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Exploring Impacts of Climate Change on Maize Yield in Two Contrasting Agro-Ecologies of Ethiopia

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ABSTRACT

Many studies indicated that agricultural production in sub Saharan Africa is likely to reduce under the future climate. However, there has been limited quantitative information as to what extent yield would change under future climate for the major food crops in the major agro-ecologies of Ethiopia. In this study the yield changes under the future climate were assessed for two major improved maize cultivars adapted to the semi-arid and sub-humid areas of Ethiopia using a well calibrated and evaluated crop growth model. Detailed field and household survey information (crop, soil, and management data inputs) gathered from two sites (Melkasa and Bako) along with climate information simulated based on 20 General climate models for three time periods each with 30 year time period under two Representative Concentration Path ways (RCPs) were used for the yield projection. Results showed that median maize yield slightly increased relative to the baseline in the sub-humid climate whereas slightly decreased in semi-arid regions of Ethiopia. However, the result of this study indicated that maize yield have not significantly changed over the three time periods for the two agro-ecologies. Therefore based on this study we conclude that climate change may not cause severe negative impacts on future productivity of experimental maize varieties at both agro-ecologies. It might be possible to bring more positive yield change easily by using improved agronomic practices hence in the future more research have to be carried out in assessing alternative adaptation strategies.

Keywords: maize, climate change, semi-arid and sub-humid, Ethiopia

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INTRODUCTION

Climate change has been considered as a future threat for the survival of human being as it is claimed to have significant impact on food security (Cooper et al., 2008; Jones and Thornton, 2009; Jon, 2009). Especially the already warmer and drier regions are expected to further negatively affected by climate change (Stern, 2006 and Stern et al., 2007).

In Ethiopia, climate related risks stands as major problem when it comes to agricultural production (Araya et al., 2010a; Araya and Stroosnjder, 2011; Conway and Schipper, 2011; Demeke, et al., 2011). However, all agro-ecologies are not likely to be affected by climate change and variability with the same magnitude. In addition, all crops and crop cultivars are not expected to respond to the threat of climate change and variability in a similar manner. There has been inadequate quantitative information on how major crops and crop cultivars grown in the arid and semi arid regions respond to impacts of climate change.

There are also uncertainties under the future climate whether the food availability (supply) meets the demands. Yield deviation assessments are thus needed to provide decision-makers with such information for appropriate plans in order to reduce the negative impacts of climate changes.

In this study we attempt to conduct synthetic research to assess the impact of climate change on maize yield taking into account major maize cultivar from semi-arid and sub-humid regions of Ethiopia whose genetic coefficients calibrated and validated in DSSAT (Decision Support System for Agro-technology Transfer) (Hoogenboom et al., 2010) with the help of experimental crop data along with site specific climate, soil and management information.

The objectives of this study are to assess the impacts of climate change on maize productivity in the semi-arid and sub-humid climate taking into account climate simulations based on 20 GCM (General Climate Models) for three time periods under two Representative Concentration Pathways (RCPs).

MATERIALS AND METHODS

Description of the study area

Location

The study areas were located in two districts of Ethiopia namely Melkasa and Bako areas. Melkasa is located in the central rift valley of Ethiopia with latitude and longitude of 8.25° and 39.20°, respectively, whereas Bako is found in the Southwestern Ethiopia with latitude and longitude of 9.6° and 37.9°, respectively. The altitude at the sites is 1550 and 1680 m a s l, respectively.

Climate

The long term mean annual rainfall for Melkasa and Bako area are 702 - 768 mm (Laike et al, 2006; Shenkut et al., 2013) and 1244 - 1260 mm (Negassa et al., 2005), respectively. About 70% and 80% of the mean annual rainfall is received from June to September. Melkasa and Bako sites have a mean maximum temperature of 28.5 and 28 °C and a mean minimum temperature of 12.6 - 13.8 and 14.8 - 15 °C, respectively (Laike et al, 2006; Shenkut, et al., 2013).

Soil

The soils at both Melkasa and Bako area are deep grey fluvisol and reddish brown nitosol, respectively. According to previous reports the textural classes of soils at Melkasa sites is dominantly clay loam and loam textural (Laike et al., 2006; Shenkut et al., 2013) while the textural classes of soils at Bako areas is dominantly clay and loam texture (Negassa, 2001). Soil physical and chemical characteristics of Melkasa and Bako sites are presented in Table 1 and 2.

