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Investigation of sorghum yield response to variable and changing climatic conditions in semi-arid central Tanzania: Evaluating crop simulation model applications

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Abstract Combination of global circulation models (GCMs), local-scale climate variability and crop simulation models were used to investigate rain-fed sorghum yield response under current and future climate in central Tanzania. Decision Support System for Agrotechnology Transfer (DSSAT) v.4.5 and Agricultural Production Systems Simulator (APSIM) v 7.4 were calibrated and evaluated to simulate sorghum *(Sorghum Bicolor* L. Moench) var. *Tegemeo* in 2050s compared to baseline. Simulated median yields from both crop models for the baseline (1980-2010) agree with the trend of yield over the years realistically. The models predicted yields of sorghum in the range from 818 to 930 kg ha-^{1} which are close to the current national average of 1000 kg ha-^{1}. Simulations by both models using downscaled weather data from two GCMs (CCSM4 and CSIRO-MK3) under the Fifth Coupled Model Intercomparison Project (CMIP5) and Representative Concentration Pathway (RCP 4.5) by mid-century show a general increase in median sorghum yields. Median sorghum yields will increase by 1.1% - 7.0% under CCSM4 and by 4.0% - 12.5% under CSIRO-MK3. Simulations for both current and future periods were run based on the present technology, current varieties and current agronomy packages. This examination of impacts of climate change revealed that increase in sorghum yield will occur despite further projected declines or increase in rainfall and rise in temperature. Modifying management practices through adjustment of sowing dates and the choice of cultivars between improved and local are seemingly feasible options under future climate scenarios depending on the GCM and the direction of the management practice. Our simulation results show that current improved sorghum cultivars would be resilient to projected changes in climate by 2050s, hence bolstering the evidence of heat and drought tolerance in sorghum crop, thus justifying its precedence as an adaptation crop under climate change. We conclude that despite the uncertainty in projected climate scenarios, crop simulation models are useful tools for assessing possible impacts of climate change and management practices on sorghum.

Key words: APSIM, central Tanzania, climate change, DSSAT, simulation modelling, sorghum yield prediction

Introduction

Rain-fed agriculture currently constitutes about 90 percent of Tanzania's staple food production though it is highly sensitive to reduced rainfall, shifts in timing and distribution, and decreased growing season length (URT, 2007). Sorghum is one of the grain crops grown under predominantly rain-fed conditions, being the main staple for the world's poorest and food insecure people in Eastern and Central Africa (ECA), and accounts for 41% of the region's grain production (Rohrbach, 2004; Bucheyeki *et al*., 2010). Even with the development and release of improved high yielding sorghum varieties with short growth cycles favourable for the semi-arid areas including central Tanzania (Monyo *et al*., 2004), weather and climate remain key factors in sorghum productivity. Indeed, there is compelling evidence that climate variability and change will affect crop yields, but significant uncertainty soil surrounds the prediction of cereal yields under projected changes in climate (Slater *et al*., 2007; Berg *et al*., 2012; Ramirez-Villegas *et al*., 2013), especially for dry-land/rain-fed regions. For instance, under projected temperature increases of 0.14 to 0.58^{0}c per decade, yield of tropical grain crops is estimated to decrease by 5-11% by 2020 and by 11-46% by 2050 (Rosenzweig & Parry, 1994; Schlenker & Lobell, 2010).

Increasing cereal crop yields and productivity to keep pace with vagaries of weather and increased future food demand is thus crucial for enhanced food security, incomes and livelihoods (Chauvin *et al*., 2012). Production of rain-fed grain crops is projected to be negatively affected through projected higher and more variable temperatures, changes in rainfall patterns and increased occurrences of extreme events such as droughts and floods (Burke *et al*., 2006; Cooper *et al*. 2008). Current crop simulation models cannot capture and quantify the effects of weather extremes, hence compounding on the already existing uncertainty regarding the direction and magnitude of climate change (White *et al*., 2011; Ramirez-Villegas *et al*., 2013) consequently our understanding of the impacts on crops and in the timing of crop adaptation strategies such as adjustments of planting dates and choice of crop cultivars is further complicated.

Despite the difficulty in predicting climate change impacts on crop production, mainly due to occurrence of extreme events, some studies e.g. Cooper *et al*. (2009) and Moore *et al*. (2012), clearly demonstrate the capacity of combining GCMs, emissions scenarios, and crop simulation models to explore the possible range of climate change impacts on crops. While some studies predict that sorghum will be worse affected by climate change and variability than other vrops like wheat or rice mainly from increased atmospheric carbon dioxide (Schlenker & Lobell, 2010; Wheeler & Kay, 2010), other studies indicate positive or contrasting results about the future yield response of sorghum (Tingem *et al.,* 2009; Srivastava *et al.*, 2010; MacCarthy & Vlek, 2012).

It is thus crucial to understand the uncertainty surrounding sorghum yield variability, but limited information exist in central Tanzania regarding the response of existing improved sorghum cultivars towards new climatic futures, considering that sorghum is one of the crops promoted under current climate variability and projected climate change. This study therefore, examined the sorghum yield response and identified the adaptation options in the sorghum based cropping system using simulation modelling. The objective was to calibrate and validate crop simulation models APSIM and DSSAT and to simulate the impacts of future climate change scenarios on sorghum productivity. The second objective was to evaluate the performance of a set of adaptation options such as changes in sowing date and cultivar selection, improved versus local.

