kebebew et al., 2011). Presently, the variety is the most commonly and widely grown by significant number of small-scale farmers across the country even though the exact area cover under *Quncho* is not known. The crop is often sown from early July to late August depending on the onset of rain, availability of enough labour and other resources. In our modeling exercises (artificial experimentation) at Debrezeit site, three sowing dates were used to represent farmers' practices as: early (July 16), normal (July, 28) and late (August 19) (Tsedale, 2014). These three sowing dates were used for assessing tef yield under future climate assuming there will be no fertilizer limitation under rainfed condition.

Model description and evaluations

AquaCrop is water driven model developed by FAO (Raes et al., 2009a, b). The model was used by large number of users for a number of crops under wider range of growing condition (Hsiao et al., 2009). AquaCrop calculates biomass based on the concepts of normalized water productivity (Steduto et al., 2007; Raes et al., 2009a, b). The model calculates the yield by multiplying the harvest index with the biomass (Raes et al., 2009a, b). The model has been applied for assessing alternative water management strategies including exploring sowing date options (Araya et al., 2010c).

Soil, climate and other management information were entered into a validated model (Hailay, 2012; Araya et al., submitted). In addition, model performance test was conducted using the observational yield data obtained from both Axum and Debrezeit. A 1:1 line graph of the observed against simulated data (biomass and yield) was plotted. Further statistical evaluation was not considered as the model was already evaluated for *Quncho* – tef. It was then only after confirmation of the satisfactory performance of the model at the two sites that we finally decided to use the model for assessing the impacts of climate change on tef yield.

Climate change scenarios

In this study, the phase Five Coupled Model Intercomparison (CMIP5) General Climate Models (GCM) delta statistics procedure based on the Agricultural Model Intercomparison and Improvement Project (AgMIP) (climate scenario generation tools under R environment) were used to generate the future climate (AgMIP, 2013a, b).

Future climate was simulated for Debrezeit area based on five GCMs: "ACCESS1-0", "bcc-csm1-1", "CCSM4", "GFDL-ESM2M" and "HadGEM2-ES", hereafter represented by 'A', 'B', 'E', 'I' and 'K', respectively. The future climate was simulated considering two Representative Concentration Pathways (RCP4.5 and RCP8.5) for near (2010-2039), mid (2040-2069) and end term (2070-2099) periods. Details of the two Representative Concentration Pathways (RCP4.5 and RCP8.5) and their equivalent CO_2 emissions and concentrations are presented in Moses et al. (2010), Rogelj et al. (2012), AgMIP (2012), and Wayne (2013). Multi-GCMs were used in this study to explore the uncertainties of climate change impacts and to describe ranges of magnitudes of the future plausible events and to understand uncertainties about the future for wider ranges of decisions (Wayne, 2013). It has been suggested that use of variety of scenarios based on many GCMs (developed from combinations of various drivers) could help for exploring uncertainties and projecting the plausible impacts of future climate (Hanson et al., 2004; Kersebaum et al., 2007; Taylor et al., 2009; HLPE, 2012; AgMIP, 2012, 2013a, b).

Scenario runs and analysis

The climate scenarios include 30 years daily values of reference evapotranspiration, maximum and minimum temperatures and rainfall. The baseline period (1980 – 2009) and three future time periods (2010 – 2039; 2040 – 2069 and 2070 – 2099) each simulated on daily basis under RCP4.5 and 8.5 based on five GCMs were prepared in separate files and entered into AquaCrop model. The scenarios were then run on season by season basis for three sowing dates (early, normal and late). Average and median yield statistics were then analyzed for each scenario and presented in Tables and

Table 2. Changes in maximum temperatures (°C) compared to the baseline across the five GCMs by RCP and time period.

RCP and period	GCM				
	A	B	E	I	K
NT4.5	1.0	0.7	1.0	0.8	1.3
NT8.5	1.0	0.9	1.0	0.8	1.3
MT4.5	1.9	1.5	1.6	1.1	2.4
MT8.5	2.7	2.0	2.2	1.9	3.1
ET4.5	2.7	1.8	1.8	1.3	3.1
ET8.5	4.4	3.8	3.7	3.2	4.8

Table 3. Changes in mean minimum temperature (°C) compared to the baseline across the five GCMs by RCP and time period.

