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Improving sorghum productivity under changing climatic conditions: A modelling approach

Folorunso M. Akinseye[a,b,*], Hakeem A. Ajeigbe[a], Pierre C.S. Traore[c,d], Samuel O. Agele[e], Birhanu Zemadim[c], Anthony Whitbread[f]

[a] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kano, Nigeria
[b] Department of Meteorology and Climate Science, Federal University of Technology, Nigeria
[c] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bamako, Mali
[d] MANOBI LLC, Fenêtre Mermoz V. 17, BP 25026, Dakar-Fann, Senegal
[e] Department of Crop, Soiland Pest Management, Federal University of Technology, Nigeria
[f] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India

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ABSTRACT

Climate variability and change will have far reaching consequences for smallholder farmers in sub-Saharan Africa, the majority of whom depend on agriculture for their livelihoods. Crop modelling can help inform the improvement of agricultural productivity under future climate. This study applies the Agricultural Production Systems sIMulator (APSIM) to assessing the impacts of projected climate change on two (early and medium maturing) sorghum varieties under different management practices. Results show high model accuracy with excellent agreement between simulated and observed values for crop phenology and leaf number per plant. The prediction of grain yield and total biomass of an early maturing variety was fair $RMSE_n$ (22.9 and 23.1%), while that of the medium maturing was highly accurate $RMSE_n$ (14.9 and 11.9%). Sensitivity analysis performed by changing the calibrated variables of key plant traits in the model, showed higher significant yield change by + or - 10 % changed in radiation use efficiency, (RUE), coefficient extinction (Coeff_ext) and Phyllocron (Phyllo) for early maturing variety while + or - 10 % changed in phyllochron and RUE showed a significant yield change for the medium maturing variety. Under climate change scenerios using RCP 8.5, the simulated yield for the early–maturing variety revealed high inter-annual variability and potential yield loss of 3.3% at Bamako and 1% at Kano in the near-future (2010–2039) compared to baseline (1980–2009). The mid-century (2040–2069) projected yield decline by 4.8% at Bamako and 6.2% at Kano compared to baseline (1980–2009). On the contrary, the medium maturing variety indicated significantly yield gain with high yielding potential in both climate regimes compared to the baseline period (1980–2009). The simulated grain yield increased by 7.2% at Bamako and 4.6% at Kano, in the near-future (2010–2039) while in the mid-century (2040–2069) projected yield increase of 12.3% and 2% at Bamako and Kano compared to baseline (1980–2009). Adaptation strategies under climate change for varying sowing dates in the near-future (2010–2039, indicated that June sowing had a higher positive yield gained over July and August sowing for early maturing variety; July sowing simulated positive gained by 5 -11% over June and August sowing for medium maturing variety in both locations. Similarly, under the mid-century (2040–2069), among the sowing dates and in both locations, June sowing indicates lowest negative yield change over July and August sowing for early maturing variety. However, for medium maturing variety, July sowing had the highest yield gain of 16% over June and August sowing at Bamako and June highest positive yield gained of 11.4% over July and August at Kano. Our study has, therefore, demonstrated the capacity of APSIM model as a tool for testing management, plant traits practices and adoption of improved variety for enhancing the adaptive capacity of smallholder farmers under climate change in the Sudanian zone of West Africa. This approach offers a promising option to design more resilient and productive farming systems for West Africa using the diverse sorghum germplasm available in the region.

1. Introduction

Better defining niches for strategic agricultural productivity improvements could help further improve the sustainability of food production in water-limited environments (Akinseye et al., 2017). Although, there is a general understanding of the impact of climate

* Corresponding author at: International Crops Research Institute for the semi-arid Tropics (ICRISAT), Sabo Bakin Zuwo Road P.M.B 3491 Tarauni Kano.
E-mail address: f.akinseye@cgiar.org (F.M. Akinseye).

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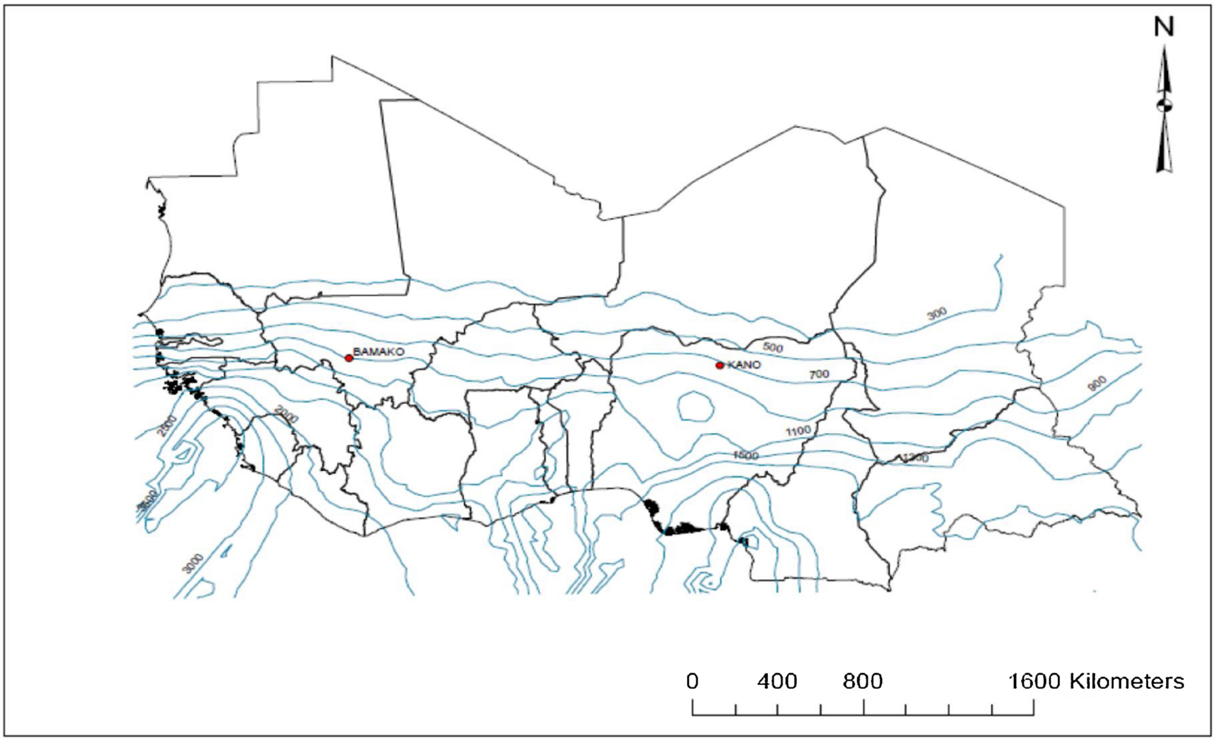

Fig. 1. Mean Rainfall gradient (1951–2000) in West Africa (Adapted from Adam et al., 2015).

change and variability on agricultural crops, the spatial and temporal variability of these impacts remains uncertain (Gebrekiros et al., 2016). Modelling the potential impact on productivity of locally important traits such as crop duration and photoperiod sensitivity could help develop adaptation and mitigation strategies, as no blanket" approach is applicable (Adiku et al., 2015a). Simulation models have proven to be excellent tools to explore the potential of certain crops and cropping strategies in diverse smallholder farming systems and different environments (Whitbread et al., 2010). They may be particularly helpful in highly heterogeneous systems which are difficult to investigate using classical agronomic experiments alone (Holzworth and Huth, 2009; Whitbread et al., 2010). Our findings offer one of the most applicable models to better understand plant growth and development in response to the environment has been the Agricultural Production Systems sIMulator (APSIM) framework (Keating et al., 2003; Holzworth et al., 2014). APSIM simulates biophysical—key soil and crop—processes for a wide range of crops and environmental conditions. Modeling frameworks may be used to address primary challenges and limitations such as inter- and intraseasonal rainfall variability as well as the variation in crop response to diverse soil types and agronomic management (Whitbread et al., 2010; Akinseye et al., 2017.