Materials and methods

Description of the study area. The central zone (Dodoma and Singida) where the study was conducted is located between latitudes 6° and 06°08' S and longitudes 34°30' and 35° 45'E. An experimental site (Hombolo) was established about 58 km North-East of Dodoma Municipality at 05°45'S latitude, 35°57'E (Fig. 1). The average annual rainfall is 589mm but the distribution is highly variable punctuated by several instances of high intensities. The zone is one of the most sensitive to climate variability and change, but it account for three-quarters of Tanzania's 500,000 to 800,000 t annual sorghum harvest. The average annual temperature is 22.7°C. Temperature

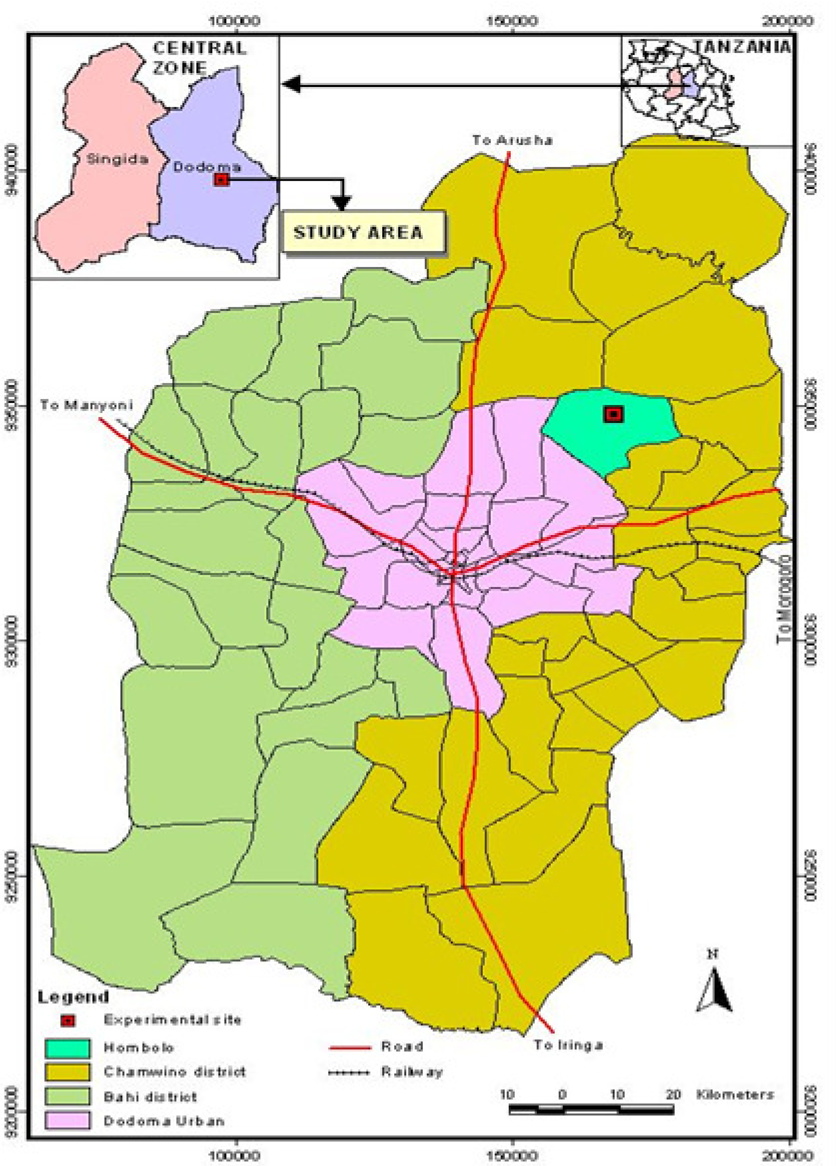


Figure 1. Location of study area.

and rainfall records during the growing season are shown in Table 1.

Soil and crop management input. Soils in this zone are mainly sandy and loamy of low fertility and seasonally waterlogged or flooded clays. They are classified as ferralic Cambisols in the FAO classification. Soil-related modules were parameterized mainly with measured data from experiments carried out under optimal growth conditions, and from related literature. Disturbed and undisturbed soil samples which were taken in soil profiles (0–15, 15–30, 30–45, 45–60, 60–75 and 75-105 cm) prior to sowing, were analysed for organic carbon (OC%), pH in water, and particle size distribution as described in Hoogenboom *et al*. (1999). Input data related to soil characteristics include soil texture, number of layers in soil profile, soil layer depth, pH of soil for each depth, clay, silt and sand contents, organic matter, cation exchange capacity, etc. The soil profile data used in the parameterization of the model is presented in Table 2.

Cultivar. Cultivar Tegemeo was chosen because it is stable and has continued to be grown since its release in 1978. Therefore, simulating the effects of climate variability and change on the cultivar would provide insights into possible impact of climate change on sorghum yield in the future.

Experiment for model parameterization for crop yield simulation. In the present study, DSSAT v 4.5 (Jones *et al*. 2003) and APSIM v7.4 (www.apsim.info/Wiki/APSIM-Documentation.ashx) were used to simulate crop yields as a function of current as well as future climatological conditions. Data from an experiment carried out between Jan- May 2013 at Hombolo Agricultural Research Station were used to parameterize the models. Daily weather data during the growing season, were obtained from observations at an agro-met station within ARI-Hombolo. These include minimum and maximum temperatures, rainfall and sunshine hours which in turn are used to estimate solar radiation. Phenological data including planting date, date of flowering, date for start of grain filling, date of physiological maturity and date of flag leaf appearance were collected. These were noted when 50% of plant population per plot attained each of these stages. Start of grain filling was determined by observing the presence of milky substance in grain at the base of the panicles. Physiological maturity is attained when dark layer forms at the point of attachment of the grain to the panicle. At final harvest, total above-ground biomass and yield were determined. Grain yield was determined by harvesting panicles from an area 9 m^2 and grains separated from it. Sub-samples with known weight were dried at 70 ^oC to a constant weight. Dried weight of sub-samples are used to determine dry weight from the harvested area and then expressed as t ha^{-1}. Above-ground biomass at maturity was harvested by cutting plants just above the surface of the ground and fresh weight noted. Sub-samples with known fresh weight were taken for each replicate and dried to a constant weight at 70 ^oC. Above- ground biomass per hectare was then determined as in the case of grain yield. The calibration was done using trial and error method of iteratively adjusting the parameters to obtain as close as possible the simulated and observed values of phenology (i. e. anthesis and maturity dates) and grain and biomass yields.