RCP and period	GCM				
	A	B	E	I	K
NT4.5	1.3	0.6	0.7	0.6	1.5
NT8.5	1.2	0.8	0.9	0.9	1.7
MT4.5	2.0	1.3	1.6	1.2	2.9
MT8.5	3.1	1.9	2.1	2.1	3.7
ET4.5	2.9	1.5	1.8	1.8	3.9
ET8.5	5.2	3.4	3.2	3.5	6.5

Where, GCM "A" = "ACCESS1-0", "B" = "bcc-csm1-1", "E" = "CCSM4", "I" = "GFDL-ESM2M", and "K" = "HadGEM2-ES"; RCP, Representative Concentration Pathway; GCM, Global Climate Model; ET, end term; NT, near term; 4.5 and 8.5 are RCP4.5 and RCP8.5.

Table 4. Changes in mean annual rainfall (%) compared to the baseline across the five GCMs by RCP and time period.

RCP and period	GCM				
	A	B	E	I	K
NT4.5	-1.5	1.4	-5.8	4.4	-0.8
NT8.5	-2.0	5.0	-4.7	-4.9	1.4
MT4.5	-2.4	-0.8	-6.6	1.4	-4.5
MT8.5	1.4	5.1	-8.7	-0.2	0.1
ET4.5	0.7	1.2	-2.2	8.0	0.0
ET8.5	7.2	9.5	1.6	4.4	12.1

Where, GCM "A" = "ACCESS1-0", "B" = "bcc-csm1-1", "E" = "CCSM4", "I" = "GFDL-ESM2M", and "K" = "HadGEM2-ES"; RCP, Representative Concentration Pathway; GCM, Global Climate Model; ET, end term; NT, near term; 4.5 and 8.5 are RCP4.5 and RCP8.5.

Charts.

RESULTS AND DISCUSSION

Climate change scenarios

There were considerable differences between the observed and simulated climate scenarios (Tables 2, 3 and 4). Simulated temperatures and mean annual rainfall were substantially affected by time period, RCP and type of GCM used. Future temperatures have generally increased with time period and RCP across all GCMs. Many reports also clearly indicated that temperatures are expected to increase throughout the three time periods (Taylor et al., 2009; Moss et al., 2010; Rogelj et al., 2012; AgMIP, 2013a, b). The highest temperatures were simulated during the end term period under RCP8.5 with GCM 'K', whereas the lowest temperatures were simulated during the near term under RCP4.5 (Tables 2 and 3) with GCM 'B'.

Similarly, highest mean annual rainfall was simulated during the end term period under RCP8.5 with the GCM 'K' (+12.1%), whereas the lowest mean annual rainfall was simulated during the near term period under RCP4.5 with the GCM 'E' (-5.8%) (Table 4). The difference among the simulated climate outputs could be mainly due to the basic modeling structures and parameterization of the GCMs. The assumptions (modeling) regarding the increase in greenhouse gases (specifically CO_2) concentration and trend (slow or rapid increase) for each of the three time periods differs between RCP8.5 and RCP4.5. Such difference is expected to cause variations among the climate simulations (for example, temperature levels). Differences in climate outputs, thus, lead to ranges of climate change impacts. It is assumed that climate impacts from multi-model predictions could help to explore the magnitude of changes and the likely occurrence of events together with their uncertainty (AgMIP, 2012).

Model evaluation and yield projection

Simple linear regression of the simulated against observed biomass and grain yield at Axum and Debrezeit sites showed satisfactory simulation performance (Figure 1a and b) of the already tested model (Hailay, 2012). Therefore this implies the model can be used for simulating *Quncho* - tef yield under future climate.