Sorghum (*Sorghum bicolor* L. moench) is regarded as a major cereal for food grain and fodder, grown predominantly rainfed conditions in both semi-arid and sub-humid West Africa (Abdel-Ghani et al., 2015) where it has a comparative advantage over other rainfed crops like maize and rice (Ajeigbe Hakeem et al., 2018a, 2018b). The growth and yield of sorghum can be limited by both abiotic and biotic factors, including weather (rainfall and temperature), soil conditions (water, and nutrients), parasitic weeds (Striga), disease incidence and management practices (cultivar, fertilization) (Ajeigbe et al., 2010b). Sorghum production in commercial situations requires maximizing grain yield on limited available water resources, which results in maximizing the ratio of yield to evapotranspiration. Climate change is expected to increase temperature and alter rainfall patterns, putting pressure and increasing uncertainty in crop production across West Africa (IPCC, 2001; Adiku et al., 2015a; Akinseye, 2015). Crop production in such regions is, expected to become increasingly risky (Slingo et al., 2005). As 89% of cereal production in sub-Saharan Africa are rainfed (IPCC, 2007; Cooper et al., 2008), climate will remain a key driver of food security in the region (Verdin et al., 2005). Although several studies project a negative net effect of climate change on cereal yields, the actual direction of change in any given area may depend on the concerned crop physiology and the current climatic condition under which it is grown, as different species have different base and optimum temperatures for development (Porter and Semenov, 2005; Lobell et al., 2008; Challinor et al., 2007).

Furthermore, rainfall projections for West Africa are highly inconsistent, involving a projected drying trend in the western Sahel (e.g. Senegal), a wetter eastern Sahel (e.g. Niger) and no change or slight increases in annual rainfall towards the subhumid zones (Adiku et al.,2015a). Under a mitigation target of 1.5 ∘C, recent studies suggest substantial effects on the agricultural sector (Ruane Alex et al., 2018a), the implications of which need to be analyzed for crop yield and yield stability in regions currently challenged by food insecurity. Because of the uncertainties in processes underpinning the changing climate, more research is needed to understand the influence of the projections on crop production at a local scale. Detailed crop simulation studies at various scales are required due to the spatial variability of climate, especially rainfall, in order to provide relevant knowledge on impacts and for evaluating possible adaptation options at farm levels and the supporting policies that may support farm level adaptation (White et al., 2011; Diiro et al., 2016). The objectives of this study are thus to (i) evaluate the reliability of APSIM model in simulating sorghum yield under different management practices and environments, and;(ii) simulate, using contrasting GCMs, the impacts of future climate change on sorghum productivity with variable sowing dates as an adaptation strategy.

2. Material and methods

2.1. Sites and cultivars

Data from field experiments used in model calibration were conducted during the 2013 growing season at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Samanko station,Bamako, Mali (12.52 ^{0}N: -8.07 ^{0}W at 328 m above sea level).

The climate is typical of the Sudan savanna, with three seasons (Dingkuhn et al., 2008), a hot and humid season from June to October during which crops are cultivated, a dry and cool season from November to February, and a dry and hot season from March to May. Depending on the onset of major rain events, local farmers plant sorghum between early June and late July (approximately 50–60 days sowing window). Detailed experimental protocol and model parameterisation of two sorghum varieties were earlier reported by Akinseye et al. (2017).

For long-term simulations,both locations used [Bamako, Mali (12.52 °N, 8.07 °W; elevation: 328 m) and Kano, Nigeria (12.0 °N; 8.59 °E; 488 m)] fall within West Africa's Sudanian agro-ecological zone, with mono-modal rainfall distribution, annually totaling 900 mm for Bamako, and 700 mm for Kano (Fig. 1). Mean monthly temperature during the growing season varied between 26.5 and 31.5 °C in Bamako and also 26.5 and 33 °C in Kano.

The two sorghum varieties used in this study were CSM63E, an early maturing variety (85–105 days) with low photoperiod sensitivity and Fadda, an improved dual-purpose, medium maturing variety (100–135 days) with intermediate plant height and photoperiod sensitivity. These varieties are widely cultivated by smallholder farmers in the Sudanian regions of Mali and Burkina Faso since their release.

2.2. Model description and parameterization

The APSIM cropping systems model was developed to simulate biophysical process in farming systems, in particular where there is interest in the economic and ecological outcomes of management practices in the face of climatic risk. APSIM's sorghum module is based on the fusion of earlier models and concepts (Rosenthal et al., 1989; Sinclair and Amir, 1992; Chapman et al., 1993; Hammer and Muchow, 1994). It simulates complex adaptive traits and genotype-to-phenotype prediction (Hammer, 2010). Crop development follows a thermal time approach (Muchow and Carberry, 1990; Hammer and Muchow, 1994), with reported base (T_b), optimal (T_{opt}) and maximum (T_m) temperatures of 11, 32, and 42 ^{0}C, respectively (Carberry et al., 1993a, b). The thermal time target for the phase between emergence and panicle initiation is also a function of day length (Hammer et al., 1989; Kumar Ravi et al., 2009) and its duration, when divided by the plastochron (^{0}C degrees per leaf), determines total leaf number. Total leaf number multiplied by the phyllochron (^{0}Cd per leaf) determines the thermal time to reach flag leaf stage, which is thus an emergent property of the model. Akinseye et al. (2017) provides detailed parameterization of the two simulated sorghum (early and medium maturing) genotypes were based on the observed data obtained from field experiment.

2.3. Model evaluation

For the sorghum cultivars used in this study, an independent model validation was undertaken using field experiments carried out in Bamako and Cinzana (Mali), between 2007 and 2008 growing seasons as summarized in Table 1. Further details on agronomic practices and soil characteristics are available in Clerget et al. (2007, 2008). Observed parameters such as days to 50% flowering, physiological maturity, total leaf number (TLN) per plant, grain yield and above ground biomass were used for model evaluation, using:

1.Root mean square error (RMSE):

$$\text{RMSE} = [n^{-1}\Sigma\ (\text{simulated} - \text{observed})\ ^2]^{0.5} \quad (1)$$

2.The normalized root mean square error ($RMSE_n$), expressed in percent, calculated following Loague and Green (1991) as

$$\text{RMSE}_n = [n^{-1}\Sigma\ (\text{simulated} - \text{observed})\ ^2]^{0.5} \text{X}\ \frac{100}{M} \quad (2)$$

where M is the mean of the observed variable. $RMSE_n$ gives a % of mean observed. Simulation output is considered excellent if

Table 1
Summary of agronomic practices and management of experimental data used for APSIM model validation.

Variety	Site	Sowing date	Planting population (plant/ha)	Management
Early maturing	Samanko	2007:16-Jul & 01-Aug	67000, 133000, 200000, 267000	A total of 128 kg of Nha^{-1}, 92 kg of P ha^{-1} 60 kg of K ha^{-1} was applied in three doses. Pre-sowing:18 kg of N (Di-ammonium phosphate; 30 DAP:64 kg of N (DAP + Urea); 50DAP: 46 kg of N (Urea)
	Cinzana	2007: 18-Jul & 04-Aug. 2008:12-Jul & 01-Aug..		
Medium maturing	Samanko	2008: 08-Jul;	67000, 133000 200000	A total of 128 kg of Nha^{-1}, 92 kg of P ha^{-1} 60 kg of K ha^{-1} was applied in three doses. Pre-sowing:18 kg of N (Di-ammonium phosphate ; 30 DAP:64 kg of N (DAP + Urea); 50DAP: 46 kg of N (Urea)
	Cinzana	12-Jul		

***Note*: DAP- Days after planting;** Samanko- Mali **(**12.52^{0}N; -8.07 ^{0}W; and Cinzana (13.25^{0}N; -5.97^{0}W)**; Soil/climate:** Sandy loam/ daily rainfall, minimum and maximum temperatures (T-max& T-min), Solar Radiation (Srad), Relative humidity (RH) **reported by** Clerget, et al., (2009).

