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UTILIZING PROCESS-BASED CROP MODELLING TO ASSESS CLIMATE-INDUCED CROP YIELDS AND ADAPTATION OPTIONS IN THE NIGER RIVER BASIN OF WEST AFRICA

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UTILIZING PROCESS-BASED CROP MODELLING TO ASSESS CLIMATE-INDUCED CROP YIELDS AND ADAPTATION OPTIONS IN THE NIGER RIVER BASIN OF WEST AFRICA

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL SUSTAINABILITY

BY

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I dedicate this research to Almighty God for giving me the good health and wisdom to study. I also dedicate this work to my late younger brother, Benjamin Hemen Akumaga, who sacrificed all for me to get an education and to my loving late younger sister, Doose Mtserkyaa Akumaga, who died of snake bite working in the farm to support me in school.

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Abstract

This dissertation used the FAO AquaCrop model to evaluate the impact of climate change on major cereal yields and adaptation options in three agro-ecological zones of the Niger River Basin. The crops analysed include maize, millet, and sorghum under rainfed cultivation systems in various agro-ecological zones within the Niger Basin. This work also investigated several adaptation strategies, including changes in the sowing dates, soil nutrient status, and cultivar. Future climate change is estimated using nine ensemble bias-corrected climate model projection results under rcp4.5 and rcp8.5 emissions scenario at mid future time period, 2021/25-2050. The study also analyzed the projected changes in the intra-seasonal rainfall characteristics in the region. The study includes three self-contained but related studies; (1) Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa; (2) Utilizing Process-based Modelling to Assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa, and (3) Projected changes in intra-seasonal rainfall characteristics in the Niger River Basin, West Africa.

Broadly, the results of this study show that the AquaCrop model satisfactory simulated cereal yields at different nitrogen fertility levels in this region. The observed and simulated yields were evaluated to be satisfactory with a normalized root mean square error (NRMSE) between 8%-17% indicating excellent to good results for grain yield while the NRMSE for biomass yields were between 20-26% indicating good to satisfactory results. The results show that on average, temperature had a larger effect on crop yields so that the increase in precipitation could still be a net loss of crop yield. The simulated results showed that climate change effects on maize and sorghum yield will be mostly positive (2% to 6% increase) in the Southern Guinea savanna zone while at the Northern Guinea savanna zone it is mostly negative (2 to 20% decrease). The results also show that at the Sahelian zone the projected temperature and precipitation changes have little to no impacts on millet yield for the future time period, 2021/25-2050. In all agro-ecological zones, increasing soil fertility from poor fertility to moderate, near optimal and optimal level significantly reversed the negative yield change respectively by over 20%, 70% and 180% for moderate fertility, near optimal fertility, and optimal fertility. Thus, management or adaptation factors, such as soil fertility, had a much larger effect on crop yield than climatic change factors.

The results further show an increase of the average rainfall of about 5%, 10-20% and 10-15% for the Southern Guinea, Northern Guinea and Sahelian Zones respectively. On the other hand, there is a significant mean change of rainfall intensities and the frequency of rainfall at the low, heavy and extreme rainfall events in the Niger River Basin. The results showed an increase in the frequency of the moderate rainfall events in all locations in the basin. However, Samaru, at the Northern Guinea, and Tahoua, at the Sahel locations show an increase in the frequency of the heavy and extreme rainfall events in the future. These results revealed a delay of onset and a late cessation of rains and a significant decline in the duration of the growing season in all locations except for Samaru location in the Basin. Finally, this study projected that climate change poses serious risks for food security of the region and therefore demands adequate change in the cropping pattern and management to adapt to these changes. The results of this study provide an actionable decision support system that demonstrates how to evaluate strategies for improving cereals yield while mitigating and managing climate risks.

Chapter 1

The Research

1.1. Background to the problem

Improved crop yield estimation and agricultural management practices are critically needed in Sub-Sahara Africa (SSA) to counter three current and emerging challenges. First, by 2030 cereal yields in Sub-Sahara West Africa are expected to decline by 20% as a result of climate change (Lobell 2008; Blanc 2012; Waha et al., 2013; Sultan et al., 2014), compounding a long history of chronic underperformance of SSA's agriculture (Sanchez, 2010 & Chauvi et al., 2012, Fig.1a). For example, between 1960 and 2013, cereal crop yields in Asia and Latin America quadrupled from around one to four tons per hectare but in West Africa, cereal yields have remained essentially flat at around one ton per hectare over the same period (Ramankutty et al., 2002; Wani et al., 2009; Sanchez, 2010; Langyintuo, 2011; Fig. 1). Second, with a population growth rate of 3%, SSA's population growth rate has outpaced every other region in the world (UN, 2012; Andersen et al., 2005; Figure 1C). In fact, the region's population is on pace to double by 2050 (FAO, 2006; UN, 2012), increasing food consumption and demand (Jalloh, et al., 2013), which will require a five-fold increase in food production just to keep pace with the population growth rate (Collomb, 1999; Van Vuren et al., 2009; Thornton et al., 2011; Rockstrom and Falkenmark, 2015).

The third challenge is climate variability and recurrent droughts, which almost invariably lead to famines and food insecurity because of razor-thin margins in the food production system (Watts, 1983, Tarhule & Woo, 1997& Boyd et al., 2013). In 2012, for example, more than 18 million people throughout the region faced starvation due to weather and other socio-political events (Boyd et al. 2013). Without sound adaptation and improved agricultural management practices, climate change will likely exacerbate drought risk in the region and further threaten livelihoods (Ben-Mohamed et al., 2002; Lobell, et al., 2008; Schlenker and Lobell, 2010; Sultan et al., 2014; Figure 1 and Table 1).

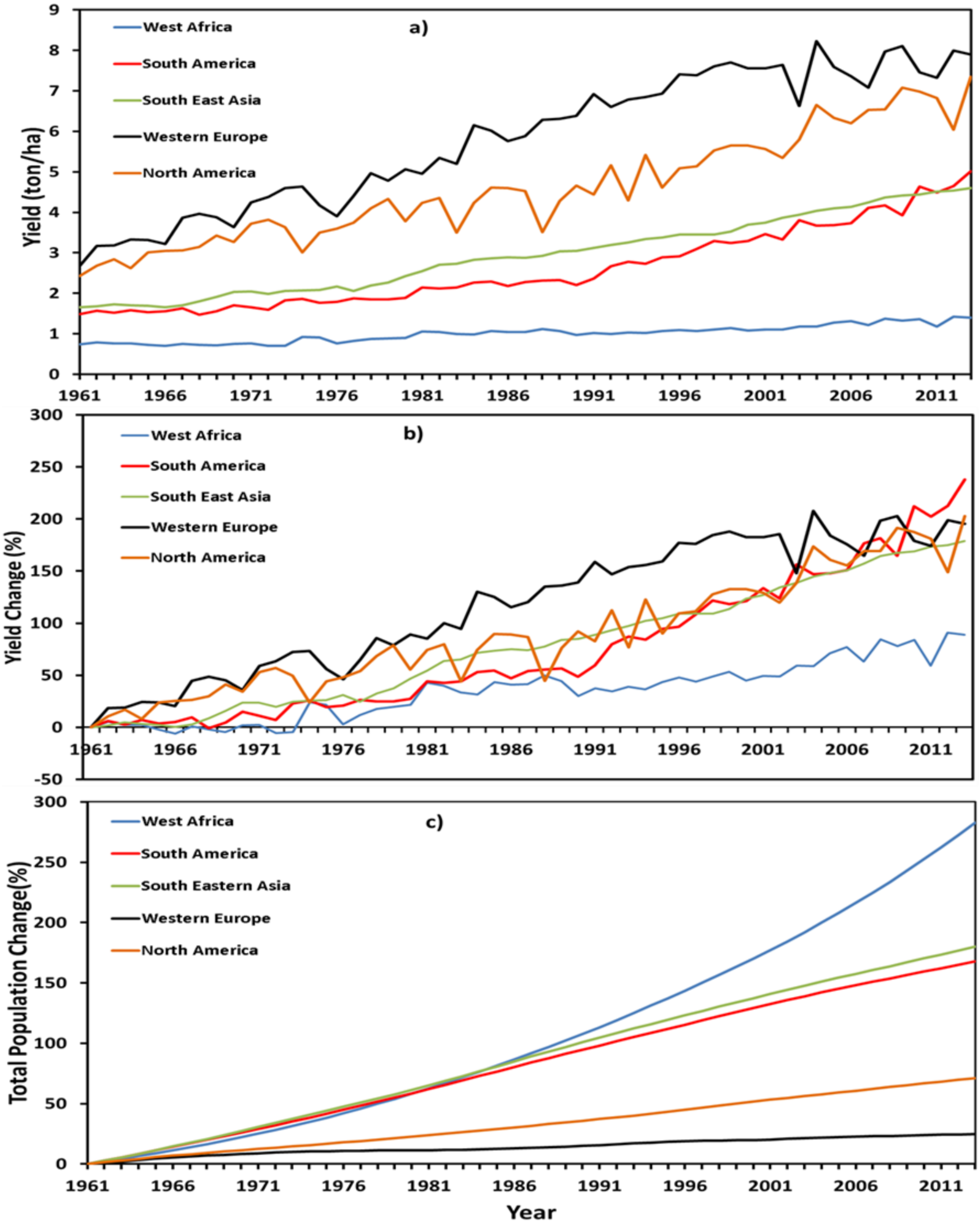


Figure 1: Cereals yield (a, b) and population(c) trend comparison. Source: FAOSTAT, 2013.

To date, research work in SSA has focused on quantifying the magnitude of risk to various crops using either empirical/statistical (e.g. Mohamed et al., 2002) or process-based modeling (Sultan et al., 2014). Empirical models estimate the relationship between agricultural output and land, labor and capital inputs (Blanc, 2012). A commonly used method in empirical modeling is regression analysis, which attempts to estimate crop yields in response to changes in weather and climate variables based on observed or historical data (Mohammed et al., 2002). An advantage of empirical methods is that they rely on relatively limited data and require much less field calibration. They also provide an assessment of the strength of the model performance through various goodness-of-fit criteria and other statistical measures, such as the percent explained variance (Lobell and Burke, 2010; Schlenker and Lobell, 2010). In terms of limitations, a common concern is that statistical methods emphasize responses to episodic shocks or extremes which may not be the same as the responses to permanent shift in climate. Additionally, regression analysis in particular, is prone to co-linearity between predictor variables, e.g. precipitation and temperature, or temperature and evapotranspiration, confounding interpretation (Sheehy et al., 2006; Peng et al., 2004; Lobell and Ortiz-Manasterio, 2007). Moreover, the assumption of stationarity inherent in the method i.e. past behavior is an indicator of future pattern, clearly is not defensible especially in the context of climate change (see Milly et al, 2008).

Process-based models use mathematical descriptions of crop physiological, chemical, and physical processes to simulate crop growth and development over time (Monteith, 1996; Steduto et al., 2009). A key characteristic of these models is that they encapsulate the best-available knowledge on plant physiology, agronomy, soil science and agrometeorology to predict how a plant will grow under specific environmental conditions. Most process-based models operate at a daily time step and require a large amount of input data to calibrate and run the model. While such climatic, soil and crop data needs pose a constraint in data-poor environments, process based models are uniquely able to capture detailed, intra-seasonal and non-linear effects of climate and environmental variables on crops. Some of the examples of process-based models used in the Niger Basin include EPIC (Environmental Policy Integrated Climate; Adejuwon, 2006) and DSSAT (Decision Support System for Agrotechnology Transfer, Jalloh et al., 2013). As expected, the climate models produce somewhat different climate futures with the result that the crop yield estimates are also different. Nevertheless, the general conclusions which emerge for this region can be summarized as follows. Taking CO_2 fertilization into account, the future climate will result in a decrease of maize yield of between 5-25% in the humid coastal regions in 2050 relative to baseline, an increase of the same amount (5-25%) in the Soudan zone, and the sharpest decrease in the Sahel regions. Sorghum yields will decline throughout West Africa by between 5-25% with the highest decreases occurring in Sahel zone as well as diffused pockets of yield decreases that vary by model in the derived savanna areas. The yields of rain-fed rice will decrease by between 5-25% in the coastal region but will increase by the same amount in the Sahel. The models also agree that groundnut yields will decline but with smaller decreases in the Mano River Union countries (i.e. Guinea, Liberia, and Sierra Leone). For each of the above crops, model outputs from the individual countries vary because of the greater degree of detail. In a very comprehensive review, Roudier et al. (2011) reviewed 16 studies on the impacts of future climate change on West African crop yields. The 16 studies consist of 11 process-based models and five statistical based models. They investigated the possible future response of maize, millet, rice, sorghum, soybean, cowpea, wheat, and cassava to climate change (See table 2). The results show that dry cereals (i.e., maize, sorghum, millet, rice etc.) cultivated in Sudano-Sahelian countries will be more affected by climate change, with a median yield decrease of 18%, than those cultivated in Guinea countries (-13%) by 2050.

One limitation of a majority of crop yield modeling studies is that adaptation or management strategies were rarely investigated except by Butt, et al., (2005), Parry et al., (2008), and Tingem and Rivington (2009). Also, with few exceptions (e.g. Sultan et al., 2014), the use of multiple models to evaluate uncertainty is rare and crop yield response to management practices is almost nonexistent. In most of the studies carried out, no or little effort was made to determine the projected changes of rainfall characteristics at the field scale in Niger River Basin. However, magnitude and timing of seasonal rainfall is vitally important to agro-ecological and social-economic systems in the Niger River Basin of West Africa and, indeed, most of Sub-Saharan Africa (SSA). Given this unique context, knowledge concerning how climate change is likely to impact future rainfall characteristics and patterns is critically needed for adaptation and mitigation planning (Sylla, *et al*., 2013; Klutse, *et al*., 2015; Guan, *et al*., 2015). Owing to a variety of reasons, however, including data constraints, the majority of studies to date have focused on changes in the mean seasonal rainfall (e.g. Afiesimama, *et al*., 2006; Sylla, *et al*., 2009, 2010; Nikulin, *et al*., 2012; Biasutti, 2013; Sultan, *et al*., 2013, and Gbobaniyi, *et al*., 2015). Relatively few studies have investigated changes in higher-order or intra-seasonal rainfall characteristics, including, for example, number, frequency, and intensity of rain events (Owosu and Klutse, 2013; Sylla, *et al*., 2013; Klutse, *et al*., 2015; Guan, *et al*., 2015).

Distinct from prior studies which focused on the region at large, the present study is site specific, providing finer detail, and therefore more actionable information, about the specific risks and changes that stakeholders at the specific location will have to respond to. Additionally, i investigate these field-scale dynamics for three agro-ecological zones, providing a basis for comparison and analysis of spatial differences. This research gap is important because in order to increase crop yield and ensure food security in this region, climate risk assessment and climate change adaptation (planning and management) must be evaluated for both rain-fed and irrigated agriculture at a finer scale. In fact, the predominance of management effects over climatic factors can be seen in the fact that since 1960, despite significant temperature increase and decades of rainfall declines, the yields of some of the major crops in the Niger Basin have increased not decreased (Figure 2). Our interpretation is that water and soil conservation practices combined with the introduction/adoption of improved cultivars have helped farmers reverse what would otherwise be significant negative trends in crop yields. This conclusion implies that climate change adaptation in this study area can be significantly enhanced by learning what those adaptation measures have been and building on them i.e. upscaling. Therefore, this study is important because it further or better predicts the impact of climate change on cereal production by taking into account climate risk assessment and climate change adaptation using process-based crop models (i.e. AquaCrop) at a finer scale. The aspects of rainfall that are most critical to agricultural production are also evaluated in this study. AquaCrop was developed explicitly to model crop yields. The model focuses on water as the major determinant of crop productivity (Hsiao *et al*., 2009 and also see the detail description of the model in section 2.). To our knowledge, AquaCrop has not been validated for any cereal crops in West Africa. Such validation is useful given differences in climatic characteristics, soil type, and farming systems between West Africa and other parts of the world where the model has been tested. Moreover, cereals represent critical staple crops in West Africa, accounting for approximately 50% of the nutritional intake (WHO, 2000; Thirtle *et al*., 2002; World Bank 2005).

1.2. Objectives:

The specific objectives of the study are the following:

i. Calibrate and validate the FAO AquaCrop Model in West Africa.
ii. Quantify the relative contributions of climate change and management scenarios to crop yield variability using process-based crop models
iii. Evaluate optimal adaptation scenarios for minimizing climate change impacts in the Niger Basin.
iv. To analyze the projected changes in rainfall characteristics in the Niger River Basin.

