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Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa

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ABSTRACT

Climate change and variability challenge crop productivity and resource use efficiency in West Africa. Despite abundant research on climate change impact on crop yields and food security, little is known about climate change effects on the resource use efficiencies of the main staple crops in the dry savanna agro-ecological zone of northern Benin, West Africa. This study assessed the impact of climate change on water- and N-use efficiencies, and yields of maize and sorghum in the dry savanna of northern Benin considering three soil fertility management options (return of crop residues, mineral NPK fertilizer application, and combinations of both) and three bias-corrected ensemble mean predictions (BNU-ESM, CanESM2, and MPI-ESM-MR models) of future climate (2080–2099) under Representative Concentration Pathways (RCPs) of 2.6, 4.5, and 8.5. Seasonal rainfall is projected to decrease by 2% under RCP 2.6 and by 4% under RCP 4.5, and to increase by 1% under RCP 8.5 relative to the baseline mean (1986–2005). Increasing trends in minimum temperature of +1.0 °C (RCP 2.6), +2.0 °C (RCP 4.5), +4.7 °C (RCP 8.5) and maximum temperature of +1.1 °C (RCP 2.6), +2.0 °C (RCP 4.5), +4.6 °C (RCP 8.5) are also predicted. Solar radiation was projected to decrease by about 0.4 MJ m^{-2} d^{-1}. Under these projected climate scenarios, both CERES-Maize and CERES-Sorghum simulated positive responses in aboveground biomass accumulation during the vegetative growth stages. The predicted increase in aboveground biomass growth will be largest under RCP8.5 and smallest under RCP 2.6. This impact can be enhanced by improved soil fertility management, albeit with a crop-specific magnitude. Across the soil fertility management options, CERES-Maize predicted decreases in water-use efficiency by 17–53%, partial factor productivity of nitrogen (N) by 10–47%, and internal N-use efficiency by 5–33% for maize. Similarly, CERES-Sorghum simulated decreases in water-use efficiency (23–51%), partial factor productivity of N (22–49%), and internal N-use efficiency (13–47%) for sorghum. The largest overall loss in resource efficiency and yield were predicted for the RCP 8.5 scenario. The projected climate change for the dry savanna in northern Benin will likely reduce water- and N-use efficiencies as well as grain yields of maize and sorghum considerably but these results should be treated with caution due to shortcomings in the models structure for dealing with effects of enhanced CO_2. For reliable assessments of climate change impact on WUE, it is critically important to update parameterization and code of the CERES crop models in DSSAT to have a sufficiently strong effect of CO_2 on stomatal conductance and on transpiration.

1. Introduction

Climate change and variability threaten the future of cropping and livelihoods and food security of the population in West Africa (Wheeler and von Braun, 2013). Current production systems in the region, including northern Benin, are already vulnerable to soil fertility depletion (Christianson and Vlek, 1991; Gemenet et al., 2015; Schlecht et al., 2007) and increasingly exposed to rainfall variability and climate change (IPCC, 2013; IPCC, 2007). These challenges will affect resource use efficiency particularly in cereal- e.g. maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) based production systems.

Historically, West Africa has experienced wet periods (e.g.

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1930–1960), followed by dry spells (e.g. 1970–1980) and again wet years (e.g. 1990, 2000), but with increased spatial and temporal variability (Paeth et al., 2009). Furthermore, temperatures in the region are expected to gradually increase possibly by as much as 6 °C by 2100 (Riede et al., 2016). The projected changes in rainfall (Cooper et al., 2008; Gbobaniyi et al., 2014; Sylla et al., 2013), increase in temperature (IPCC, 2007, 2007; Paeth et al., 2009; Riede et al., 2016), and enriched CO_2 environments (IPCC, 2013) may alter the soil nutrient pools (Delgado-Baquerizo et al., 2013). The climate-driven changes in soil water and nutrient dynamics (Dintwe and Okin, 2018; Robertson and Rosswall, 1986) will seriously test the resilience of the major production systems (Lal, 1993; Whitehead and Crossman, 2012) and even more worsen food insecurity (Lal, 2004; Wheeler and von Braun, 2013). The projected variability in climate and weather parameters will negatively impact the Dry Savanna zones such as those of Benin, but the magnitude of the impacts remains uncertain. This hampers the development and implementation of appropriate adaptation measures and policies to assist farmers and decision-makers.

A number of studies have addressed climate change impacts on crop yields and food security worldwide (e.g. Wheeler and von Braun, 2013). Localized studies on crop yield responses to soil fertility under future climate conditions are coming on stream (Guan et al., 2017; Webber et al., 2014). Climate change impact assessment in West African Dry Savanna showed generally decreases in grain yield of maize (Rosenzweig et al., 2014; Thornton et al., 2011) and sorghum (MacCarthy and Vlek, 2012; Sultan et al., 2013). Reportedly, climate change impact on cereal yields will likely be more negative with an increased warming (Faye et al., 2018; Traore et al., 2017). However, little is known about the impact of climate change on water- and nutrient-use efficiencies of major cereals like maize and sorghum in West African Dry Savanna agro-ecological zones, including northern Benin, which presently have low to very low resource use efficiencies (Christianson and Vlek, 1991). Understanding the magnitude of resource use efficiency under climate change and variability is, therefore, crucial for the development of site- and crop-specific adaptation techniques.

Improving resource use efficiencies requires understanding of the often complex genetic-environment-management interactions. Crop simulation models that integrate the soil-plant-atmosphere complex can be useful tools to predict the consequences of climate change and climate variability on resource use efficiency, and help to design sustainable cropping systems. Several Cropping System Models (CSM) exist, e.g. Decision Support System for Agrotechnology Transfer (DSSAT-CSM) (Hoogenboom et al., 2015; Jones et al., 2003), Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1989). Such models permit the quantification of crop growth and yields, the evaluation of alternative production systems, and the climate change impact assessment (Hoogenboom et al., 2015). However, these models need first to be parameterized and evaluated for the target region (Hoogenboom et al., 2012; Hunt and Boote, 1998). Furthermore, when envisaging localized climate change impact assessment and in turn the development of adaptation or mitigation options, outputs of Global Circulation Models (GCM) must be bias-corrected with station observations (Gudmundsson et al., 2012; Hawkins et al., 2013) to significantly minimize systematic errors in weather inputs and improve crop model predictions of climate change impact on crops (Challinor et al., 2017; Glotter et al., 2014). Among these crop models, the DSSAT-CSM considers soil-water (Ritchie et al., 1998) and nutrient-related (Godwin and Singh, 1998; Godwin and Vlek, 1985) as well as environmental and plant physiological processes. In addition, CERES-Maize and CERES-Sorghum of the DSSAT-CSM were recently calibrated with data from a researcher-managed field trial (2014), validated with independent findings (2015), and next evaluated with datasets collected from researcher- and farmer-managed field trials conducted under rainfed and supplementary irrigation systems (2014–2015) in the dry savanna areas of northern Benin (Amouzou et al., 2018a, 2018b). Both models are, therefore, appropriate tools to explore potential impact of the projected climate change on water- and nutrient-use efficiencies of these crops and to assess sustainable intensification measures for the smallholders in northern Benin, West Africa. The objective of this study was to assess the impact of climate change on water- and N-use efficiencies, as well as on yields of maize and sorghum in the dry savanna areas of northern Benin.

2. Materials and methods

2.1. Study area

The study was conducted in 2014 and 2015 in the village of Ouri-Yori (10°49′16″N, 1°4′7″E) in the Dassari basin (10°44′0.15″-10°56′0.6″ N, 01°01′37″-01°11′33″ E) located in the administrative department of Atakora in North-west Benin, West Africa. The site is representative of the Dry Savanna climate regime with a distinct wet (May to October) and a dry season (November-April). The annual mean minimum and maximum temperatures were 21.3 ± 0.5 °C and 33.6 ± 0.5 °C, respectively over 1986-2005. During the same period, mean annual rainfall amounted to 1067 ± 185 mm. Major soil groups in the Ouri-Yori catchment are Plinthosols and Luvisols on the crests and upper slopes of the inland valleys and Alisols on the lower slopes and valley bottom lands (Steup, 2016). In general, the soils are shallow due to the presence of concretions and thus sampling depth was restricted to 60 cm. Soil profile information and weather data used as inputs for models calibration and evaluation were previously reported (Amouzou et al., 2018a, 2018b).