$RMSE_n$ < 10%, good when $RMSE_n$ is ≥ 10% and ≤ 20%, fair when $RMSE_n$ is ≥ 20% and ≤ 30% and poor if $RMSE_n$ is ≥ 30% (Jamieson et al., 1991).

3.Additionally, for comparison, the traditional R^2 regression statistic (least-squares coefficient of determination) was determined.

2.4. Climate change impact assessment

A complete set of daily weather data (1980–2009) was obtained from the global bias-shifted Modern Era Retrospective analysis for Research and Applications dataset (MERRA; Rosenzweig et al., 2013). R scripts were used to generate delta-based, downscaled future climate scenarios for the near-future (2010–2039) and mid-century (2040–2069) periods in APSIM format, used within AgMIP project for climate change projections from the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012; Rosenzweig et al., 2012).These scenarios are based on historical daily weather time series perturbed for future time periods using the high representative concentration pathways (RCP8.5; Knutti, 2014). The identified five GCMs (CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR) out of twenty (20) GCMs outputs captured a profile of the full ensemble of temperature and precipitation changes within the growing season for West Africa region (Rosenzweig et al., 2012; Adiku et al., 2015a; Ruane Alex et al., 2017).

We used a planting density of 6.7 plants m^{-2} and a total application of 41 kg N ha^{-1} in two doses, deemed to be recommended application rate for smallholder farmers in Bamako, Mali. The first fertilizer dose was 18 kg of nitrogen di-ammonium phosphate (DAP) applied at sowing while the second dose was urea (46%N) at 40 days after sowing (DAS). In Kano, Nigeria, recommended practices for both plant population and fertilizer application (NPK 60:30:30) were used with plant population set at 4.5 plants m^{-2}, first NPK fertilization(NPK 30:30:30) at sowing and urea top-dressing (30 kg N) also at 40 DAS. Following high emission scenerios of RCP 8.5, the simulations for current (future) climate assumed a CO_2 concentration of 360 (571) ppm (Rosenzweig et al., 2013). Relative yield deviations from baseline were calculated to assess impacts of climate change.

2.5. Sensitivity analysis

Sensitivity analysis was carried out on the key model parameters for the calibrated varieties by assessing changes in grain yield and total above ground biomass (AGB). Five (5) model parameters: radiation use efficiency (RUE), light extinction coefficients of crop, phyllochron (phyllo) and photoperiod sensitivity (ppsen) were changed by adding or subtracting 10% to the calibrated values. Similar to Zuidema et al. (2005), such analysis will identify parameters that have a strong influence on modelled output and potentially related to traits that can be selected for in crop improvement programs.

Additionally, as a measure of adaptation strategy to climate change, simulation was carried out to test the sensitivity of both varieties (early and medium maturing) to varying sowing dates in the two locations. Three (3) sowing dates were simulated covering the typical range of sorghum sowing windows, including June 14th, July 9th and August 5th.The simulation was run for each sowing date over the baseline and (for all GCMs) near-future and mid-century 30-year periods. Percentage yield change for each planting date, location, and variety were calculated.

3. Results

3.1. Model evaluation

The detailed cultivar-specific coefficients reported earlier by Akinseye et al. (2017). However, model evaluation for 50% flowering and physiological maturity using the calibrated cultivar-specific parameters for early maturing variety and medium maturing variety are presented in Table 2. The statistical indices for evaluation of simulated and observed values showed high accuracy for crop phenology (Table 2) and total leaf number per plant (Fig.2c). The estimated RMSE values indicate equal or less than 5 days for days to 50% flowering, < 7 days for days to physiological maturity (Table 2). The accuracy of the

Table 2
Model evaluation performance for days to 50 % flowering and physiological maturity.

Variety / Parameters	Early maturing		Medium maturing	
	Flowering	Maturity	Flowering	Maturity
	Days		Days	
RMSE	4.7	5.8	4.1	6.8
$RMSE_n$(%)	7.7	5.1	5.1	8.5
R^2	0.58	0.66	0.81	0.73
SD_{obs} (CV%)	5.7 (9.2)	4.5 (5.2)	7.1 (8.6)	8.8 (8.1)
SD_{sim} (CV%)	1.5 (2.6)	1.5 (1.7)	9.3 (10.9)	9.3 (8.0)
N	24	24	8	8

SD- Standard deviation from mean; obs-observed value, sim-simulated value; CV- coefficient of variation; N-number of observations.

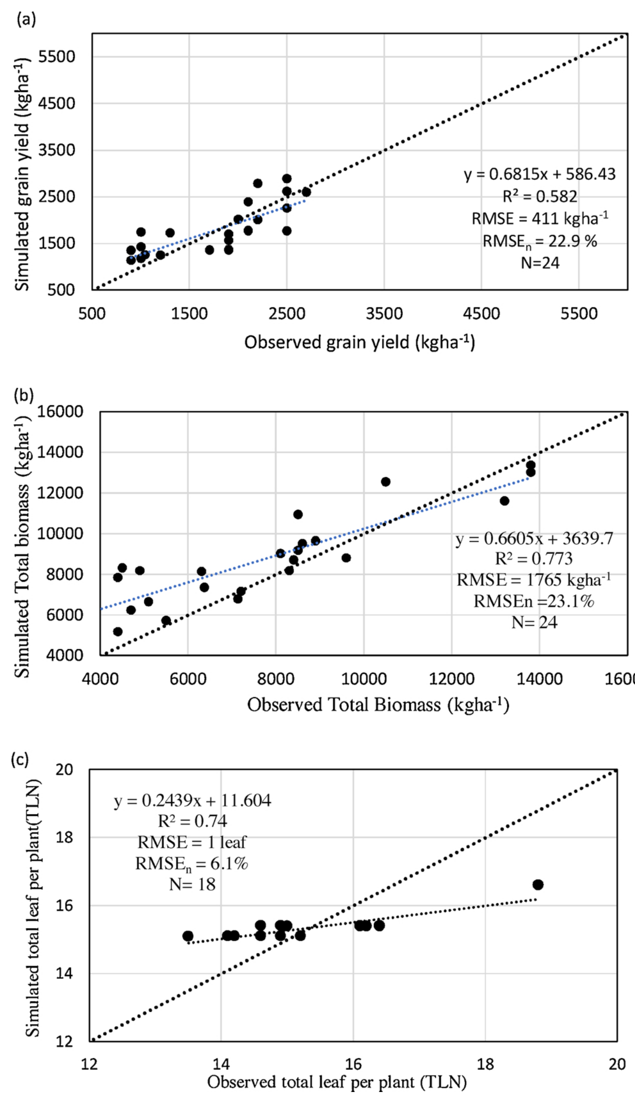

Fig. 2. Model comparison between the observed and simulated values (a) grain yield; (b) total biomass and (c) Total leaf number per plant for early maturing variety.