Table 1: Summary of models used in the studies of climate change impacts on crop yields in West Africa and Sub-Sahara Africa. Adapted from Roudier, et al., (2011)

Reference	Climate Model	Crop Model	Scenario	Area	Horizon	Crop	C.Fert	Baseline
Adejuwon(2006)	HadCM2	EPIC	1%/year in Co2	Nigeria	2035/2055/2085	Cassava, maize, millet rice, sorghum	Yes	1960/1990
Ben-Mohamed et al.(2002)	MAGICC+ SCENGEN	Empirical	-10%rain;+10%temp//-20%;+20	Niger	2025	Millet	No	1968/1998
*Butt et al. (2005	HadCm, CGCM	EPIC+PHYGROW+NUTBAL	Greenhouse gasess integrations	Mali	2030	Cotton,cowpea, groundnut, maize,millet,sorghum		1960/1991
Fischer et al. (2005)	HadCM3, CSIRO, ECHAM4 CGCM2,NCAR	AEZ+BLS	A2	SSA	2080	Global	YES	1961/1990
Nelson et al. (2009)	NCAR, CSIRO	IMPACT+DSSAT	A2	SSA	2050	Global,maize, millet,rice, Sorghum,wheat, soybean groundnut	Yes /No	2000
Jones and Thornton (2003)	HadCM2	CERES-maize	Not found	WA	2055	maize	No	1990 normals
Liu et al. (2008)	HadCM3	GEPIC	A1F1,B1,A2,B2	SSA, WA	2030	Global,cassava, maize,millet,ric	Yes	1990/1999

						e,Sorghum,wheat,		
Lobell et al. (2008)	20 GCMs	Empirical	AIB,A2,B1	WA	2030	Cassava, maize, millet rice, sorghum,groundut,yams,	No	1998/2002
Muller et al.(2010)	CGCM3+CHAMS+ECHO-G+GFDL+HADCM3	LPJML	A1B+A2+B1	WA	2050	Global	Yes/No	1996/2005
Paeth et al.(2008)	REMO	MOS(empirical)	B2	Benin	2025/2020	Beans,cassava, cotton,groundnut,maize,rice,sorghum,yams	No	1979/2003
*Parry et al.(2004)	HadCM3	Empirical+BLS	AIFI,A2A, A2B,A2C, B1A,B2A, B2B	WA	2020/2050/2080	Global	Yes/No	1990
Salack (2006)	Scenario	DSSAT 4	(+1^{O}C,+1.5^{O}C,+3^{O}C)/(+5%,+10%, +20%)	Niger/Burkina	2020/2050/2080	Millet mtdo/zatib,sorghum	No	1961/1990
Schlenker and Lobell (2010)	16 GCMs	Empirical	AIB	WA	2055	Cassava,groundnut, maize, millet rice, sorghum	No	1960/2002

Smith et al (1996)	CCM,GFD3,GISS	DSSAT 3	2Co2	Gambia	2075	Groundnut,maize,millet late/early	Yes	1951/1990
*Tingem and Rivington (2009)	GISS,HadCM3	Cropsyst	A2, B2	Cameroon	2020/2080	Bamb.nut,groundnut,maize,sorghum,soybean	Yes	1961/1990
Vanduivenbooden et al. (2002)	MAGICC+SCENGEN	Empirical	-10%rain;+10%temp//-20%;+20	Niger	2025	Cowpea,groundnut	No	1968/1998

Note: *Only few of these studies investigated adaptation scenarios

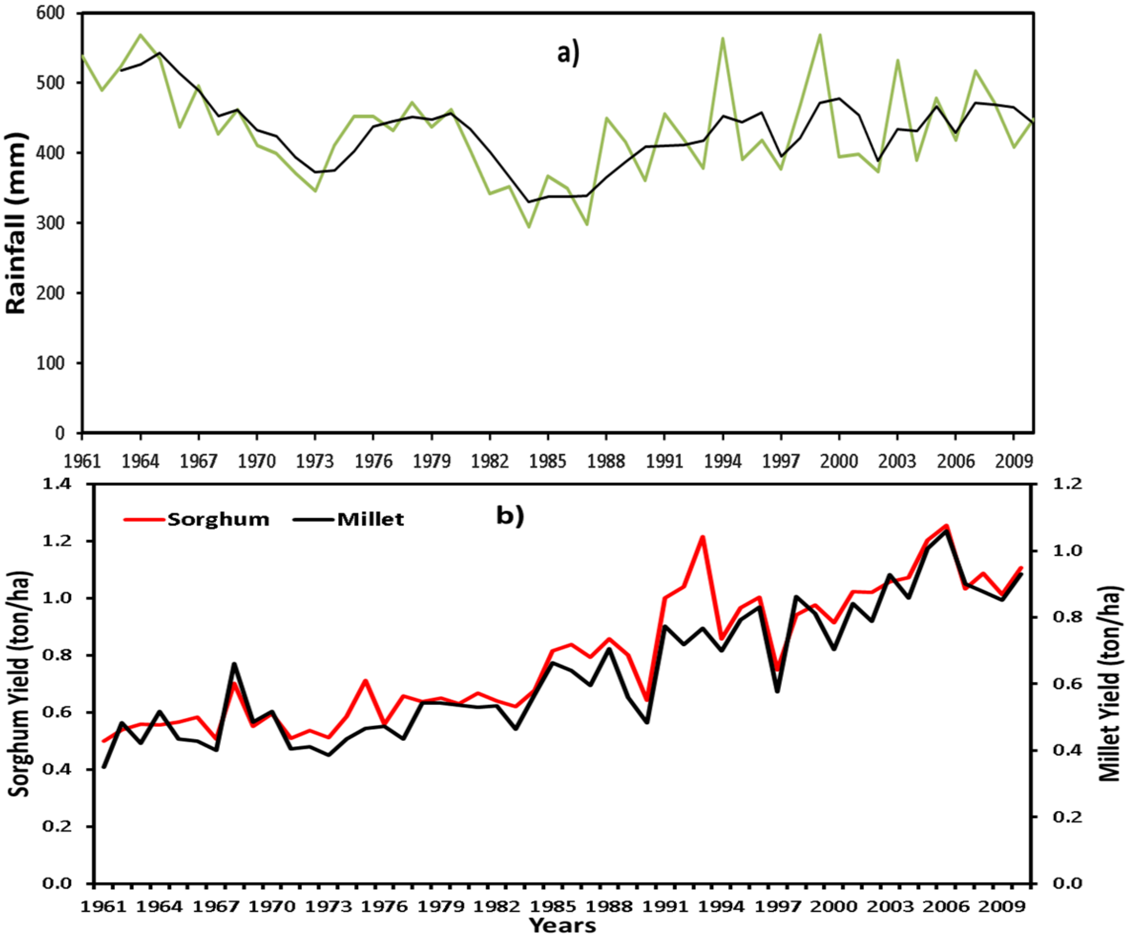


Figure 2: Decreasing rainfall (a) and increasing yields (b) at Dori in Burkina Faso

1.3. Research contribution

This study will validate AquaCrop in the major agro-ecological zones in the study area for the first time, thereby helping the research community to gain improved understanding of the climate-environmental-cereals yield nexus. To our knowledge, AquaCrop has not been validated for any cereal crops in West Africa. The results will also add to the growing literature on the model's efficacy in different bio-ecological systems. Researchers and scientists will also be able to use the calibrated/validated AquaCrop model to investigate the impacts of climate change on crops within the region's agro-ecological zone.

A broader impact of this research will be filling a critical gap regarding the understanding of climate change agricultural adaptation in semi-arid West Africa, particularly, the role of management strategies in mitigating climate change impacts. By evaluating the efficacy of several adaptation scenarios to future climate change and analyzing the projected changes in the intra-seasonal rainfall characteristics in the Niger River Basin, the study also provides a proactive approach to agricultural adaptation options for smallholder farmers in this region.

The results of this study will provide an actionable decision support system that demonstrates how to evaluate strategies for improving cereals yield while mitigating and managing climate risks.

1.4. Organization of the dissertation.

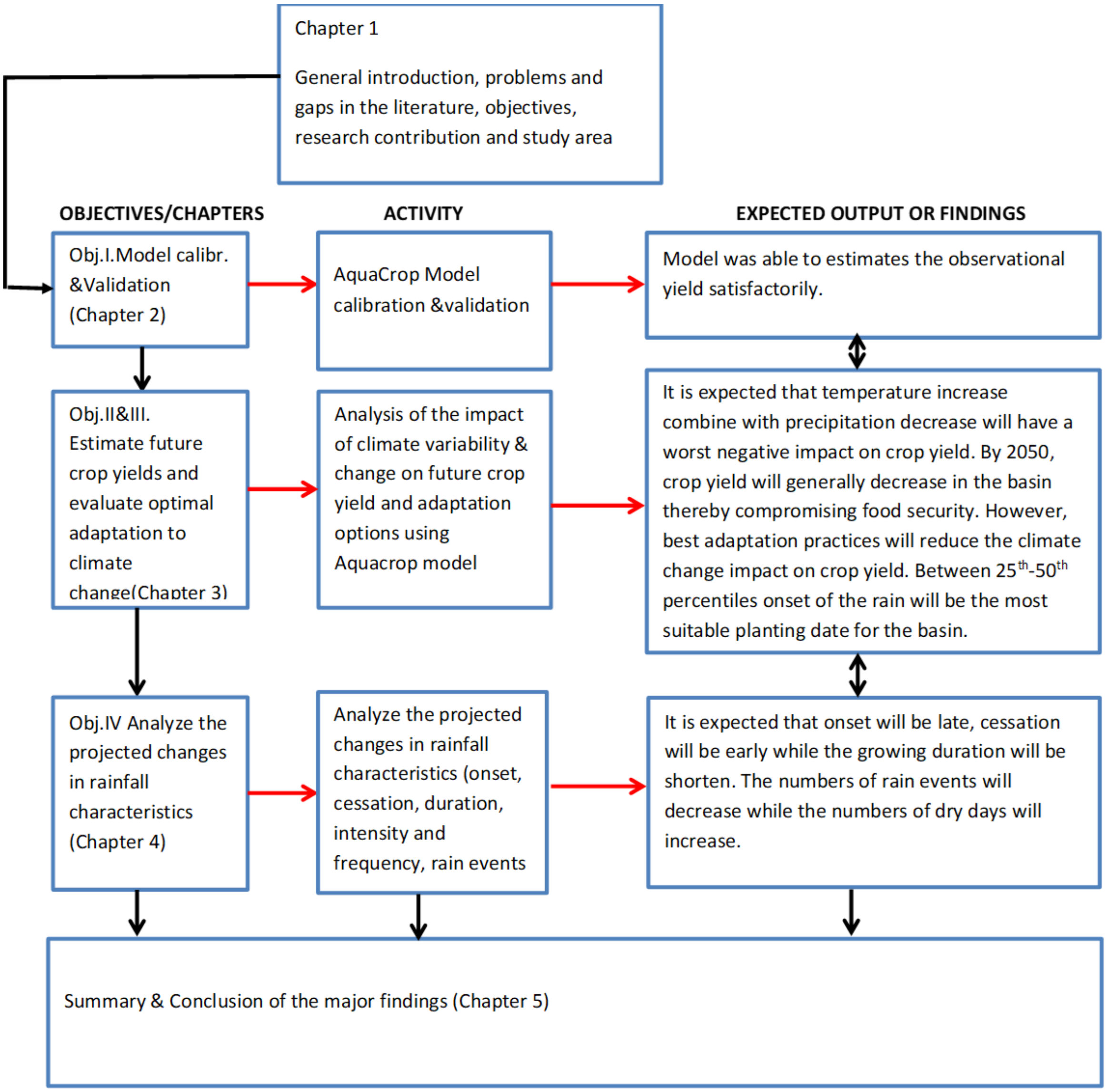
Figure 3 presents a conceptual framework and organization of the five chapters of the dissertation. Chapter (1) introduces the study problem, research objectives of the study, state the research contribution, and describe the study area. Chapter 2 describes the model calibration and validation (i.e. Objective I). Chapter 3 focuses on the analysis of future crop yields in response to climate variability and change and the implication of such crop yield to food security of the study area and the adaptation options available for decreasing cereals vulnerabilities to climate risk (i.e. Objectives II and III). Chapter (4) analyzed the projected changes in the intra-seasonal rainfall characteristics at representative agro-ecological sites in the Basin (i.e. Objective IV). The final chapter (chapter 5) summarizes the major findings and provide conclusions and recommendation to policymakers and practicing farmers.

Chapters (2) through (4) are written as stand-alone technical papers and they are formatted according to specific journal styles. As a result of this arrangement, each of these chapters will have a separate abstract, introduction, methodology, discussion, and conclusions. This arrangement results in unavoidable repetition. In particular, key background information, such as problem statement, location map, site-specific information, and references are repeated in order to achieve the desired chapter autonomy. The status of each stand-alone technical manuscript (chapter 2 through 4) is shown below:

Chapter 2- Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rain-fed maize in Nigeria, West Africa. Published in, *Agricultural and Forest Meteorology* 2017, vol. 232, Pp225-234

Chapter 3- Utilizing Process-based modelling to assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa. Published in the *Special Issue "Climate Change in Agriculture: Impact and Adaptations" of the Agronomy Journal 2017*, vol.7

Chapter 4- Projected changes in intra-seasonal rainfall characteristics in the Niger River Basin, West Africa. Submitted to, *International Journal of Climatology*.



Chapter 1

General introduction, problems and gaps in the literature, objectives, research contribution and study area

Obj.I.Model calibr. &Validation (Chapter 2)

AquaCrop Model calibration &validation

Model was able to estimates the observational yield satisfactorily.

Obj.II&III. Estimate future crop yields and evaluate optimal adaptation to climate change(Chapter 3)

Analysis of the impact of climate variability & change on future crop yield and adaptation options using Aquacrop model

It is expected that temperature increase combine with precipitation decrease will have a worst negative impact on crop yield. By 2050, crop yield will generally decrease in the basin thereby compromising food security. However, best adaptation practices will reduce the climate change impact on crop yield. Between 25th-50th percentiles onset of the rain will be the most suitable planting date for the basin.

Obj.IV Analyze the projected changes in rainfall characteristics (Chapter 4)

Analyze the projected changes in rainfall characteristics (onset, cessation, duration, intensity and frequency, rain events

It is expected that onset will be late, cessation will be early while the growing duration will be shorten. The numbers of rain events will decrease while the numbers of dry days will increase.

Summary & Conclusion of the major findings (Chapter 5)

Figure 3: Conceptual and organizational view of the dissertation.

1.5. The study location, physiography and climate

1.5.1. The study area

The Niger River Basin located in West Africa is bounded approximately by latitudes 5°N and 22°N, and longitudes 11°30' W and 15° E and has a total drainage area of 2,170,500 km^2 (Figure 4). Conventionally, the Niger Basin is divided into four recognizable physiographic units namely: the upper Niger, Inland Delta, Middle Niger, and the Lower Niger.

