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Potential benefits of drought and heat tolerance and yield enhancing traits in Sorghum with climate change at selected sites in India and West Africa

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Abstract

Climate change will alter growing conditions of sorghum crop in semi-arid tropical areas of the world. This will require developing high yielding cultivars that are able to perform better under drought and heat stress and with maturity durations to match the water availability period of target sites. The CSM-CERES-Sorghum model was used to quantify the potential benefits, in current and future climates, of incorporating crop maturity duration, yield enhancing, drought and heat tolerance traits in the commonly grown cultivar types at two sites (Akola and Indore) in India and one site (Samanko) in Mali, West Africa. Decreasing crop maturity duration by 10% decreased yields at all the three sites. Whereas, increasing crop maturity by 10% increased yield up to 12% at Akola and 9% each at Indore and Samanko. Increasing yield potential of the baseline, short and longer duration cultivars by increasing RUE (radiation use efficiency), G1 (scale for relative leaf size) and G2 (scale for partitioning of assimilates to the panicle) coefficients increased the grain yield to varying degree. This yield increase for the longer duration cultivar was 11 to 18% at Akola, 17 to 19% at Indore and 6 to 7% at Samanko in current and future climates of the sites. At the three sites the yield gains were larger by incorporating drought tolerance than heat tolerance trait in current climate, however, with climate change the yield gains due to heat tolerance increased trait increased especially at the Akola site.Net benefit of incorporating both drought and heat tolerance traits increased up to 17% at Akola, 9% at Indore and 7% at Samanko with climate change. It is concluded from this study that different combination of traits will be needed to increase and sustain productivity of sorghum in current and future agro-climates of the target sites and that the CSM-CERES-Sorghum model for sorghum can be used to quantify benefits of incorporating such plant traits.

Keywords: Climate change factors, genetic adaptation, heat and drought tolerance, crop modeling, CSM-CERES-Sorghum model

JEL classification: C6, C8

Contents

1 Introduction

Sorghum is an important staple food for poor people and source of feed and fodder for livestock production in India. It is primarily grown in semi-arid moist (LGP of 90-150 days) and in semi-arid dry (LGP of 90-120 days) climates. Currently, Maharashtra, Karnataka, Andhra Pradesh and Madhya Pradesh are the major sorghum producing states. As per current estimates (mean of 2006-2010), sorghum is grown on 8.02 M ha in India with an average productivity of 920 kg ha^{-1} (FAOSAT, 2012). Despite the declining trends in per capita consumption of sorghum as food, it remains as the important and easily accessible staple cereal for economically deprived people in India. Considering its importance in the near future as a source for food for people and feed and fodder for animal and also as source of bio-energy, its production and productivity must be increased. In West Africa, Nigeria is the largest producer of sorghum (5.69 M t) followed by Burkina Faso (1.38 M t), Mali (0.93 M t) and Niger (0.85 M t) (mean of 2006-2010 production data, FAOSTAT, 2012). In Mali it is grown on 1.06 M ha with an average productivity of1020 kg/ha. In Niger is grown on 2.89 M ha with very low average productivity of 360 kg/ha due to harsh growing conditions. Along with other cereals sorghum is the major source of food and feed and income for the poor people in West African countries.

Climate change, in terms of higher temperatures, changing precipitation patterns, changing water availability and increased frequency of extreme weather events (IPCC, 2007), will alter the current crop growing conditions on the globe and crop yields will be either negatively or positively affected by climate change. However, in the arid and semiarid tropical regions its effect will be mostly negative thus threatening the food security in these regions (Easterling, 1996, Fischer et al., 2005, Howden et al., 2007). In the semi-arid tropical regions the changes in rainfall coupled with rise in temperature may reduce length of growing season as determined by the duration of soil water availability (Cooper et al., 2009). Therefore, in future the maturity durations of crops and cropping systems should match the periods of water availability to achieve higher and stable yields. The optimum air temperature range for vegetative and reproductive growth of sorghum is 26 to 34 ^{o}C (Hammer et al., 1993; and Alagarswamy and Ritchie, 1991) and 25 to 28^{o}C (Maiti, 1996 and Prasad et al., 2008), respectively. In semi-arid tropics where sorghum is currently grown during the rainy season, the mean crop-season temperatures are already close to or above these optimum temperatures. As with other crops, climate change most likely will adversely impact the production and productivity of sorghum, thus interfering with the goal of meeting future food demand. However, increased CO_2 will have some beneficial effects on the growth and yield of sorghum and could partially negate the detrimental effect of rising temperatures depending on the degree of temperature rise.

Srivastava et al. (2010) assessed the vulnerability of rainy and post rainy season sorghum to climate change in India using the Info Crop-Sorghum simulation model and the HadCM3 output for the A2a scenario. They projected that climate change in different regions of India will reduce the monsoon sorghum yield by 3 to 16% by

2020 and by 17% to 76% by 2050 and 2080. Climate change impacts on winter crop likely to reduce yields up to 7% by 2020, up to 11% by 2050 and up to 32% by 2080. Earlier, Rao et al (1995) used CERES-Sorghum model to simulate the impact of three climate change scenarios (GISS, GFDL and UKMO) on the productivity of sorghum at three sites (Hyderabad, Indore and Solapur) in India. The simulated results indicated marginal decrease in biomass and grain yield of sorghum at Hyderabad and Indore under climate change scenarios. Post rainy season sorghum grown at Solapur on stored soil water showed marginal increase in yield. Blane (2012) used panel data approach to relate crop yields to standard weather variables and estimated 7 to 47% reduction in yield of sorghum for Sub-Saharan Africa by 2100. Using EPIC crop model and climate model output (HadCm, CGCM), Butt et al. (2005) predicted 11 to 17% reduction in sorghum yield for Mali by 2030. There are a few other studies done for Africa (Tingem et al., 2008 and 2009; Chimpansi et al., 2003) and reported substantial reductions in sorghum yield with climate change in future.

When climate changes are relatively small, the current agronomic adaptation measures can help farmers adapt. As climate change proceeds, more extensive changes may be needed including genetic improvement of crops for greater tolerance to elevated temperatures and drought, improved responsiveness to risingCO_2 and the development of new technologies (Boote et al., 2011). Increasing temperatures affect growth and development of crops, thus influencing potential yields. A critical variable is the number of days a crop is exposed to supra-optimal temperatures at critical growth stages, i.e., flowering, pollination or grain filling, thus reducing quantity and quality of yield (Prasad et al., 2003).Yields of most agricultural crops will increase under elevated CO_2 concentration. Free air carbon enrichment (FACE) experiments indicate crop productivity to increase in the range of 15-25% for C3 crops (like wheat, rice and soybean) and 5-10% for C4 crops (like maize, sorghum and sugarcane) (Tubiello et al., 2007). Higher levels of CO_2 also improve water use efficiency of both C3 and C4 plants. Temperature increases are likely to support positive effects of enhanced CO_2 until temperature thresholds are reached. Beyond these thresholds, crop yields are negatively affected despite enhanced CO_2.Because agriculture will not experience the same vulnerability to climate change in all regions, site-specific improved crop varieties/cropping systems and management practices will be needed to fit future characteristics of climate and other natural endowments of each area. Plant breeders across research institutes are targeting plant traits to breed new crop varieties that will perform better in future climates. Therefore, it is imperative to make an early assessment of the potential benefits of technologies in the target environments before significant investments are made to pursue these goals.