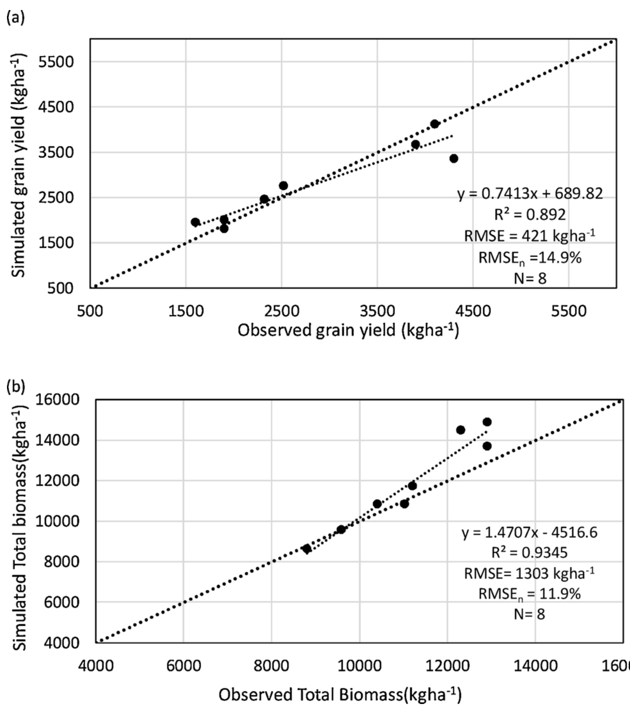

Fig. 3. Model comparison between the observed and simulated values (a) Grain yield and (b) Total biomass for medium maturing variety.

model in predicting grain yield and total biomass for the early maturing variety was relatively good with $RMSE_n$ values of 22.9% and 23.1% respectively (Fig. 2a & b) while RMSE of 1.1 and $RMSE_n$ of 6.1% was estimated for total leaf number (TLN) (**Fig.2c). Also, the model performance was excellent for medium maturing variety represented by very low $RMSE_n$ values of 14.9 and 11.7% for grain yield and total biomass respectively (**Fig.3**).**

3.2. Historical and future climatic trend in the study sites

Fig.4 shows the analyses of seasonal rainfall in Bamako, Mali and Kano, Nigeria both at near future (2010–2039) and mid-century (2040–2069) in comparison with baseline period (1980–2009). The results indicated no significant changes in seasonal rainfall among the 5 GCM scenarios at Bamako, Mali in the near future (2010–2039) but significant changes occurred at Kano, Nigeria. 3 out of 5 GCMs (CCSM4,GFDL-ESM2M and MPI-ESM-MR) projected decline in rainfall varying from 3 to 12.5% while HadGEM2-ES and MICRO5 predicted increased rainfall compared to the baseline climate (1980-2009) (1980–2009). Also, in the mid-century (2040–2069), at Bamako, Mali (Fig.4a), seasonal rainfall had projected significant changes with 4 out of 5 GCMs predicted decline rainfall from baseline climate which varied from 2 to 28%. In contrast, at Kano, Nigeria (Fig.4**b)** the result shows projected increase in rainfall from 3 out of 5 GCMs by 4.8–31.2%. The highest projected annual rainfall decline is shown in GFDL-ESM2M (14%) followed by MPI-ESM-MR (2%).

Analyses of monthly minimum and maximum temperature at Bamako, Mali and Kano, Nigeria by near future (2010–2039) and mid-century (2040–2069) as compared to baseline period are shown in Figs. .5 & 6 . All the 5GCMs both in the near-future (2010–2039) and mid-century (2040–2069) projected warming for both minimum and maximum temperatures and uniformly increase throughout the growing season in both locations. Table 3 however shows the magnitude of increase was larger in the mid-century (2040–2069) than near-future (2010–2039) while the increase in minimum temperature was higher by 0.2^0C over the change of maximum temperature. The change in temperatures in the near-future over baseline period was almost the

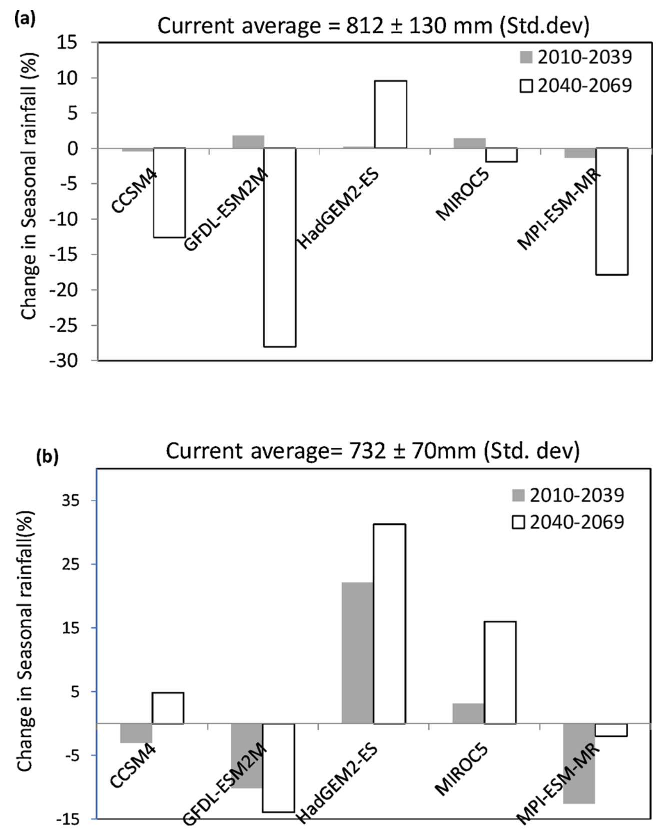

Fig. 4. Projected change (%) in the seasonal (May to October) rainfall across GCMs for both near-future(2010–2039) and mid-century (2040–2069) scenarios **(a)** Bamako, Mali; (**b)** Kano, Nigeria.

same (mean change varied from 0.9^0C -1.2^0C) at both locations. On the contrary, in the mid-century (2014–2069), the maximum and minimum temperatures increase by 2.2^0C and 2.1^0C over Bamako and 2.3^0C and 2.2^0C over Kano respectively across 5GCMs.

3.3. Simulated yield variability between the baseline and future climate across GCMs

The result shows comparison of yield variability between the baseline (1980–2009) and two (2) climate regimes [near-future (2010–2039) and mid-century (2040–2069)] using five(5) contrasting GCMs (Figs. 7 & 8). In accordance with simulation results from both baseline and two (2) climate regimes (near-future and mid-century), both varieties displayed high inter-annual variability across GCMs. For early maturing variety (**Fig. 7**), simulated grain yields were low, relatively stable (< 1000 $kgha^{-1}$) with less inter-annual variability between baseline (1980–2009) and climate change in the near-future (2010–2039) and mid-century (2040–2069). At Bamako, GCMs projected grain yield decline between 2.5% and 4.4% in the near future (2010–2039) while mid-century (2040–2069) projected grain yield decline from 3.3 to 5.7%. In contrast at Kano, two (GFDL-ESM2M and MPI-ESM-MR) out of five(5) GCMs projected increase in grain yield by 2% while other 3 GCMs indicated yield declines between 1.6 and 4.7% in the near future (2010–2039). Similary, in the mid-century (2040–2069), GFDL-ESM2M and MPI-ESM-MR predicted yield increase between 11.3% and 14.5% while other 3GCMs showed yield decline between 1.5 and 4.7%.

Furthermore, Fig. 8 shows that medium maturing variety exhibited significant high yielding potential, high inter-annual variability at Kano but low inter-annual variability at Bamako across the GCMs. The mean simulated yield ranged from 1340 - 2310 kg ha^{-1} at Bamako, Mali and 960 - 3870 $kgha^{-1}$ at Kano, Nigeria between baseline and GCMs. At