2.2. Crop simulation models

The CSM CERES-Maize and CERES-Sorghum models, which are part of the DSSAT V4.6 (Hoogenboom et al., 2015; Jones et al., 2003), were used to assess the impact of climate change on water- and N-use efficiencies and yields of maize and sorghum. The models simulated the growth and development of both crops using a daily time step from planting to maturity or specified harvest date. Potential growth is a function of the photosynthetically active solar radiation and its interception by crops but constrained by suboptimal air temperature, soil water, nitrogen (N), and phosphorus (P) deficits. Both models account for temperature effects on crop growth and grain filling rate based on cardinal temperatures (base, lower and upper optimum, maximum), assuming trapezoidal responses with 34 °C as optimum temperature (White et al., 2015; Wilkens and Singh, 2003). The potential effects of atmospheric CO_2 fertilization on crop physiological processes are taken into consideration by both crop models (White et al., 2015). Soil fertility effect (other than N) on daily biomass growth rate is integrated through a generic soil fertility factor (SLPF) (Hoogenboom et al., 2010; White et al., 2015). Both models simulate soil water (Ritchie et al., 1998), N (Godwin and Singh, 1998), P (Adam et al., 2018; Dzotsi et al., 2010) and carbon (C) balances and their dynamics (Gijsman et al., 2002; Porter et al., 2009). These crop models have not only been widely tested in Sub-Saharan Africa (Adnan et al., 2017; MacCarthy et al., 2010) but have also been used to assess climate change impacts (Faye et al., 2018; Jones and Thornton, 2003; Singh et al., 2014).

2.3. Models calibration and evaluation

Both models have recently been calibrated and validated for an improved variety of maize (cv. EVDT-97 STR) and a local variety of sorghum (cv. local), typical for the study region. The datasets (crop anthesis, physiological maturity, growth, and yields) for models calibration and validation were collected from researcher-managed on-farm experiment during the 2014 and 2015 cropping seasons. Independent datasets (In-season soil moisture and nitrate, crop growth,

Table 1
Observed (Obs.) and simulated (Sim.) anthesis (Days after planting, DAP), physiological maturity (DAP), harvest index, and final aboveground biomass (AGB, kg ha^{-1}) and grain yields (kg ha^{-1}) for maize and sorghum in the researcher-managed on-farm experiment during the 2014 and 2015 cropping seasons in the dry savanna region of Benin, West Africa.

Years	Variables	Maize (cv. EVDT-97 STR)				Sorghum (cv. Local)			
		Obs.	Sim.	RMSE	nRMSE (%)	Obs.	Sim.	RMSE	nRMSE (%)
2014	Anthesis	52	52	0	0	78	76	2	3
	Maturity	80	80	0	0	103	103	0	0
	Grain yield	2887	2840	47	2	1778	1822	44	2
	HI	0.32	0.34	0.02	5	0.22	0.22	0.00	0
	AGB yield	9110	8489	621	7	8265	8250	15	0.2
2015	Anthesis	53	54	1	2	99	78	21	21
	Maturity	86	85	1	1	128	109	19	15
	Grain yield	3718	3970	252	7	2455	2965	510	21
	HI	0.37	0.41	0.04	11	0.23	0.28	0.05	25
	AGB yield	9416	9669	253	3	11623	10281	1342	12

nitrogen (N) and phosphorus (P) uptake, and yields)), collected from separate researcher-managed and farmer-managed on-farm experiments (2014–2015), permitted the evaluation of the robustness of the parameterized models under rainfed and supplementary irrigations systems (Amouzou et al., 2018a; Amouzou et al., 2018b).

The inputs data (soil, weather, and management) and the results of the models calibration, validation, and evaluation were reported (Amouzou et al., 2018b). However, key highlights are recapped here. The accuracy of the models outputs was assessed with the root mean square error (RMSE) (Willmott, 1981), normalized-RMSE (nRMSE), and Index of agreements (d) (Yang et al., 2014). The acceptance thresholds for the models outputs were the lowest RMSE and nRMSE with d-value $\geq$ 0.75 for the yield components and d-value $\geq$ 0.60 for N and P uptake and soil moisture (Yang et al., 2014).

The parameterized models simulated accurately crop development, and yields of maize (cv. EVDT-97 STR) and sorghum (cv. Local) in 2014 and 2015 (Table 1). There was relatively large uncertainty between observed and simulated phenology for sorghum in the validation period (Table 1). This discrepancy resulted from the photoperiod sensitive characteristic of the local sorghum variety. Due to a lack of data, the models were not calibrated and validated against measured Leaf Area Index (LAI), which is important for accurate simulation of biomass accumulation, but still both models showed satisfactory goodness of fit between the observed and measured yield components.

CERES-Maize and CERES-Sorghum simulated satisfactory in-season soil moisture dynamics in various layers of the soil profile in the researcher-managed on-farm experiment in 2015 (Table 2). The models predicted accurately early season dynamics of N and P but tended to under-predict the dynamics from mid- to the end of the season (Amouzou et al., 2018b). Both CERES-Maize and CERES-Sorghum predicted well the total N uptake given the nRMSE (d) of 9% (0.91) and 14% (0.88), respectively. Both models predicted P uptake with lower accuracy than N uptake (Fig. 1), but still fitting in the threshold for the acceptance of the accuracy of plant nutrient demand outputs. CERES-Maize and CERES-Sorghum showed satisfactory performance and are, therefore, suitable tools for exploring water- and N-use efficiencies and yields of maize and sorghum as affected by the current and improved soil management regimes in the face of projected climate variability in the region.

2.4. Climate change scenarios

Historical data on observed daily minimum and maximum temperatures and solar radiation were collected from the National Meteorological Agency of Benin records at Natitingou ($\approx$63 km from the study site). Daily rainfall was collected from a rain gauge station at Tanguieta ($\approx$27 km from the study site) for the period 1986–2005, which represents the climate baseline.

Future (2080–2099) bias-corrected ensemble mean predictions of climate parameters were estimated with the use of three Global Circulation Models (GCMs : BNU-ESM, CanESM2, and MPI-ESM-MR) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC) (Gudmundsson et al., 2012; Hawkins et al., 2013). The late century (2080–2099) climate changes scenarios were assumed because the Second National Communication on Climate Change of Benin Republic (MEHU, 2011) projected greater rainfall variability and warming trend towards 2100. The three RCPs (RCP 2.6, RCP 4.5, and RCP 8.5 (IPCC, 2013) differ from each other in the assumptions of population, economic growth, energy consumption and sources, and land use (van Vuuren et al., 2011). The RCP 2.6 is a low level (peak and decline) Greenhouse Gases (GHG)

Table 2
Agreement between measured and simulated in-season soil moisture content with CERES-Maize and CERES-Sorghum in the 0–20, 20–40, and 40–60 cm soil layers under rainfed (RF) and supplementary irrigated (SI) conditions with fertilization (+F) in the 2015 cropping season in the dry savanna region of Benin, West Africa.

CSM	Treatments	Soil layers (cm)	Observations (cm^3 cm^{-3})	Simulations (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})	nRMSE (%)	d-values
CERES-Maize	RF + F	0-20	0.215	0.214	0.014	6	0.87
		20-40	0.251	0.262	0.280	11	0.65
		40-60	0.280	0.295	0.035	13	0.71
	SI + F	0-20	0.232	0.219	0.028	12	0.61
		20-40	0.284	0.259	0.035	12	0.64
		40-60	0.314	0.292	0.041	13	0.69
CERES-Sorghum	RF + F	0-20	0.188	0.196	0.035	19	0.85
		20-40	0.237	0.242	0.038	16	0.89
		40-60	0.323	0.273	0.062	19	0.75
	SI + F	0-20	0.237	0.195	0.480	20	0.83
		20-40	0.290	0.238	0.055	19	0.84
		40-60	0.302	0.267	0.043	14	0.87