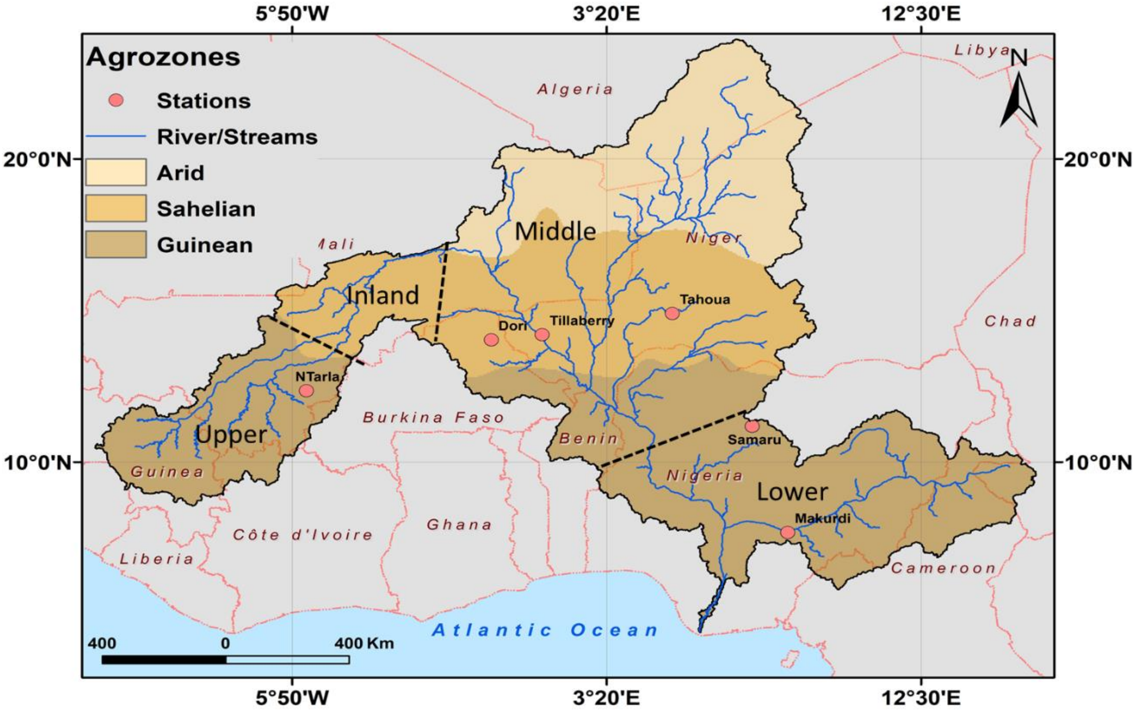


Figure 4: The sites and location of the Niger Basin in West Africa showing study location (red dots), Sub-basin (dashed line) and agro-ecological zones

As a result of the flow path of the Niger River, the basin cuts across different ecological zones and all the major climatic zones of West Africa, which includes the Guinean or Equatorial forest zone, the Transitional tropical belt, the Sudan Savanna zone, the Semi-arid or Sahel Savanna belt, and the Desert (Andersen, 2005; Tarhule et al., 2014, Figure 4). Temperature follows a steep gradient as one moves from the coast to the hinterland while the reverse is the case for rainfall and humidity (Figure 5). A large area of the river basin is located in the Sahel, a semiarid area between the Sahara and the Sudanian savannas. Annual rainfall of the basin ranges from 250 to 750 mm in the Sahelian/desert zone to over 2,000mm around the Guinean/ coastal zone, with the length of the rainy season varying from three to eight months (Figures 6). Vegetation consists of tropical Rainforest, the Guinean moist forests, the Savanna—grassland, the semi-desert and desert land cover (Figure 4). The three major soil types of the Niger River Basin are ferralitic soils, tropical ferruginous soils, and hydromorphic soils (World Bank 1986, Andersen et al., 2005). Texturally, sand soil covered about 95% of the Basin (Sultan, et al., 2013).

The Niger River's hydrologically active basin covers nine countries, namely Benin, Burkina Faso, Cameroon, Chad, Cote D`Ivoire, Guinea, Mali, Niger and Nigeria (see Figure 4). The nine countries shared by the basin in West and Central Africa are among the poorest in the World. Four are among the bottom 20 countries on the World Development Indicators (WDI) scale (World Bank, 2014), and six are among the bottom 20 on the United Nations Development Programme (UNDP) Human Development Index (UNDP, 2014). The basin has a population of 105 million as estimated in 2005 (World Bank, 2005). Seventy percent of the population engaged in subsistence (largely rain-fed) farming (Sling et al., 2005; Tarhule, 2011 and Knox et al., 2012) and are therefore highly susceptible to climatic variability and change (Tarhule al., 2009, figure 4). The major crops grown in the basin are Maize, Millet, Sorghum, Cowpea, Rice, Groundnut, Yams and Cassava.

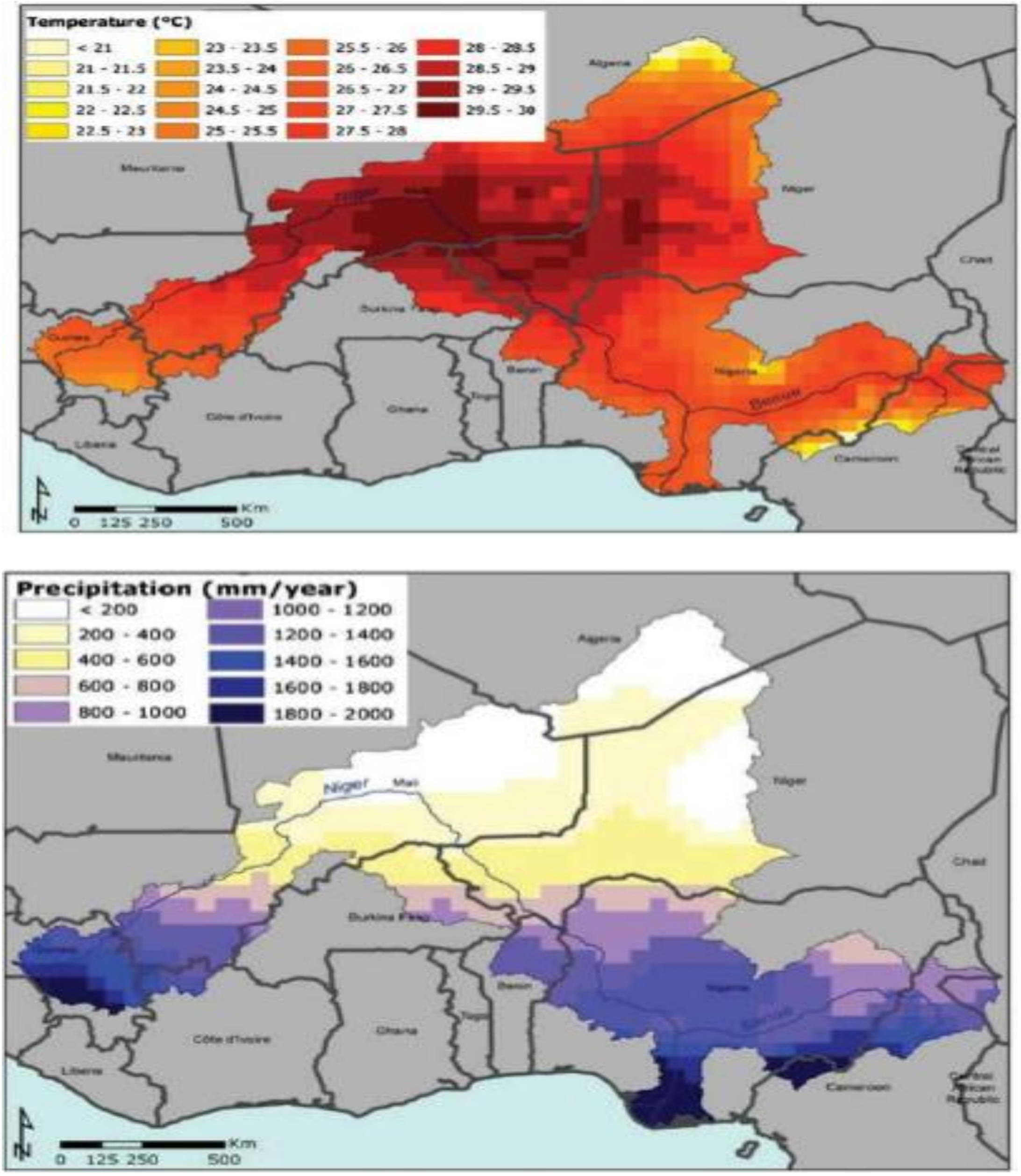


Figure 5: The Niger Basin showing precipitation and Temperature gradients (Adopted from Tarhule et al., 2014).

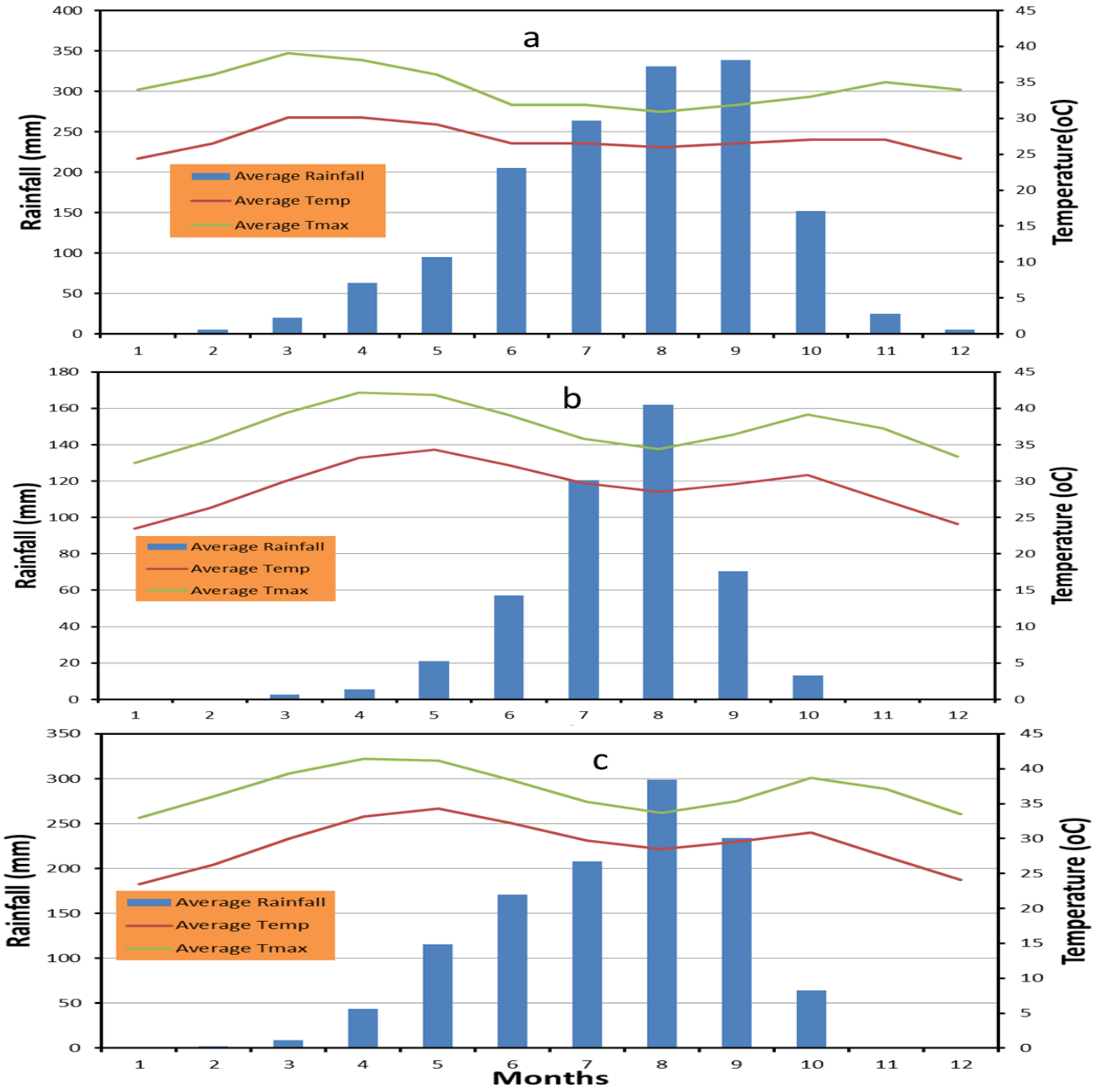


Figure 6: (a) Makurdi, (b) Dori and (c) Samaru Average Monthly Rainfall (1981-2010).

The IPCC 2014 report projects that by 2030 the Niger basin will experience on average a 1˚C warming, increasing to 3.5ºC by 2080 of average temperature and a decrease of about 20% of annual rainfall in the Niger basin of West Africa for Scenario AIB (RCP8.5) (Sultan et al., 2014, IPCC, 2014). This decrease in rainfall combined with increase in temperature would have a direct impact on agricultural productivity. For example, Schlenker and Lob ell (2010) assesses the impacts of temperature and rainfall changes on future yield of five staple crops (i.e. maize, sorghum, millet, groundnuts and cassava) for SSA and noted that even if rainfall remains constant, the yield will decrease by 15% by 2030 due to the effect of higher temperature which will reduce the crop growth cycle length and increase water stress as a result of higher evaporation.

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Chapter 2

Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa

Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa.

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Abstract: The objectives of this study were to evaluate AquaCrop's ability to simulate the cumulative grain yield of rainfed maize for different soil fertility levels in the northern Guinea Savanna zone of Nigeria. Seven years (2007-2013) of field experimental data on maize grown under rainfed condition at the Institute for Agricultural Research were used to calibrate (2007 data set) and validate (2008-2013 data set) AquaCrop. We assessed the agreement between model simulated and actual maize yields using correlation coefficient, R^2, and the index of agreement, d, as well as the NRMSE. R^2 values ranged from 0.82 to 0.99 while values of d ranged from 0.6 to 0.88, indicating a moderate poor agreement to very good agreement. The NRMSE varied between 8% (indicating "excellent" agreement) and 17% (good agreement). On the other hand, in percentage terms the differences between actual and simulated yield range from +19% to -30%. Of the 19 treatments evaluated, 13(68%) are within 10% of each other, generally considered very good, three (16%) are within 20%, considered acceptable; and 3 (16%) are > 20%, considered poor. Furthermore, simulated yields systematically over-estimate observed yields a not uncommon result that suggests the need for additional calibration. The grain and biomass yields evaluation results were consistent with other validation studies of the model.

KEY WORDS: AquaCrop, Calibration, Crop Modeling, Maize, Nigeria, Rainfed Cereals

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1. Introduction

Owing to failure of the green revolution in Sub-Saharan Africa (SSA), food productivity in the region has lagged prevailing trends in other developing parts of the world (Chauvin, *et al*., 2012). For example, between 1960 and 2013, cereal crop yields in Asia and Latin America tripled from around one to four tons per hectare raising crop production by between 66% and 88% (Sanchez, 2010). In contrast, in SSA, progress has been spatially patchy, and cereal yields have remained essentially flat at around one ton per hectare since the 1960s (see, Wani, *et al*., 2009; Sanchez, 2010). Similar patterns of underperformance and contrast between SSA and the rest of the world also exist in root crop production (Chauvin, *et al*., 2012), irrigation (Calzadilla, 2013), and livestock (Chauvin, *et al*., 2012). Recurring explanations adduced to account for this situation include SSA's high dependence on rainfed agriculture, low use of fertilizers, degraded soils, the lack of infrastructure and supporting institutions and unfavorable market conditions (World Bank, 2007; Calzadilla, *et al*, 2013).

In contrast to low agricultural productivity rates, SSA's population growth rate, estimated at 2.7% during the past three decades, has outpaced every other region in the world, doubling from 370 to 830 million between 1980 and 2010 (UN, 2013). The population is expected to double again by 2050 (UN, 2013). This combination of sluggish food productivity growth on one hand and, on the other, explosive population growth appears likely to exacerbate an already tenuous food security situation (Otsuka and Kijima, 2010), undermine efforts to alleviate poverty (Chauvin, *et al*., 2012), and potentially destabilize socio-economic systems (Chauvin, *et al*., 2012; Boyd, *et al*., 2013).

Climate variability and change further confound above dynamics. More so than other parts of the world, devastating famines frequently accompany periods of extreme climatic variability in SSA, such as droughts or floods, due to razor thin margins of food supplies (Boyd, *et al*., 2013). As temperatures rise, crop yields will decrease while encouraging weeds and pest proliferation (IFPRI, 2009). Meanwhile, changes in rainfall patterns may increase the likelihood of short-run crop failures and long-run production declines. Although there will be modest gains in some crops, the overall impacts of climate change on SSA agriculture are expected to be negative (IFPRI, 2009; Rouldier, *et al*., 2011).

The above trends all point to a strong need for risk assessments and decision-making to support agricultural productivity (Calzadilla, 2013). This paper is a contribution toward that goal. We seek to validate AquaCrop, a relatively new process-based model (http://www.fao.org/nr/water/aquacrop.html) developed by the United Nation's Food and Agricultural Organization. Compared to other process based models, AquaCrop has strong appeal due to its simplicity of use, relatively low data and input requirements, and ability to produce accurate and robust results (Hsiao, *et al*., 2009; Raes, *et al*., 2009; Heng, *et al*., 2009).