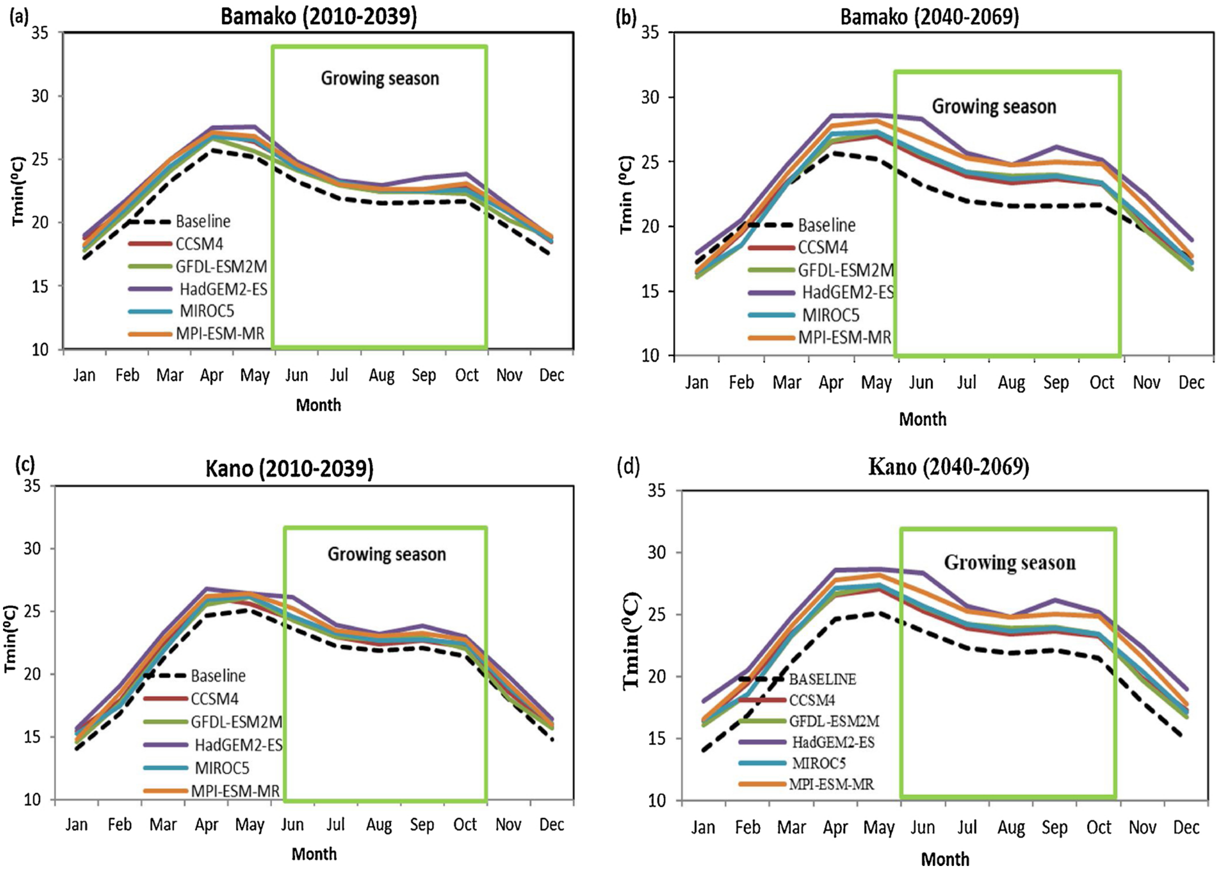

Fig. 5. Comparison of mean monthly minimum temperature variability between baseline (1980–2009) and GCMs in the near-future (2010–2039) and mid-century (2040–2069) in Bamako and Kano under RCP8.5.

Bamako, across the GCMs, the simulated grain yield projected increase between 4.5 % and 12.2 % in the near future (2010–2039) and 11.6 and 18 % in the mid-century (2040–2069) respectively. Meanwhile, at Kano, 4 out of 5 GCMs projected an increase in yield varied from 2 to 26.6 % while only HadGEM2-ES indicated yield loss by 1.7 % in the near future (2010–2039). In the mid-century(2040–2069), GFDL-ESM2M and MPI-ESM-MR predicted greater mean yield increase of 11.3% and 14.5% while other 3GCMs showed slightly mean yield decrease varied from 1.5 and 4.7%.

3.4. Model sensitivity to change in the cultivar selected parameters and sowing dates effects on sorghum yields

Changes in radiation use efficiency (RUE), light extinction coeffient (Coeff_ext) and phyllochron (phyllo) indicated a strong effect on grain yield change for early maturing variety while RUE and phyllo traits driven the yield changes for medium maturing variety **(**Fig.9**)**. RUE accounted for + or - 10% yield deviation followed by light extinction coeffient (Coeff_ext) with yield deviation of 7% for (Fig.9a). Similarly, for medium maturing 10% increase in phyllochron trait (Phyllo), accounted for 19% increase in grain yield while 10% decrease resulted to 13% decrease in grain yield. Also, 10% increase in RUEaccounted for positive grain yield change by 4% and vice- versa. while changes in photoperiod sensitivity factor (PPsens) had a minor effect on yield deviation for both varieties tested.

The simulated grain yield change (%) for 30-year period seasonal analysis between baseline and climate change scenerios at the different sowing dates is shown in Fig. 10. The simulated grain yield revealed significant changes (both positive and negative) at varying sowing in both locations between baseline (1980–2009) and two climate periods [near-future (2010–2039) and mid-century (20140-2069)]. At Bamako, Mali across the sowing dates, the early maturing variety showed yield decrease of 2–5 % between baseline (1980–2009) and near-future (2010–2039), and also yield decrease of 1.2–7% between baseline and mid-century (2040–2069). Medium maturing variety showed significant increase in yield of 5–8.2 % between baseline(1980–2009) and near-future (2010–2039) and 5.3–15.6 % yield increase between baseline (1980–2009) and mid-century (2040–2069). At Kano, the early maturing variety showed yield increase in June and August sowing dates by 1.2–15.9 % while July sowing date indicates yield decrease by 3.2% between baseline(1980–2009) and near-future(2010–2039), and also yield decrease between 0.6 and 12% across sowing dates by mid-century (2040–2069). For the medium maturing variety, June sowing date indicates imulated yield decrease by 12.7% while July and August sowing dates simulated increase in yield by 0.2-5.3% in the near-future (2010–2039). For mid-century(2040–2069), June sowing date indicates predicted yield increase by 11.4% while July and August sowing dates predicted yield decrease ranged from 3.2 to 9.7%

4. Discussion

Using the calibrated cultivar-specific parameters in APSIM, we evaluated the genetic traits of sorghum for yield changes and also adaptation strategies to climate change at two locations within the West Africa semi-arid region.The study revealed important differences in growth, development and resource use of sorghum varieties, emphasizing the suitability of specific characteristics and traits for different applications within the smallholder farming systems. The high model accuracy simulated for crop phenology and morphological traits compared to grain yield and total biomass for both varieties, possibly reflecting the additive effects of errors in simulating the different level of plant populations, and quality of the observed data. However, the