Table 1: Soil physical and chemical characteristics of Melkasa area, central rift valley of Ethiopia

Depth (cm)	LL (mm^3/mm^3)	DU (mm^3/mm^3)	SAT (mm^3/mm^3)	BD (g/cm^3)	OC (%)	Clay (%)	Silt (%)	Coarse stone	pH	CEC (cmol/kg)	sat.hydraulic con. (cm/hr)
10	0.114	0.240	0.541	1.130	0.884	24.000	36.000	0.000	6.600	12.00	0.10
30	0.150	0.290	0.457	1.300	0.936	30.000	42.000	0.000	6.960	10.00	0.09
60	0.160	0.300	0.457	1.130	0.696	36.000	38.000	0.000	6.650	10.00	0.13
90	0.180	0.330	0.457	1.110	0.455	38.000	40.000	0.000	6.670	10.00	0.04
120	0.210	0.330	0.457	1.080	0.221	36.000	44.000	0.000	7.030	10.00	0.04
150	0.170	0.330	0.457	0.990	0.091	32.000	48.000	0.000	7.890	10.00	0.00
180	0.170	0.370	0.457	1.100	0.091	32.000	40.000	0.000	8.390	10.00	0.00

Source: Melkasa Agric. Res. Center

BD, is bulk density, SAT, is water content at saturation, DU, is drainage upper limit, LL, soil lower limit

Table 2: Soil physical and chemical characteristics of Bako area, South Western Ethiopia

Depth (cm)	LL (mm^3/mm^3)	DU (mm^3/mm^3)	SAT (mm^3/mm^3)	BD (g/cm^3)	OC (%)	Clay (%)	Silt (%)	TN, %
5	0.245	0.344	0.392	1.06	1.6	54	18	0.18
15	0.245	0.344	0.392	1.06	1.6	54	18	0.18
25	0.245	0.344	0.39	1.06	1.6	54	18	0.18
35	0.26	0.321	0.39	1.06	1.6	63	12	0.07
50	0.26	0.321	0.39	1.06	0.53	63	12	0.07
65	0.26	0.321	0.395	1.1	0.2	63	12	0.07
80	0.26	0.321	0.395	1.1	0.2	63	12	0.07
99	0.26	0.321	0.408	1.1	0.1	63	12	0.07
122	0.26	0.321	0.41	1.1	0.09	-	-	0.07
137	0.159	0.288	0.399	1.1	0.09	-	-	-
159	0.11	0.242	0.402	1.1	0.1	-	-	-
184	0.047	0.177	0.351	1.1	8	-	-	-
209	0.05	0.193	0.41	1.1	8.5	-	-	-

Source: Birhanu Dinsa (2011). where TN is total nitrogen, BD, is bulk density, SAT, is water content at saturation, DU, is drainage upper limit, LL, soil lower limit

Farm Survey and site data management

At least 30 and 180 maize growing farmers were interviewed both at Melkasa and Bako sites, respectively. Focus group discussion with elders, young and other model farmers were also conducted. During the farm survey the crop, soil and crop management information was gathered. Crop characteristics data that includes crop varieties grown in the sites, yield by cultivar and phenology (flowering and maturity date) were gathered. Crop management information such as fertilization (type and amount and depth and time of application and technology used), planting (density, depth and method and date of planting), other cultural practices such as weeding (number of labor days, time and frequency), hoeing (number of labor days, time and frequency), irrigation (type, method, frequency, amount per interval), and harvesting and the technologies used were also gathered. Soil information that includes the general soil characteristics such as the soil physical (texture, bulk density, wilting point, field capacity, water content at saturation) and chemical characteristics (pH, initial crop residue, soil organic carbon and total nitrogen) were obtained from the respective research centers. In addition, some profiles were opened and sampled for laboratory analysis.