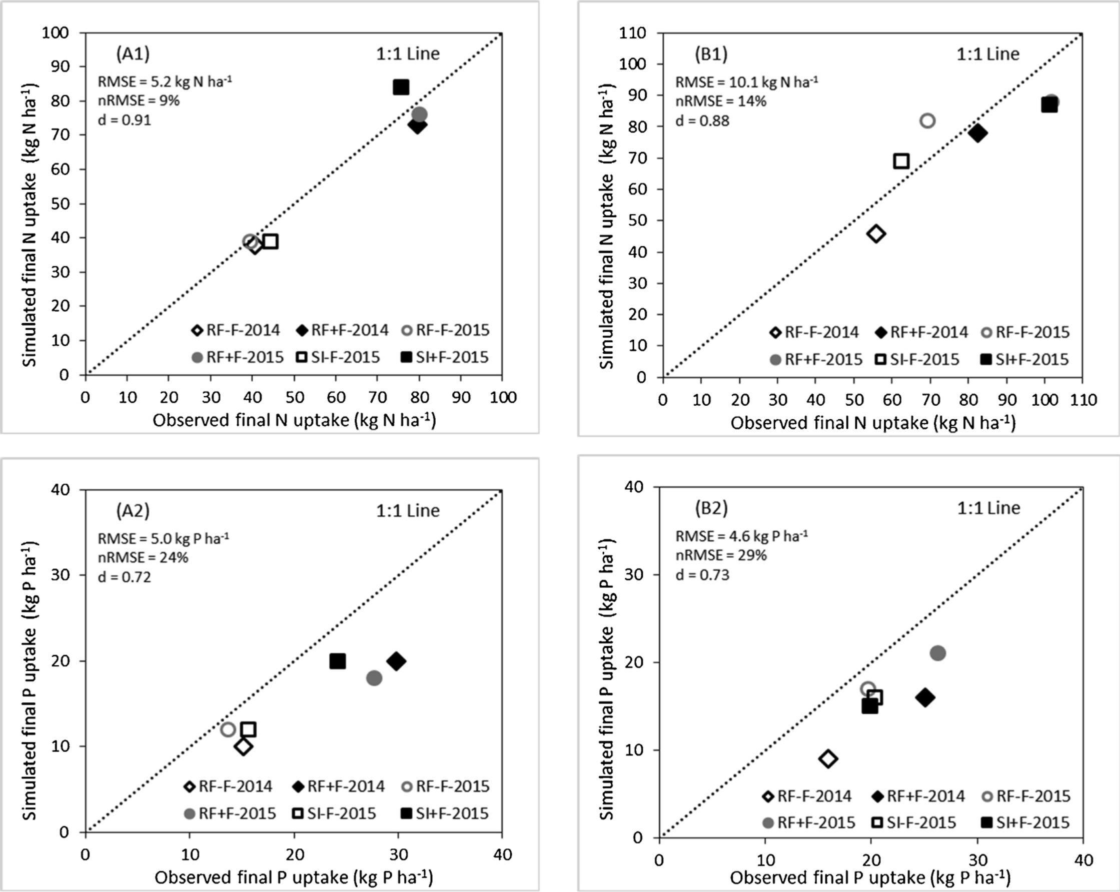

Fig. 1. Observed and simulated N (A1, B1) and P (A2, B2) uptake for maize (A1, A2) and sorghum (B1, B2) under rainfed and supplementary irrigation without (open symbols) and with fertilization (solid symbols) in researcher-managed experiment for the 2014 and 2015 cropping seasons.

forcing scenario, aiming to limit the increase in global mean temperature to 2 °C (van Vuuren et al., 2011). The RCP 4.5 is a medium pathway to stabilize the radiative forcing at 4.5 W m^{-2} by 2100 without overshoot (Thomson et al., 2011), while RCP 8.5 assumes a rising GHG pathway in absence of climate change policy (Riahi et al., 2011). The daily bias-corrected rainfall, solar radiation, minimum and maximum temperature outputs for the baseline and future periods were obtained from the CGIAR Research Program on Climate Change Agriculture and Food Security (CCAFS, 2017). We selected the three climate models among 21 GCMs available, i.e. BNU-ESM of the College of Global Change and Earth System Science, Beijing Normal University (Ji et al., 2014), CanESM2 of the Canadian Center for Climate Modeling and Analysis (Chylek et al., 2011), and MPI-ESM-MR of the Max Plank Institute for Meteorology (Jungclaus et al., 2010). The selection was based on the high correlation between historical projections and observations (Fig. 2), as well as on a realistic representation of the seasonal rainfall cycle with the lowest deviations in rainfall, temperatures, and solar radiation. The ensemble mean (Guan et al., 2017) of the three climate models was considered for the future weather parameters (2080–2099). The ensemble mean of weather parameters from several climate models considerably improves the prediction accuracy compared to individual model predictions (Gbobaniyi et al., 2014; Guan et al., 2017; Mugume et al., 2017). The default atmospheric carbon dioxide (CO_2) concentration of Mauna Loa (NOAA/ESRL, 2018) was used for the baseline period, while predicted CO_2 concentrations (Table 3) reported for RCP 2.6, 4.5, and 8.5 scenarios towards 2100 were used for the future period (Meinshausen et al., 2011).

The historical and future climate datasets served as inputs to run the models for investigating the responses of both crops to soil fertility management options under the three climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5, Section 2.2).

2.5. Soil fertility management scenarios

Crop responses under the historical and future climates were assessed based on three soil fertility management strategies, namely (1) an un-amended soil as control (no fertilization), (2) integrated soil-crop management (recommended rates of NPK at 44, 15 and 18 kg ha^{-1}, respectively, and recycling of crop residues), and (3) a high mineral fertilizer use of 80, 26, and 30 kg NPK ha^{-1} (Igue et al., 2015; Saidou et al., 2012). With the high mineral fertilizer use treatment, N was split-applied as urea (46%), 50% of the total amount at 20 Days after planting (DAP) and the remaining 50% at 45 DAP. We assumed the planting date of June 25th, fitting in the optimum planting window (Jibrin et al., 2012) in the West African Dry Savanna. Along with the first N application, P was input in the management file as triple superphosphate (46% P_2O_5) and K as potassium chloride (60% K_2O) at rates of 26 kg P ha^{-1} and 30 kg K ha^{-1}, respectively. In the integrated soil-crop management, N, P, and K were set at the rates of 21, 15, and 18 kg ha^{-1} for the first fertilization (20 DAP) under each crop as urea, triple superphosphate, and potassium chloride, respectively. The first application was top dressed with 23 kg N ha^{-1} as urea for the second fertilization (45 DAP) bringing the total N applied to both crops to 44 kg ha^{-1}. The combination of climate change scenarios and soil fertility management strategies was run with each CSM model in a seasonal mode to simulate various parameters as a proxy for crop responses including aboveground biomass accumulation, N and P uptake, water- and N-use efficiencies as well as yields. The assessment of climate change impact was conducted on Alisols since they represent the dominant agriculturally used soil type in the case study region