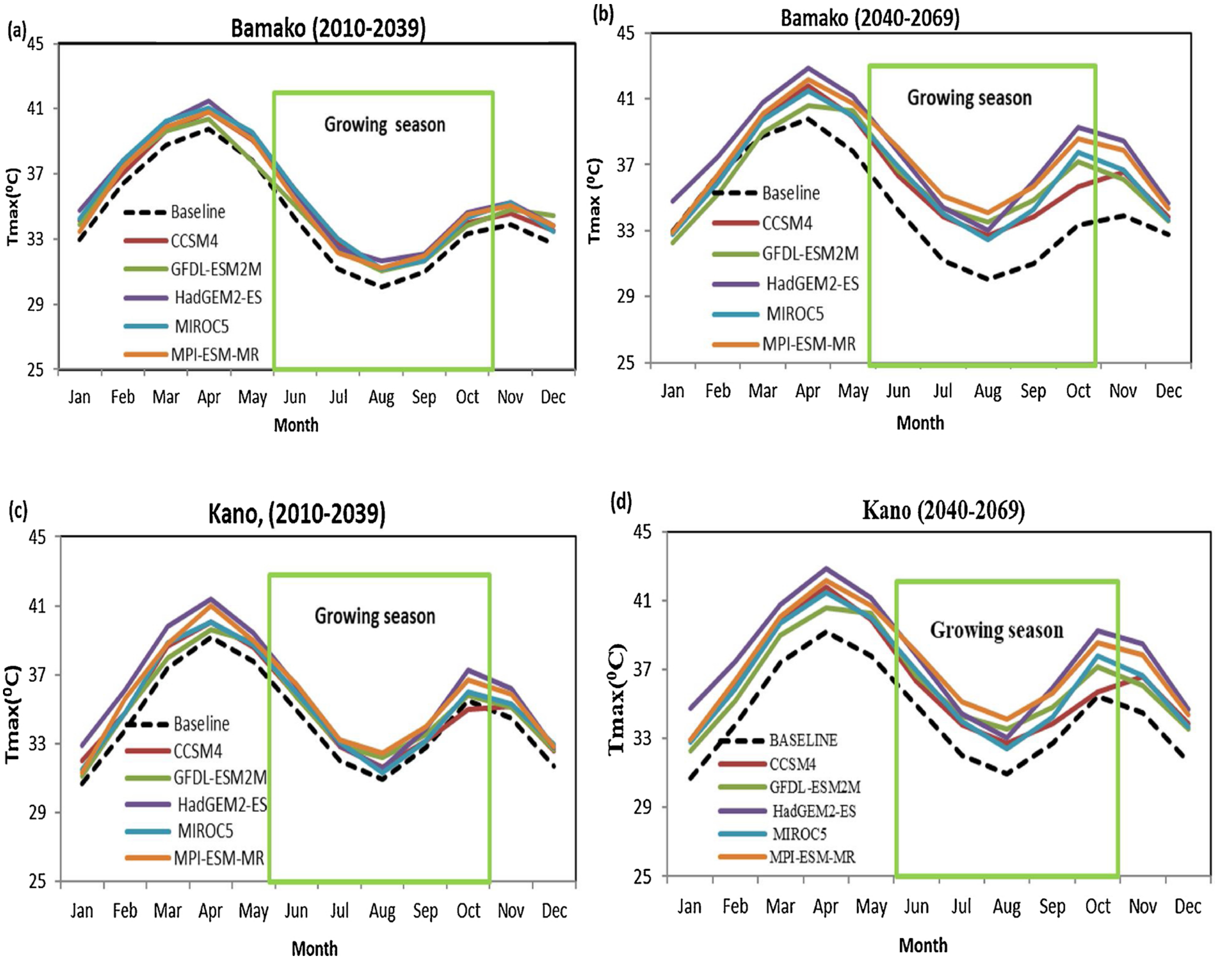

Fig. 6. Comparison of mean monthly maximum temperature variability between baseline(1980–2009) and GCMs in the near-future (2010–2039) and mid-century (2040–2069) in Bamako and Kano under RCP8.5.

Table 3
Ensemble of future changes of rainfall, minimum temperature (Tmin) and maximum temperature (Tmax) across GCMs scenarios.

Location	Parameter	Baseline	Near-Future (2010–2039)	Mid-Century (2040-2069)
Bamako	Rainfall(mm)	812	+1.5%	−10.2%
	Tmin (°C)	21.5	+1.2 °C	+2.2 °C
	Tmax (°C)	33.0	+1.2 °C	+2.1 °C
Kano	Rainfall(mm)	732	−1.1%	+7.4 %
	Tmin (°C)	21.2	+1.1 °C	+2.3 °C
	Tmax (°C)	33.8	+0.9 °C	+2.2 °C

results show high model accuracy with lower $RMSE_n$ estimated for total biomass and grain yield for medium maturing variety while low model accuracy with fair $RMSE_n$ for total biomass and grain yield estimated for early maturing variety. The variations in biomass and yield as observed in the present study could be associated model inability to simulate tillering response to changes in plant density as reported by Suchit et al., 2004

The yielding ability of any crops are determined by genotype,time of sowing, environmental factors and management practices where it is used to grow (Ajeigbe et al., 2018a,b). As earlier reported by Akinseye (2015), the difference in yield potential of the two sorghum varieties tested was attributed to genetic make-up of the varieties. For instance, early maturing variety is an improved local landrace, targeted to more drier areas with potential yield < 2000 kg/ha under good production management while medium maturing variety is an improved hybrid, targeted dual purpose for grain (approx.3500 kg/ha) and fodder for livestock feed. However, our results have also confirmed that rainfall and temperature could be a limiting environmental factors for sorghum productivity in semi-arid areas. On the sensitivity of current agricultural system to climate change, the increase in rainfall amounts projected by some GCMs (e.g. HadGEM2-ES, MIROC5) did not result to projected increase in mean simulated yield. Thus, the relative role of rainfall and temperatures in projections of crop yields create a plausible divergence such that the two variables are closely linked and interact and depend on scale and geographical location. For instance, over Kano, Nigeria, the significant increase in rainfall (22% and 31%) for HadGEM2-ES both in the near-future (2010–2039) and mid-century (2040–2069) climate regimes, indicated that simulated yield decline by 5% in the near-future (2010–2039) and approximately 11% in the mid-century (2040 - 2069)(2040–2069) for both varieties. The yield loss was found to be largely associated to projected increase in both minimum temperature (1.7 °C and 3.7 °C);maximum temperature (1.3 °C and 3.0 °C) in the near-future (2010–2039) and mid-century (2040–2069) during growing season.This result corroborates previous studies reported by on sorghum crop by Grossi et al. (2015), Faye, et al. (2018), Msongaleli et al. (2014) and for maize and pearl millet, Lizaso et al. (2018), Singh et al. (2017) respectively. Furthermore, simulated baseline yield < 1000 $kgha^{-1}$ in both locations for early maturing variety, the result revealed high inter-annual variability and potential yield loss which varied from 1% to 3.4% in the near-future (2010–2039) and 4.8%–6.2% in the mid-century (2040–2069) across GCMs. In contrast, the medium maturing variety remained the high yielding under climate change regimes resulting in significant yield gains of 8.5 % in the near-