Crop and management

According to the survey, Melkasa - 1 and BH – 540 were noted as major maize varieties grown in Melkasa and Bako areas. Both cultivars have been managed by resources poor farmers under rainfed condition. The cultivars differ in their length of growing period and resistance to water stress. Based on the assessment, both maize varieties at their respective sites are planted at a seeding rate of 3.3 to 5.3 plants per m^2 in rows with an average density of 4.4 plants per m^2. Assessment results showed that planting window was between 10th and 20th of June for Melkasa – I and between 20th of May and 10th of June for BH – 540. Majority of the farmers do not apply irrigation and farm yard manure.

Some general assumptions were also used to fill missing information during the survey. These assumptions were: 200 kg/ha and 500 kg/ha of residues were estimated to have remained from previous crop with an estimated nitrogen content of the residues to be 0.8% at Melkasa and Bako sites, respectively. In addition, presence of 10 kg/ha of inorganic soil nitrogen, 0.1 ppm of NO3 and 0.01 ppm of NH4 and 50% of the total available water was assumed at start of sowing. The planting depth and row spacing were assumed to be 50 mm 0.75 m, respectively. From the survey most farmers used lower fertilizer rate but some of them used up to a maximum of 64 kg/ha. In this simulation exercise about 33% of the fertilizer was assumed to be applied at sowing to a depth of 0.1m and the rest 67% of fertilizer was applied at 45 day after planting.

Climate simulation and CO_2 assumptions

Long term daily climate data from 1980 - 2009 was obtained from national meteorological agency (NMA). The climate data (1980 - 2009) was filled for gaps based on AgMIP procedures (AgMIP, 2013a&b). The daily baseline climate data (1980 - 2009) was used to simulate the future climate by applying delta statistical technique across 20 GCMs with two RCPs. R script was used to prepare the delta based climate scenarios in format required by the crop model. The climate simulation was done for three terms each with 30 years that includes near term (2010 - 2039), mid term (2040 - 2069) and end term (2070 - 2099). In this study, the central year CO_2 concentration that corresponds to each RCP under the different time periods presented in AgMIP (2012) was used (near term under RCP4.5 = 423 ppm; near term under RCP8.5, 432 ppm; midterm under RCP4.5, 449 ppm, midterm under RCP8.5, 571 ppm; end term under RCP4.5, 532 and end term under RCP8.5, 801 ppm).

Model calibration and evaluation

CSM CERES in DSSAT Version 4.5 (hereafter DSSAT) (Hoogenboom et al., 2010) was calibrated using an independent maize data set of the year 1999 for Melkasa-1 and the season 2009 for BH-540 (Table 6). The simulation performance of the model was evaluated based on several year phenological and yield data collected at the respective research sites. Table 4 and 5 shows the observed against simulated maize phenology and yield data used for model calibration and evaluation. Site specific soil, climate and management information were also used as data inputs in the model when evaluating the simulation performance of the model.

Table 3: Agro-ecology of the study sites and the cultivar's pheological and yield characteristics under experimental and farmers growing conditions

Agro-climatic zone	Site	Altitude (meters above sea level)	Dominant maize variety	Days to silking	Days to maturity	Observed median Yield under the present farmer's growing condition (t/ha)	Experimental Yield range (t/ha)
Semi-arid	Melkasa	1550	Melkasa -1	52 - 58	104 - 116	1.1	1.3 - 5.6
Sub-humid	Bako	1680	BH-540	70 - 80	136 - 150	3.8	6.5 - 9.7

Eleven years of experimental observations (2000 - 2011) for BH-540; 1999 to 2009 for Melkasa -1

Table 4: Experimental yield and statistical evaluation for Melkasa - 1

	Flowering		Maturity		Yield t/ha	
Year	OBS	SIM	OBS	SIM	OBS	SIM
*1999	52	53	104	105	4.3	5.7
2000	54	54	108	107	4.7	4.8
2004	57	55	114	111	5.3	5.2
2005	58	60	116	114		
RMSE		1.63		2.16		1.60
I		0.73		0.70		0.81

* calibration data set

Table 5: Experimental yield and statistical evaluation for BH-540

	Flowering (days)		Maturity (days)		Yield (t/ha)	
Year	Obs	Sim	Obs	Sim	Obs	Sim
2004	75	75	147	145	8.9	9.5
2005	73	70	140	136	8.9	9.0
2006	76	75	140	140	7.5	6.1
2007	74	74	146	145	7.8	8.8
*2009	83	78	154	154	8.8	9.0
RMSE		0.95		2.23		1.56
I		0.52		0.79		0.51
R2		0.63		0.85		0.67

Climate change scenarios and yield projection

Once calibrated and evaluated, future climate data simulated based on 20 GCM and two RCPs together with other crop, management and soil information was entered in AgMIP multi-model friendly data storage templates. AgMIP tools were used to integrate the stored information (crop, soil, management, assumptions and climate scenarios) in the data sheets with crop model to produce model ready data input files and subsequently run to simulate maize yield. Simulated yield for each site and maize cultivar was then arranged by GCM, RCP and time period.