The simulation result indicates that the expected yield slightly varied among the five GCMs. Both the highest and lowest yield extremes were simulated when climate scenario based on GCM 'K' was applied. The highest and lowest yield was projected when early and late sowing was applied respectively (Figures 2 and 3, and Tables 5 and 6). Generally, yield over the future time period (based on all GCMs) slightly increased when early sowing was used, whereas a considerable decrease was simulated under late sowing (Table 5, Figure 2). This was indicated by the percent yield change, for the respective sowing dates, when compared to baseline across the three time periods (Tables 5 and 6). Results showed that tef yield reduced by 50% and 46%, 40% and 43% and by

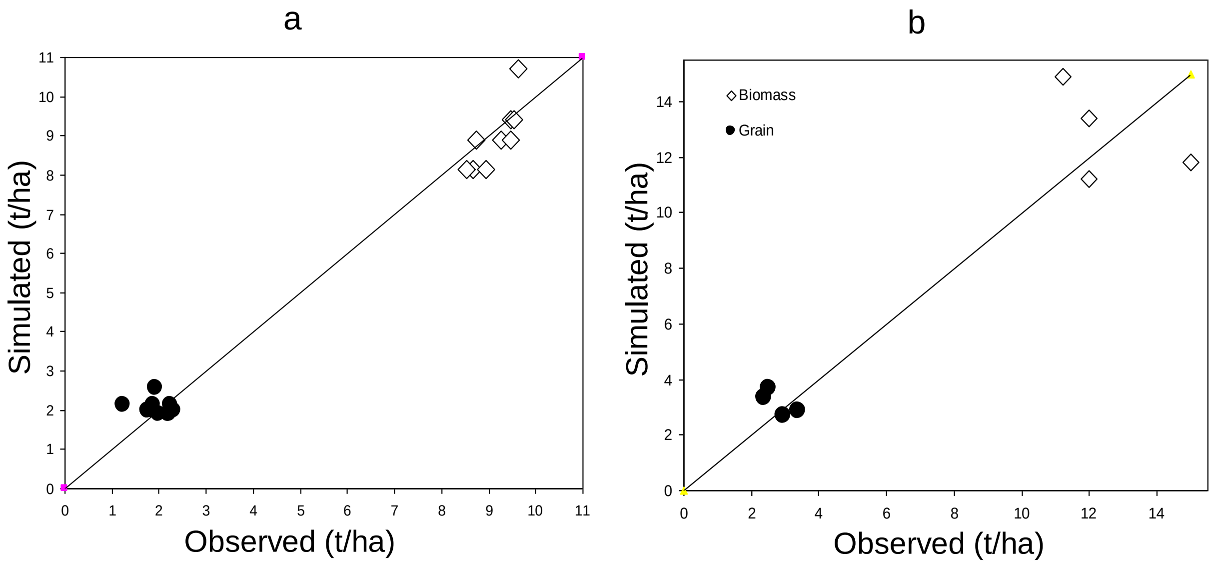

Figure 1. Simulated versus observed tef yield and biomass at: (a) Axum and (b) Debrezeit sites.

39% and 26% when late sowing was applied under both RCP4.5 and RCP8.5 during the near, mid and end term, respectively (Figures 2 and 3, and Tables 5 and 6).

The rainy period over the study site is limited to a maximum of four months during which tef is grown as a major crop. Tef crop sown early in the season (July 16) is expected to spend the majority of its growth cycle within the rainy period, whereas late sowing at the end of the rainy period (August 19) will have higher chance of exposure to mid and late season dry period. Therefore, the main possible reason for the decrease in tef yield with late sowing could be due to the extended exposure of the reproductive and grain filling crop stages to the late season dry spells. Thus, poor matching of the crop growing cycle with rainy period could severely reduce yields. In line with Araya et al. (2010b, 2012) reported that early and normal sowing enhances early seedling establishment and improves productivity whereas late sowing exposes the crop to late season dry period. However, sowing too early (dry seeding) was discouraged as tef requires wet/moist seedbed for good seedling establishment.

Exploring yield based on alternative sowing dates under the future climate as presented in this study might help to reduce risks of crop failure. Thus, use of early sowing, short maturing cultivars and other management practice that could improve soil water availability (such as use of irrigation) could help in minimizing the negative impacts of climate change on the crop.