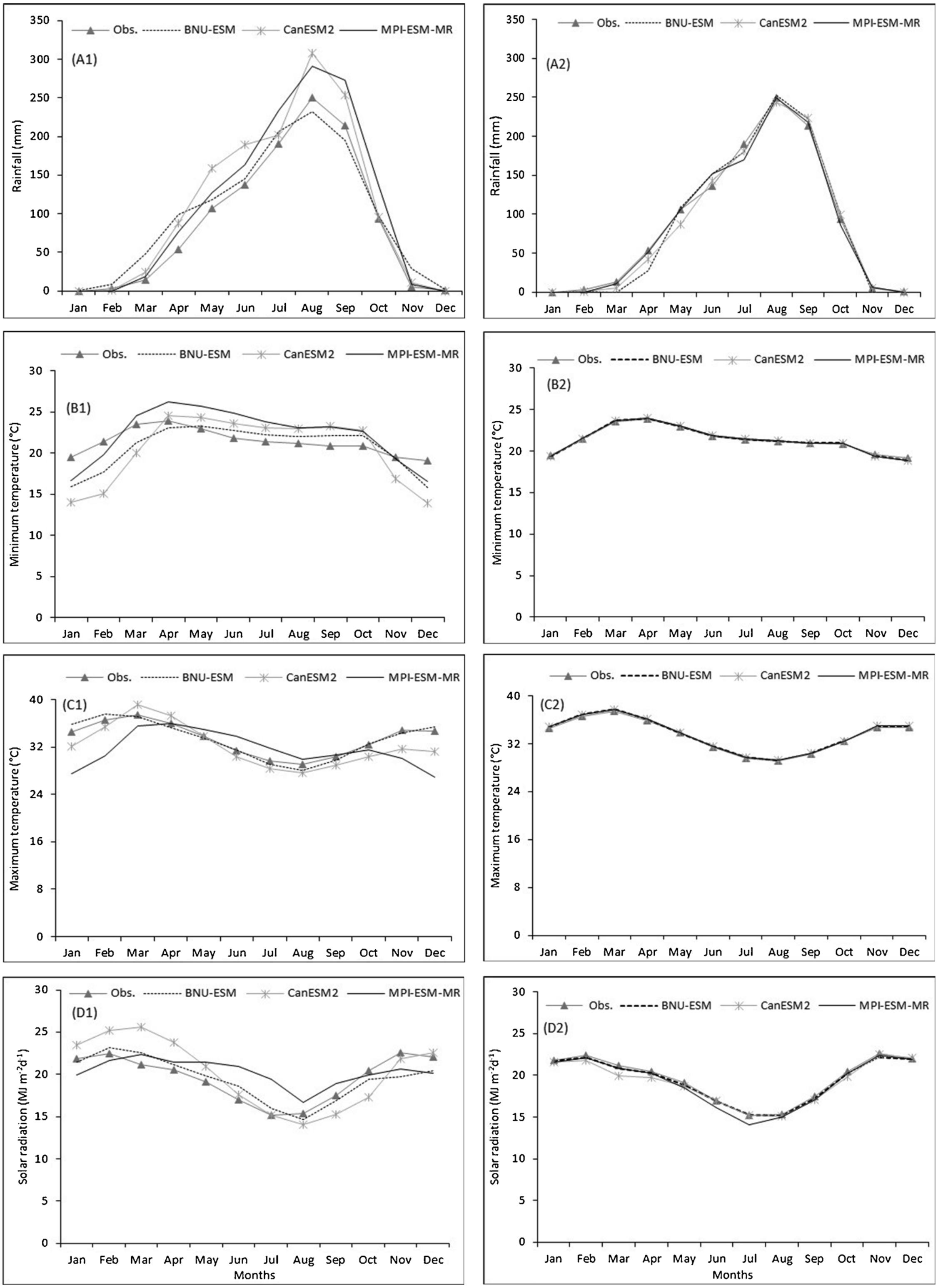

Fig. 2. Historical observations (1986–2005) and GCM-(BNU-ESM, CanESM2, and MPI-ESM-MR)-based projections of rainfall (mm), maximum and minimum temperatures (°C), and solar radiation (MJ m^{-2} d^{-1}) before (A1, B1, C1, D1) and after calibration (A2, B2, C2, D2) of the models outputs.

(Amouzou et al., 2018b; IUSS Working Group WRB, 2014; Steup, 2016).

2.6. Data analysis

Climate change impact on grain yields, N and P uptake, and water- and N-use efficiencies were evaluated by comparing predicted responses of maize and sorghum for each of the three soil fertility management options under historical climate data (1986–2005) with responses to the same options assuming the same initial soil conditions under a future climate (2080–2099) for the RCPs 2.6, 4.5, and 8.5. Model outputs for water use efficiency (WUE), N-partial productivity (N-PFP), and N-internal utilization efficiency (N-IE) were expressed as grain yield per unit of evapotranspiration [kg grain (mm ET)$^{-1}$], grain

Table 3
Climate change scenarios used in the weather input files and the environmental modifications.

Scenario	GCM	Variables	Atmospheric CO_2 (ppm)
Baseline	Observation	Rainfall Min. and max. temperatures,and solar radiation	347-380
RCP 2.6	BNU-ESM		421
RCP 4.5	CanESM2		538
RCP 8.5	MPI-ESM-MR		936

yield per N fertilizer applied [kg grain (kg N fertilizer)$^{-1}$], and grain yield per N uptake [kg grain (kg N uptake)$^{-1}$], respectively.

3. Results

3.1. Predicted changes in key climate parameters

Based on the averages across the climate models BNU-ESM, CanESM2, and MPI-ESM-MR, the predicted seasonal rainfall change (%) were -2 ± 6 (RCP 2.6), -4 ± 8 (RCP 4.5), and +1 ± 9 (RCP 8.5) (Fig. 3A1, A2). Temperatures (°C) are predicted to increase, i.e. minimum temperatures (Fig. 2B1, B2) by +1.0 ± 0.2, +2.0 ± 0.2, +4.7 ± 0.4, and maximum temperatures (Fig. 3C1, C2) by +1.1 ± 0.2, +2.0 ± 0.3, +4.6 ± 0.5, for RCPs 2.6, 4.5, and 8.5,

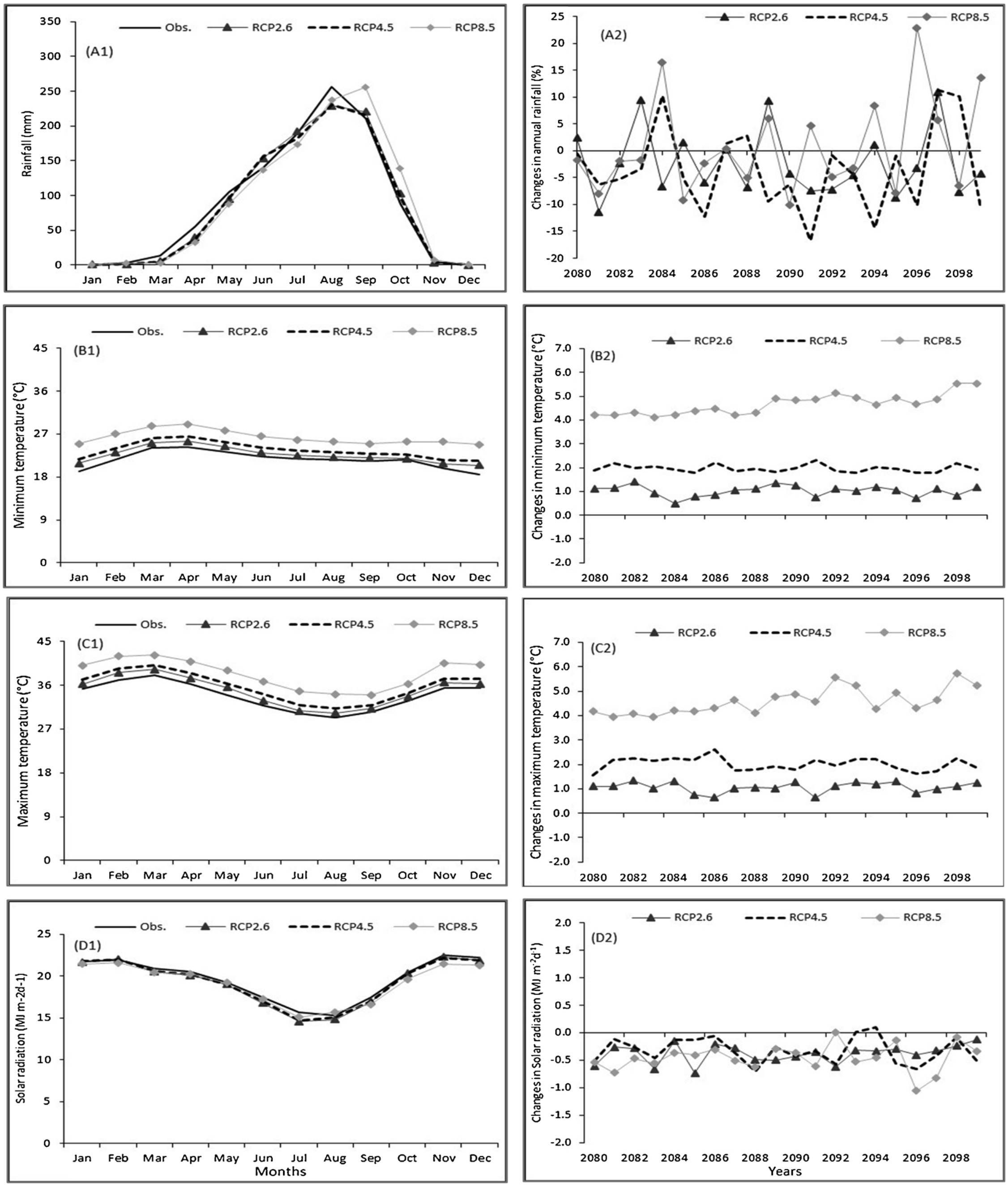

Fig. 3. Changes in monthly (A1, B1, C1 D1) and inter-annual (A2, B2, C2, D2) trends based on averages of bias-corrected predictions of BNU-ESM, CanESM2, and MPI-ESM-MR models (2080–2099) for rainfall (A1, A2), minimum temperature (B1, B2), maximum temperature (C1, C2), and solar radiation (D1, D2). Changes are relative to baseline mean (1986–2005) under three Representative Concentration Pathways (RCPs): RCP 2.6, 4.5, and 8.5.