Plant growth simulation models, which integrate various physical and physiological processes of plant growth and development, can be used to assess crop growth and yield advantages due to new technologies in different environments by using environment-specific weather, soil and agronomic management data (Boote et al., 2001, Boote et al., 2003). Since these models incorporate parameters representing genetic traits of cultivars, they can be modified within the observed limits of their genetic variability and the potential benefit in terms of crop performance can be evaluated singly or in multiple combinations of traits in a target environment (Boote et al., 2001, Singh et al., 2012). Using crop models, many researchers in the past have proposed plant ideotypes or genetic improvement of crops for higher yields (Landivar et al., 1983; Boote and Jones, 1986; Whisler et al., 1986; Boote and Tollenaar, 1994; Hammer et al., 1996; Yin et al., 1999; Boote et al., 2001, Boote et al., 2003; Hammer et al., 2002, 2004, 2005; Tardieu, 2003: White and Hoogenboom, 2003; Messina et al., 2006; Suriharn et al., 2011). As new constraints and opportunities for crop production are emerging with climate change, these studies need to be further extended to determine new plant types for obtaining higher yields and improved adaptation in future climates of the target regions. With improved knowledge, understanding and modeling of crop response to climate change factors (high temperatures, increased rainfall variability, increased atmospheric CO_2 concentration and their interactions), crop models have excellent potential to assess benefits of genetic improvement for higher yields and adaptation to current and future target environments.

The objective of the study was to quantify the potential benefits of genetic improvement, particularly crop life-cycle, yield potential, drought tolerance and heat tolerance traits and their combinations, on yield of sorghum current and future climates of selected sites in the sorghum growing areas of India and West Africa

2 Theoretical framework

2.1 Study sites

Simulations of sorghum crop were carried out for Indore and Indore sites in India and Samanko (Mali) in West Africa. Baseline cultivars were CSM 388 for India and CSM 388 for Samanko (Mali). The geographical and soil characteristics of the sites are given in Table 1. Baseline climatic characteristics and projected changes in climate for the sites are given in Table 2.

Table 1 Geographical and soil characteristics of the target sites

	India		West Africa
	Akola	**Indore**	**Samanko**
Latitude (deg.)	20.70	22.40	12.53
Longitude (deg.)	77.03	75.50	-8.07
Elevation (m)	282	567	330
Soil type	Inceptisol	Vertisol	Oxisol (Latosol)
Soil depth (cm)	120	160	155
EWHC (mm)*	123	195	126

* Extractable water holding capacity of soil

Table 2 Baseline (Base) and projected (Proj) increase in maximum and minimum monthly temperatures and percent change in monthly rainfall by 2050 at the target sites as per the UKMO-HADCM3 GCM model for the SRES A1B scenario

	Akola		Indore		Samanko	
Month	Base 1968-1998	Proj 2050	Base 1975-2004	Proj 2050	Base 1997-2010	Proj 2050
			Maximum temperature (^oC)			
Jun	37.3	1.2	36.8	1.7	32.8	3.4
Jul	32.1	1.0	30.9	0.6	29.7	3.5
Aug	30.4	1.0	29.1	0.2	28.7	2.8
Sept	32.3	1.9	31.2	0.7	30.3	3.3
Oct	33.7	2.3	33.2	1.2	33.0	4.0
Mean max.	33.2		32.2		30.9	
			Minimum temperature (^oC)			
Jun	25.7	2.0	25.2	2.6	23.7	2.7
Jul	23.7	1.7	23.6	1.8	22.3	2.6
Aug	23.0	1.7	22.8	1.6	21.8	2.1
Sept	22.6	2.5	22.0	2.2	21.6	2.5
Oct	19.5	3.2	18.6	2.7	22.5	3.2
Mean min.	22.9		22.4		22.4	
Mean temp.	28.1		27.3		26.6	
			Rainfall (mm) and % change			
Jun	143	-33	149	-65	170	-13
Jul	192	17	275	22	228	-6
Aug	197	12	280	17	315	-2
Sept	125	27	170	54	223	-1
Oct	50	30	41	47	79	-6
Total	707		915		1015	

2.2 The model

We used the CMS-CERES-Sorghum model, which is a part of the DSSAT v4.5 (Hoogenboom et al., 2010), to study the impact of climate change factors and genetic modifications on the productivity of sorghum. The major components of the sorghum model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. It simulates sorghum growth and development using a daily time step from sowing to maturity and ultimately predicts yield. The physiological processes that are simulated describe crop response to major weather factors (temperature, precipitation and solar radiation) and include the effect of soil characteristics on water and nitrogen availability for crop growth. Total biomass production is a function of light interception and light use efficiency (Ritchie et al., 1998). Daily biomass produced is partitioned to vegetative and reproductive growth as a function of the development stage. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are input to the model. The soil water balance is a function of precipitation, irrigation, transpiration, soil evaporation and runoff from the soil surface and drainage from the bottom of the soil profile and is calculated on a daily basis. Soil water is distributed among different soil layers with depth increments specified by the user. The water content of any soil layer can decrease by soil evaporation, root absorption or flow to an adjacent layer (Ritchie, 1998). Actual transpiration or plant water uptake is the minimum of potential atmospheric evaporative demand and the potential supply of water to roots in the soil. If potential transpiration demand is higher than potential uptake by the root system, a water stress factor is calculated. Water stress reduces canopy expansion, but enhances canopy abscission of plant material, depending on the timing and severity of water deficit.

The model is sensitive to various factors of climate change such as high temperature, variability in rainfall and increased CO_2 concentrations in the atmosphere. In the model, high temperatures influence growth and development and reduce allocation of biomass to the reproductive organs through decreased seed set and seed growth rate. Changes in rainfall characteristics influence soil water balance and thus the pattern of water availability to the crop during its life cycle. Increased CO_2 concentrations in the atmosphere increases crop growth and biomass production through increased light use efficiency (LUE). Increased CO_2 concentration 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 the impact of climate change on growth and development of sorghum.

2.3 Model inputs

The minimum data set required to simulate a crop for a site are described by Jones et al. (2003). Briefly, it includes site characteristics (latitude and elevation), daily weather data (solar radiation, maximum and minimum air temperatures and precipitation), basic soil profile characteristics by layer (saturation limit, drained upper limit and lower limit of water availability, bulk density, organic carbon, pH, root distribution factor, runoff and drainage coefficients) and management data (cultivar, sowing date, plant population, row spacing, sowing depth and dates and amounts of irrigation and fertilizers applied). The cultivar data include the genetic coefficients or the cultivar-specific parameters (quantified traits) which distinguish one cultivar from another in terms of phonological development, photoperiod sensitivity, growth and partitioning to vegetative and reproductive organs. Crop-specific parameters, which describe the basic processes of crop growth, development and yield formation of sorghum and are common across cultivars, are also input to the model.