Yields slightly improved under RCP8.5 when compared to RCP4.5 of the same time period. This could be attributed to the positive roles of CO_2 to plant growth with an increase in CO_2 concentration. The concentration and trend of CO_2 is assumed to be relatively higher and rapid under RCP8.5 compared to RCP4.5 (Moss et al., 2010; Wayne, 2013). High CO_2 concentration levels were reported to have positive impacts on crop yield (Hatfiled et al., 2011). According to U.S. Global Change Research Program (2009), the negative effects of higher temperatures under future climate might be reduced by slight increase in rainfall and CO_2. For example, high CO_2 is associated with high rate of photosynthesis, improved water use efficiency, and increased extension of plant root system (U.S. Global Change Research Program, 2009).

Extreme temperatures under future climate is expected to decrease yield because higher temperatures is likely to increase evapotranspiration, shorten pollination and grain filling period (Sofield et al., 1974, 1977; Chowdhury and Wardlaw, 1978; Goudriaan and Unsworth, 1990; Bender et al., 1999; Lawlor and Mitchell, 2000; Wheeler et al., 2000). Under such extreme conditions, presence of higher CO_2 concentrations may not offset the negative impacts of various interacting factors (Hatfield et al., 2011). However, this level of stress may not be a threat for tef production up to 2100 since the simulated temperatures are below the upper threshold limits.

Conclusion

Tef yield under future climate is expected to vary with sowing date, time period, RCPs and type of GCMs used. Median yields increased and decreased by up to 10% and 39% for early and late sowing, respectively during the end term period whereas it reduced by up to 4% and 50% for early and late sowing, respectively during the near term period.

Yield reduction was relatively low for RCP8.5 as compared to RCP4.5 across the three time periods. This could be attributed to the assumptions of higher