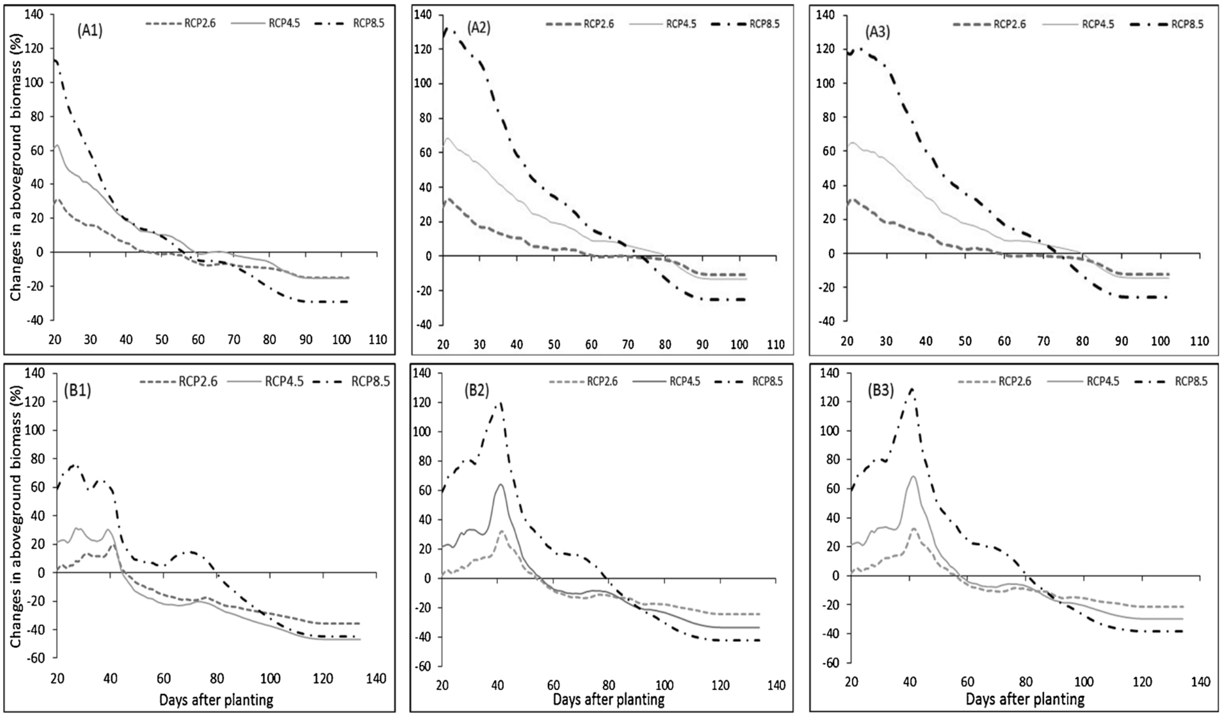

Fig. 4. Changes in cumulative aboveground biomass responses of maize (A1, A2, A3) and sorghum (B1, B2, B3) under future climate (2080–2099) relative to historical means (1986–2005) assuming an un-amended soil as control (A1, B1), integrated soil-crop management (A2, B2), and high mineral fertilizer use (A3, B3) and three Representative Concentration Pathways (RCPs): RCP 2.6, 4.5, and 8.5.

respectively. Solar radiation (MJ $m^{-2}d^{-1}$) is predicted to decrease by -0.4 ± 0.6 for RCP 2.6, -0.3 ± 0.6 for RCP 4.5, and -0.5 ± 0.4 for RCP 8.5 (Fig. 3D1, D2).

3.2. Changes in cumulative aboveground biomass

Under the projected climate, both CERES-Maize and CERES-Sorghum predict more vigorous biomass accrual under climate change scenarios than under the historical condition during the vegetative growth (Fig. 4). The predicted enhanced initial aboveground biomass growth was crop specific and in general greater under RCP 8.5 and RCP 4.5 than under RCP 2.6. With integrated soil-crop management or high mineral fertilizer use, the vegetative growth enhancement was greater than for the un-amended soil conditions. CERES-Maize predicted lower biomass accrual in the 2080-99 run than in the historical run from ≈ 60 days after planting (DAP) (Fig. 4A1) under all three climate scenarios in the un-amended treatment, whereas this would occur from approximately 70 DAP with integrated soil-crop management or high mineral fertilizer use (Fig. 4A2, 3). Regardless of the soil fertility management strategy, the predicted losses in biomass under RCP 2.6 and RCP 4.5 were similar and RCP 8.5 being higher than in the other 2 RCPs (Fig. 4A1, 2, 3). CERES-Sorghum predicted an extended biomass accumulation for RCP 8.5 (up to ≈ 80 DAP) compared to RCP 2.6 and 4.5 (< 60 DAP). CERES-Sorghum simulated also smaller difference in biomass accrual for RCPs 2.6 and 4.5 compared to RCP 8.5, except for the un-amended conditions (Fig. 4B1, 2, 3).

3.3. Impact on seasonal N and P uptake

The CERES-Maize model predicted general decreases in N (Fig. 5A1) and P (Fig. 5A2) uptake by maize under future climate conditions, but the extent of the reductions depended on soil fertility management and RCP (Table 4). The decreases in N and P uptake by maize were predicted to be highest with RCP 8.5, irrespective of the soil fertility scenarios. CERES-Sorghum also predicted declines in N and P, though to a lesser degree (Fig. 5B1, B2, Table 4).

3.4. Biomass and grain yield trends

The improved soil fertility management strategies, integrated soil-crop management and high use of mineral fertilizer, increased biomass and grain yields of maize and sorghum under both historical and future climate compared to the un-amended soil control (Fig. 6). Both models predicted decreases in biomass and grain yields, irrespective of the soil fertility management strategy (Fig. 6, Table 4). The CERES-Maize simulated a decrease in harvested maize biomass of 11–15%, 13–15%, and 25–29% and grain yield reduction of 10–17%, 17–19%, and 44–46% for RCP 2.6, 4.5 and 8.5, respectively. The decreases in the predicted total sorghum biomass at harvest were 21–35% for RCP 2.6, 30–47% for RCP 4.5, and 38–45% for RCP 8.5, and grain yields declined by 22–38%, 31–49%, and 44–51%, for RCP s 2.6, 4.5 and 8.5, respectively (Table 4). The largest reductions in grain yield and biomass accumulation were estimated under RCP 8.5, irrespective of crop and soil fertility management (Fig. 6).

3.5. Impact on water- and N-use efficiencies

Both methods of soil fertility management, sole mineral and combined mineral and organic amendment, enhanced water-use efficiencies (WUE) of maize and sorghum significantly as compared to the control (Fig. 7A1 and B1). The response of WUE to soil fertility management was, however, higher for maize than for sorghum. The WUE were consistently lower in all future scenarios than with historical condition and more so for the RCP 8.5. CERES-Maize predicted a decrease in water-use efficiency of 17–53% and CERES-Sorghum of 23–51% (Table 4).