Table 1. Mean monthly maximum and minimum temperature, and monthly total rainfall from December 2012 to June 2013 at Hombolo, Dodoma Tanzania.

Month	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)
December	31.3	20.1	56.1
January	30.6	20.4	237.2
February	31.8	20.0	33.1
March	30.6	20.0	112.8
April	30.1	19.4	72.5
May	29.2	17.8	9.3
June	28.3	15.7	0

Table 2. Soil analytical data for a soil profile at experimental site.

Depth of bottom	Clay%	Silt%	Organic carbon %	pH in water	Cation Exchange Capacity (cmol/kg)	Total nitrogen(%)	Lower Limit (LL) cm3/cm3	Drained upper limit (DUL)cm3/cm3	Saturation (SAT)cm3/cm3
15	19	5	0.31	4.8	6.0	0.07	0.122	0.188	0.375
30	20	4	0.31	4.6	8.2	0.06	0.121	0.181	0.366
45	23	4	0.41	4.5	9.2	0.12	0.145	0.206	0.366
60	25	5	0.14	4.5	10.2	0.05	0.145	0.205	0.361
75	34	2	0.14	4.6	10.0	0.05	0.190	0.249	0.364
105	30	4	0.06	4.6	6.0	0.04	0.166	0.227	0.367

Data for model evaluation. Data from a previous experiment namely "tillage cum fertilizer application experiment" (Hatibu *et al.* 1993) with variety *Tegemeo* were used for evaluation. The treatments were Farm Yard Manure at 10 t/ha plus mulch and Triple Superphosphate applied at 100kg/ha and Nitrogen fertilizer applied at 40kg-N/ha. The calibrated model was evaluated by comparing observed values for parameters of 50% flowering, total dry matter (TDM) and grain yield with those from model simulations. The thermal time requirement for three phenological phases ranged from 88 to 97 growing degree days (GDD) for seedling emergence, 457–473 GDD for the period from emergence to end of juvenile (P1) and 626-633 for the grain filling period. Model performance was assessed through various statistical parameters viz., model efficiency (ME), root mean square error (RMSE) and index of agreement (IA) as per Nash & Sutcliffe (1970), Fox (1981) and Willmott (1981) respectively.

Testing management strategies and identifying possibilities of adaptation. Two treatments were evaluated in order to identify feasible adaptation options. First, sowing dates were adjusted to capture early sowing by putting the planting date at two weeks earlier (19th Dec) than the planting date of the experiment (i.e. 4th Jan) and two weeks later (19th Jan). Secondly, mimicking late-maturing local cultivars was undertaken by creating hypothetical cultivars. This was made possible through adjusting the genetic coefficients of the currently used and calibrated cultivars in such a way that they would prolong the vegetative period under climate change conditions. According to Staggenborg & Vanderlip (2005), genetic coefficients can be modified for long term simulation to incorporate the anticipated advancements in the breeding program by the mid-century.

Impact assessment methodology. Impact of climate change on grain yield of sorghum was studied using two approaches. In the first approach, impact of fixed rise in temperature and percent change in daily rainfall was analysed using a 2-factorial matrix combination of these two parameters to depict the ranges of very dry to dry and very wet to wet periods. For this, temperature (minimum and maximum) was raised at fixed levels of 1, 2, 3, and 4. Change in daily rainfall amounts starting from a deficit of 20% to a 20% increase were used at 10% increment intervals. Yields were simulated after coupling the changes in above parameters to the observed weather data of the baseline years (30 years). For the projections on rainfall, in order to accommodate the uncertainty, the climate variability (including rain fall distribution and variability) that existed in baseline years was assumed to occur in changed scenarios as well. A methodology used by Mohamed *et al.* (2002) who considered two warmer and drier climate change projections for 2025 for millet production in Niger and Al-Bakri *et al.* (2010) testing twenty-three climate change scenarios, representing the possible average climatic conditions around year 2050 for barley and wheat in a semi-arid basin in Jordan was followed.

In the second approach, a combination of the Commonwealth Scientific and Industrial Research Organization mark 3.0 (CSIRO-MK3.0) and Community Climate System Model (CCSM4) GCMs under CMIP5 and two time periods: 1981–2010 (baseline) and 2041–2070 (mid-century). The predictions were made using a fixed concentration of atmospheric $C0_2$ of 390 ppm (the value reported for the year 2010 in the fourth assessment report of IPCC). The two GCMs were chosen based on their proven better representation of present and projected climate, in terms of temperature and rainfall patterns in East Africa.

Results and discussion

Model calibration and evaluation. Results of model calibrations and the derived parameters are presented in Tables 3 and 4 for DSSAT and APSIM respectively.

Simulated days to anthesis, days to physiological maturity and grain yield closely matched with their observed values (Table 5). However, biomass simulations were above the observed values in both models.