For India, the soil profile data for both model calibration and impact study sites were obtained from the soil survey bulletins published by the National Bureau of Soil Survey and Land Use Planning, Nagpur, India (Lal et al., 1994). Based upon the latitude and longitude of the sites, the nearest soil series was selected for the soil survey information. Soil parameters were estimated from this soil survey data using the S Build program available in DSSAT v4.5 (Hoogenboom et al., 2010). Long-term weather (daily records of rainfall, maximum and minimum temperatures) recorded at the nearest possible weather stations to the sites was obtained from the India Meteorology Department, Pune, India. Solar radiation for the sites was estimated from the temperature data following the method of Bristow and Campbell (1984). For Samanko in Mali, the soils data for the dominant soil order was taken from the WISE database (Batjes, 2012). For Samanko site the weather data was downloaded from the NASA site (http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov). For Samanko (Mali) site the NASA rainfall data was replaced by the measured rainfall data of the site. Soils data were entered in the soils data file (.SOL) and the daily weather data in the weather files (.WTH) for each site.

3 Model calibrations of genetic coefficients

3.1 Calibration of baseline cultivar for India

Annual reports of the All India Coordinated Research Project on Sorghum (AICRPS) were reviewed for data availability of sorghum cultivars being evaluated at various sites in India. In the AICRPS trials, cultivar CSV 15 was used as one of the national checks at most test sites in India. Considering data availability of cv. CSV 15 and its dual purpose (grain and fodder) characteristics, this cultivar was considered as the most suitable baseline cultivar for the major sorghum growing regions of India. To determine the genetic coefficients of cv. CSV 15, the past crop data sets (which years?) available with ICRISAT and the data of the Advanced Variety Trials (AVT) conducted at six sites in India and obtained from the Annual Reports of the AICRPS (AICRPS, 1994-2008) were used. The six sites were: Surat (Gujarat), Dharwad (Karnataka), Indore and Parbhani (Maharashtra), Indore (Madhya Pradesh) and Coimbatore (Tamil Nadu). Agronomic data available was sowing date, harvest date, N, P and K application and number of irrigations given, if any, to the crop. Measured data available from the variety trials were days to 50% flowering, harvest maturity, grain and fodder yield. Data on seed size was available for a few sites and years.

To determine the genetic coefficients of cv. CSV 15, crop management files (*.SGX) and observed data files (*.SGA) were created. Agronomic and measured data were available for multiple years (1994 to 2008) and each year was considered as treatment in the management file. For some sites the sowing date information and the dates and amounts of irrigation given were missing. Information on plant population at sowing for all sites was also missing. A plant population of18plants/m^2 with a row-to-row spacing of 45 cm recommended for the rainy season sorghum was considered for this analysis. This is the recommended practice for rainy season sorghum. At the six sites sorghum is grown during the rainy season on high water holding capacity vertisols and associated soils. At the time of sowing in June/July these soils retain some available water in the sub-soil (below 60 cm soil depth).

Therefore, initial soil water content at the start of simulation date (1, January each year) was considered to be at field capacity (DUL) and sowing was done in the month of June/July at the onset of rainy season after a prolonged dry period.

About 50% of the available crop data for the sites was used for model calibration of the genetic coefficients of cv. CSV 15 and the remaining was saved for model validation. First the phenology coefficients were set by several model iterations such that the simulated days to anthesis and physiological maturity matched the observed data across locations. This was achieved first by adjusting the coefficients P1 (thermal time from seedling emergence to the end of the juvenile phase), P2O (the longest day length at which development occurs at a maximum rate), and P2R (extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above the P2O) to calibrate days to anthesis and later P5 (thermal time from beginning of grain filling to physiological maturity) to calibrate the days to physiological maturity. Crop canopy expansion, total biomass production and its partitioning to panicle and seeds were set by adjusting the G1 (scale for relative leaf size) and G2 (scale for partitioning of assimilates to the panicle) coefficients. Soil fertility parameter (SLPF) and relative root distribution (SRGF) parameters located in the soil file (soil.sol) were also set to match the simulated yields with the observed data both for the water-stressed and non-stressed conditions. The SLPF values used were 0.85, 0.95, 0.86, 0.75, 0.95 and 0.68 for Indore, Surat, Indore, Parbhani, Dharwad and Coimbatore, respectively. Since the weather and soils data used for simulation did not exactly belong to the trial sites and the information on of agronomic management and crop growth during the season had some gaps, we calibrated the genetic coefficients such that the maximum, minimum and mean grain yields simulated by the model over the years matched with the reported maximum, minimum and mean grain yields for the sites. We assumed that the maximum yields were obtained without any major abiotic or biotic constraints, while minimum yields were obtained under the overriding impact of drought. Thus we established that the maximum rain fed potential yield, the minimum yield and the mean yield for each site are simulated accurately.

3.2 Calibration of baseline cultivar for West Africa

Cultivar CSM 388 is the recommended cultivars for cultivation in the Sudanian zones of West Africa. This is a highly photoperiod sensitive cultivars grown in the region. The genetic coefficients of the baseline cultivar for Samanko were provided by Mr. SibiryTraore (personal communication).

4 Development of virtual cultivars

To simulate crop response to the changes in genetic traits and climate scenarios, virtual cultivars incorporating various plant traits, were developed from the two baseline cultivars calibrated for the Indian (cv. CSV 15) and West Africa (cv. CSM 388) conditions. These are described below:

4.1 Crop life cycle and yield potential

Three life cycles of sorghum crop were considered for developing virtual cultivars-- baseline (no change in the genetic coefficients of the baseline cultivar), 10% short and 10% longer duration cultivars. To make changes in the crop duration of sorghum, the genetic coefficients P1 (thermal time from seedling emergence to the end of the juvenile phase), P2O (critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate) and P5 (thermal time from beginning of grain filling to physiological maturity) located in the cultivar file were considered. To decrease the crop duration by 10%, first P1 was decreased and P2O increased to have 10% reduction in days to anthesis and later the value of P5 was decreased to have overall 10% reduction in days to physiological maturity. Similar approach was followed to determine the genetic coefficients for the 10% longer duration cultivar. First P1 was increased and P2O was decreased and then P5 was increased to have desired longer duration cultivar. After making these changes in the genetic coefficients, multi-year model simulations were made for the target sites to check if the days to flowering and physiological maturity were accurately simulated for both the short and longer duration virtual cultivars. If not, minor adjustments were made in these coefficients to get the desired results. To increase the yield potential of cultivars, G1 (scale for relative leaf size) and G2 (scale for partitioning of assimilates to the panicle) coefficients in the cultivar file and RUE (radiation use efficiency) in the ecotype file (*.ECO) were increased by 10% each.