The integrated soil-crop management practice sustained higher partial factor productivity (N-PFP) of maize (Fig. 7 A2) and sorghum (Fig. 7 B2) compared to the high use of mineral fertilizer considering both historical climate and future climate scenarios. Compared to the

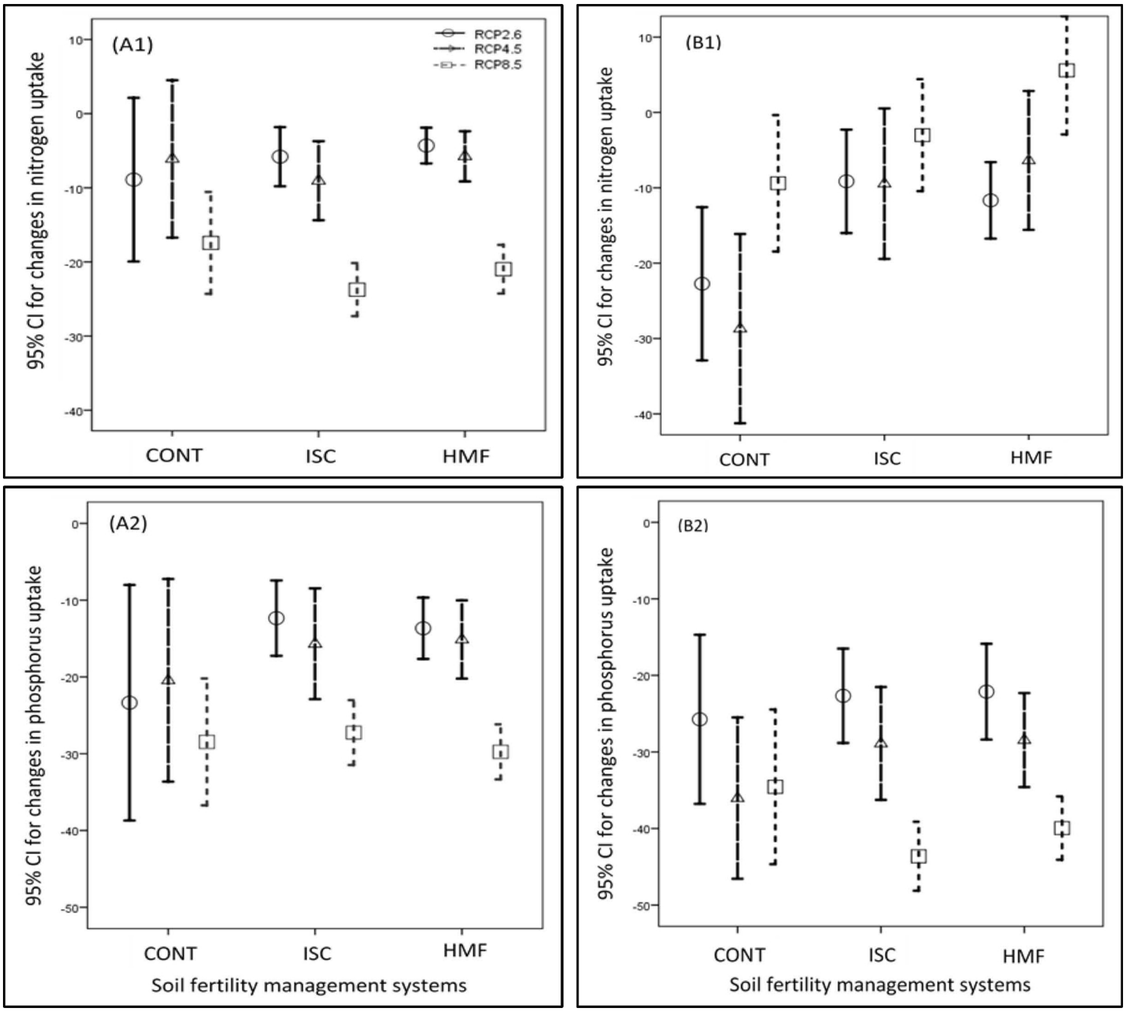

Fig. 5. Confidence intervals (CI, 95%) for changes in seasonal N (A1, B1) and P (A2, B2) uptake by maize (A1, A2) and sorghum (B1, B2) relative to historical means (1986–2005) assuming three soil fertility management levels (un-amended soil as control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer (HMF) under future climate (2080–2099) under three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5 (see Section 2.5).

Table 4
Changes (%) in grain and biomass yield, N and P uptake; Water use efficiency (WUE), N-partial productivity (N-PFP), and N-internal utilization efficiency (N-IE) under climate change scenarios compared to the historical condition.

Crops	Treatments		Changes in grain yield (%)	Changes biomass yield (%)	Changes in N uptake (%)	Changes in P uptake (%)	Changes in WUE (%)	Changes in N-PFP (%)	Changes in N-IE (%)
Maize	CONT	RCP 2.6	−17	−15	−9	−23	−23		−10
		RCP 4.5	−17	−15	−6	−20	−26		−13
		RCP 8.5	−44	−29	−17	−28	−51		−32
	ISC	RCP 2.6	−10	−11	−6	−12	−17	−10	−5
		RCP 4.5	−18	−13	−9	−16	−25	−18	−10
		RCP 8.5	−46	−25	−24	−27	−52	−46	−29
	HMF	RCP 2.6	−12	−12	−4	−14	−18	−12	−8
		RCP 4.5	−19	−14	−6	−15	−26	−19	−14
		RCP 8.5	−47	−26	−21	−30	−53	−47	−33
Sorghum	CONT	RCP 2.6	−38	−35	−23	−26	−42		−18
		RCP 4.5	−49	−47	−29	−36	−51		−27
		RCP 8.5	−51	−45	−9	−35	−48		−45
	ISC	RCP 2.6	−26	−25	−9	−23	−27	−26	−19
		RCP 4.5	−36	−34	−9	−29	−34	−36	−29
		RCP 8.5	−49	−42	−3	−44	−42	−49	−47
	HMF	RCP 2.6	−22	−21	−12	−22	−23	−22	−13
		RCP 4.5	−31	−30	−6	−29	−31	−31	−26
		RCP 8.5	−44	−38	6	−40	−44	−44	−47

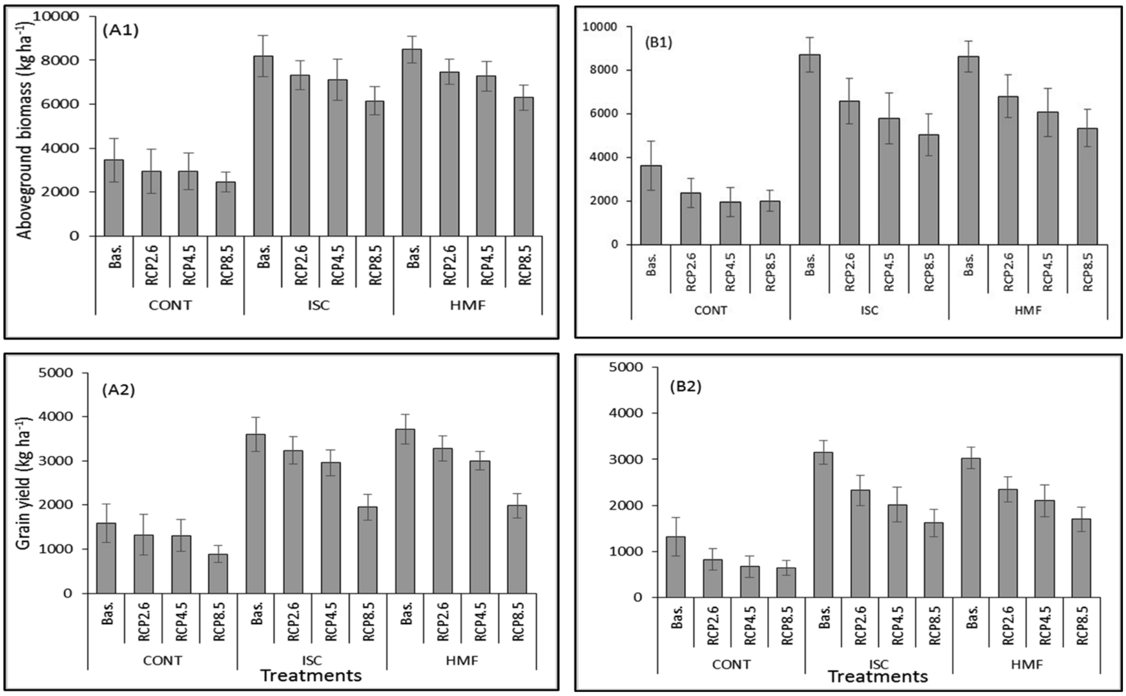

Fig. 6. Predicted aboveground biomass (A1, B1) and grain yield (A2, B2) of maize (A1, A2) and sorghum (B1, B2) as impacted by an un-amended soil as control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer use (HMF) assuming a historical climate (Baseline: Bas., 1986–2005) and future climate (2080–2099) and considering three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5 (see Section 2.5).