Modelling efficiency compares the variability between simulated and measured sorghum yields, where the variability ranges from 0 to 1. Data indicate that the simulated grain yield values reasonably matched observed values. However, the variation in biomass simulations constitute a high error level as indicated by very low values of IA in both models, where values close to 1 are regarded as better simulations and a negative value of modelling efficiency in APSIM indicating unreliability of the model in predicting biomass (Table 6), both models seem to over predict biomass.

Climate change projections and impacts. There are considerable differences between the two GCMs and CMIP5 ensemble in terms of projected changes in temperatures and rainfall. Annual temperatures in central Tanzania are expected to rise by 1.5æ%C and 2.0 æ%C by midcentury (2050s) as compared to baseline, based on the CCSM4 model (Collins *et al*., 2006) and CSIRO-MK3, respectively, as illustrated in Figure 1. However, the two models exhibit a similar trend in temperature variation.

The two GCMs temperature projections are in agreement with the projections of IPCC which show increases of about 1- 2 ^{o}C to the 2050s and about 1.5 - 3 ^{o}C for the 2080s (Meehl *et al.* 2007) in Eastern Africa. Rainfall analysis of the baseline (1980-2010) at the experimental site indicate that, the number of days without rainfall shows an increasing trend while total annual rainfall shows a decreasing trend (Fig. 3a). Rainfall is expected to decrease or increase depending on the GCM used. For the CISRO-MK3 and CCSM4 expected average changes in rainfall ranged between -7.0% to - 4.0% and 5.3% to 10.2%, respectively as illustrated in Figure 3b.

As a pre-requisite for the crop models to estimate the impact of climate change on grain yield, observed yields for sorghum for 20 years (1988-2008) (FAOSTAT 2008) were compared with simulated yields (Fig. 4). Sorghum grain yield data from FAOSTAT were used with the

Table 3. Final ecotype and cultivar coefficient settings for CERES-Sorghum after calibration and evaluation of Tegemeo.

Coefficient	Definition	Setting
TBASE	Base temperature below which no development occurs, °C	8.0
TOPT	Temperature at which maximum development rate occurs during vegetative stages°C	34.0
ROPT	Temperature at which maximum development rate occurs for reproductive stages °C	34.0
RUE	Radiation use efficiency, g plant dry matter MJ PAR^{-1}	4.0
KCAN	Canopy light extinction coefficient for daily PAR	0.85
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod	465
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced	12.50
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20.	1.0
P5	Thermal time (degree days above a base temperature of 8°C) frombeginning of grain filling (3-4 days after flowering) to physiological maturity.	633.0
G1	Scaler for relative leaf size.	15.0
G2	Scaler for partitioning of assimilates to the panicle (head).	6.0
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	49.00

Table 4. Derived values of parameter used in APSIM-sorghum module.

Parameter	Source	Units	Tegemeo
Thermal time accumulation			
Duration-end of juvenile to panicle initiation	C	°C day	245
Duration- flag leaf to flowering stage	C	°C day	250
Duration- flowering to start of grain filling	C	°C day	60
Duration- flowering to maturity	C	°C day	700
Duration- maturity to seed ripening	L	°C day	1
Shoot lag (time lag before linear coleoptile growth starts)			
Photoperiod			
Daylength photoperiod to inhibit flowering	D	H	11.5
Daylength photoperiod for insensitivity	D	H	13.5
Photoperiod slope	L	°C/h	0.01
Soil water stress factor	D	-	1.125
Plant height (max)	O	mm	1650
Base temperature	L	°C day	8
Optimum temperature	D	°C day	30

C: calibrated; D: Default;L: literature; O: observed.

Table 5. Comparison of observed and simulated parameters (cv *Tegemeo*) after models validation.

	Current study experiment			Fertilizer-cum experiment		
	Observed	Simulated		Observed	Simulated	
		DSSAT	APSIM		DSSAT	APSIM
Anthesis days	73	72	71			
Maturity days	114	115	114	114	115	114
Grain yield	3789	4111	4105	2657	3030	3235
Above-ground biomass	10334	10830	11533	9213	9321	9801

assumption that although they represent national averages, the central regions of the country account for three-quarters of Tanzania's annual sorghum harvest. Simulation results indicate that, with the exception of some years where APSIM either overestimated or underestimated the grain yield, the two models captured the trend over the years realistically. Moreover, rainfall data from one weather station in central Tanzania (ARI-Hombolo) were used to gauge if there was any trend in annual total rainfall and both observed and simulated grain yield. Results indicate no clear relationship between the annual total rainfall and both simulated and observed grain

Table 6. Statistical indicators of model performance.

Crop parameters	DSSAT			APSIM		
	RMSE	IA	ME	RMSE	IA	ME
Grain yield (kg ha^{-1})	348	0.5	0.62	428	0.50	0.43
Biomass (kg ha^{-1})	359	0.29	0.59	987	0.47	-2.09