4.2 Drought tolerance

To enhance the drought tolerance of cultivars, changes were made in the relative root distribution function (WR) and the lower limits of water availability (LL) for each soil layer. Currently the WR for different soil layers are estimated as per the following exponential equation:

WR (L) = EXP (-0.02*Z (L)), where Z (L) is the depth to the midpoint of the soil layer L. The drought resistant cultivars are assumed to have greater access to and ability to have greater root density for mining soil water. The greater rooting density was computed by a power equation given below:

WR (L) = $[1.0\text{-}Z\ (L)/5]^{p,}$ where 5 (in meters) was used for all soils and p was equal to 6. This progressively increased WR (over the default) with depth in the soil profile starting at 30-cm soil depth and below for greater soil water extraction. In addition to increased WR with depth, the available water in each soil layer was increased by 5% by reducing the lower limit (LL) of soil water extraction as follows: LL(TOL)= LL-0.05*(DUL-LL), where LL(TOL) is the LL for the drought tolerant cultivar. The presumption of the latter trait is that a cultivar can extract water more effectively from each given layer.

4.3 Heat tolerance

Currently heat tolerance is not a cultivar coefficient in the sorghum model, but rather is a species-wide trait described in the species file whereby high temperatures reduce seed set, individual seed growth rate and partitioning of assimilates to reproductive organs. Temperature tolerance of sorghum was increased by increasing the two temperature threshold values of RGFIL (relative grain filing rate) located in the species file (*.SPE) each by 2 ^{O}C, i.e., the upper optimum temperature threshold value increased from 27 ^{O}C to 29 ^{O}C and the damaging temperature threshold value increased from 35 ^{O}C 37 ^{O}C.

5 Projected climate changes at the target sites

Simulation of climate change impacts required projected climate change data to modify the observed weather data of sites. Statistically downscaled (delta method) projected climate data for the 2050 time slice with 2.5 arc-minute resolution (5 km^2 resolution) and the WorldClim baseline (1960-90) climate data with 30 arc-second resolution (1 km^2 resolution) were downloaded for the target sites from the CIAT's climate change portal (http:/ccafs-climate.org//download_sres.html#down). The projected climate data comprised of monthly values of maximum and minimum temperatures and rainfall predicted by the UKMO-HADCM3 GCM model for the SRES A1B scenario. The difference between projected monthly maximum and minimum temperatures by 2050 and the baseline values gave changes in temperature. The percent deviations in monthly rainfall from the baseline values were also calculated (Table 2). Monthly changes in maximum and minimum temperature and rainfall along with CO_2 increase as per the ISAM model (IPCC, 2001) were input to the 'environmental modifications section' of the management files of sorghum (.SGX). Temperatures were entered as change in temperature (delta values), rainfall as ratio of projected rainfall to baseline rainfall and CO_2 as absolute value against first day of each month. During simulation process these climate change values modified the observed baseline weather data of a given month until it read the new set of values for the next month. As the rainfall was entered as ratio, it affected the value of each rainfall event rather than altering the pattern of rainfall distribution.

6 Simulating the impact of climate change and genetic traits

The CSM-CERES-Sorghum simulation model coupled with the seasonal analysis program available in DSSAT v4.5 was used to simulate the impact of climate change on sorghum productivity. Simulations were carried out for the baseline climate and the projected climate change by 2050 for each site. For each time period the impacts of changes in temperature (Temp.), changes in temperature and rainfall (Temp. + CO_2) and changes in temperature, rainfall and CO_2 (Temp. + CO_2 + Rain) were evaluated separately to quantify the impact of each factor. The atmospheric CO_2 concentration considered was 380 ppm for the baseline climate and 530 ppm for the 2050 climate projections (IPCC, 2001).

For the Indian sites, the simulations were initiated on 1January each year and the soil profile on that day was considered to be at the upper limit of soil water availability (DUL).Considering the spatial and temporal variations in the onset of rainy season and farmers' practice of start of sowing in the target region, the sowing window assumed was 6 July to 30 August for Indore and 23 June to 15 August for Indore each year. The simulated crop was sown on the day when the soil moisture content in the top 30 cm soil depth had reached at least 40% of the extractable water-holding capacity during the sowing window. A plant population of 18 plants m^{-2} with a row-to-row spacing of 45 cm was considered for simulating sorghum growth. Di-ammonium phosphate (DAP) at 100 kg/ha was applied to supply 20 kg N and 20 kg P/ha at the time of sowing. Additional dose of 30 kg N/ha each was applied as urea at 30 and 60 days after sowing. The SLPF (photosynthesis factor for the soil) values were 0.86 and 0.85 for Indore and Indore, respectively. The simulations were carried out for 30 years each for Indore (1968 to 1998) and Indore (1975 to 2004).

For the Samanko in Mali, simulations were initiated on 15 May each year and the soil profile was considered to be at the lower limit (LL) of soil water availability on that day. Sowing window was 25 June to 10 July and the conditions to initiate sowing were the same as for the Indian sites. Plant population, row-to-row spacing and nutrient management were the same as for the Indian sites. The SLPF value was 0.85 for Samanko. Simulations were carried out for 14 years (1997-2010) for the Samanko site. The crop was simulated as rain fed at all sites in India and West Africa. As the sorghum model does not account for the effects of pests and diseases on crop growth and yield, the crop was considered free from pests and diseases.

The impact of climate change scenarios on sorghum grain yield at a site was assessed relative to their respective mean yield simulated with baseline climate. The effect of changes in plant traits on grain yield of sorghum was assessed by comparison to the mean grain yield of their counterparts (virtual cultivars without plant trait incorporated) simulated for the respective climate scenario of the sites.

7 Results

Simulated values of grain yields for the baseline cultivar CSV 15 were significantly correlated with observed data ($Y = 1.042X – 137.2$; $R^2 = 0.91$; Figure 1). The d-value, a measure of model predictability (Wilmot, 1982), was also high for the cultivar (d-value = 0.97). These results confirm that the genetic coefficients of the cultivars are accurate and that the sorghum model can be reliably used to simulate growth and yield of sorghum in response to climate change factors and genetic modifications for different soil-climate environments of India. The genetic coefficients of the West African cultivars CSM 63 and CSM 388 were provided by Mr. Sibiry Traore (personal communication).