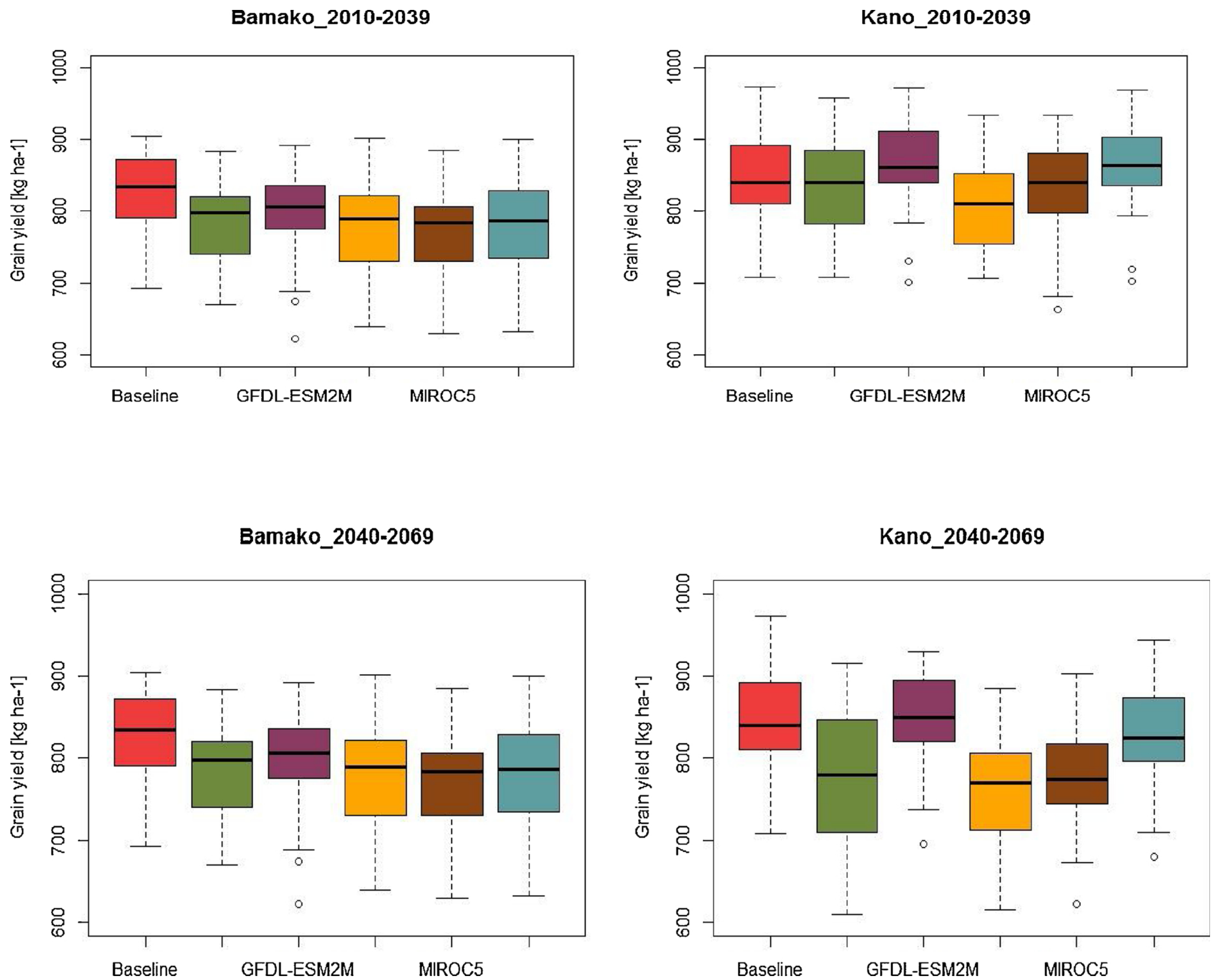

Fig. 7. Simulated grain yield variability between baseline (1980–2009) and climate change for the near-future (2010–2039) and mid-century (2040–2069) for Early maturing variety in Bamako, Mali and Kano, Nigeria.

future (2010–2039) in both locations while the mid-century (2040–2069) projected 14.2% yield increase over Bamako and 2% over Kano respectively. The results imply that rainfall pattern will be more favorable to the variety that are of medium to late maturity due to ability to recover from any moisture stress and also adjust to higher temperatures during growing season. The current climate will generally be more suitable as the warmer climate typically shortens the life cycle and more longer vegetative variety will be compensated for these conditions and produce higher yields than the early maturing variety that has short vegetative growth (Msongaleli et al., 2014; Gebrekiros et al., 2016). The projected increase in temperatures by GCMs (e.g HadGEM2-ES and MPI-ESM-MR) during growing season suggests increase in growing degree days (GDD) thereby accelerate crop development andfloral initiation processes resulting to poor grain filling and grain yield loss particularly for early maturing variety. Similar results were reported by Sennhenn et al., 2017 for short season grain legumes over semi-arid Eastern Kenya. Therefore, Identifying a proper variety according to length of growing period could be best ways to tackle climate change impacts on genetic diversity that exists in sorghum maturity groups (Singh et al., 2017). This would minimize drought and heat stress during the crop life cycle and the available seasonal resources would be fully utilized.

The sensitivity of some calibrated cultivar-specific parameters to 10% increase or decrease changes, showed the yield driver of both sorghum test in APSIM. RUE and light exintiction coeffiecient (coeff_ext) accounted for significant yield change varying from 7 to 10% for early maturing variety Medium maturing variety indicated Phyllo and RUE have stronger effects to yield changes compared to light exintiction coeffiecient. However, the little or no effect of PPsen confirmed less sensitivity to photoperiod of both varieties. Yield variations by both varieties could be associated to the differences in sources and sink size as reported by Rai et al. (1999) for pearl millet. Based on this study it was clearly evident that the medium maturing variety driven by Phllo and RUE (source), dm_per_seed and Maximum grain filling rate (sink) will produce higher yields under climate change. Though, the simulated grain yield shows decrease between baseline and future climate periods for early maturing variety, June sowing date had a significant yield advantage over July and August sowing dates in both locations while implies less risk to production. Also, for medium maturing variety, July sowing window revealed the highest yield gain over June and August sowing month except for Kano that indicated June sowing in the mid-century (2040–2069). According to the studies reported by Singh et al., 2017, drought and heat stress will be on the increase due to expected warming even during growing season. This implies that there may be little opportunity to adopt longer season varieties along with target sowing date to gain back the portion of the season (and radiation capture) lost due to accelerated development. This will be highly needed as adaptable strategy under climate change to avoid huge yield losses.

5. Conclusion

Understanding crop response towards projected changes in climate is required for formulating and disseminating adaptation strategies for

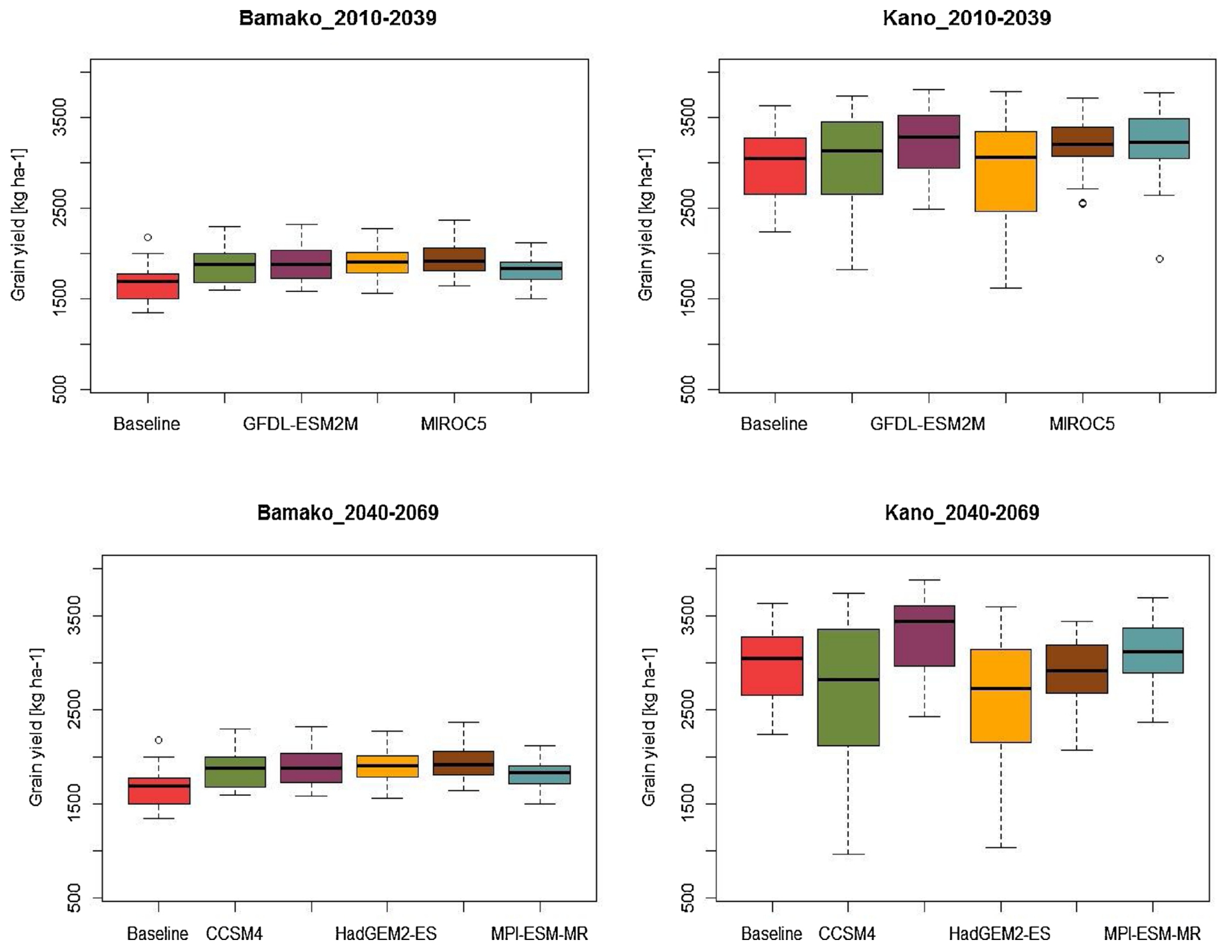

Fig. 8. Simulated grain yield variability between baseline (1980–2009) and climate scenarios in the near-future (2010–2039) and mid-century (2040–2069) for Medium maturing variety in Bamako, Mali and Kano, Nigeria.

yield improvement in a water-limited environments for smallholder farming system. This study has shown the capacity of crop simulation model to test crop dynamism using sowing dates strategies under changing climatic conditions towards modifying management practices. The long-term simulation for two climate periods had given more insight into the influence of variability in temperature and rainfall regimes on the sorghum varieties tested. However, the simulated yield under climate change showed increase in yields for medium maturing variety and decrease in yield for early maturing variety at both sites.