The percent of yield changes were used to evaluate the change from the baseline yield. The baseline yield was simulated based on the historical climate while future yield was simulated based on the changed climate as presented in section above. Both baseline yield and future yield were then compared and percentage of yield changes were calculated by subtracting the baseline yield from the respective future yield and dividing it by the baseline yield and then multiplying the equation by hundred.

RESULT

Model calibration and evaluation

The agro-ecology of the study sites and the cultivar's pheological and yield characteristics under experimental and farmers growing conditions is presented in Table 3.

The genetic coefficient for Melkasa - 1 and BH-540 were well calibrated in DSSAT (Kassie et al., 2014). Further recalibration has however slightly improved the simulation of the observed values.

The observed yield was satisfactorily simulated by the model for both cultivars at both sites with index of agreement (I) of 0.81 and 0.51; Root Means of Square Error (RMSE) of 1.6 t/ha and 1.56 t/ha for Melkasa-1 and BH-540, respectively. The phenology for the respective cultivars was also well simulated by the model with I value of 0.73 and 0.52 and RMSE values of 1.63 and 0.95 days for flowering, and I of 0.7 and 0.79 and RMSE of 2.16 and 2.23 days for maturity (Table 4 and 5). The genetic coefficient of the cultivars is presented in Table 6.

Table 6: Genetic coefficient for maize cultivars calibrated in DSSAT

Cultivar	P1	P2	P5	G2	G3	PHINT
Melkass-1	130	0.5	720	450	9.0	40
BH-540	220	0.84	850	500	10.6	38.9

P1 *Thermal time from seedling emergence to the end of the juvenile phase (degree days)*
P2 *Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (days)*
P5 *Thermal time from silking to physiological maturity (degree days)*
G2 *Maximum possible number of kernels per plant.*
G3 *Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).*
PHINT *Phylochron interval; the interval in thermal time between successive leaf tip (degree days)*

The simulated median yield for Melkasa-1 and BH-540 cultivars under the different three time period scenarios based on 20 GCM under RCP4.5 and RCP8.5 is presented in Table 7.

Table 7: Simulated median yield using 20 GCM based on RCP4.5 and 8.5 and the corresponding yields for Melkasa-1 and BH-540 cultivars under the different time period scenarios

	BH-540			Melkassa -1		
Time period	RCP8.5	RCP4.5	baseline	RCP8.5	RCP4.5	baseline
2010 - 2039	6.57	6.61	6.44	1.12	1.13	1.15
2040 - 2069	6.58	6.59		1.11	1.12	
2070 - 2099	6.35	6.66		1.10	1.11	

Yield change by GCM

There was moderately big difference in the simulated percent yield change by GCM with a standard deviation of 0.13 - 1.2 t/ha. The highest yield change for BH - 540 was observed with GCM "BNU-ESM", and "CanESM2", during end term under RCP8.5 whereas the highest yield changes for Melkasa - I was observed with GCM "NorESM1-M" (Fig. 1) during midterm under RCP4.5. With few exceptions (including the mentioned GCMs) simulated maize yield based on most GCMs were very similar.

Yield changes by time period and RCPs

Climate change induced future yield variations by time period were not considerably big when observed in comparison with the simulated baseline yield. The percent of yield changes were small for both cultivars and all climate scenarios (-4.7 to 3.5%) (Table 8). The maximum yield change was observed during the end century under RCP 4.5 with an increase by 3.5% whereas the minimum was observed over the same time period (end century) with a decrease by 1.4% under RCP8.5 for the cultivar BH-540. On the other hand, for Melkasa - 1, the highest yield change was observed during the end century under RCP8.5 (-4.7%) whereas the lowest yield changes was observed during the end century under RCP4.5 (-1.3%).