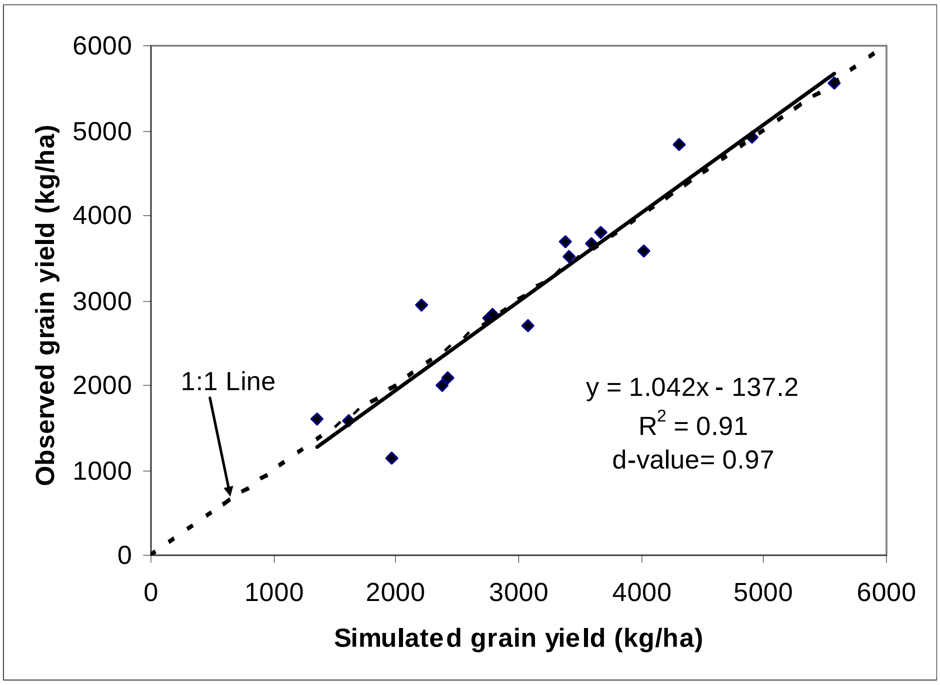

Figure1. Relationship of simulated sorghum grain yield of cv. CSV 15 with the observed yield across locations in India.

7.1 Response to genetic traits and climate scenarios

Akola

At Akola site the baseline cultivar CSV 15 took 71 days to anthesis and 108 days to physiological maturity and on average produced 3792 kg of grain yield per ha with baseline climate (Table 3). The short and long duration cultivars took 65 and 78 days to anthesis and 99 and 120 days to physiological maturity, respectively. With short growing cycle, grain yield decreased by 16% and with long duration it increased by 4%. By modifying the yield potential traits (G1, G2 and RUE), the grain yield of baseline, short, and long duration cultivars increased by 16, 26 and 11%, respectively as compared to their counterparts with lower yield-potential traits With climate change the grain yield of baseline cultivar decreased by 23% (2902 kg/ha) with the increase in temperature, 19% (3070 kg/ha) with the increase in temperature + CO_2 and 18% (3127 kg/ha) with the change in temperature + CO_2 + rainfall. With the three climate change effects (Temp.,Temp. + CO_2 and Temp. + CO_2 + Rain) the yield of short duration cultivar decreased by 20 to 22% and increased by 10 to 12 for the longer duration cultivar, indicating that longer duration cultivar will be more suitable under climate change conditions at Akola. Under climate change scenarios the benefit of yield potential traits increased by 21 to 23% for the baseline cultivars, 30 to33% for the short duration cultivar and 16 to 18% for the longer duration cultivar when compared the yield of counterparts without yield potential traits incorporated. Across climate scenarios the maximum yield was simulated for the longer duration cultivar with high yield potential traits incorporated. For the baseline climate (4382 kg/ha) it represented 16% increase in yield over the baseline cultivar yield without yield potential traits. Whereas for the climate change scenarios (3807 to 4004 kg/ha) it represented 28 to 31% increase in yield over the baseline cultivar yield in the respective climate scenario. These results indicate that enhancing yield potential and increasing crop growth life cycle each by 10% made major contribution to yield increase in both baseline and future climate scenarios at the Akola site.

When drought tolerance trait was incorporated in the virtual cultivars, the yields increased by 3 to 6% with baseline climate and 3 to 5% with climate change across virtual cultivars compared to their counterparts without drought tolerance trait (Table 4 versus Table 3). Benefit of incorporating heat tolerance trait was up to 4% increase in grain yield with baseline climate, which increased to 8 to 12% with climate change scenarios across virtual cultivars. These results indicate that yield gains were greater with drought tolerance than with heat tolerance trait in current climate; however in future climates heat tolerance will be relatively more important than drought tolerance for sustaining yields at Akola. The combined benefit of drought and heat tolerance traits ranged from 5 to 8% with baseline climate and 12 to 17% under climate change scenarios across virtual cultivars. The overall yield gain by incorporating these two traits in the longer life cycle cultivars with high yield potential was22% (4612 kg/ha) with baseline climate and 14 to 20% (4320 to 4555 kg/ha) with climate change scenarios as compared to the mean grain yield of the baseline cultivar (3792 kg/ha) simulated with baseline climate for the Akola site.

Table 3. Impact of changes in temperature (T), rainfall (R) and CO_2 on grain yield of virtual sorghum cultivars derived from cv. CSV 15 at Akola, India. Percent change (% ch.) is the yield gain or loss due to crop life cycle or yield potential traits for a given virtual cultivar.

	Baseline climate				Temp.		Temp.+ CO_2		Temp.+ CO_2 +Rain	
Cultivar	**Flow.**	**Mat.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**
Baseline	71	108	3792	0	2902	0	3070	0	3127	0
10% short cycle	65	99	3177	-16	2277	-22	2466	-20	2494	-20
10% longer cycle	78	120	3939	4	3238	12	3368	10	3449	10
Base + Yield Pot.	71	108	4389	16*	3569	23	3728	21	3785	21
10% short + Yield Pot.	65	99	3994	26*	3019	33	3202	30	3236	30
10% long + Yield Pot.	78	120	4382	11*	3807	18	3922	16	4004	16

*Yield improvement compared to cultivar with same life cycle.

Table 4. Effect of incorporating drought resistance and heat tolerance traits on the mean grain yield of virtual sorghum cultivars derived from cv. CSV 15 at Akola, India. Percent change (% change) is the yield gain due to the trait with reference to the yield of a virtual cultivar given in Table 3 for a climate scenarios.

	Baseline climate		Temperature		Temperature + CO_2		Temperature + CO_2+Rain	
Cultivar	Kg/ha	% Change	Kg/ha	% Change	Kg/ha	% Change	Kg/ha	% Change
Drought resistance								
Baseline	3978	5*	3002	3	3175	3	3229	3
10% short cycle	3281	3	2348	3	2541	3	2565	3
10% longer cycle	4164	6	3384	5	3519	4	3604	4
Base + Yield Pot.	4613	5	3708	4	3859	4	3910	3
10% short + Yield Pot.	4125	3	3106	3	3298	3	3331	3
10% long + Yield Pot.	4615	5	4001	5	4109	5	4183	4
Heat tolerance								
Baseline	3885	2	3215	11	3413	11	3466	11
10% short cycle	3307	4	2490	9	2702	10	2730	9
10% longer cycle	3992	1	3586	11	3733	11	3850	12
Base + Yield Pot.	4458	2	3952	11	4120	11	4179	10
10% short + Yield Pot.	4088	2	3284	9	3506	9	3548	10
10% long + Yield Pot.	4401	0	4104	8	4238	8	4324	8
Drought resistance + Heat tolerance								
Baseline	4077	8	3323	15	3531	15	3579	14
10% short cycle	3422	8	2579	13	2791	13	2815	13
10% longer cycle	4204	7	3762	16	3934	17	4031	17
Base + Yield Pot.	4664	6	4096	15	4286	15	4329	14
10% short + Yield Pot.	4227	6	3377	12	3606	13	3643	13
10% long + Yield Pot.	4612	5	4320	13	4459	14	4555	14