AquaCrop has been validated for several crops and locations in North America (Hsiao, *et al*., 2009, Heng, *et al*., 2009), Europe (Todorovic, *et al*., 2009), and Asia (Abedinpour, *et al*., 2012). Within SSA, the model has been validated in Southern Africa (Bello, *et al*., 2011), and Eastern Africa (Araya, *et al*., 2010; Van Gaelen, *et al*., 2015). These studies showed that the model could satisfactorily simulate crop yield and biomass as well as soil water productivity under rainfed, full and deficit irrigation and soil fertility stress (Van Gaelen, *et al*., 2014). To our knowledge, AquaCrop has not been validated for soil fertility in West Africa even though this is the major constraint on food production in the region (Wani, *et al.,* 2009). Such region-specific validation is essential given differences in climatic characteristics, soil type, and farming systems between West Africa and other parts of the world where the model has been tested. Moreover, cereals represent critical staple crops in West Africa, accounting for approximately 50% of the nutritional intake (World Bank 2005).

To validate the model, we make use of a 7-year data for maize (*Zea mays*) cultivated under rainfed field experiment in northern Nigeria. We focus on maize because of its crucial role in SSA`s food security and poverty reduction strategy. Over 650 million people throughout the region "currently consume annually an average of 43 kg of maize per person, an increase of 35% since 1960" (Abdoulaye, *et al*., 2012, p.1). Demand is expected to increase further still in response to population growth and economic expansion. Maize also accounts for more than 50% of all of the acreage devoted to cereals in more than half of SSA countries. This study demonstrates how AquaCrop could be used to estimate maize yield response to variations in environmental, climatic, and management factors, thereby facilitating proactive planning. The results add to the growing literature on the model's efficacy in different bio-agro-ecological systems.

2. Materials and Methods

2.1 Field experiment and data

For this study, we utilized results of field experiments on hybrid maize grown under rainfed conditions from 2007 to 2013 at the Institute for Agricultural Research, Ahmadu Bello University (I.A.R/ABU) Zaria, Nigeria. All crop, weather, and soil information from the maize experiment were used as input into the model to simulate yields, which were then compared to the actual yields obtained from the experiment. The study area is located in the northern Guinea savanna bioclimatic zone. The climate is sub-humid and semiarid or tropical wet and dry (Aw) according to Köppen’s climatic classification. The mean minimum temperature is 21.05 °C (1980-2010) and mean maximum is 33.47 ^{o}C with average relative humidity of 55% (see Figure 1). The seasonal rainfall is unimodal, concentrated almost entirely in five months (May to September/October), permitting a growing period of 150-180 days. For the study period (2007-2013), total seasonal rainfall varied between 900 and 1400 mm per year with a mean of 1033 mm.

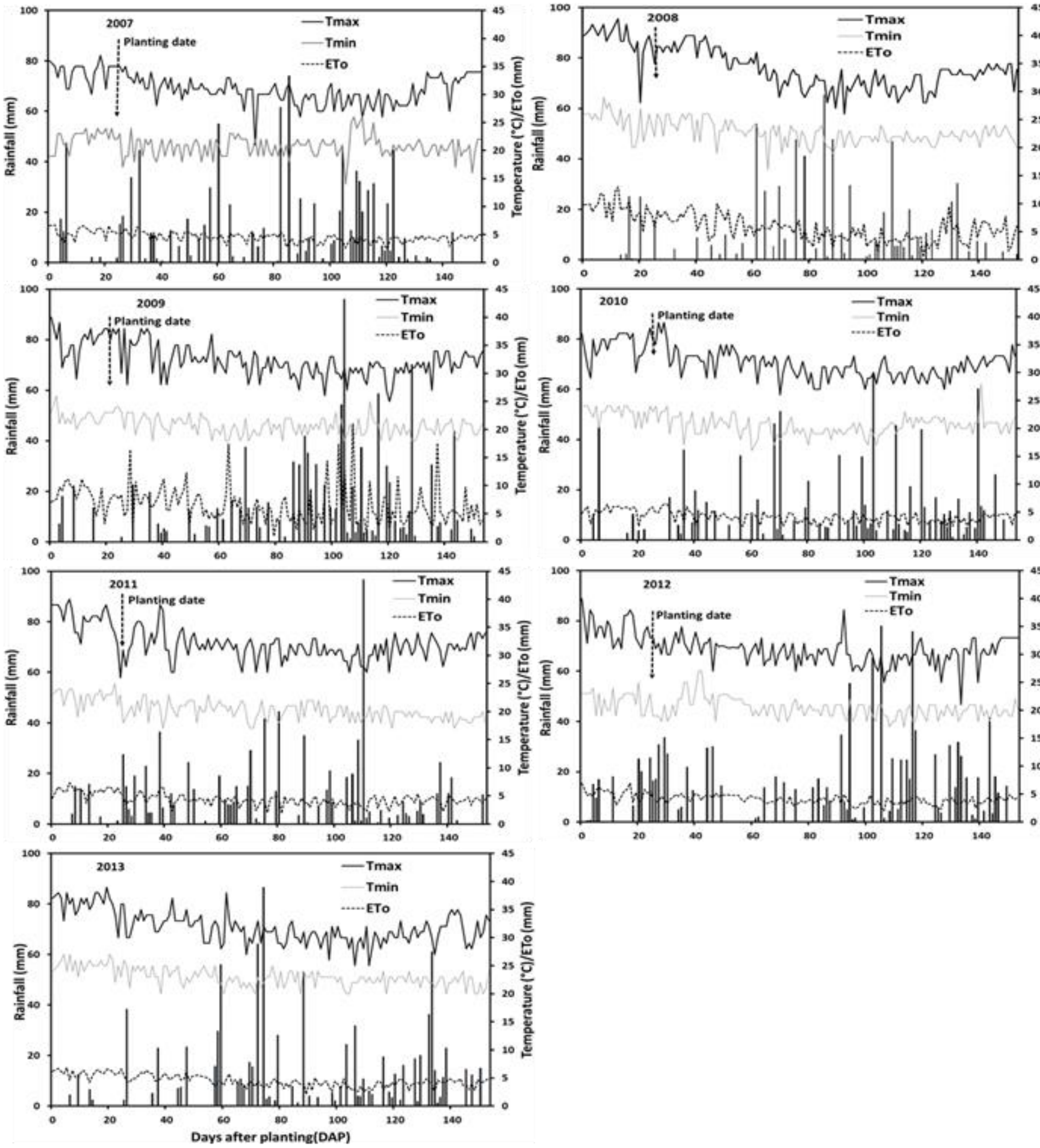

Figure 1: Daily rainfall (solid bar), maximum and minimum temperature during the cropping season in Samaru, Zaria, Nigeria. Black arrow indicates planting date, 25thMay.

The experimental plots were ploughed, disc-harrowed, and ridged at an inter-row spacing of 75 cm. Yusuf provide the initial nutrient status as well as the physical and chemical properties of the soil at the experimental plots. All measurements and analyses followed standard methods (IITA, 1989). The soil was classified as loam and the results of the tests provided information on the inherent soil fertility status of the site. The measured physical soil characteristics at the site were used as input into Soil Water Hydraulic Properties Calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) to calculate various soil parameters required by AquaCrop (Table 1). These include, Volumetric soil water content at field capacity (FC), permanent wilting point (PWP), saturation (SAT), and saturated hydraulic conductivity (Ksat).

The specific cultivar grown was oba Super 2 a yellow-colored maize developed by Premier Seed, Nigeria Limited (http://www.premier-seeds.com/services/production/field-crops.html). This cultivar was selected based on its high yield, climatic adaptability, and resistance to diseases and pests (e.g. *striga*). The records describing the field experiments state that the seeds were planted between 25th and 30th May, each year but the exact planting date is available only for 2007. Based on the method of Stern et al., (1982) and Sivakumar (1988) for determining season onset, May 25th satisfied the requirement for the start of the planting season during each year of the study period. Consequently, for our simulation, we fixed our planting date on May 25th for all years. The planting density was 53,333 plants per hectare at 25 cm and 75 cm intra- and inter-row spacing, consistent with the density recommended for use on farms in the region (See Bello, *et al*., 2012).

The aim of this experiment was to investigate the response of nitrogen application to maize grain yield and yield components. The study focused on nitrogen (N) because it is the most limiting nutrient element for maize production in the zone (Morris, *et al*., 2007; Jaliya, *et al*., 2008). Thus, fertilizer treatments during crop growth comprised four nitrogen (i.e. Urea, $CO(NH_2)_2$) rates (i.e. 0, 30, 60, and 90 kg ha^{-1}), while phosphorous (i.e. P_2O_5) and potassium (i.e., K_2O) were applied at 60 kg ha^{-1} to all the plots. Each plot size was 27 m^2, comprising six ridges of 6 m long. The treatments were arranged in a randomized complete block design (RCBD) with three replications. One-third of the N was applied at two weeks after sowing (WAS) while the remaining two-third was applied at six WAS.

The time from sowing to flowering and duration of flowering, maximum canopy cover, senescence and maturing stage after planting were determined based on the field experiment. The plots were harvested after 120 days and grain and stover yields were measured. The stover yields were added to the grain yield to obtain total above-ground biomass. It is worth noting that cob weight was not included in the stover yield measurement thereby reducing the total above-ground biomass measured but the difference should have little or no effect on our conclusion. Examination of the observed experimental yield data identified a number of caveats. For example, the observed maize yields in 2008 appear to be anomalously high across all fertility levels (in fact, they are the highest yields during the experimental period). Yet, the rainfall during each month of the growing season in 2008 was more than 35% below the average for the corresponding month during the experimental period except July (+17%) and also the crop experienced the highest water stress of any year during the experimental period, between 20 and 65 days after planting (DAP), resulting in 15% adverse effect on canopy expansion. Similarly, the observed yield for 30 N kg/ha in 2009 also appears counterintuitive because it is higher than the yield obtained for 60 N kg/ha treatment. Unfortunately, the records of the field experiments available to us do not explain these anomalies and we have opted to exclude the data for 2008 and the treatment for 30 N kg/ha (2009) from further analysis.

The rest of the data contains no other obvious defects, except the fact that the sample size is small, an unavoidable constraint of the experimental data available to us.

The main data required to run AquaCrop are climatic data--minimum and maximum air temperature (°C), humidity (%), wind speed (km/day), sun shine (hours), solar radiation (MJ/m^2/day), rainfall (mm), and reference evapotranspiration (ETo; mm/day), a measure of atmospheric evaporative demand. ETo is derived from FAO's Penman-Monteith equation which is embedded in FAO ETo calculator (FAO, 2012). The climate data were obtained from the meteorological unit of IAR/ABU Zaria, Nigeria. The weather station (11.18° N, 7.58° E,) is located within 500 m from the site of the field experiment. The annual CO_2 concentration data from Mauna Loa Observatory, Hawaii, is inbuilt in the AquaCrop Model database. AquaCrop also contains an inbuilt database with several input parameters whose values are considered conservative, meaning that they generally suffice at all locations and do not change significantly with time (Heng, *et al*., 2009, Hsiao, *et al*., 2009 and Raes, *et al*., 2009, Table 2). These values may be substituted for site specific data where the latter are not available.

All soil data used in the AquaCrop model are the same as the soil information based on the maize experiment (Table 1). The experimental design followed the same procedure by Yusuf, *et al*. (2009) and were in fact carried out by the same person.

Table 1: The soil description and properties of the experimental site.

Textural class	PWP (vol. %)	FC (vol. %)	SAT (vol. %)	TAW (mm m^{-1})	Ksat (mm day^{-1})
Loam	12.6	27.1	46.0	145	432.8

Note; TAW=Total available water

2.2. AquaCrop model description

AquaCrop is a water-driven crop model that was developed by the FAO for simulating crop yield response as a function of water consumption (Raes, *et al*., 2009; Steduto, *et al*., 2009). The model simulates crop transpiration (Tr) and soil evaporation (E) separately and then sums them up to obtain evapotranspiration (ET). The effects of water stress on crop growth are segregated into four components: canopy growth, canopy senescence, Tr and harvest index (HI). One of the most important parameters used in AquaCrop is the normalized water productivity (WP), which tends to be constant regardless of climatic conditions (Steduto et al., 2009).

AquaCrop models crop growth based on five major components and their responses to water stress, namely phenology/development, canopy cover, rooting depth, biomass production, and harvest yield (Raes, *et al*., 2009). The plant responds to water stress by (1) limiting canopy expansion; (2) early canopy senescence; and (3) stomata closure. If severe water stress persists, the (4) water productivity (WP) and (5) HI parameters may also be adversely affected (Steduto, *et al*., 2009).

AquaCrop does not explicitly consider nutrient cycles or balances. However, soil fertility stress is determined by its expected effect on crop biomass production, using a semi-quantitative assessment to establish the degree of stress resulting from various levels of nutrient deficiency. This approach yields a ratio (Brel), calculated as the total dry above ground biomass at the end of the growing season in a field with soil fertility stress (B_{stress}) divided by the total dry above-ground biomass at the end of the growing season in a field without soil fertility stress (B_{ref})(see Eqn. 1 and Van Gaelen, *et al*., 2015).

$$B_{rel} = \frac{B_{stress}}{B_{ref}} \quad X \ 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

As shown in equation (1), B_{rel} ranges from 0%, meaning complete crop failure from nutrient deficiency, to 100%, indicating no nutrient stress. This characteristic of the model allows the user to simulate the combined effect of soil fertility and water stress, which is a major strength of the model.

A major limitation of the model is that pests and diseases are not considered, which at times can lead to crop yield over-estimation. Additionally, the model has been shown to produce poor estimates under severe water-stress treatments especially during senescence (Heng, *et al*., 2009). Steduto *et al*., (2009) contains a very comprehensive description of the model's conceptual design.

2.3. Model calibration

Tables 2 and 3 show the crop parameters used for calibration. The parameters in Table 2 are assumed to be conservative.

Table 2: Conservative crop parameters (from Hsiao, et al., 2009, and Heng, et al., 2009) used in simulation of maize growth at Samaru, Zaria.

Parameter description	Value	Units or Meaning
Base temperature	8	°c
Cut-off temperature	30	°C
Canopy cover per seedling at 90% emergence(CC_o)	6.5	cm^2
Canopy growth coefficient(CGC),	1.3	% Increase per GDD
Crop coefficient for transpiration at CC=100%	1.03	Full canopy transpiration relative to ET_0
Decline in crop coefficient at reaching CCx	0.30	% decline per day due to leaf aging
Canopy decline coefficient (CDC) at senescence	1.06	% decrease in CC relative to CC per GDD
Water productivity(WP)	33.7	g(biomass)m^{-2}, function of atmosphere CO_2
Leaf growth threshold p-upper	0.14	as fraction of TAW, above which leaf growth is inhibited

Leaf growth threshold p-lower	0.72	Leaf growth stops completely at p-lower value
Leaf growth stress coefficient curve shape	2.9	Moderately convex curve
Stomatal conductance threshold p-upper	0.69	Above this stomata begin to close
Stomatal stress coefficient curve shape	6.0	Highly convex curve
Senescence stress coefficient p-upper	0.69	Above this early canopy senescence begins
Senescence stress coefficient curve shape	2.7	Moderately convex curve
Coefficient, inhibition of leaf growth on HI	7.0	HI increased by inhibition of leaf growth at anthesis
Coefficient, inhibition of stomata on HI	3.0	HI reduced by inhibition of stomata at anthesis

The non-conservative parameters (Table 3) were fine-tuned to field experiments and local agronomic conditions of the study area. The measurements for 2007 were used for model calibration because of the availability of data on soil properties, as well as ample rainfall and excellent intraseason distribution, which assured that crops would not experience water stress.

Table 3: Non-Conservative parameters adjusted to year 2007 experimental and agronomic information for Samaru, Zaria.

Parameter description	Value	Units or Meaning
Time from sowing to emergence(days or GDD)	7(120)	Day(GDD)
Time to maximum canopy cover(days or GDD)	74(1208)	Day(GDD)
Time from sowing to maximum rooting depth(days or GDD	65(1062)	Day(GDD)
Time from sowing to start of canopy senescence(days or GDD)	91(1456)	Day(GDD)
Time from sowing to maturity(days or GDD)	120(2040)	Day(GDD)
Time from sowing to flowering(days or GDD)	67(1096)	Day(GDD)
Duration of flowering(days or GDD)	30(472)	Day(GDD)
Maximum effective rooting depth, Z	1.0	meter
Minimum effective rooting depth, Zn	0.30	meter
Reference harvest index, HI	40	%
Building up of HI(days or GDD)	56(888)	Day(GDD)
Cultivar(Oba super 2)	-	Oba super 2
Plant population	53,333	Plant/ha
Sowing date	25th May	Date
N fertilizers levels	0,30,60,90	N Kg/ha

The crop's response to soil fertility stress was calibrated based on the field observations during the growing season of 2007. In the automatic calibration procedure (Table 4), the biomass yields for the treatment with 0 N kg/ha (i.e. total fertility stress) but not experiencing water stress is divided by a reference biomass yield (Bref) for a plot experiencing neither water stress nor fertility stress (i.e. equation 1). For this region, 120 N kg/ha is reference (Yusuf Ado, personal communication). Examination of the plots of soil fertility stress confirms that the assumption of no water stress is justified. The calibrated crop response to soil fertility stress for this treatment was used to simulate maize yields for the remaining growing seasons and treatments. Based on the values of Brel calculated from the various growing seasons and treatments, we have associated the first four of the inbuilt soil fertility levels in AquaCrop (i.e. poor, about half, moderate and near optimal) with the four levels of nitrogen treatments used in the maize experiment namely, 0, 30, 60 and 90 kg/ha. It is worth noting that the maximum fertilizer application rate in the experiment (i.e. 90 kg/ ha) is below the amount considered optimum in the model. The Brel for the various growing seasons and treatment ranges from 40% to 77% (see figure 2 for the calibrated Brel and soil fertility stress).