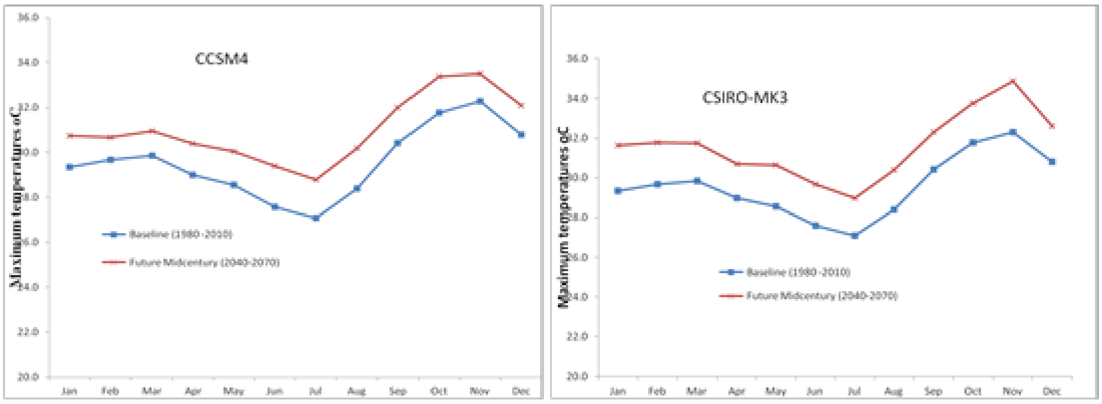
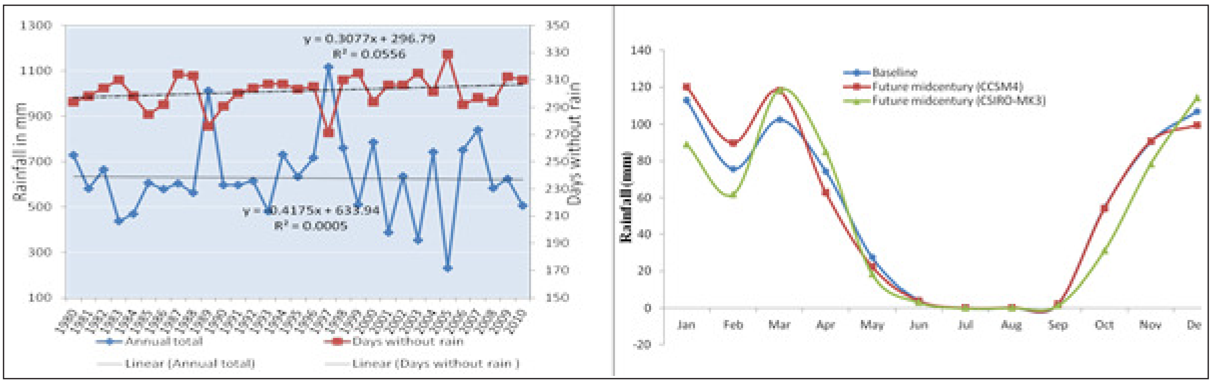


Figure 2. Change of maximum temperature from baseline by the two GCMS.



(a) (b)

Figure 3. (a) Change in trend of annual rainfall and days without rain (b) illustration of the uncertainty in rainfall projections by 2050s for Hombolo station.

yields. Elsewhere in sub-Saharan Africa, some studies observe that a critical source of risk emanate from the temporal distribution of rainfall during the cropping season rather than the total amount, because it determines the productivity and yield of the crop in that particular season (Mishra *et al*. 2008; Batisane & Yarnal, 2010; Laux *et al*., 2010).

Simulation results under hypothetical scenarios show a trend of increase in median sorghum yields varying according to the scenario and the crop model used as shown in Figure 5. The trend in sorghum yields under both APSIM and DSSAT predictions reveal consistency only with the increase of temperature, while neither the increase nor decrease in rainfall by up to 20% caused a corresponding increase or decrease in median yields compared to the baseline. The results suggest that the changes in rainfall amounts could not cause substantial increase/reduction in sorghum yields, but that the simulated yield variability could be attributed to the intra-seasonal rainfall variability. Simulations by both models under scenario of increased air temperature (with no change in rainfall) by 1, 2, 3 and 4æ%C, indicate subsequent increase in sorghum yields. The results are in agreement with IPCCs projections that, change from present to 2080-2099 indicate 20-48% increase in sorghum yields in East Africa under projected temperature increase of 3.2ºC and rainfall increase of 7% (IPCC, 2007).

On the other hand, the relative role of temperature and rainfall in projections of crop yields constitute a plausible discrepancy in that the two variables are closely linked and interact and depend on scale and geographical location. For instance, Berg *et al*. (2012) observe that yield changes in arid zones appear to be mainly driven by rainfall changes; in contrast, yield appears proportional to temperature in equatorial and temperate zones. According to Prasad *et al.* (2006) significant reduction in sorghum