*Yield improvement from drought tolerance, heat tolerance, or both drought and heat tolerance compared to cultivar with same life cycle and yield potential traits within a climate scenario from Table 3

Indore

At Indore site the baseline cultivar CSV 15 took 75 days to anthesis and 115 days to physiological maturity and on average produced 3540 kg of grain yield per ha with baseline climate (Table 5). The short and long duration cultivars took 67 and 82 days to anthesis and 104 and 126 days to physiological maturity, respectively. With short growing cycle, grain yield decreased by 15% and with long duration it increased by 4%. By modifying the yield potential traits (G1, G2 and RUE), the grain yield of baseline, short, and long duration cultivars increased by 19, 23 and 18%, respectively as compared to their counterparts with lower yield-potential traits. With climate change the grain yield of baseline cultivar decreased by 7% (3280 kg/ha) with the increase in temperature, 1% (3490 kg/ha) with the increase in temperature + CO_2 and 6% (3329 kg/ha) with the change in temperature + CO_2 + rainfall. With the three climate change effects (Temp., Temp. + CO_2 and Temp. + CO_2 + Rain) the yield of short duration cultivar decreased by 20 to 22% and increased by up to 9% for the longer duration cultivar, indicating that longer duration cultivar will be more suitable under climate change conditions at Indore. Under climate change scenarios the benefit of yield potential traits increased by 20 to 22% for the baseline cultivars, 26 to30% for the short duration cultivar and 17 to 19% for the longer duration cultivar when compared the yield of counterparts without yield potential traits incorporated. Across climate scenarios the maximum yield was simulated for the longer duration cultivar with high yield potential traits incorporated. For the baseline climate (4360 kg/ha) it represented 23% increase in yield over the baseline cultivar yield without yield potential traits. Whereas for the climate change scenarios (4207 to 4427 kg/ha) it represented 27 to 29% increase in yield over the baseline cultivar yield in the respective climate scenario. Like for the Akola site, these results also indicate that enhancing yield potential and increasing crop growth life cycle each by 10% made major contribution to yield increase at Indore with both baseline and future climate scenarios.

When drought tolerance trait was incorporated in the virtual cultivars, the yields increased by 4 to 10% with baseline climate and 2 to 9% with climate change across virtual cultivars compared to their counterparts without drought tolerance trait (Table 5 versus Table 6).Generally the higher benefit due to drought tolerance was associated with longer duration cultivars as compared to the baseline and the short duration cultivar, which decreased marginally with the increase in rainfall projected for the site during July to October. Incorporating heat tolerance trait did not benefit the crop with baseline climate, which marginally up to 3% in case of short duration cultivar with climate change scenarios. These results show that drought tolerance than temperature tolerance will remain an important trait for sorghum in both the current and future climate scenarios at the Indore site. Combining drought and heat tolerance traits did not improve the yields above those simulate with drought tolerance trait for each virtual cultivar. The overall yield gain by incorporating drought tolerance trait in the longer life cycle cultivars with high yield potential was 34% (4746 kg/ha) with baseline climate and 30 to 36% (4600 to 4819 kg/ha) with climate change scenarios as compared to the mean grain yield of the baseline cultivar (3540 kg/ha) simulated with baseline climate for the Indore site.

Table 5. Impact of changes in temperature (T), rainfall (R) and CO_2 on grain yield of virtual sorghum cultivars derived from cv. CSV 15 at Indore, India. Percent change (% ch.) is the yield gain or loss due to crop life cycle or yield potential traits for a given virtual cultivar.

	Baseline climate				Temp.		Temp.+ CO_2		Temp.+ CO_2 +Rain	
Cultivar	Flow.	Mat.	Kg/ha	% Ch.	Kg/ha	% Ch.	Kg/ha	% Ch.	Kg/ha	% Ch.
Baseline	75	115	3540	0	3280	0	3498	0	3329	0
10% short cycle	67	104	3016	-15	2582	-21	2800	-20	2589	-22
10% longer cycle	82	126	3688	4	3574	9	3781	8	3624	9
Base + Yield Pot.	75	115	4213	19*	3985	22	4197	20	4051	22
10% short + Yield Pot.	67	104	3718	23*	3280	27	3516	26	3355	30
10% long + Yield Pot.	82	126	4360	18*	4207	18	4427	17	4308	19

*Yield improvement compared to cultivar with same life cycle.

Table 6. Effect of incorporating drought resistance and heat tolerance traits on the mean grain yield of virtual sorghum cultivars derived from cv. CSV 15 at Indore, India. Percent change (% change) is the yield gain due to the trait with reference to the yield of a virtual cultivar given in Table 3 for a climate scenarios.

	Baseline climate		Temperature		Temperature + CO_2		Temperature + CO_2+Rain	
Cultivar	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**
Drought resistance								
Baseline	3779	7*	3463	6	3706	6	3482	5
10% short cycle	3147	4	2688	4	2903	4	2667	3
10% longer cycle	4065	10	3893	9	4115	9	3910	8
Base + Yield Pot.	4502	7	4195	5	4419	5	4234	4
10% short + Yield Pot.	3865	4	3409	4	3640	4	3432	2
10% long + Yield Pot.	4746	9	4600	9	4819	9	4625	7
Heat tolerance								
Baseline	3542	0	3298	1	3528	1	3364	1
10% short cycle	3037	1	2628	2	2844	2	2654	3
10% longer cycle	3679	0	3594	1	3801	1	3648	1
Base + Yield Pot.	4195	0	3992	0	4221	1	4065	0
10% short + Yield Pot.	3723	0	3304	1	3536	1	3390	1
10% long + Yield Pot.	4313	-1	4207	0	4418	0	4301	0
Drought resistance + Heat tolerance								
Baseline	3774	7	3489	6	3728	7	3516	6
10% short cycle	3166	5	2734	6	2951	5	2737	6
10% longer cycle	4056	10	3906	9	4130	9	3939	9
Base + Yield Pot.	4476	6	4215	6	4452	6	4245	5
10% short + Yield Pot.	3876	4	3429	5	3663	4	3475	4
10% long + Yield Pot.	4732	9	4589	9	4813	9	4606	7

*Yield improvement from drought tolerance, heat tolerance, or both drought and heat tolerance compared to cultivar with same life cycle and yield potential traits within a climate scenario from Table 5.