Table 4: The relative dry above-ground biomass production (Brel), maximum canopy cover (CCx) and canopy decline in the season as observed for the soil fertility-stressed calibration plots (0 kg/ha), together with the resulting calibrated local effect of soil fertility stress on canopy development (canopy growth coefficient CGC, CCX, canopy decline) and biomass water productivity (WP*) used in simulation of maize growth at Samaru, Zaria.

Crop: Maize	
Calibration location	Samaru
Input for calibration	
Brel (%)	40
CC_x under soil fertility stress (%)	25
Canopy decline	medium
Results of calibration	
CGC reduction (%)	14
CC_x reduction (%)	37
Average canopy decline (%/ha)	0.47
WP* reduction (%)	53

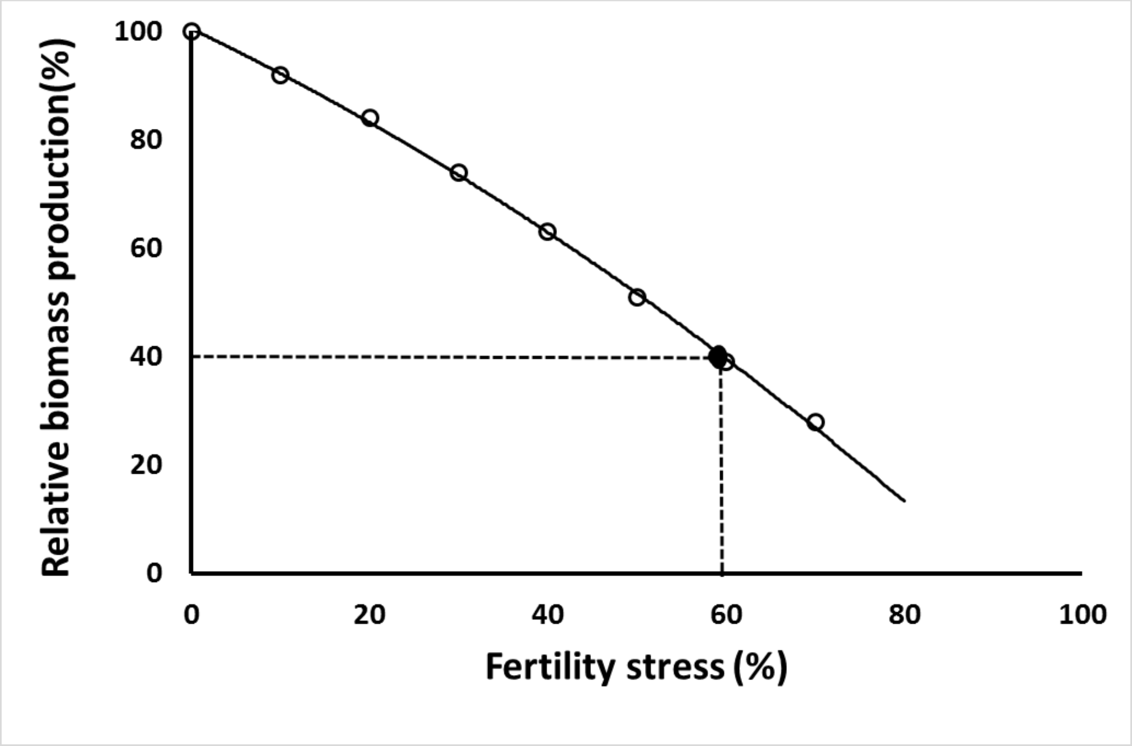

Figure 2: **The relationship between relative biomass production (Brel) and soil fertility stress. The black dot indicates the calibration point for 0 kg/ha. 0% soil fertility stress indicates no stress and 100% full stress (crop failure)**.

2.4. Model validation

The agreement between observed and simulated grain yield was analyzed using the coefficient of determination (R^2), which describes the proportion of the total variance explained by the model, as well as Willmott`s statistics measures, namely the index of agreement (d), the root mean squared error (RMSE), the mean absolute error (MAE), and the mean biased error (MBE) (Willmott 1981, 1982).

The index of agreement (*d*), is a measure of the degree to which simulated values, S, match observed values, O. Values range between zero, denoting complete disagreement and one, denoting perfect agreement. The relationship described by *d* tends to complement the information contained in RMSE. Given a set of n paired values, *d* is calculated as (Willmott, 1982):

$$d = 1 - \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} (S_i - O_i)^2}{\sum_{i=1}^{n} (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \ldots\ldots\ldots\ldots..(2)$$

Where $\bar{O}$ is the mean value of O_i.

The RMSE is the sum of the differences between simulated and the observed values. It is calculated as:

$$RMSE = \sqrt{\frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} (S_i - O_i)^2}{n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

While RMSE is a widely used and good overall measure of model performance, it is sensitive to the effects of extreme values and it does not differentiate between over- and underestimation (Willmott, 1982). Consequently, it is advisable to also use the normalized root mean square error (NRMSE) where normalization is achieved using the mean of the observed values. NRMSE is expressed as a percentage and gives an indication of the relative difference between model and observation. A model can be classified as excellent if NRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30% (Jamieson, 1991).

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} X100 / \bar{O} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

We also calculated the MAE which does not suffer from the effect of extreme values like the RMSE:

$$\text{MAE} = \frac{\sum_{i=1}^{n}|S_i - O_i|}{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (5)$$

Finally, the MBE provides an indication of the bias in the total difference between the measured and simulated values. It is calculated as:

$$\text{MBE} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6)$$

All results appear in the same units as S_i and O_i.

3. Results and Discussion

3.1 AquaCrop model calibration results

Table 5 and Figure 3 present the final grain yield and the total above-ground biomass of maize at Samaru using the calibration data for year 2007. The NRMSE comparison between the simulated and measured yields showed a maximum difference of 10.6%, which indicates a very good result. Figures 3 presents the scatter plot of the model's simulated and observed grain yield and above-ground biomass values for the four fertility levels analyzed for year 2007. These results show that the model estimates the final grain yield reasonably well with R^2 of 0.93. Wilmott's index of agreement (d) showed excellent agreement (d=0.997) between the observed and simulated yield and a RMSE (NRMSE) of 0.238 t/ha (10.6%). The above-ground biomass also showed a good fit with the observed yield with R^2 of 0.98 (d = 0.660, NRMSE = 17%). Not surprisingly, the results show that the major limiting factor for maize yield in this region is soil fertility (Figure 4).

Table 5: The simulated vs. measured results for calibration treatments (2007) for rainfed maize at Samaru.

Year	**Soil Fert. Level**	**Measured Y. t ha^{-1}**	**Simulated Y. t ha^{-1}**	**Deviation (%)**	**Measured B. t ha^{-1}**	**Simulated B. t ha^{-1}**	**Deviation (%)**
2007	Poor Nitrogen rate=0 kg/ha	1.61	1.63	1.62	5.35	5.27	-1.44
	About half Nitrogen rate=30 kg/ha	1.79	1.97	9.83	6.14	6.34	3.36
	Moderate Nitrogen rate=60 kg/ha	2.07	2.42	16.83	6.48	7.56	16.61
	Near Optimal Nitrogen rate=90 kg/ha	3.47	3.20	-7.76	8.00	9.99	24.91
Median Deviation (%)				5.73			9.99

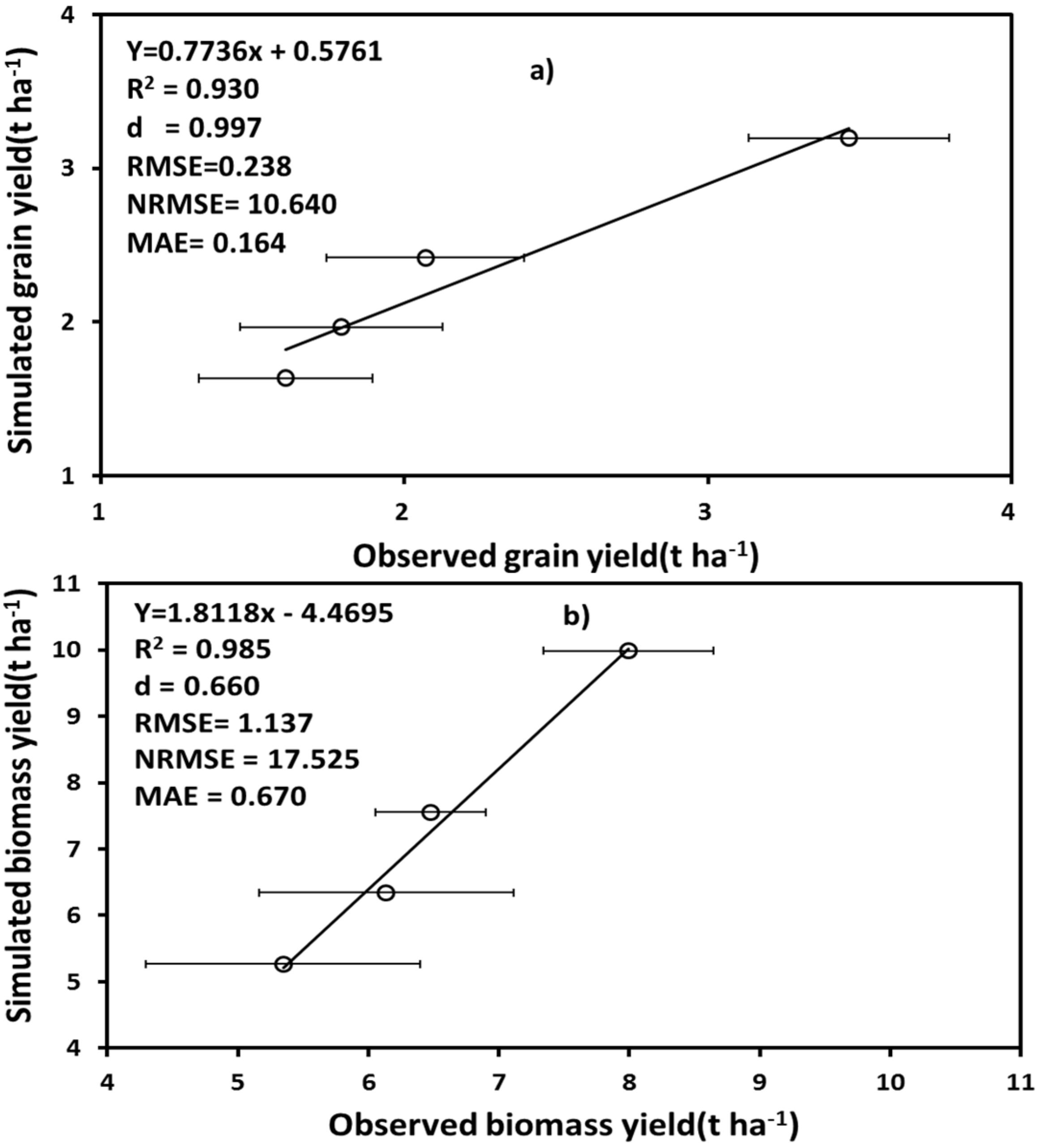

Figure 3: The results of the simulated vs. observed final grain yield (a) and biomass yield (b) for poor (0 N), about half (30 N), moderate (60 N), and near optimal (90 N) soil fertility for 2007. Error bars indicate ± standard error of the measured yield.

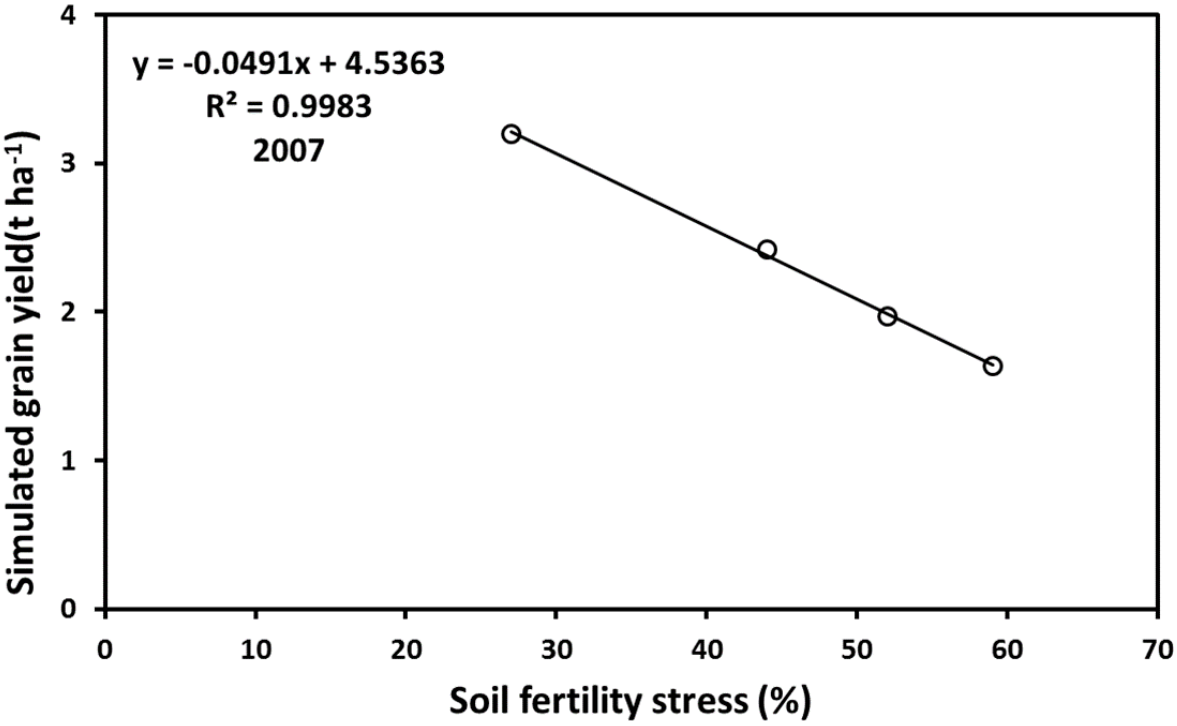

Figure 4: **The relationship between crop yield and soil fertility stress for poor (N=0 kg/ha), about half (N=30 kg/ha), moderate (N=60 kg/ha), and near optimal (N=90 kg/ha) soil fertility for 2007. Soil fertility stress ranges from 0% indicating no stress to a maximum of 100%, indicating full stress**.

3.2. Final Grain Yield (Y) and total above-ground biomass (B)

Table 6 and Figure 5 show the results of the final simulated and observed grain yields. The results show that the model estimates the final grain yield quite well, accounting for explained variance of between 94% and 99%.

The simulated grain yield varies from 1.41 to 3.70 t ha^{-1}, while the observed yield varies from 1.12 to 4.26 t ha^{-1}. It is worth noting that the yields achieved with low levels of fertilizer application are higher than those obtained by farmers in the region. As noted previously, maize yields achieved by farmers in SSA rarely exceed about 2 tons/ha and generally are much less, suggesting the farmers likely use less than 30 kg/ha. Indeed, SSA farmers use less than 10 kilograms per ha (Morris, *et al.*, 2007, IFDC, 2012). Consistent with the findings of other studies (e.g. Jaliya, *et al*., 2008; Undie, *et al*., 2012), the results show clearly that increasing soil nutrient status significantly increases maize yield in this region (Table 6 and Figure 5). As a matter of fact, the higher yields obtained in Asia, Europe, and North America are due largely to higher fertilizer rates generally in excess of 100 kg of fertilizer per ha on their farms. Regression analysis of the observed yields (Table 6) during the experimental period (2008-2013) shows that there is 0.64 kg/ha increase on average, for each 30 kg/ha increase in fertilizer application.