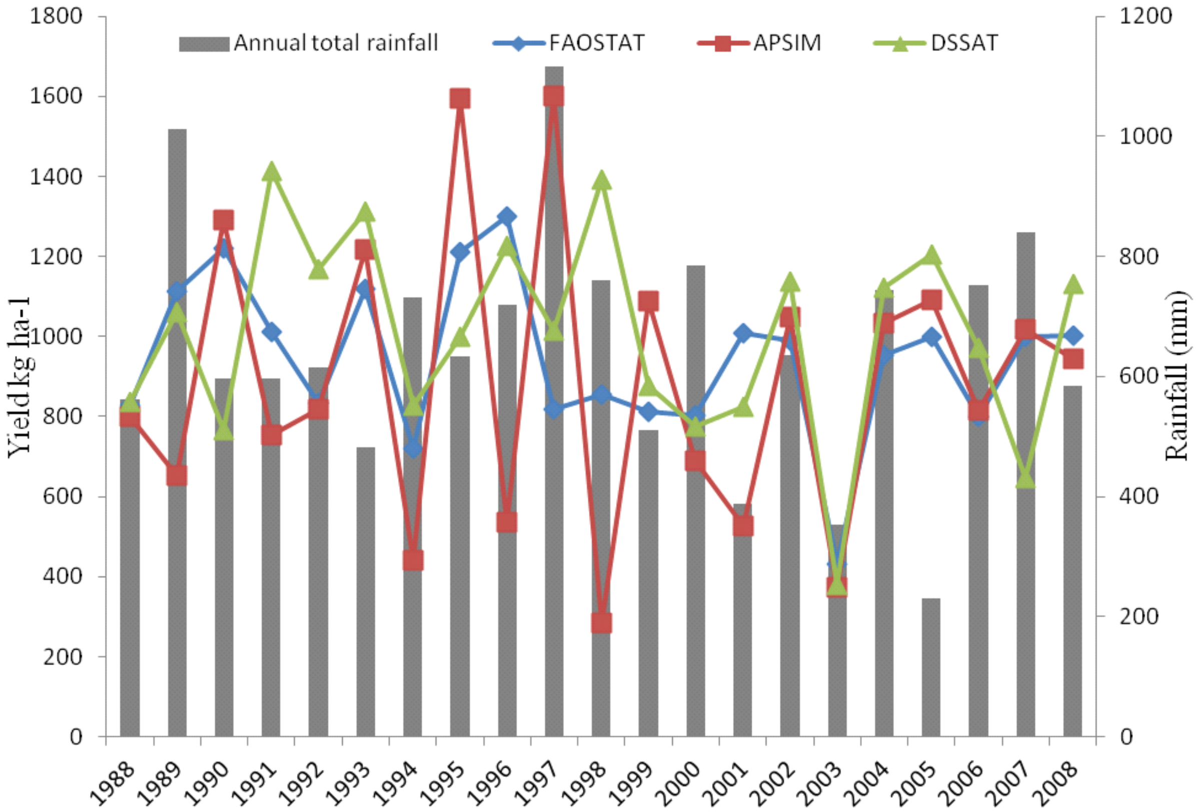


Figure 4. Comparison between simulated and observed (FAOSTAT) grain yield for sorghum c.f. annual total rainfall.

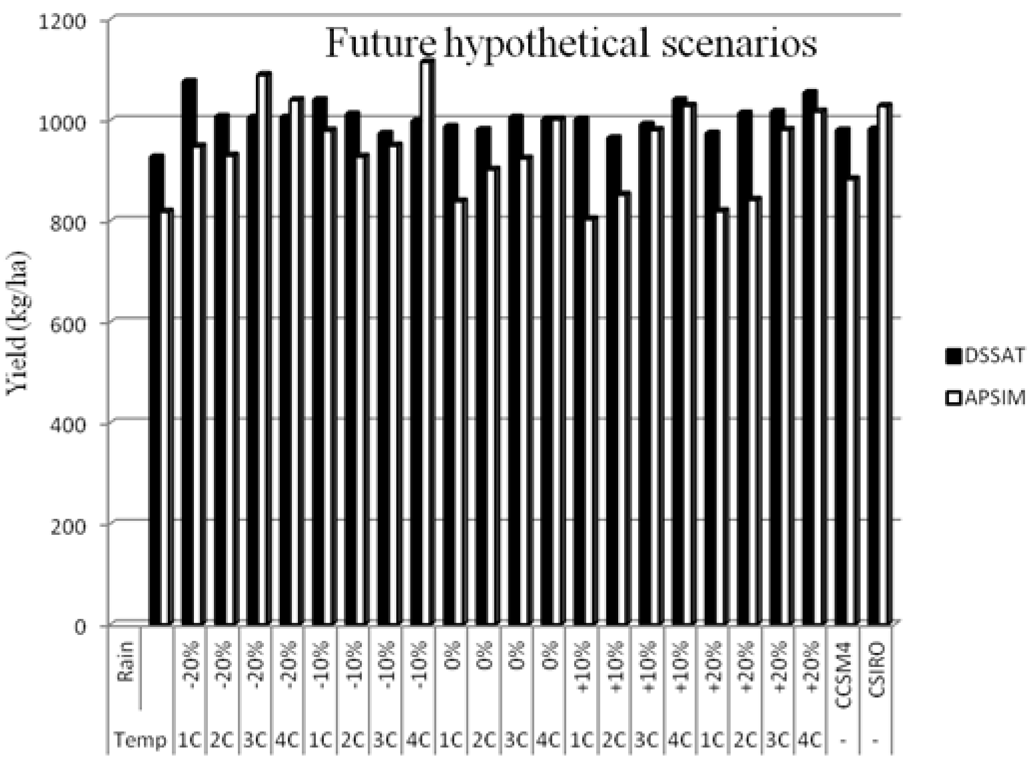


Figure 5. Change in trend of simulated median sorghum yields under different hypothetical scenarios (rainfall and temperature) and GCMs.

yields would occur when temperatures rise by 4 to 7 °C above optimum (32/22 °C) in combination with appreciable reduction in rainfall. Similarly, Luo (2011) and Asseng *et al*. (2011) observe that when temperature thresholds are exceeded for important crops such as maize, wheat, and sorghum, then significant yield reductions may occur. Lobell *et al*. (2011) indicate that global yields of maize and wheat would decline by 3.8% and 5.5% respectively, under the effects of temperature trends. A most recent study (Sultan *et al*., 2013) similarly observe that when