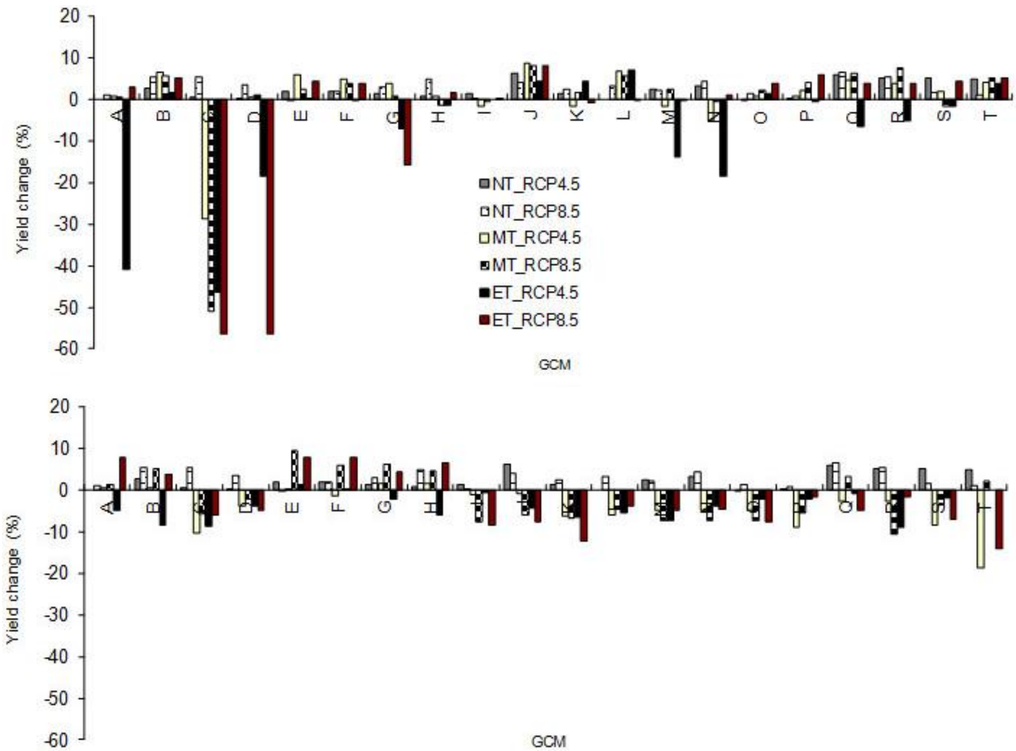

Fig. 1: Median yield changes by GCM and RCPs for Melkasa -1 and BH-540 maize cultivars over the near term, midterm and end century period

where, GCM is global climate models; A- T are the codes for the various GCMs used in this study : "A" = "ACCESS1-0", "B" = "bcc-csm1-1", "C" = "BNU-ESM", "D" = "CanESM2", "E" = "CCSM4", "F" = "CESM1-BGC", "G" = "CSIRO-Mk3-6-0", "H" = "GFDL-ESM2G", "I" = "GFDL-ESM2M", "J" = "HadGEM2-CC", "K" = "HadGEM2-ES", "L" = "inmcm4", "M" = "IPSL-CM5A-LR", "N" = "IPSL-CM5A-MR", "O" = "MIROC5", "P" = "MIROC-ESM", "Q" = "MPI-ESM-LR", "R" = "MPI-ESM-MR", "S" = "MRI-CGCM3", and "T" = "NorESM1-M".

Table 8: Median yield changes based on 20 GCM under RCP4.5 and 8.5 for two different maize varieties adapted to semi-arid and sub-humid climate

Time period	Crop model	RCP	Assumed average CO_2 concentration	Melkasa -1	BH-540
2070 - 2099	DSSAT	RCP4.5	532	-3.9	3.5
2070 - 2099	DSSAT	RCP8.5	801	-4.7	-1.4
2040 - 2069	DSSAT	RCP4.5	499	-3.2	2.3
2040 - 2069	DSSAT	RCP8.5	571	-3.9	2.1
2010 - 2039	DSSAT	RCP4.5	423	-1.3	2.8
2010 - 2039	DSSAT	RCP8.5	432	-1.6	2.0

Yield changes by agro-ecology and cultivar

Median yields showed negative changes in semi-arid regions for the cultivar Melkasa - 1. However, the changes were very small that ranges between - 4.7% and -1.3% during the end and near century period, respectively. On the contrary, yield changes were dominated by positive results in the sub-humid region for the cultivar BH-540. These changes (ranged between -1.4% and +3.5%) were observed during the end century period.