Table 6: The results of the final grain yield (simulated vs. observed) for rainfed maize at Samaru from 2008-2013.

Year	**Poor Nitrogen rate=0 kg/ha**			**About Half Nitrogen rate=30 kg/ha**			**Moderate Nitrogen rate=60 kg/ha**			**Near Optimal Nitrogen rate=90 kg/ha**		
	Obs. Y t ha^{-1}	**Sim. Yt ha^{-1}**	**% of dev.**	**Obs. Y t ha^{-1}**	**Sim. Y t ha^{-1}**	**% of dev.**	**Obs. Y t ha^{-1}**	**Sim. Y t ha^{-1}**	**% of dev.**	**Obs. Y t ha^{-1}**	**Sim. Yt ha^{-1}**	**% of dev.**
2008*	2.16	1.37	-36.39*	3.51	1.71	-51.40*	3.91	2.14	-45.19*	5.51	3.16	-42.70*
2009	1.18	1.41	19.66	2.33*	1.85	-20.82*	1.99	2.15	8.09	2.90	3.01	3.86
2010	1.39	1.45	4.53	1.89	1.98	4.50	2.19	2.37	8.08	3.29	3.19	-3.04
2011	1.72	1.72	0.47	2.23	2.24	0.81	2.97	2.98	0.47	3.24	3.63	12.17
2012	1.90	1.77	-6.89	2.81	2.30	-18.15	3.12	3.02	-3.24	3.91	3.70	-5.37
2013	1.69	1.59	-6.15	2.70	2.07	-23.44	3.57	2.77	-22.52	4.26	2.98	-30.09

* was excluded in this evaluation because it is anomalous.

Table 6 shows also that the percentage differences between observed and simulated yields ranges between +19% to -30%. Of the 19 treatments evaluated, 13 (68%) are within 10% of each other, generally considered very good, three (16%) are within 20%, generally considered acceptable; and 3 (16%) are > 20%, generally considered poor.

In two thirds of the treatments analyzed, the differences are within 10% of the actual yields, indicating acceptable results.

The year-to-year variations in maize yields assuming only ambient levels of soil fertility can be explained in terms of the rainfall variability. Results of multiple regression analysis (results not shown) suggest that the total rainfall in May (sowing and germination), August (flowering and grain filling) and the number of dry days during the growing season, collectively explain 61% of the variability in maize yields. Rainfall in May and the number of dry days is positively correlated with yield while total rainfall in August is negatively correlated with yield. Although the small sample size did not permit more rigorous exploration of these relationships, we suspect that there is a maximum rainfall amount (threshold) in August beyond which additional rainfall produces adverse effects on yields.

In general, the highest percent differences occurred in 2009 and 2013. In 2009, the crop experienced water stresses. First, a period of water deficit occurred between one and 44 DAP and then between 54 and 61 DAP. The combination of these events adversely affect canopy expansion by 11% and likely explains the observed yields variations. In 2013, the differences between observed and simulated yields are high and appear to diverge with increasing levels of fertilizer application. The simulation reproduced the observed yield nearly perfectly at poor fertility status but thereafter fell progressively behind with each additional fertility level. The analysis of the water stress profile shows that the first period of water stress deficit occurred between one and 29 DAP. The crop also suffered water stress deficit at the mid-season period (66-80 DAP). The combination of these events may likely explain the high difference between observed and simulated. However, we believe additional data and calibration utilizing site specific values could improve the simulation results. It is worth noting that Tsegay *et al*., (2012), observed that under non-limiting soil fertility conditions, AquaCrop performs less well in the estimation of t*eff* grain yield under water-stressed.

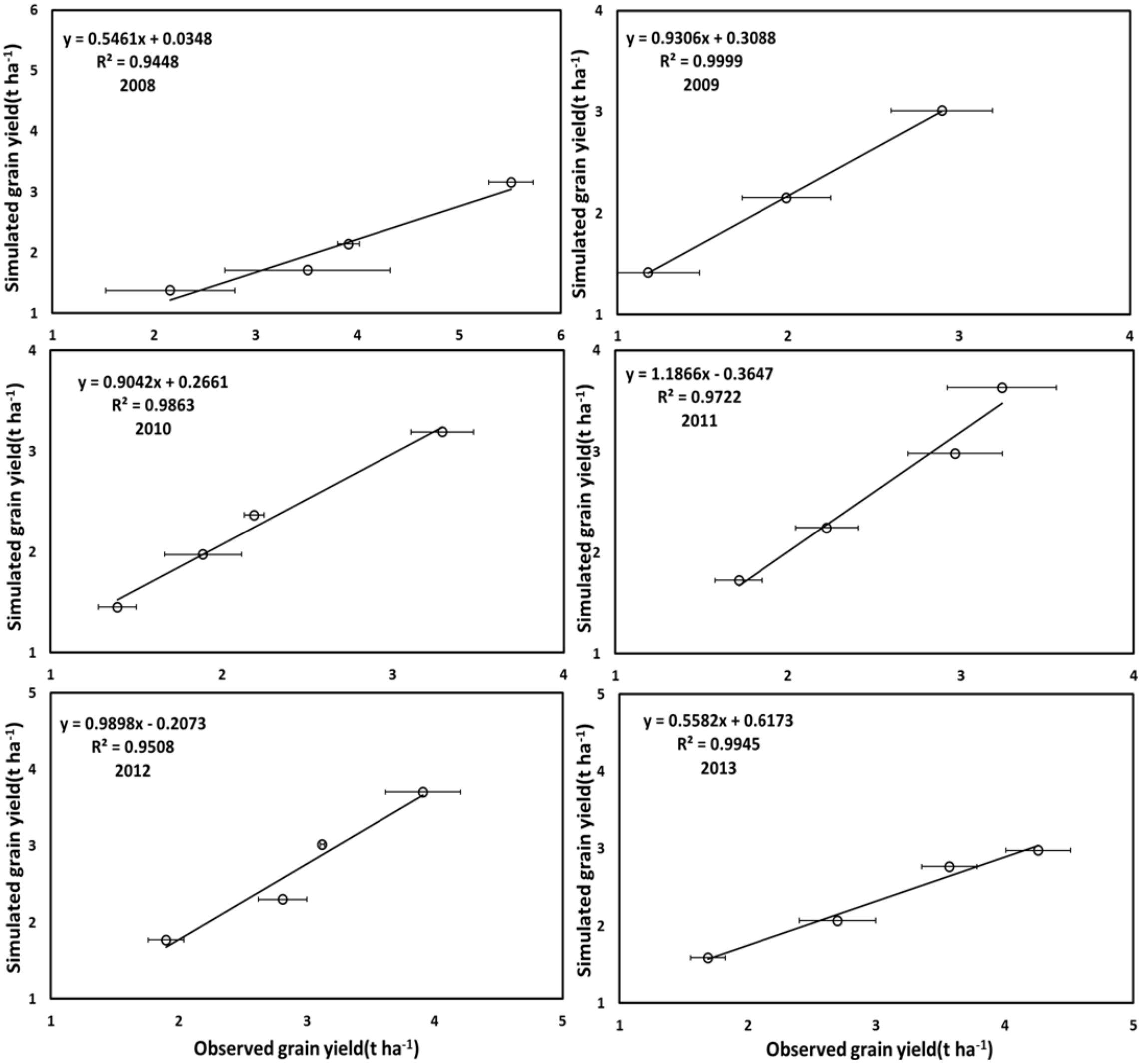

Figure 5: The results of the simulated versus observed grain yield of maize for poor-near optimal (0, 30, 60 and 90) fertility levels at Samaru, Nigeria. Error bars indicate ± standard error of the measured yield.

All model evaluation statistics are satisfactory with high degree of agreement (d-index), R^2, and low RMSE, MAE and MBE (Table 7). These results indicate that the model simulated grain yield with acceptable degree of accuracy with NRMSE of between 8-17% (Van Gaelen *et al*., 2015). The grain yield R^2 results are consistent with the results obtained in other studies (for example Abedinpour, *et al*., 2012, R^2=0.96; Mebane, *et al*., 2013, R^2=96 and Van Gaelen, *et al*., 2015, R^2= 0.97). However, on average the model systematically overestimates grain yield for most conditions. This overestimation is not surprising, given that the model was designed specifically to estimate *potentially attainable* yield. In other words, it represents the yield that theoretically would be achieved given the input variables. In reality, the observed yield may be reduced by factors not accounted for in the model, for example, disease and pests, inadequate quantity or poor timing of the fertilizer application among other factors.

Figure 6 presents the scatter plot of the model`s simulated and observed above-ground biomass yield values for individual years and all treatments. The simulated biomass yield varies from 4 to 12 t ha^{-1}, while the observed yield varies from 3 to 11 t $ha^{-1.}$ The corresponding R^2 values range from 0.82 to 0.99, also consistent with the results obtained in other studies (for example Abedinpour, *et al*., 2012, R^2=0.96; Mebane, *et al*., 2013, R^2=96 and Van Gaelen, *et al*., 2015, R^2= 0.97). The NRMSE of the simulated biomass was 19%, 24%, 20% and 26% for poor, about half, moderate, and near optimal nutrient status respectively (see table 7). These values are well within the range reported elsewhere in other AquaCrop validation for soil fertility (e.g. Van Gaelen *et al*., 2015). As with the crop yield, all evaluation statistics are satisfactory with moderate degree of agreement (d-index from 0.65 to 0.81), high R^2, (from 0.82 to 0.99), low RMSE, (from

0.95 to 2.28 ton/ha.), (Table 7, and Figure 8). The model again systematically overestimates biomass, likely due in part to the fact that AquaCrop is designed to simulate potential or achievable yields and the yield biomass obtained for calibration did not include the cobs.

Table 7: Model evaluation statistics based on soil fertility levels (0, 30, 60, 90 N), 2008-2013

Statistics	**Poor Nitrogen rate=0 kg/ha**		**About Half Nitrogen rate=30 kg/ha**		**Moderate Nitrogen rate=60 kg/ha**		**Near Optimal Nitrogen rate=90 kg/ha**	
	Grain Y	Biomass	Grain Y	Biomass	Grain Y	Biomass	Grain Y	B
d	0.88	0.82	0.63	0.71	0.83	0.68	0.67	0.66
RMSE, t ha^{-1}	0.13	0.95	0.43	1.374	0.378	1.456	0.611	2.280
NRMSE (%)	8.32	19.22	17.78	24.24	13.66	20.21	17.35	26.74
MAE, t ha^{-1}	0.108	0.725	0.346	1.045	0.251	1.293	0.419	1.902
MBE, t ha^{-1}	0.014	0.391	-0.305	1.001	-0.111	1.293	-0.217	1.902

Note: NRMSE<10% as excellent, NRMSE10-20 as Good, NRMSE 20-30% as Satisfactory, NRMSE>30%, as Unsatisfactory (Threshold based on the recommendation by Jamieson, 1991 and Singh, et al., 2004), d≥ 0.9 as very good, 0.80-0.89 as good, 0.65-0.79 as moderate good, 0.50-0.64 as moderate poor, 0.25-0.49 as poor, d<0.25 as very poor (Threshold based on AquaCrop version 5.0 model's evaluation, p45).

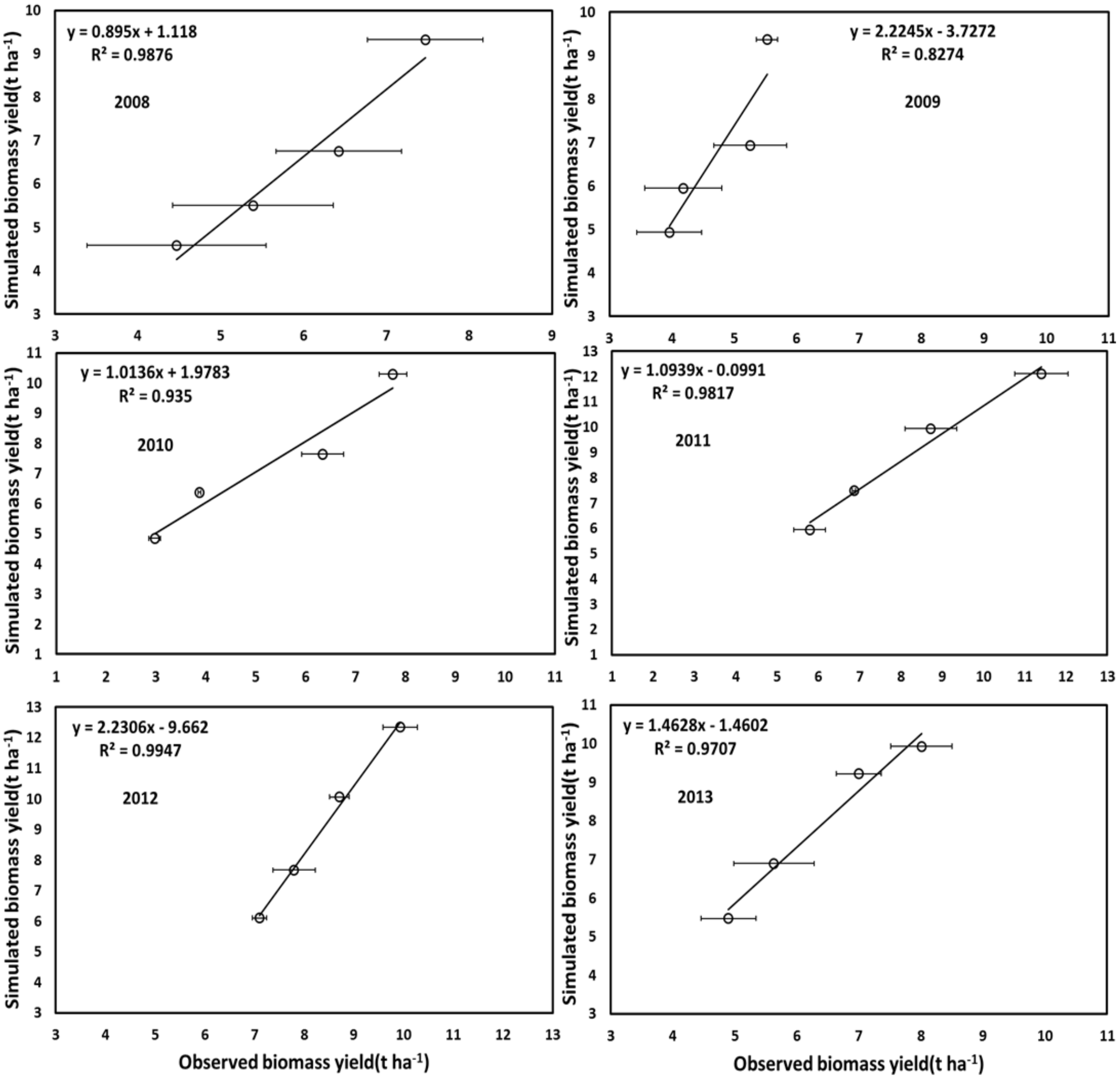

Figure 6: **The results of the simulated vs. observed final biomass yield of (a) poor (0 N), (b) about half (30 N), (c) moderate (60 N), and (d) near optimal (90 N) soil fertility for 2008-2013. Error bars indicate ± standard error of the measured yield**.

4. Conclusion

During the past half century, food productivity in Sub-Saharan Africa (SSA) has lagged the rest of the world while population growth has outpaced the rest of the world. These contrasting trends portend serious risk for the food security of the region. To arrest or mitigate the situation, concerted action is needed, including improved decision-making informed by scientific evidence. Toward that goal, this study calibrated and validated AquaCrop on maize production in northern Nigeria. The model is capable of producing robust and accurate results given relatively few input variables, making it uniquely suited to data-scarce regions like SSA. Model performance was evaluated in two ways using actual maize yields from an experimental field plot at the Institute for Agricultural Research, Zaria. First, simulated yields were compared against actual yields for each year of the study period. With the exception of one anomalous year (2008), simulated yields reproduced actual yields to within 90% or better. Second, observed and simulated yields were compared by nutrient status across all years; the NRMSE for grain yields were around 8% for poor, 17% for about half, 13% for moderate fertilizer levels and 17% for near optimal fertilizer levels while the NRMSE for biomass yields were around 19% for poor, 24% for about half, 20% for moderate fertilizer levels and 26% for near optimal fertilizer levels. While encouraging, simulated yields systematically over-estimate observed yields, likely because AquaCrop is designed to simulate potential or achievable yields. The results can be improved if data on more site-specific parameters are available. Overall however, the agreement between simulated and observed yields is consistent with those reported elsewhere and suggest that the model can be utilized as a tool in the study and modeling of maize productivity in this region.