Additionally, the June sowing date was found favourable compared to July and August sowing dates for the early maturing variety under climate change in both locations. Meanwhile, July sowing could be

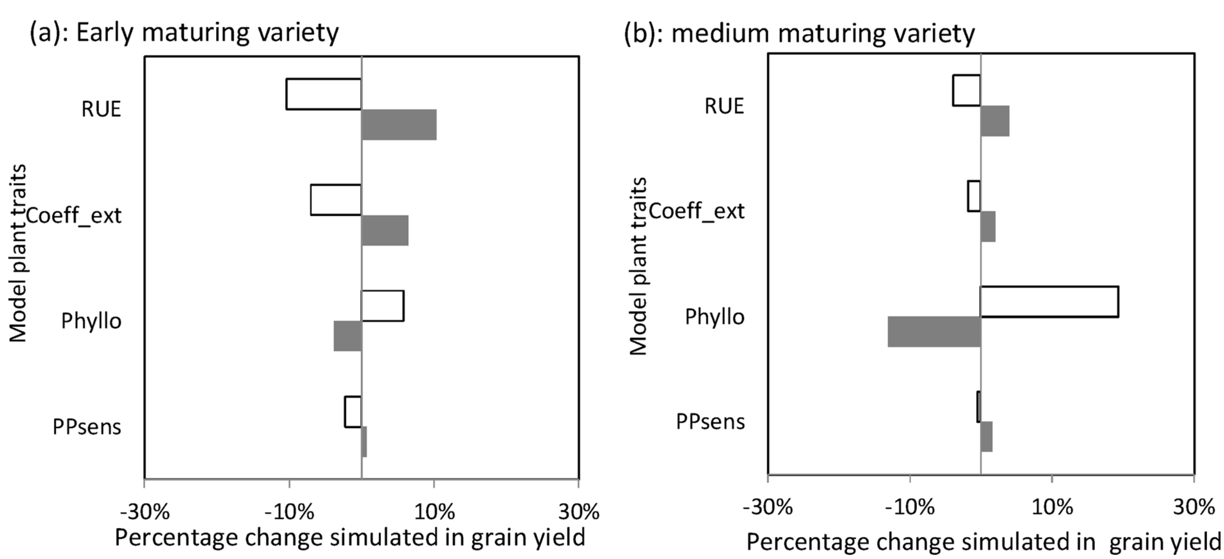

Fig. 9. Results of sensitivity analysis to change in key model plants traits for potential grain yield (**a**) Early maturing variety; (**b**) Medium maturing variety. The percentage change in potential yield after increasing or decreasing the value of the parameter along the y-axis with 10% is shown.

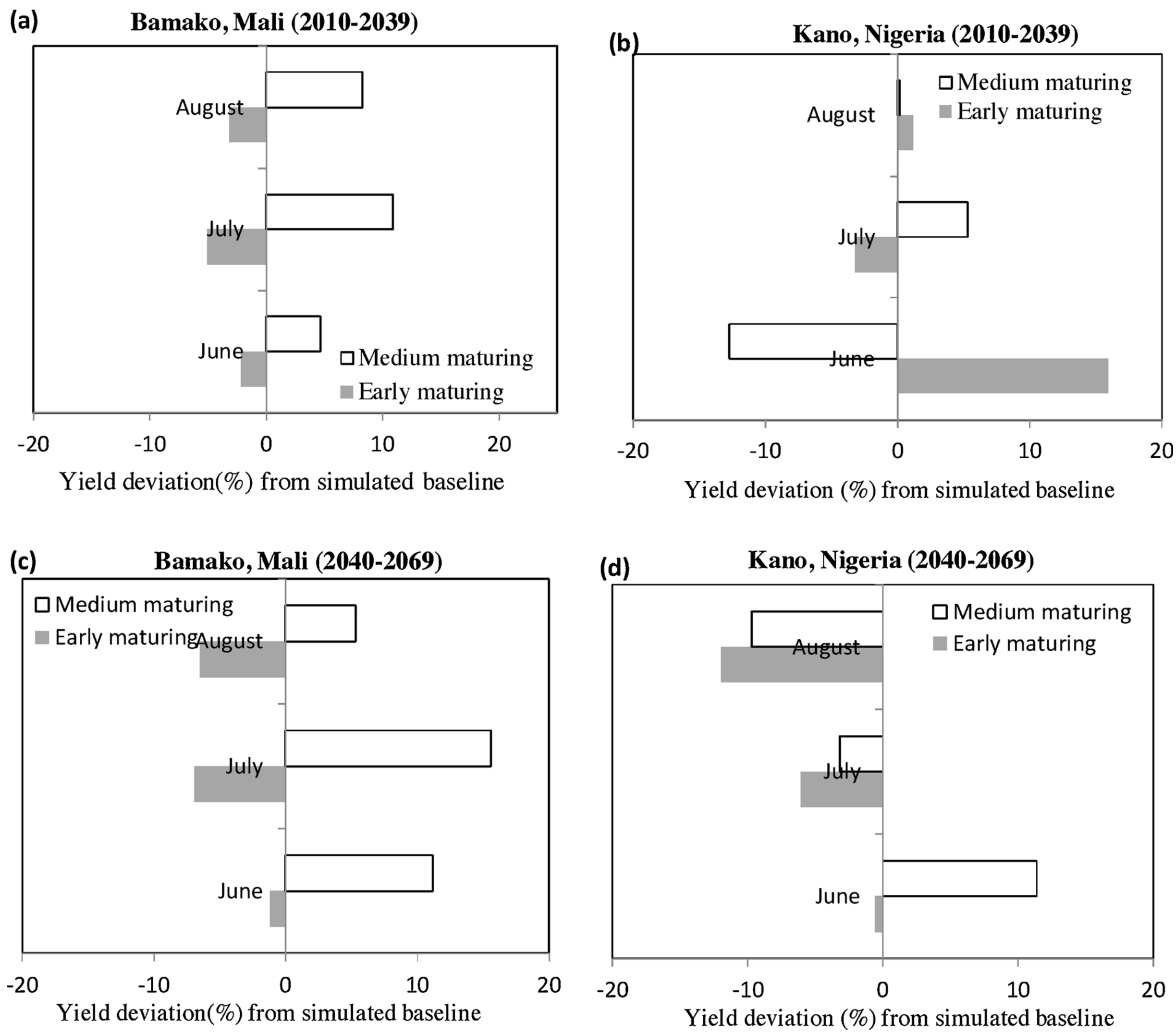

Fig. 10. Impact of sowing dates on simulated grain yield based on ensemble of contrasted GCMs for two climate periods [near-future(2010–2039 and mid-century (2040–2069)].

more appropriate for medium maturing variety resulted to higher yield gains under climate change. Our study, therefore conclude that modifying management practices through the deliberate choice between improved sorghum hybrid variety and local landraces accompanied by an appropriate time of sowing can be feasible options for enhancing the adaptive capacity of many smallholder sorghum farmers in Sudanian zone of West Africa. The approach will enable increasing production of sorghum crop for enhanced food security and livelihoods.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. However, there is no conflict of interest among the authors on the manuscript.

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