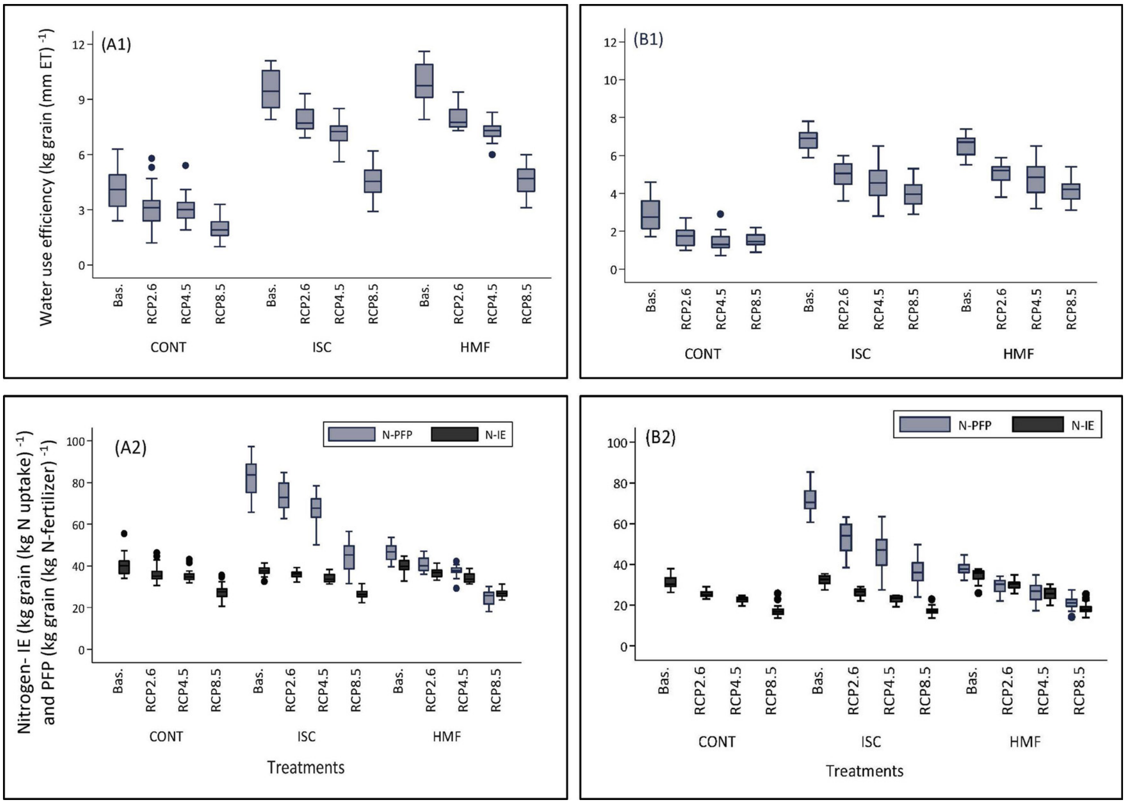

Fig. 7. Simulated water-use efficiency (WUE), nitrogen-internal use efficiency (N-IE) and partial factor productivity (N-PFP) of maize (A1, A2) and sorghum (B1, B2) under an un-amended soil as control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer (HMF) considering the historical climate (Baseline: Bas.,1986–2005) and future climate (2080–2099) and according to three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5 (see Section 2.5).

period 1986–2005, the partial factor productivity of applied N (N-PFP) was significantly reduced in all future scenarios, and more so with RCP 8.5. The projected decreases in the N-PFP factor varied from 10 to 47% with CERES-Maize and 22 to 49% with CERES-Sorghum (Table 4).

The simulated N-internal utilization efficiency (N-IE) did not change too much with soil fertility management options. However, the predicted N-IE showed a declining trend under the climate change scenarios moving from RCP 2.6 to RCP 8.5 with RCP 8.5 showing the highest decrease (Fig. 7A2, B2). Under RCP 8.5, the predicted changes in internal N-use efficiency dropped by about 33% with CERES-Maize and by 47% with CERES-Sorghum (Table 4). Hence, the climate assumptions under RCP 8.5 would considerably reduce water- and N-use efficiencies of both maize and sorghum.

4. Discussion

Future trends of rainfall, temperature, and solar radiation under the low (RCP 2.6), medium (RCP 4.5), or high (RCP 8.5) level of GHG-forcing scenarios for the dry savanna region of northern Benin were used for the first time in northern Benin to quantify the impact of projected climate changes on water- and N-use efficiency, N and P uptake as well as on biomass and grain yields of maize and sorghum considering three soil fertility management strategies.

4.1. Future climate trends

The predicted changes in temperatures for the study region are in line with existing estimates of warming trends (Dike et al., 2015; Riede et al., 2016). For instance, the Benin Second National Communication on Climate Change predicts temperature increases varying from 2.6 °C in the southwest to 3.3 °C in northern Benin towards 2100 (MEHU, 2011). In contrast, large discrepancies in seasonal rainfall cycles were previously reported (Sylla et al., 2013) for the whole of West Africa, including the study region. The (MEHU, 2011) reported an increase in mean annual rainfall by 13% in the northwest and by 15% in the northeast of Benin. The newly developed bias-corrected predictions, as estimated here with the ensemble mean of BNU-ESM, CanESM2, and MPI-ESM-MR models (Fig. 2), matched these estimates quite well and thus served as input for the crop model simulations reported here.

4.2. Climate effects on biomass accrual and resource use efficiency

Key climate projections for the dry savanna region of Benin generally depict a warming trend and inter-annual rainfall variability for all three climate scenarios considered. The warming temperatures led to increases in growing degree days (GDD) or thermal time, which resulted in the accelerated vegetative growth predicted for maize and sorghum under the climate change scenarios compared to the baseline. Improved soil fertility management options, e.g. integrated soil-crop management and high use of mineral fertilizers, boost the effects of warming temperatures on biomass accumulation of maize and sorghum under future climate conditions, but only during the vegetative growth stages (Fig. 4A2, A3, B2, and B3). In addition, the warming temperatures will accelerate N mineralization and that could drive early growth. The decline in late biomass accumulation under all the three climate change scenarios compared to the historical run, regardless the soil fertility management options results from the shortening of growing period (e.g. reproductive phase) under warming conditions. The higher temperatures drive early crop growth at the expense of soil water use (Rosenzweig and Iglesias, 1998), which is then not available for grain filling. This phenomenon is commonly known as haying-off (van Herwaarden et al., 1998). The increased water loss through evapotranspiration under warming temperatures amplify water deficit late in the season (Peng et al., 2018). This probably reflected in the reduced WUE predicted under all climate change scenarios compared to the historical conditions.

The water deficit threatens nutrient uptake (Bowen and Baethgen, 1998) and use efficiency as warmer temperatures under climate change also alter nutrient assimilation (Brouder and Volenec, 2008). The combination of the predicted warming and rainfall variability will negatively impact water- and N-use efficiencies in the maize and sorghum-based production systems in the Savanna region of Benin.

Of particular interest for biomass growth and WUE is an enrichment of atmospheric CO_2 that occurs under all the three scenarios. Our results show that WUE were consistently lower in all future climate scenarios. Both CERES-Maize and CERES-Sorghum predicted decreased WUE under elevated CO_2 levels. The physiological effects of elevated CO_2-levels on biomass growth and WUE are reportedly larger with C_3 crops than for C_4 crops (Kimball and Mauney, 1993; Leakey, 2009; Mauney et al., 1994; Poorter, 1993; Reddy et al., 1995). Physiological responses of C_4 crops such as maize and sorghum to elevated CO_2 concentrations occur mainly via reduced stomatal conductance, which leads to lower canopy transpiration and crop water use (Leakey, 2009; Leakey et al., 2006). Thus, there is an increase in WUE. In contrast to the negative WUE reported here, (White et al., 2015) simulated positive responses of WUE to elevated atmospheric CO_2 for rainfed sorghum experiment in Manhattan, Kansas, USA but their result was predominantly driven by a greater growth in biomass. Both CERES-Maize and CERES-Sorghum account for CO_2 fertilization effects assuming enhanced radiation use efficiency (RUE), resulting in biomass growth effect, instead of transpiration decrease (White et al., 2015). It is also likely that there are direct effects of temperature on canopy development that might enhance early growth and lead to increased early season crop water use. In addition, WUE is closely related to transpiration efficiency which is inversely proportional to the mean saturation deficit of the atmosphere which increases with temperature. Thus, increased vapor pressure deficit with increased temperature will cause increased water use.