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Chapter 3

Utilizing Process-based Modelling to Assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa.

Utilizing Process-based Modelling to Assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa.

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Abstract: Climate change is estimated to substantially reduce crop yields in Sub-Saharan West Africa by 2050. Yet, a limited number of studies also suggest that several adaptation measures may mitigate the effects of climate change induced yield loss. In this paper, we used AquaCrop, a process-based model developed by the FAO, to quantify the risk of climate change on several key cereal crops in the Niger Basin. The crops analysed include maize, millet, and sorghum under rainfed cultivation systems in various agro-ecological zones within the Niger Basin. We also investigated several adaptation strategies, including changes in the sowing dates, soil nutrient status, and cultivar. Future climate change is estimated using nine ensemble bias-corrected climate model projection results under rcp4.5 and rcp8.5 emissions scenario at mid future time period, 2021/25-2050. The results show that on average, temperature had a larger effect on crop yields so that the increase in precipitation could still be a net loss of crop yield. Our simulated results showed that climate change effects on maize and sorghum yield will be mostly positive (2% to 6% increase) in the Southern Guinea savanna zone while at the Northern Guinea savanna zone it is mostly negative (2 to 20% decrease). The results show that at the Sahelian zone the projected temperature and precipitation changes have little to no impacts on millet yield for the future time period, 2021/25-2050. In all agroecological zones, increasing soil fertility from poor fertility to moderate, near optimal and optimal level significantly reversed the negative yield change respectively by over 20%, 70% and 180% for moderate fertility, near optimal fertility, and optimal fertility. Thus, management or adaptation factors, such as soil fertility, had a much larger effect on crop yield than the climatic change factors. These results provide actionable guidance on effective climate change adaptation strategies for rain fed agriculture in the region.

Keywords: Climate Change; Agriculture; Crop Yield; Adaptation, Niger Basin; AquaCrop

1. Introduction

The results of numerous studies (e.g. Schlenker and Lobell, 2010; Rosenzweig *et al*., 2013; Sultan *et al*., 2014) show that cereal yields in West Africa will likely decline by 10% by 2050 due to climate change. Other studies (e.g. IFPRI, 2009; Muller *et al*., 2010 and Thornton *et al*., 2011) show that parts of the region will also experience a decrease in the length of the growing season potentially worsening West Africa's already chronic history of agricultural underperformance (Sanchez, 2010; Knox *et al*. 2012; FAO 2017, see supplementary Figure S1). Looking ahead, the region's population is on pace to double by 2050 (FAO, 2006; UN, 2013), which will require a five-fold increase in food production just to keep pace (Thornton et al., 2011; Rockstrom and Falkenmark, 2015).

Despite such projections, studies investigating potential mitigation and adaptation options in the region have often reached surprisingly optimistic conclusions. For example, using the crop simulation model Cropsyst, Tingem and Rivington (2009), investigated the effects of changing sowing dates and crop cultivars on yields of maize and sorghum crops in Cameroon. The authors concluded that simply changing the sowing dates results in yield gains of about 8% for maize and 12% for sorghum, nearly compensating for the expected yield loss due to climate change. While impressive, that effect pales in comparison to adopting new cultivars designed to take advantage of a possible longer growing season. Notably, a 14.6% reduction in maize yield due to climate change was changed to a 32.1% increase i.e. (+46.7%) and a 39.9% decrease in sorghum yield was changed to a 17.6% increase (i.e. +57.5%), even without additional changes in other management options. Other evidence also suggest strongly that farm management practices could significantly mitigate effects of climate variability and change (IFPRI, 2009; Lahmar, *et al*., 2012; Blanc, *et al*., 2012; Challinor *et al*., 2014). For example, despite significant temperature increase (0.95°C) and unprecedented rainfall variability in semi-arid West Africa since 1960, farmers have managed to approximately double yields of several major crops (see supplementary Figure S2).

Somewhat surprising given such promising results, the use of crop models for investigating climate change mitigation and adaptation options in West Africa remains limited. In this paper we utilized the Food and Agricultural Organization (FAO)-developed AquaCrop, a process based model, first to quantify crop yield response to climate change in the Niger River Basin (NRB), and second, to investigate the effects of various adaptation measures in mitigating climate change impacts on crop yields. AquaCrop simulates crop yield as a function of water consumption (Raes, *et al*., 2009; Hsiao, *et al*., 2009) and has been shown to satisfactorily model crop yields in various parts of Africa (Araya, *et al*., 2010; Van Gaelen, *et al*., 2015). Within the Niger River Basin, Akumaga *et al*., (2017, p.233-234) calibrated and validated the model for maize (Oba Super 2), using field experimental data at the Institute for Agricultural Research (IAR), Zaria in Nigeria. The authors concluded, "the agreement between simulated and observed yields is consistent with those reported elsewhere and suggests that the model can be utilized as a tool in the study and modeling of maize productivity in this region."

Here, we extend our previous work by further calibrating AquaCrop for sorghum and millet grown in other agro-ecological zones within the Niger Basin. The results add to the growing literature on climate change impacts on crop yields in this famine-and drought-prone region. Additionally, the results provide actionable information for improving crop yields to mitigate climate risks in Sub-Saharan Africa (SSA). Following this introduction, section two provides a brief description of the study area, section three focuses on data and methods, results and discussions appear in section four, and finally, major findings and conclusions are presented in section five.

2. Study area

With a total drainage area of 2,170,500 km^2, the Niger River Basin cuts across all the major agro-climatic and ecological zones of West Africa namely, the Guinean or Equatorial forest zone, the Transitional tropical belt, the Sudan Savanna zone, the Semi-arid or Sahel savanna belt and the Desert (Tarhule *et al*., 2014; Figure 1). Our study focused on six locations within the Niger River Basin, namely Dori, Tahoua and Tillabery within the Sahel zone; Makurdi, (within the Southern Guinea zone); and Samaru and NTarla (Northern Guinea zone).

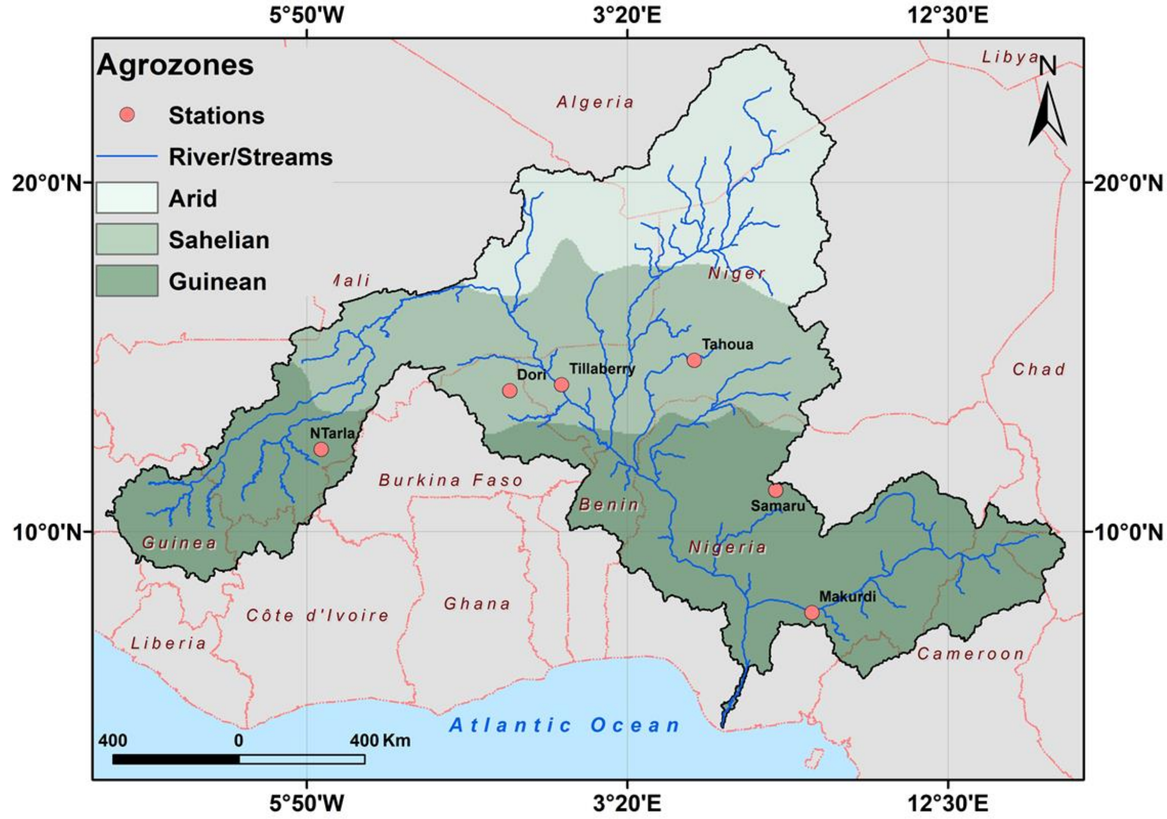


Figure 1: The Location of the Niger Basin in West Africa showing study locations (red dots) and agro-ecological zones.

Shared by nine countries (Benin, Burkina Faso, Cameroon, Chad, Cote D`Ivoire, Guinea, Mali, Niger and Nigeria), the Niger River Basin had a population (2005) of 105 million (Andersen, 2005). Seventy percent of the labor force is engaged in subsistence (largely rainfed) agriculture (Tarhule, 2011; Knox *et al.*, 2012) and is therefore highly susceptible to climatic variability and change (Tarhule *et al.*, 2009). The major cereal crops grown in the basin in terms of both tonnage and acreage are Maize, Sorghum, Millet, and Rice.

3. Materials and Methods

3.1. AquaCrop model description

AquaCrop simulates crop growth based on five major components and their responses to water stress, namely phenology/development, canopy cover, rooting depth, biomass production, and harvest yield (Raes, *et al*., 2009).

Compared to other process-based crop models, AquaCrop uses a relatively small number of crop and environmental parameters. The parameters specific to the crop which do not change with time, management practices, geographic location or climate, and cultivar are considered conservative (e.g. base temperature, cut off temperature, water productivity, canopy growth coefficient). Non-conservative crop parameters (e.g. sowing date, effective rooting depth, and maturity date) are those that change with location and management practices and therefore need to be fine-tuned to local agronomic conditions. The detailed formulation can be found in Raes *et al* (2009) and Steduto *et al* (2009).

The climatic data required to run AquaCrop include: minimum and maximum air temperature (^{o}C), humidity (%), wind speed (km/day), sun shine (hours), solar radiation (MJ/m^{2}/day), rainfall (mm), and reference evapotranspiration (ETo; mm/day). ETo is derived from FAO Penman-Monteith equation which is embedded in FAO ETo calculator (FAO, 2012). In this study, two time periods were used: historical time period (1981 or 85 to 2010) for model calibration and the future time period (2021 or 2025 to 2050) for climate change-induced yield estimation. Differences in the reference time periods at some locations are the results of data constraints. Daily rainfall and minimum and maximum temperature data were obtained from the National Meteorological Agencies of

Nigeria, Burkina Faso, Guinea, and Niger and from agricultural research station of NTarla in Mali. The relative humidity, solar radiation, sunshine and wind speed were extracted from AgMERRA climate forcing dataset for Agricultural forcing (https://data.giss.nasa.gov/impacts/agmipcf/agmerra/), and the future climate projections from CORDEX Africa (http://esg-dn1.nsc.liu.se/esgf-web-fe/**).** The datasets are available at 0.5 x 0.5 degree resolution for West Africa. The annual CO_2 concentration data from Mauna Loa Observatory, Hawaii is built in the AquaCrop Model. The historical crop yield data were obtained from various agricultural agencies within the basin (Table 1)

Table 1: Crop data sources

Study site	Agroecological	Data Source	Period
Makurdi	Southern Guinea	BNARDA	1985-2010
Samaru	Northern Guinea	I.A.R/ABU Zaria/ KADP	1980-2010
NTarla	Northern Guinea	IER NTarla	1985-2010
Tillabery and Tahoua	Sahel	AGRHYMET	1980-2010
Dori	Sahel	FAO for Dori district	1980-2010

Note:Institute for Agricultural Research, Ahmadu Bello University (I.A.R/ABU) Zaria/ Kaduna State Agricultural Development Project (KADP); Benue Agricultural and Rural Development Authority (BNARDA; Center for Agriculture, Hydrology, Meteorology (AGRHYMET); Agricultural Research Station NTarla, Institut D'Economie Rurale (IER), Programme Coton, Station de Recherche Agronomique de N'Tarla, Mali, and Food and Agriculture Organization of the United Nations (FAO).

3.2 Climate scenarios and bias correction technique

To assess the impact of climate change on crop yields, nine general circulation models (GCMs) climate models and one downscaled regional climate model (RCM) were selected. The GCMs/RCM models include: CCCma-CanESM2/RCA4, CNRM-

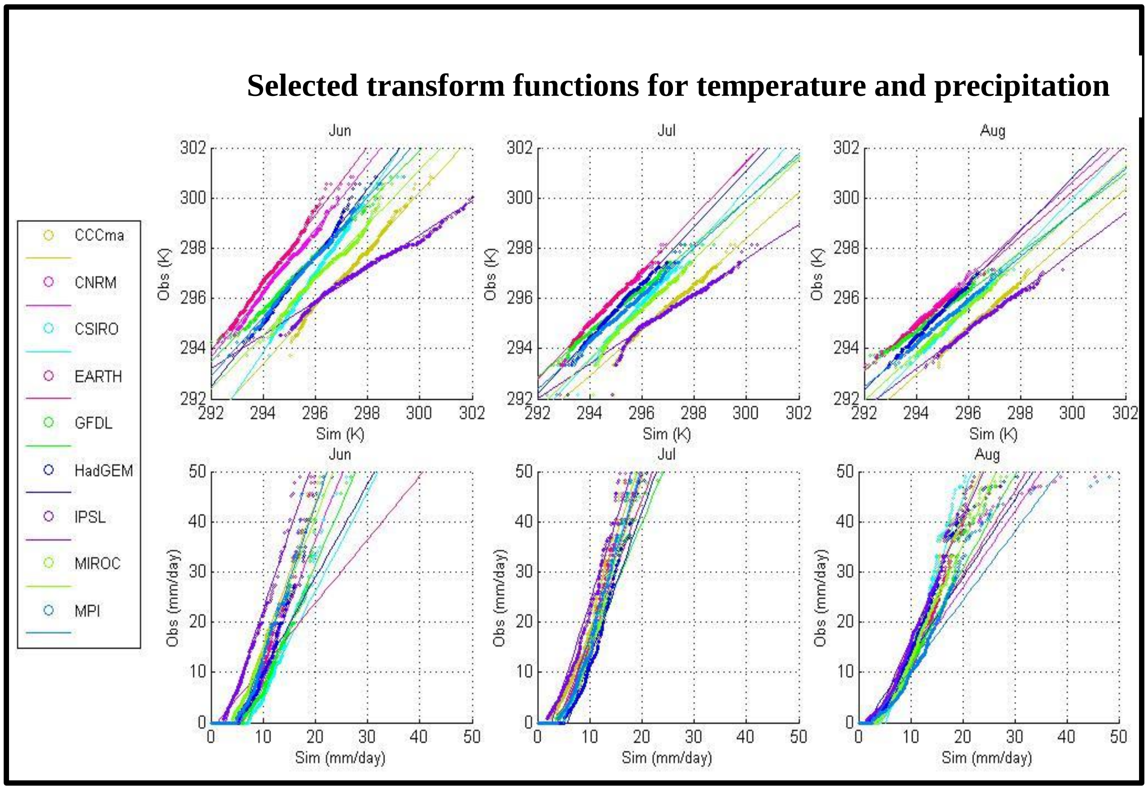
CERFACS/ RCA4; CSIRO-Mk3-6-0/ RCA4; IPSL-CM5A/ RCA4; MIROC-MIROC5/ RCA4; HadGEM2-ES/ RCA4; MPI-ESM/ RCA4; GFDL-ESM2M/ RCA4; ICHEC-EC-EARTH/ RCA4. The resolution of all the models is 0.5° with a baseline period, 1976-2005 and future period, 2021-2050 under rcp4.5 and rcp8.5 scenarios. The selected models have all been shown to have skill in reproducing the key features of the present-day precipitation and temperature over West Africa (Nikulin, *et al*., 2012; Gbobaniyi, *et al*., 2014).