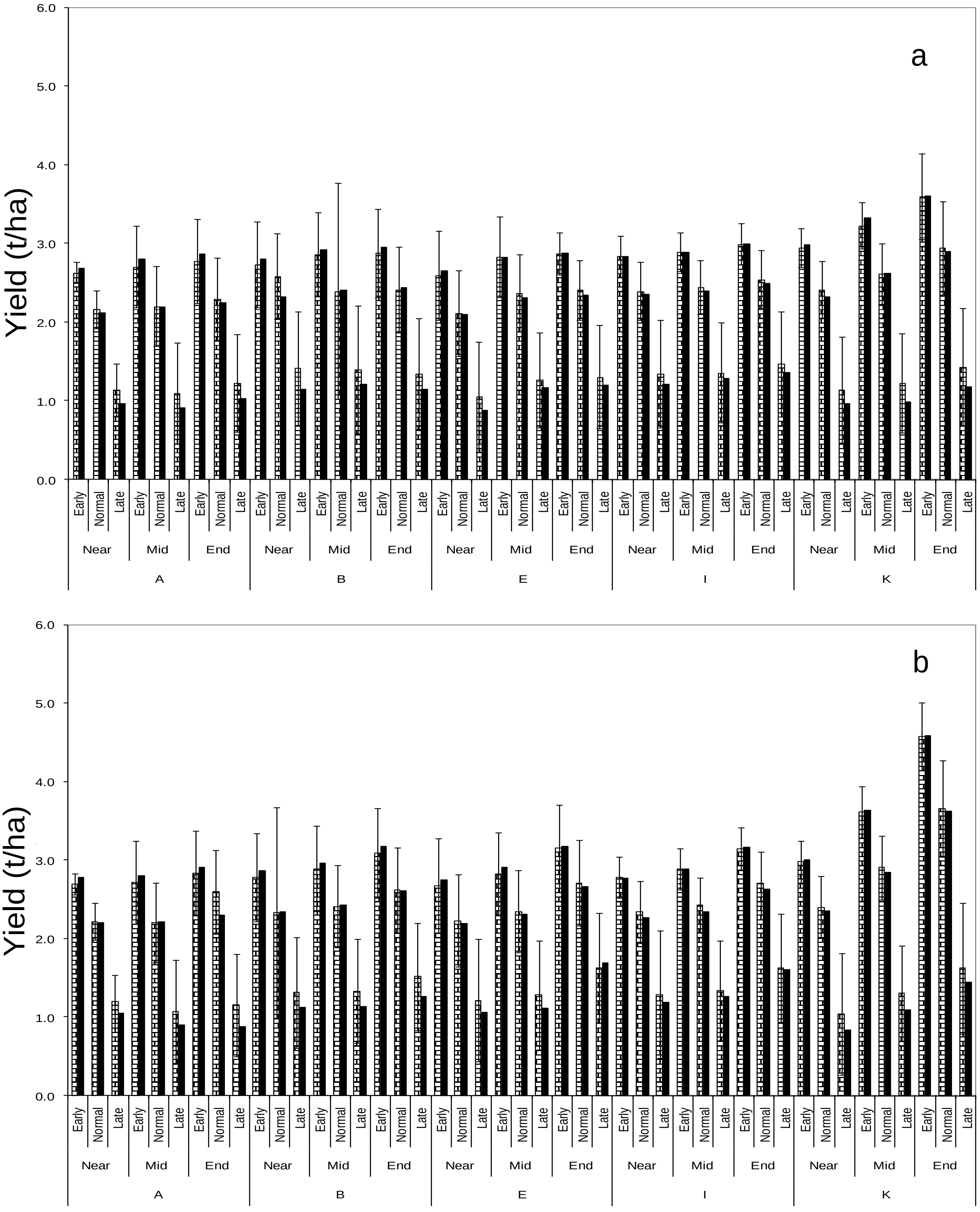

Figure 2. Simulated tef yield under three time periods and sowing dates based on 5 GCM under (a) RCP4.5 and (b) RCP8.5. Where, GCM "A" = "ACCESS1-0", "B" = "bcc-csm1-1", "E" = "CCSM4", "I" = "GFDL-ESM2M", and "K" = "HadGEM2-ES". Black bar = median yield; white spotted bar = average yield; thin bars at top of average yield are error bars.