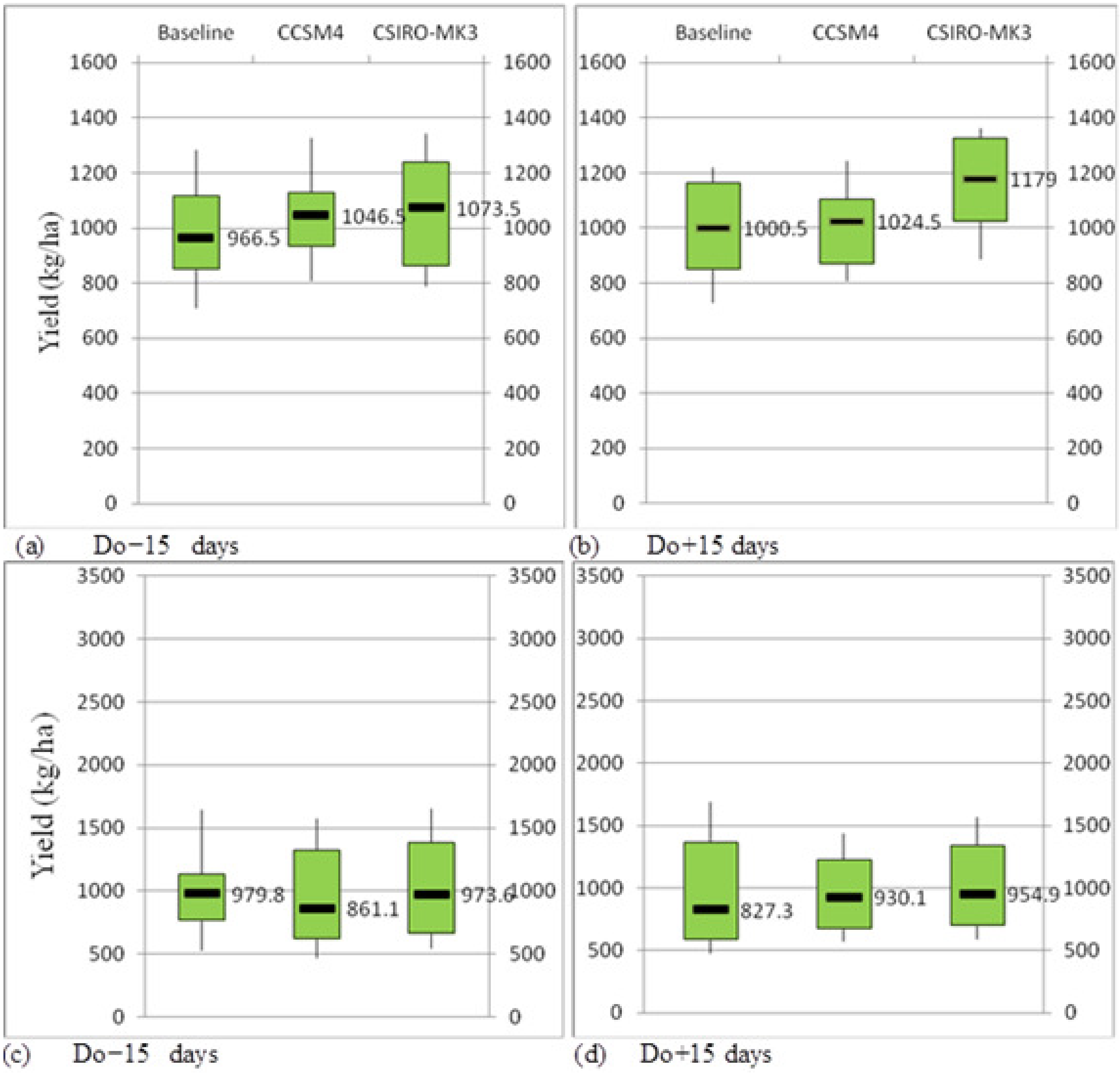


Figure 6. Predicted sorghum yield under climate change by 2050s compared to the baseline with sowing at fifteen days earlier (Do”15) and fifteen days later (Do +15) using DSSAT (a) & (b) and APSIM (c) & (d). CCSM: Community Climate System Model, CSIRO-MK3: Commonwealth Scientific and Industrial Research Organization. Solid bar-median yield, Boxes 25th-75th percentile and whiskers 10th/90th percentile.

temperatures are already high as in the case of the Sahel, impacts of a 2 °C rise cannot be counteracted by any change in rainfall.

Climate variability and projected future climate change harbour significant uncertainty on future Tanzanian crop production systems (and, consequently, on food security and rural livelihoods), and may obscure the direction of adaptation in the most vulnerable agricultural zones (URT, 2007). The corresponding factors toward this uncertainty include entity of climate change, crop species and varieties, geographical area, crop management techniques and technological development. In the same respect, a review by Knox *et al.* (2012) show that despite the robust evidence of climate change impact on crop yield for wheat, maize, sorghum and millet, with conflicting results for rice, cassava and sugarcane; concluding on recommendations pertaining to future policies for adaptation in agriculture is still a dilemma. Other crop modelling studies also suggest that there can be either positive or negative impacts on agriculture in Africa, and that the impacts could vary according to farm and crop type (Muller *et al*., 2011). Results from the current study are in agreement with previous studies (e.g. Tingem *et al.* 2009, Srivastava *et al.* 2010) which show that sorghum yields are expected to increase, decrease or remain unchanged under different GCMs, scenarios and locations hence collaborating the intrinsic uncertainty in crop yield predictions using the current methodologies. Moreover, earlier studies (Chipanshi *et al*., 2003; Butt *et al*., 2005) also show contrasting results. While the former predicted yield losses ranging from 11.5% to 17.1% under both the UKMO and CCC scenarios, the latter show both yields decline by 4.6% and 11.9% under the CCC and UKTR scenarios in the eastern region and 11.6 % and 22.5% under similar scenarios in the western region of Botswana; and sorghum yields increase by 13.8% and 7.2% in the eastern and western regions respectively, under a wet scenario (OSU).

Crop responses to modified management practices

Adjustment of sowing dates. Adjustment of sowing dates for sorghum as one of the adaptations in future climate

Table 7. Genetic advancement of sorghum under future climate scenario.