Samanko

At Samanko site the baseline cultivar CSM 388 took 70 days to anthesis and 110 days to physiological maturity and on average produced 4569 kg of grain yield per ha with baseline climate (Table 7). The short and long duration cultivars took 63 and 77 days to anthesis and 100 and 120 days to physiological maturity, respectively. With short growing cycle, grain yield decreased by 10% and with long duration it increased by 2%. By modifying the yield potential traits (G1, G2 and RUE), the grain yield of baseline, short, and long duration cultivars increased by 5, 13 and 6%, respectively as compared to their counterparts with lower yield-potential traits. With climate change the grain yield of baseline cultivar decreased by 14% (3936 kg/ha) with the increase in temperature, 12% each with the increase in temperature + CO_2(4032 kg/ha) and temperature + CO_2 + rainfall (4043 kg/ha).With the three climate change effects (Temp., Temp. + CO_2 and Temp. + CO_2 + Rain) the yield of short duration cultivar decreased by 26 to 30% and increased by 7 to 9% for the longer duration cultivar, indicating that longer duration cultivar will be more suitable under climate change conditions at Samanko. Under climate change scenarios the benefit of yield potential traits increased up to 11% for the baseline cultivars, 29 to 30% for the short duration cultivar and 7% for the longer duration cultivar when compared the yield of counterparts without yield potential traits incorporated. Across climate scenarios the maximum yield was simulated for the longer duration cultivar with high yield potential traits incorporated. For the baseline climate the yield increased to 4939 kg/ha, which represented 8% increase in yield over the baseline cultivar yield without yield potential traits. Whereas for the climate change scenarios the yields increased to 4585 to 4658 kg/ha, which represented 15 to 16% increase in yield over the baseline cultivar yield in the respective climate scenario. These results indicate that enhancing yield potential and increasing crop growth life cycle each by 10% made major contribution to yield increase in both baseline and future climate scenarios at the Samanko site.

When drought tolerance trait was incorporated in the virtual cultivars, the yields increased by 3 to 5% with baseline climate and 1 to 4% with climate change across virtual cultivars compared to their counterparts without drought tolerance trait (Table 7 versus Table 8).Incorporating heat tolerance trait did not benefit the crop with baseline climate, however the benefit increased up to 4% with climate change scenarios. The benefit was relative larger with virtual cultivar without yield potential trait. These results indicate that yield gains were greater with drought tolerance than with heat tolerance trait in current climate; however in future climates heat tolerance will be equally important than drought tolerance for sustaining yields at Samanko. The combined benefit of drought and heat tolerance traits ranged from 3 to 5% with baseline climate and 2 to 7% under climate change scenarios across virtual cultivars. The overall yield gain by incorporating these two traits in the longer life cycle cultivars with high yield potential was 12% (5103 kg/ha) with baseline climate and 5 to 6% (4803 to 4843 kg/ha) with climate change scenarios as compared to the mean grain yield of the baseline cultivar (4569 kg/ha) simulated with baseline climate for the Samanko site.

Table 7. Impact of changes in temperature (T), rainfall (R) and CO_2 on grain yield of virtual sorghum cultivars derived from cv. CSM 388 at Samanko, Mali. Percent change (% ch.) is the yield gain or loss due to crop life cycle or yield potential traits for a given virtual cultivar.

	Baseline climate				Temp.		Temp.+ CO_2		Temp.+ CO_2 +Rain	
Cultivar	**Flow.**	**Mat.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**	**Kg/ha**	**% Ch.**
Baseline	70	110	4569		3936		4032		4043	
10% short cycle	63	100	4103	-10	2754	-30	2992	-26	2954	-27
10% longer cycle	77	120	4641	2	4286	9	4315	7	4335	7
Base + Yield Pot.	70	110	4796	5*	4385	11	4426	10	4431	10
10% short + Yield Pot.	63	100	4633	13*	3646	32	3848	29	3801	29
10% long + Yield Pot.	77	120	4939	6*	4585	7	4622	7	4658	7

*Yield improvement compared to cultivar with same life cycle.

Table 8. Effect of incorporating drought resistance and heat tolerance traits on the mean grain yield of virtual sorghum cultivars derived cv. CSM 388 at Samanko, Mali. Percent change (% change) is the yield gain due to the trait with reference to the yield of a virtual cultivar given in Table 3 for a climate scenarios. SPLF = 0.85

	Baseline climate		Temperature		Temperature + CO_2		Temperature + CO_2+Rain	
Cultivar	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**	**Kg/ha**	**% Change**
Drought resistance								
Baseline	4781	5	4047	3	4151	3	4163	3
10% short cycle	4212	3	2770	1	3013	1	2991	1
10% longer cycle	4814	4	4409	3	4471	4	4478	3
Base + Yield Pot.	4988	4	4515	3	4575	3	4582	3
10% short + Yield Pot.	4794	3	3685	1	3899	1	3851	1
10% long + Yield Pot.	5079	3	4736	3	4758	3	4777	3
Heat tolerance								
Baseline	4566	0	4098	4	4190	4	4221	4
10% short cycle	4116	0	2858	4	3099	4	3052	3
10% longer cycle	4651	0	4421	3	4447	3	4465	3
Base + Yield Pot.	4773	0	4466	2	4510	2	4529	2
10% short + Yield Pot.	4629	0	3699	1	3918	2	3889	2
10% long + Yield Pot.	4967	1	4643	1	4687	1	4702	1
Drought resistance + Heat tolerance								
Baseline	4785	5	4225	7	4316	7	4340	7
10% short cycle	4226	3	2873	4	3119	4	3088	5
10% longer cycle	4829	4	4556	6	4613	7	4627	7
Base + Yield Pot.	4949	3	4597	5	4665	5	4660	5
10% short + Yield Pot.	4790	3	3737	2	3966	3	3938	4
10% long + Yield Pot.	5103	3	4803	5	4834	5	4843	4

*Yield improvement from drought tolerance, heat tolerance, or both drought and heat tolerance compared to cultivar with same life cycle and yield potential traits within a climate scenario from Table 7.

Using the CSM-CERES-Sorghum, we have quantified the contribution of crop life cycle, yield potential, drought tolerance and heat tolerance traits and their combinations on Sorghum yield in the current climate and to sustain or enhance productivity in the future climates at the target sites in India and West Africa. As climate change will alter the length of growing period (LGP) due to changes in rainfall and temperature, the first step to achieve higher yields is to fit the life cycle of crops to the changed LGPs. This will ensure least possible water and heat stress to the crop during its life cycle. The study revealed that with 10% longer duration cultivars, up to 12% increase in grain yield could be realized at Akola and up to 9% each at Indore and Samanko sites with climate change. Fitting crop duration to the changed LGPs in future will be an easy adaptation process because sufficient genetic variability exists in life-cycle traits among sorghum genotypes.