DISCUSSION

Model calibration and evaluation

The statistical evaluations have indicated that the model has satisfactorily simulated the corresponding observed crop data. In terms of yield, better simulation performance was observed for BH-540 (see I and RMSE values). There were almost similar statistical evaluation values for the days to flowering and maturity for both cultivars. This indicates, the model has able to simulate the yield and phenology of both cultivars adequately.

Climate change and scenario analysis

Median yield by cultivar based on 20 GCM have shown an overall of small changes but when assessed by each individual GCM, the simulation using GCM ''BNU-ESM", and "CanESM2", under RCP8.5 were highly variable for the cultivar BH-540 (Fig. 1a). The main reason for this disparity among GCMs was not clearly understood but could be due to their difference in their internal modeling structure.

Although temperature, CO_2 and rainfall under the future climate differ from the baseline, there was an overall small difference in yield among the simulations across the time periods until the end of the century. Median yield have not shown substantial difference among the time periods and RCPs however, relatively lower yield changes was observed during the near term when compared with the mid and end term scenarios and relatively higher yield reduction was observed for RCP8.5 compared to RCP4.5 in the semi-arid regions (Table 8). This was unclear but could happen due to the increased temperatures as a consequence of increased greenhouse gases. Increased temperatures may have some impact on water demand of the crop while moisture in the semi arid regions is not enough for growing maize.

On the other hand, there were small positive yield changes for the sub-humid environment where there was slight difference across the three time periods and two RCPs. The positive yield changes could be caused by the yield compensating roles of CO_2 (U.S. Global Change Research Program, 2009). However, yields have started to decline when temperatures increased under higher RCPs during the end term period. In line with this some reports indicated that higher temperatures which are simulated by the end of the century may have negative impact such as shortening of the grain filling period (Badu-Apraku et al., 1983; Jones et al., 1984; Muchow et al., 1990; Hatfield, et al., 2011).

Generally, yield change from the baseline for both agro-ecologies and cultivars was not substantially different. Although this difference was not big, we expect a slight increase in maize yield for sub-humid agro-ecology while a slight decrease for the cultivar grown in semi-arid (Melkasa - 1) agro-ecologies (Table 8). The increase for sub-humid climate could be due to increase in CO_2 levels which claimed to have positive compensating impact by many authors (Woodrow, 1994; Wittwer, 1997; Kimball et al., 2007; U.S. Global Change Research Program, 2009) and rainfall in that agro-ecology remains relatively better than the semi-arid regions of the same time period (data not shown) whereas the slight decrease in yield in the semi-arid regions could be due to many interacting factors among which cultivar characteristics in responding to increased temperature and water stress may have the biggest share. Some reports indicated that other cultivars that grow in similar semi-arid environment are expected to have better yield in the future than in the baseline period (AgMIP, 2014). Despite the slight variations among cultivars, maize production in semi-arid environment will continue to be far below its potential yield without provision of adequate crop management. The current yield levels for Melkasa – I under farmer's management condition are already low and will continue to be low under the future climate unless yield enhancing practices are used. Given that temperatures are expected to increase by up to 4 ^{o}C (by 2100) according to some models, maize yield under the future rainfed agriculture, especially in already hot semi-arid regions, is expected to decline. However, climate change – induced yield reductions are considerably low when compared with the yield declines due to improper crop management (data not shown). It may be possible to significantly increase the maize yield with slight improvement in crop management practices.

Conclusion

Median maize yield slightly increased in sub-humid climate whereas slightly decreased in semi-arid regions of Ethiopia. However, the result of this study indicated that future maize yield will not decrease significantly relative to the baseline. Therefore climate change may not have severe negative impacts based on this study. Moreover, it might be possible to bring more positive yield change easily by introducing some climate smart agronomic practices. Hence, in the future more research has to be carried out for assessing alternative adaptation strategies.

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