Genetic traits	Ranges	Initial value	Final value	Yield change range (%)	Avg yield change (%)
Thermal time grain filling to maturity (P5)	450 -640	580	640	2-9	+5
Relative leaf size (G1)	3-22	11	15	0.3-1.1	+0.7
Partitioning to panicle (G2)	4.5-6.5	6	6.5	7-9	+8
Management cultivar duration (days)	90-150	110	130	0-100	+15

change scenarios was tested in the modelling framework through shifting by either bringing forward or delaying sowing within a regular interval (Do-15, Do+15 days) with respect to the baseline case, Do being the normal sowing date . Results from the adjustments are shown in Figure 5 and indicate decrease in median sorghum yields under historical climate when early sowing is considered. But slight increase is obtained in median sorghum yields under both GCMs and crop models when late sowing is done, suggesting that future (2040-2070) climate would enhance sorghum growth and yield in comparison to the present day (1980-2010). There is however a trend towards higher inter-annual variability, i.e. more years with high or low yields. For example both DSSAT and APSIM simulations under CCSM4 show little variations in inter-annual yields but a tendency towards low yields. Contrastingly, CSIRO-MK3 show wide variations in yields and a trend towards higher yields. These results seem to suggest that depending on the GCM, adapting sowing dates may be effective in counteracting adverse climatic effects as shown by the slight increases in median yields compared to yields from baseline. Similar results were reported by Tingem *et al.* (2009) for Cameroon and Waha *et al.* (2012) for sub-Saharan Africa, but that there remains a high level of variability in climate projections between different GCMs. However the erratic nature of rainfall, characteristic of semi-arid areas (which unfortunately cannot be captured by the model) tend to shorten the planting window, such that a delay of two weeks in sowing may cause significant reduction in yields due to shortening of the length of growing period.

Crop cultivar selection. Choice of cultivar (short and long duration) and genetic advancements as adaptation options, were tested through adjustment of the genetic coefficients, and results of simulations are shown in Table 7

Heywood (2007) pointed out the importance of conserving landraces and crop wild relatives as a pre-requisite for developing new varieties that can be adapted to marginal environments and the expected changes in environmental conditions due to the effects of climate change. He observed that the search for desired genetic material should start with the identification of landraces and crop wild relatives with particular, resistance to drought, flooding and heat stress. Moreover, Abdalla & Gamar (2011) demonstrated a need for developing cultivars which are adaptable and stable across a wide range of rainfall environments as a way of adapting to threats of climate variability and change. However, results from Sultan *et al.* 2013 show that the photoperiod-sensitive traditional cultivars of millet and sorghum that have been used by local farmers for centuries may be more resilient to future climate conditions than introduced cultivars bred for their high yield potential. They contend that, photoperiod-sensitive cultivars counteract the effect of temperature increase on shortening cultivar duration and thus would likely avoid the need to shift to cultivars with a greater thermal time requirement. Their results corroborate those from Dingkuhn *et al.* (2006) who proposed the reinserting of photoperiod sensitivity back into modern sorghum cultivars in order to give farmers more flexibility in sowing dates in semi-arid environments where the onset of the rainy season is highly variable. Despite some studies showing that temperature rise will lead to sorghum yield reduction (Prasad *et al.*, 2006 and Prasad & Staggenborg, 2009), future projections in temperatures by the GCMs for central Tanzania show that the underlying conditions for yield reduction may not be attained by the 2050s.

Conclusions

Central Tanzania may experience warmer temperatures and temporal shifts of rainfall patterns in the future. Understanding crop response towards projected changes in climate is an essential step in formulating adaptation strategies and policy. Crop simulation models are potential agronomic and decision making tools to understand crop biodynamism under variable climatic conditions of dry-land agriculture. The evaluation of crop models in central Tanzania has enhanced our understanding of the influence of variability in temperature and rainfall regimes on sorghum. Considering future climates up to 2050s, productivity of grain sorghum will be less affected despite the differences in the GCMs projections in temperature and rainfall. Slight increase of (1.1- 7.0%) and (4.0- 12.5%) in sorghum yields have been estimated by both models under CCSM4 and CSIRO-MK3, respectively. The results from this study depict that advancing or delaying the sowing dates decreased simulated median sorghum yields under historical (baseline) weather conditions. For future scenario, late (delayed) sowing increases median sorghum yields under both GCMs and crop models due to projected increase in rainfall in the months of March and April, therefore it could be a feasible option in the future under central Tanzania conditions. However, early (advanced) sowing gives conflicting results, in that DSSAT show an increase in median yields under both GCMs, while APSIM show a decrease in median sorghum yields. Genetic advancements can minimize these yield losses. We conclude that with proper calibrations and evaluations, crop models can reasonably predict future crop yields. However, the limitations of the current study stem from the fact that, data used for model evaluation were from an experiment not specifically designed for that purpose. It is also likely that the impacts of climate change on productivity are underestimated because the effects of increasing weather extremes have not been included. Extreme weather events (mainly drought and floods) under future climate change seem to have features of increasing frequency, duration and intensity, so further research and analyses are needed to understand how the meteorological disasters would influence sorghum yield and productivity. Nonetheless, this study, quantitatively ascertains the current promotion of sorghum production as an appropriate crop, instead of the continued reliance on maize as a staple crop which is currently at risk under projected climate change scenarios. Moreover, the study shows the possibility of adjusted management practices under sorghum production to enhance the adaptive capacity of smallholder farmers in central Tanzania, as a result ensure increased production of the crop for enhanced food security and livelihoods.

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