Enhancing yield potential by increasing RUE (radiation use efficiency), G1 (scale for relative leaf size) and G2 (scale for partitioning of assimilates to the panicle) coefficients of the baseline cultivars each by 10%, increased yields at all the three sites. For the longer duration virtual cultivars, the yield increased up to 18% at Akola, up to 19% at Indore and up to 7% at Samanko in different climate scenarios. For baseline and shorter duration virtual cultivars the yield gains due to yield potential traits were even larger. Such high yield gains in case of sorghum crop are possible as these estimates are based on both increased source (RUE) and sink size (G1 and G2 coefficients) of sorghum virtual cultivars and such variation in these plant traits exists among sorghum genotypes. The benefits of incorporating drought tolerance in Sorghum were variable depending upon the amount and distribution of rainfall and water retention properties of the soil profiles at the target sites. Simulated yield gains due to drought tolerance among virtual cultivars were the largest (4 to 10%) at Indore site in current climate, followed by Akola (3 to 6%) and the least at Samanko (3 to 5%). Because of the projected increase in rainfall after the month of June at Akola and Indore sites, the percent yield gains due to drought tolerance trait decreased with climate change. Similar response to climate change was simulated for the Samanko site in spite of slight decrease in projected rainfall. Though drought tolerance in sorghum could be attributed to multiple plant traits, increased rooting depth in the soil profile and/or increased root length density (RLD) in subsoil resulting in greater water extraction during the periods of water stress is the prominent mechanism for drought tolerance and higher yields under water stress in sorghum (Jordan et al., 1979; Passioura, 1983; Monteith, 1986, Lafolie et al., 1991; and Salih et al., 1999). Genotypic variation in sorghum for root traits exists, which can be utilized for developing drought resistant cultivars (Bhan et al., 1973; Mayaki et al., 1976; and Jordan et al., 1979). Deeper roots or increased RLD must result in greater water uptake by the crop during the periods of water stress to give yield advantage over the drought susceptible genotypes. Thus the approach used in the model to simulate the benefits of drought tolerance trait is appropriate. While drought is the major yield reducing factor in current climate, temperature increase with climate change will reduce yields drastically at places like Akola. Thus incorporating heat tolerance in sorghum will increase yields by 8 to 12 % in future climate at Akola, followed by Samanko (up to 4%) and Indore (up to 3%). As Indore site currently has high rainfall and moderate temperatures during the growing season, incorporating heat tolerance trait will not benefit the crop in near future. Heat tolerance already exists among sorghum genotypes, thus it will be possible to breed cultivars for higher yield for the future climate conditions considered in this simulation study. The yield gains due to heat tolerance simulated in this simulation study are also realistic as the mechanisms that cause yield losses due to high temperature stress in the sorghum model are the same as reported by Prasad et al. (2008). However more research is needed under field conditions to explore the effect of high temperatures on plant processes affecting crop yields when imposed at various stages of plant growth and development.

8 Discussion

Using the CSM-CERES-Sorghum, we have quantified the contribution of crop life cycle, yield potential, drought tolerance and heat tolerance traits and their combinations on Sorghum yield in the current climate and to sustain or enhance productivity in the future climates at the target sites in India and West Africa. As climate change will alter the length of growing period (LGP) due to changes in rainfall and temperature, the first step to achieve higher yields is to fit the life cycle of crops to the changed LGPs. This will ensure least possible water and heat stress to the crop during its life cycle. The study revealed that with 10% longer duration cultivars, up to 12% increase in grain yield could be realized at Akola and up to 9% each at Indore and Samanko sites with climate change. Fitting crop duration to the changed LGPs in future will be an easy adaptation process because sufficient genetic variability exists in life-cycle traits among sorghum genotypes.

Enhancing yield potential by increasing RUE (radiation use efficiency), G1 (scale for relative leaf size) and G2 (scale for partitioning of assimilates to the panicle) coefficients of the baseline cultivars each by 10%, increased yields at all the three sites. For the longer duration virtual cultivars, the yield increased up to 18% at Akola, up to 19% at Indore and up to 7% at Samanko in different climate scenarios. For baseline and shorter duration virtual cultivars the yield gains due to yield potential traits were even larger. Such high yield gains in case of sorghum crop are possible as these estimates are based on both increased source (RUE) and sink size (G1 and G2 coefficients) of sorghum virtual cultivars and such variation in these plant traits exists among sorghum genotypes. The benefits of incorporating drought tolerance in Sorghum were variable depending upon the amount and distribution of rainfall and water retention properties of the soil profiles at the target sites. Simulated yield gains due to drought tolerance among virtual cultivars were the largest (4 to 10%) at Indore site in current climate, followed by Akola (3 to 6%) and the least at Samanko (3 to 5%). Because of the projected increase in rainfall after the month of June at Akola and Indore sites, the percent yield gains due to drought tolerance trait decreased with climate change. Similar response to climate change was simulated for the Samanko site in spite of slight decrease in projected rainfall. Though drought tolerance in sorghum could be attributed to multiple plant traits, increased rooting depth in the soil profile and/or increased root length density (RLD) in subsoil resulting in greater water extraction during the periods of water stress is the prominent mechanism for drought tolerance and higher yields under water stress in sorghum (Jordan et al., 1979; Passioura, 1983; Monteith, 1986, Lafolie et al., 1991; and Salih et al., 1999). Genotypic variation in sorghum for root traits exists, which can be utilized for developing drought resistant cultivars (Bhan et al., 1973; Mayaki et al., 1976; and Jordan et al., 1979). Deeper roots or increased RLD must result in greater water uptake by the crop during the periods of water stress to give yield advantage over the drought susceptible genotypes. Thus the approach used in the model to simulate the benefits of drought tolerance trait is appropriate. While drought is the major yield reducing factor in current climate, temperature increase with climate change will reduce yields drastically at places like Akola. Thus incorporating heat tolerance in sorghum will increase yields by 8 to 12 % in future climate at Akola, followed by Samanko (up to 4%) and Indore (up to 3%). As Indore site currently has high rainfall and moderate temperatures during the growing season, incorporating heat tolerance trait will not benefit the crop in near future. Heat tolerance already exists among sorghum genotypes, thus it will be possible to breed cultivars for higher yield for the future climate conditions considered in this simulation study. The yield gains due to heat tolerance simulated in this simulation study are also realistic as the mechanisms that cause yield losses due to high temperature stress in the sorghum model are the same as reported by Prasad et al. (2008). However more research is needed under field conditions to explore the effect of high temperatures on plant processes affecting crop yields when imposed at various stages of plant growth and development.

9 Conclusions

It is concluded that different combination of plant traits will be needed to increase and sustain productivity of sorghum in current and future agro-climates of the three target sites in India (Akola and Indore) and West Africa (Samanko, Mali). Increasing crop maturity duration and enhancing yield potential traits consistently increased crop yields in both current and future climates at all sites. In current climates at Akola, Indore and Samanko, yield gains were larger with drought tolerance trait than with heat tolerance. Yield gains due to heat tolerance at Indore and Samanko sites were nil in current climate and marginal with climate change. However, yield gains due to the combination of these two traits increased with climate change at these sites, especially at Akola. The CSM-CERES-Sorghum model can be used to quantify yield benefits of incorporating individual or combination of traits to cope with climate change.

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