The interacting effects of CO_2, stomatal conductance, and canopy temperature are expected to exacerbate impacts of warming temperatures (White et al., 2011). Crop photosynthesis and transpiration are also regulated by stomatal resistance and affected by CO_2 and vapor pressure deficit (VPD) (Stöckle et al., 1992). The RUE is closely related to VPD (Kiniry et al., 1998), which increase with warming temperatures (Lobell et al., 2015; Shekoofa et al., 2016) and drive stomatal closure (Ben-Asher et al., 2013) and leaf level CO_2 exchange rate (Kiniry et al., 1998). The integration of effects of these factors is crucial and the model must be able to deal with that in a biologically realistic manner to be credible. The CERES framework is currently unable to accommodate this and therefore, it needs to be adapted for these physiological mechanisms under enrichment of atmospheric CO_2 and warming conditions.

4.3. Climate effects on biomass and grain yields

The simulations reveal an overall future decrease in biomass and grain yields of maize and sorghum even though the crop models do not sufficiently capture the effects of CO_2 on transpiration of these C_4 crops. The reduction in the yields predicted for northern Benin is in line with findings in other regions for maize (Chipanshi et al., 2003; Faye et al., 2018; Rosenzweig et al., 2014; Thornton et al., 2011) and sorghum (Chipanshi et al., 2003; Faye et al., 2018; Singh et al., 2014) although the simulated impact of climate change shows strong spatial variability. A decrease in sorghum grain yield of up to 20% was predicted for the semi-arid region of Ghana using APSIM (MacCarthy and Vlek, 2012), and by more than 40% for the Sudan and Sahelian Savanna regions of Senegal, Mali, Burkina Faso, and northern Togo and Benin with the SARRAH model (Sultan et al., 2013). In contrast, for the Guinean zone of Ghana, (Srivastava et al., 2017), using the LINTUL5 crop model, predicted an increase in maize grain by 57% and biomass yields by 59% under climate change. The present results combined with those of a comprehensive review of climate change impact on crop yields in West

Africa (Roudier et al., 2011) indicate that negative impacts are most likely to prevail in the drier Sudan and Sahelian regions.

The simulated decreases in maize and sorghum grain yields could be caused by increased temperatures and corresponding heat stress, particularly during key phenological stages such as anthesis and grain filling (Deryng et al., 2014; Gabaldón-Leal et al., 2016). Both maize and sorghum respond to heat stress by regulating water and gas exchange (Sultan et al., 2013) and thus reducing photosynthesis (Sunoj et al., 2017), particularly during the reproductive stages. In contrast to these C_4 crops, C_3 crops (e.g. soybean and cotton) benefits from high atmospheric CO_2 concentrations through both a reduction of the stomatal conductance and an increase in photosynthesis and in turn improved biomass growth and yields (Roudier et al., 2011). The latter cannot be expected unless temperatures approximate the optimum for crop growth and water remains available for grain filling. Reportedly, high-temperature episodes or heat stress close to anthesis will be more detrimental for crop yields than the effects of the increases in mean seasonal temperature (Tesfaye et al., 2016). When air temperatures are near the upper limit, growth and yield reductions are predicted irrespective of the CO_2 concentrations (Polley, 2002). Testing effects of maximum and minimum temperature regimes of 32/22, 36/26, 40/30, and 44/34 °C at ambient and elevated CO_2 on reproductive processes and yields of sorghum, (Prasad et al., 2006) reported that elevated CO_2 increased grain yield at 32/22 °C, but decreased it at 36/26 °C.

The findings reported here suggest an increase in the average maximum and minimum temperatures during the growing cycle of maize and sorghum from 30/21 °C up to 35/25 °C for the RCP 8.5 scenario. Therefore, the grain yield depressions predicted with CERES-Maize and CERES-Sorghum under RCP 8.5 for northern Benin are most plausible due to the predicted warming, but those with RCPs 2.6 and 4.5 underscored again haying-off. The high-temperature effects on seed set and growth can be captured by CERES-Maize and CERES-Sorghum through the cardinal temperatures, assuming 34 °C as the optimum temperature (Wilkens and Singh, 2003). Reportedly, heat stress leads to a tremendous reduction in pollen germination (Prasad et al., 2006; Sunoj et al., 2017) that in turn decreases seed numbers and hence yields (Deryng et al., 2014; Sultan et al., 2013).

4.4. *Limitations of the study*

Similar to several crop modeling studies and climate change impact assessments (Faye et al., 2018; Sultan et al., 2013; Tubiello and Ewert, 2002), this study has its limitations. Hence, the findings of the study must be considered with caution. The first limitation is the biological mechanism shortcomings in the structure of the models used in simulating water- and nitrogen use responses to elevated CO_2 environment. The modeling approach of DSSAT-CSM to enhanced CO_2 is to increase RUE, rather than transpiration (Hoogenboom et al., 2015; White et al., 2015). This generates more rapid accumulation of biomass and enhanced water use that generally lead to earlier onset of stress and reduced yield, and thus reduced resource use efficiencies. The insufficient capture of the effects of CO_2 on transpiration of maize and sorghum could result in an over-prediction of the depressive effects of future climate.We note that our assessments were constrained by incomplete datasets. Due to lack of data, one sorghum sowing date experiment was considered for the CERES-Sorghum calibration and validation. The accuracy of the CERES-Sorghum in simulating the sorghum phenology could be more satisfactory if responses on several sowing dates within the range of farmer's sowing window were available for the study area and considered in the calibration and validation processes.-This shortcoming in simulating accurately the phenology of the local sorghum likely affects the growth response and thus yield and resource use. Model calibration and evaluation would also benefit from more data on leaf area.

4.5. *Mitigating future climate effects*

To ease the climate change and variability implications for maize and sorghum supply in the region, climate-smart actions are thus urgent. Recently, it has been postulated that for many regions in Sub-Saharan Africa, such actions include the use of inorganic and organic fertilizers (Montpellier Panel, 2013; Vanlauwe et al., 2014) as strategies to enable a sustainable intensification of smallholder maize- and sorghum-based production. On the one hand, the simulations in this study, subject to the limitations of the model structure used, show that both an integrated soil-crop management and high mineral fertilizer use are likely to sustain higher WUE and grain yields compared to an unamended soil, even when assuming different future climate conditions. Furthermore, the current projections reveal that an integrated soil-crop management would result in higher N-partial factor productivity compared to a high use of mineral fertilizers. Since integrated soil fertility management aims at enhancing both productivity and resource use efficiencies, it is acknowledged as an important strategy for sustainable intensification of smallholder agriculture in Sub-Saharan Africa (Vanlauwe et al., 2014). Our results, indicate that these increases will still not be able to offset the negative effects on productivity and resource use efficiencies due to projected late-season heat and dry conditions. However, the predicted yields under the improved management options tested for the future climate scenarios are higher than the observed average yields of maize and sorghum in farmers' fields in Benin (Amegnaglo, 2018; Amouzou et al., 2018a).

This study did not explicitly assess the effects of the adjustment of planting dates and shifting in crop cultivars to cope with climate change impacts. Reportedly, varying planting dates (Kassie et al., 2015), changing crop cultivars (White et al., 2011), improved soil fertility strategies (Faye et al., 2018; Liniger et al., 2011), and water management (Fox and Rockström, 2003; Reddy, 2016) mitigate the negative impacts of climate change. A combination of these strategies could significantly buffer the negative impacts of climate change in maize and sorghum-based production systems in West Africa Dry Savanna, and probably beyond.

5. Conclusions

Despite the shortcomings in the models structure for dealing with effects of enhanced CO_2, the evaluated CERES-Maize and CERES-Sorghum models permitted exploring effects of soil fertility management options on water- and nutrient-use efficiencies, and yields in the prevailing maize- and sorghum-based production systems under both historical and future climate in the dry Savanna region of northern Benin, West Africa. Under projected climate scenarios, it is most likely that water- and N-use efficiencies, and N and P uptake of maize and sorghum will decrease as well as grain yields, which in turn will enhance food stress in the region. Soil fertility management practices must embrace a combination of inorganic fertilizer and organic matter from various sources to sustain soil quality, high yields, and enhanced N- and P-use efficiencies of maize and sorghum in the case study region. The present DSSAT CERES frameworks do not have enough reduction in transpiration due to elevated CO_2 levels with present code. We propose that the DSSAT model developers address the issue of not having sufficiently strong reduction of transpiration by improving how stomatal conductance is reduced by CO_2 for credible assessment of climate change impacts on WUE.

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