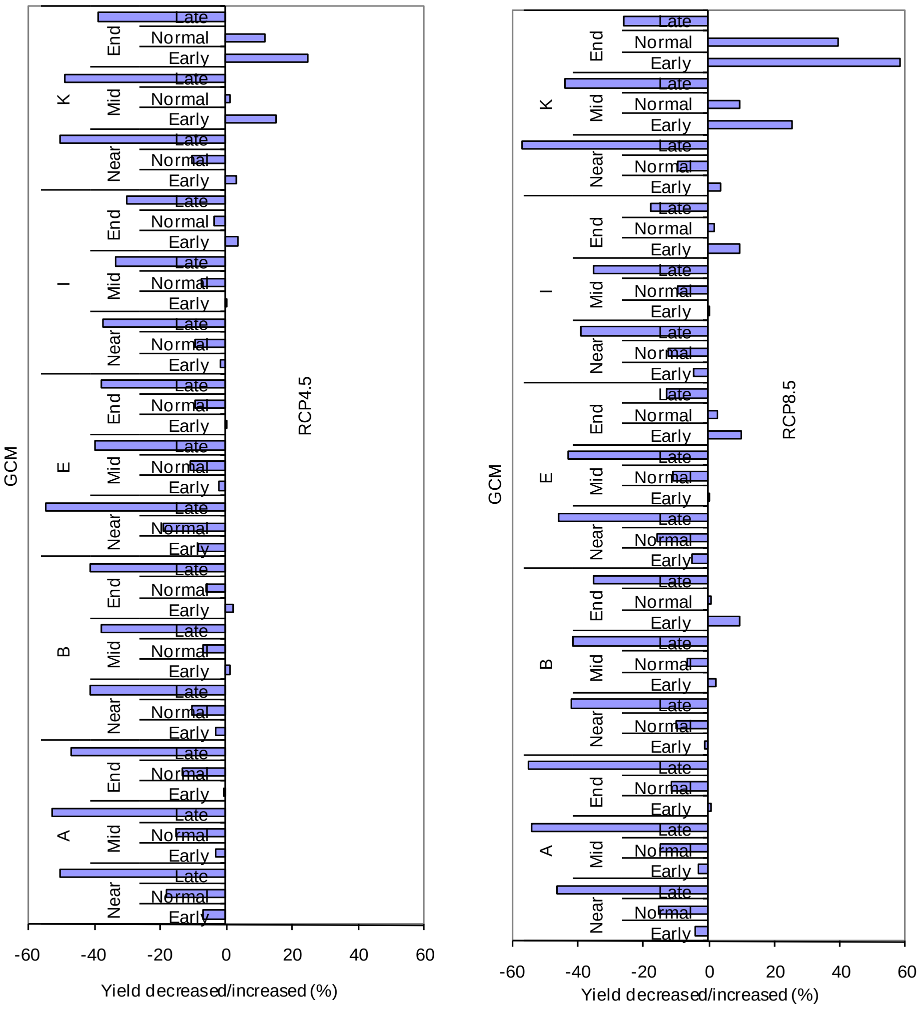

Figure 3. Percent tef yield gained/lost as simulated using AquaCrop model based on 5 GCM under three time periods and sowing dates. Where, GCM “A” = “ACCESS1-0”, “B” = “bcc-csm1-1”, “E” = “CCSM4”, “I” = “GFDL-ESM2M”, and “K” = “HadGEM2-ES”; GCM = Global Climate Model.

Table 5. Percent yield changes (%) simulated using AquaCrop model for three sowing dates, three time periods with RCP4.5 based on five GCMs as compared to the baseline.

Time period	Sowing date	GCM					Mean	Median
		A	B	E	I	K		
	Early	-7	-3	-8	-2	3	-3	-3
Near	Normal	-18	-10	-19	-9	-10	-13	-10
	Late	-50	-41	-55	-37	-50	-47	-50
	Early	-3	1	-2	0	15	2	0
Mid	Normal	-15	-7	-11	-7	2	-8	-7
	Late	-53	-38	-40	-34	-49	-42	-40
	Early	-1	3	0	4	25	6	3
End	Normal	-13	-6	-9	-3	12	-4	-6
	Late	-47	-41	-38	-30	-39	-39	-39

Table 6. Percent yield changes (%) simulated using AquaCrop model for three sowing dates, three time periods with RCP8.5 based on five GCMs as compared to the baseline.

Time period	Sowing date	GCM					Mean	Median
		A	B	E	I	K		
Near	Early	-3.8	-0.9	-4.9	-4.2	4.1	-2	-4
	Normal	-14.9	-9.6	-15.4	-12.3	-9.1	-12	-12
	Late	-46.1	-42.0	-45.6	-38.9	-56.8	-46	-46
Mid	Early	-2.9	2.4	0.7	0.0	25.8	5	1
	Normal	-14.6	-6.2	-10.9	-9.5	9.9	-6	-9
	Late	-53.8	-41.5	-42.8	-34.8	-43.8	-43	-43
End	Early	0.9	9.8	10.1	9.6	58.7	18	10
	Normal	-11.0	0.7	3.0	1.7	40.0	7	2
	Late	-54.9	-34.8	-12.8	-17.4	-25.6	-29	-26

Where, GCM “A” = “ACCESS1-0”, “B” = “bcc-csm1-1”, “E” = “CCSM4”, “I” = “GFDL-ESM2M”, and “K” = “HadGEM2-ES”; RCP, Representative Concentration Pathway; GCM, Global Climate Model.

concentrations and rapid trend of CO_2 under RCP8.5 which might have positive implication on rate of photosynthesis, water use efficiency and yields. Higher CO_2 concentrations were also reported to offset the negative impacts of moisture stress and higher temperatures to some extent.

Under future climate, rainfall amount and distribution will have significant impact on tef yield. Early sowing could be used as one of the climate change adaptation strategy for growing tef under the future climate. Early sowing, keeping all other factors constant, allows efficient use of available moisture (rainfall). Further research is needed to understand the response of tef to climate change under various agro-ecologies, GCMs, and cultivars with and without climate change adaptation options.

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