The projected time series of daily temperatures and total daily precipitation (2021/25-2050) were bias-corrected using the weather station nearest to the downscaled grid cell, following the method described by Piani *et al* (2010). For precipitation, the basic steps and assumptions of the method are as follows (interested readers may consult Piani *et al*., 2010 for details).

1. For each station, the nearest model grid point is identified and used for the bias correction process. This approach has been shown to be superior to averaging multiple grid point time series which degrades the statistics, in particular at the high intensity end of the distribution (Haerter *et al*. 2015).
2. The bias correction is done separately for each individual month. That is, all daily values corresponding to a given calendar month, for the observed and the historical simulation, over the observational period are collected in two time series of equal length. For example, all the 31 daily precipitation values for the month of January from 1976 to, and including 2005, are used to calculate the January bias correction parameters. The years 1976 to 2005 are used for the bias correction of the stations of

Samaru, Tahoua and Dori, while the years 1980 to 2005 are used for Makurdi, NTarla, and Tillabery. In each case we used all available observational data. For the analysis of the impact of climate change on crop yield, we used the historical climate data and different historical simulation period corresponding to the available historical crop yield data for the baseline (1981/85-2010).

3. The two time series are sorted in order of increasing intensity from lowest, generally corresponding to zero precipitation or "dry days", to most intense. Then the observed time series is plotted against the simulated. The resulting plot is sometimes referred to as the emerging perfect transform function (Piani at al. 2010) or simply the perfect transform function (PTF). Note that a straight forward plot of the intensity-sorted time series of precipitation yields its cumulative distribution function (CDF). Examples of the PTF for precipitation for June, July and August for selected stations are shown in the bottom panel of Figure 2. A considerable portion of the PTF is contained near the origin (0,0) because the initial sections of the sorted precipitation time series are dominated by zeros. Furthermore, since it is often the case that models have considerably less dry days than the observations and correspondingly more days of light precipitation, the PTFs usually lie along the x-axis close to the origin



Selected transform functions for temperature and precipitation

Figure 2: Bias correction transform functions for temperature (top panel) and precipitation (bottom panels).

4. The portion of the perfect transform function that lies off the x-axis, is fitted with an analytic function of choice, in this case a first degree polynomial. The fact that we consider only the portion of the PTF that lies off the x-axis is mathematically similar, though not identical, to applying what many authors call a "dry day correction" and is standard practice.
5. The fitted TF can then be used to correct projections of future scenario precipitation values. The corrected values will have, by construction, the same CDF as the observations to the extent that the PTF is well approximated by a first degree polynomial (Figure 3). In essence, the fact that the nine bias-corrected CDFs in figure 3 (green lines) are almost

perfectly superimposed onto the observed CDF (blue line) while the non-bias-corrected CDFs (red lines) are spread out, shows that the PTF is well approximated by a linear fit.

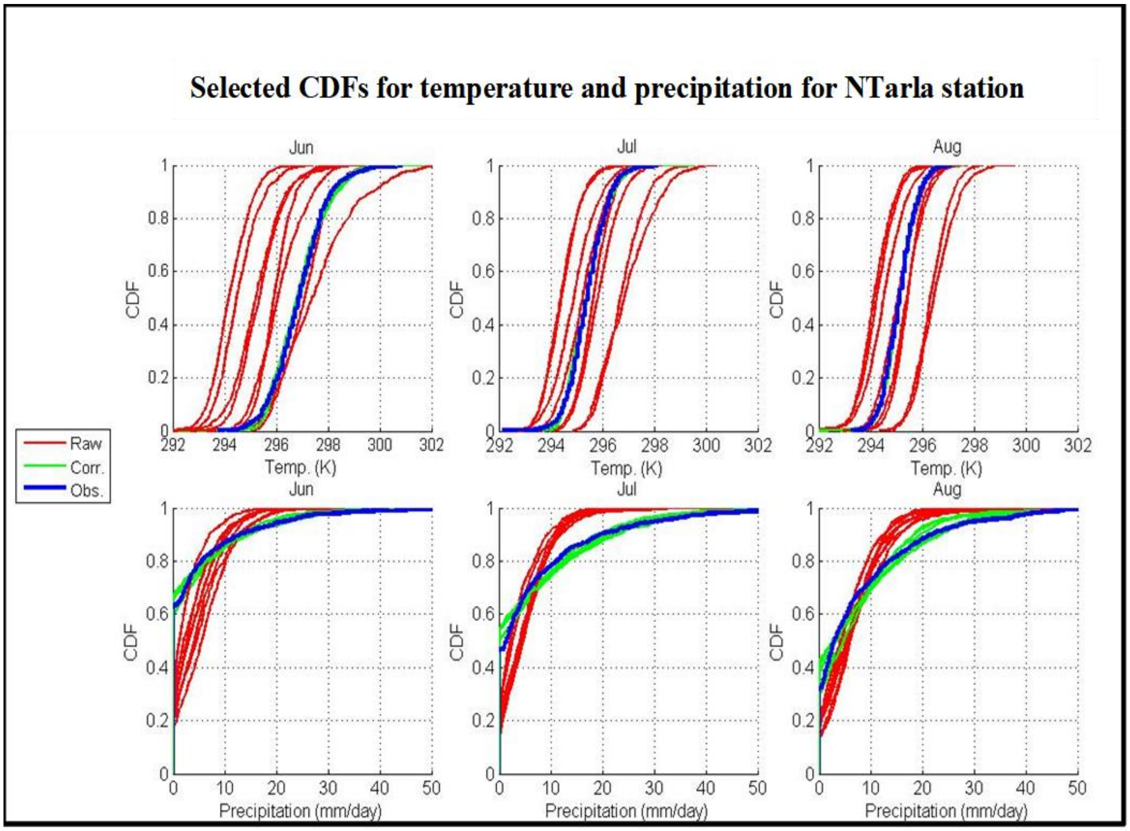


Figure 3: CDFs for the NTarla station. Minimum daily temperatures are in the top panel while precipitation values are in the bottom. Red CDFs are raw model data, green CDFs are bias corrected and blue CDFs are observed.

While the above steps appear straightforward, a number of caveats and limitations are worth noting:

First, the applicability of bias corrected climate projections is limited by the stationarity of the bias itself. Bias is the difference between the statistical distribution of the intensity, or intensity statistics, of observed and simulated variables. The difference between the intensity statistics of observed and simulated precipitation may change in time especially over long periods. Second, the fitting procedure may fail in cases where there are insufficient data points, that is, where there is little precipitation during the time interval chosen to derive the TF. In other instances, the resulting fitted TF may have unrealistic parameters, for example the intercept, or additive correction factor, may be positive. In general, one expects the intercept of a linear bias correction for precipitation to be negative because observations usually have many more dry days compared to simulations. Positive intercepts convert all dry days into wet days, which is both unrealistic and undesirable. To avoid this, a simpler analytical form of the TF is chosen, for example a multiplicative constant may be determined, constraining the TF to pass through the origin.

By comparison, bias correction of Tmax and Tmin is far simpler. The choice of TF is always a first degree polynomial as there is never a lack of data and the resulting TF is always well constrained (Figures 2 and 3).

3.3. Crop model calibration and evaluation

To calibrate AquaCrop, we followed the procedure described in detail in Akumaga *et al*. (2017) and Van Gaelen *et al*., (2014). Briefly, the procedure is as follows:

First, for each site the model is run using historical climate data and the same cultivar, time of planting, plant density, soil characteristics, and fertility levels obtained from field experiments. The calibrated model and historical climate data are used to simulate crop yields and then compared with the actual historical yields obtained at the experimental field plots nearest the study location. Calibration involves fine tuning selected non-conservative model parameters (see Raes *et al*., 2009 and Heng *et al*., 2009) to improve the match between observed and simulated yields. The same values of the fine-tuned parameters are used throughout the time series for yield prediction.

Second, we assessed model fidelity between the simulated historical yield and the measured historical yield using the index of agreement (d) which measures the degree to which simulated values, match the observed values, the root mean squared error (RMSE), which is the sum of the differences between simulated and the observed values, the normalized root mean squared error (NRMSE), which is a measure (%) of the relative difference between model simulated and observed values, the mean absolute error (MAE), which summarizes the mean differences or measures the weighted average magnitude of the absolute errors, and the mean biased error (MBE), which is an indicator of whether the model is over or under predicting the observed. Positive values of MBE indicate over prediction while negative values indicate under prediction (Willmott, 1981; 1982).

Third, with the confidence achieved from the simulation of the historical yield, the calibrated model is used without further adjustment to predict the future crop yield to analyze the yield change relative to the historical yield baseline. Note we used ensemble results which is the average of the nine GCM models.

3.4. Climate change adaptation and management scenarios

Figure 4 shows the possible adaptation scenarios investigated for mitigating the effects of climate change on agricultural production in the Niger Basin. They include:

1. Adjusting sowing dates. Climate change may result in an increase or decrease in the length of the growing season relative to the historical period. We investigate the effects of these changes using three planting windows defined by the FAO crop calendar for the various locations and agro ecological zones. These are: early planting date (EP), medium planting date (MP) and late planting date (LP). Note, EP=15-25/May, MP= 9-19/June and LP= 9-19/July for Samaru and NTarla locations (i.e. Northern Guinea), EP=15-25/April, MP=15-25/May, LP=15-25/June for Makurdi location (i.e. Southern Guinea) while for Dori, Tillabery and Tahoua locations (i.e. Sahelian zone), EP=1/June, MP= 20/June and LP= 10/July.

2. Increased soil nutrients. The AquaCrop model has four levels of soil fertility: poor (P), moderate (M), near optimal (NP) and optimal (OP) levels corresponding to the Nitrogen rate of 0 kg/ha, 60 kg/ha, 90 kg/ha and 120 kg/ha respectively (Akumaga *et al.*, 2017). We tested the fertility levels for each location. Assuming that climate change reduces crop yields, could an increase in soil fertility compensate for that decrease, ameliorating the impacts of the expected climate change induced yield loss? To investigate this scenario, we simulated future crop yield for the periods 2021/25-2050 for each of the fertility levels and then compared the results with the historical yield.
3. Change in cultivar: We used two cultivars, long duration (V1) and medium duration (V2) cultivars to determine the yield and response of each crop variety to climate change. For adaptation policy formulation, these scenarios will determine the most suitable varieties to be used in a changing climate conditions.

Thus, the resulting simulation (Figure 4) integrates all of the above management and adaptation scenarios.

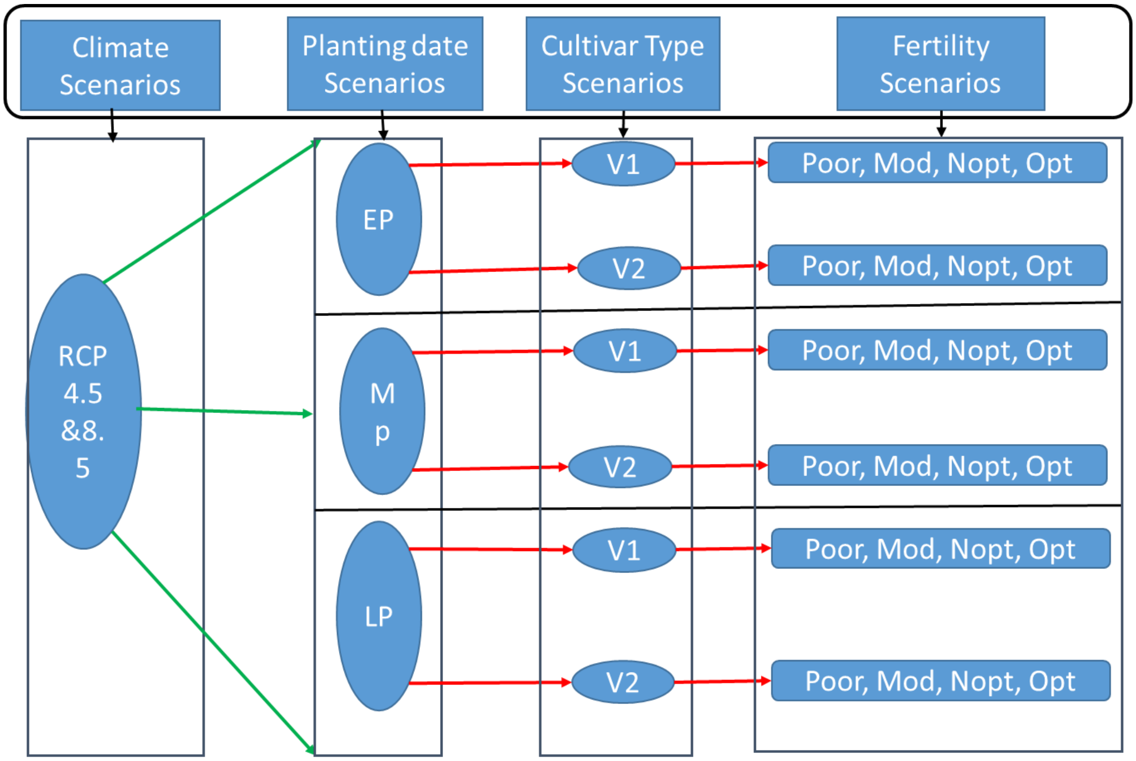


Figure 4: Flowchart showing the various climate change adaptation scenarios. Note, EP=early planting (D1), MP=medium planting (D2), LP=late planting (D3), V1=long duration (110-125 DAP), V2=medium duration cultivar (105-110), Mod=moderate fertility, Nopt=Near optimal fertility and Opt=Optimal fertility. Note: Sorghum V1=130-145 DAP, V2=110-125, DAP

4. Results and discussion

4.1 Evaluation of the simulated crop yields under the historical period

Tables 2 and 3 present the results of the model evaluation statistics for maize, sorghum, and millet in three agroecological zones. In all cases, soil fertility is assumed to be poor so that crop yield is a function of ambient soil fertility status only. The model performance shows a high to poor degree of agreement for maize and sorghum yields (See Table 2). The d-index values show that AquaCrop simulated sorghum and maize yields can be considered good to very good in all ecological zones, except the sorghum yields at Makurdi which are poor. The poor result in terms of d-index shows that the model was unable to capture year to year yield variation for this location. The most likely explanation is inadequate calibration due to lack of data on some non-conservative parameters at this site. We also observed that the observed yield significantly increased above the simulated yield from 1999 to 2010, which may suggest increased fertilizer use in the region, but our model was calibrated for poor fertility level. Future average yield was compared with the historical simulated average yield to reduce the effect of poor agreement between the simulated and the observed yields. On average, our simulated historical yields are less than 5% higher than the observed (1.501 vs. 1.565 tons/ha), although significant variations between observed and simulated yields occur in some years. For millet, the d-index suggests that the simulated values are moderately good.

The NRMSE results show excellent agreement between the simulated and actual yields for maize at Makurdi and sorghum at Zaria on this indicator, but only good to satisfactory for sorghum at Makurdi and NTarla, respectively. Simulated millet yields, on average, are only good to satisfactory across all locations on these statistics. The low MAE values indicate that our results are good across all ecological regions.

The MBE evaluation results presented in Tables 2 and 3, show that in most cases the model overestimates grain yields of maize, millet, and sorghum. This is not surprising because AquaCrop was designed to simulate potential or achievable yields, i.e., the yields that would be realized under optimum management, which is a condition rarely satisfied in practice. In all cases the median yield differences between the observed and simulated are between 7%-20%, indicating good results.

Table 2: Model evaluation statistics for maize and sorghum based on poor soil fertility, 1981/85-2010

Statistics	**MAKURDI (Obs VS. Simulated) Southern Guinea**		**Samaru (Obs VS. Simulated) Northern Guinea**		**Ntarla (Obs VS. Simulated) Northern Guinea**
	Sorghum Y	Maize Y	Sorghum Y	Maize Y	Sorghum Y
d	0.379	0.978	0.858	0.821	0.948
RMSE, t ha^{-1}	0.291	0.096	0.375	0.210	0.355
NRMSE (%)	19.404	7.531	6.921	13.944	20.622
MAE, t ha^{-1}	0.255	0.085	0.076	0.166	0.283
MBE, t ha^{-1}	0.064	0.005	-0.012	0.091	-0.058

Note: NRMSE<10% as excellent, NRMSE10-20 as Good, NRMSE 20-30% as Satisfactory, NRMSE>30%, as Unsatisfactory (Threshold based on the recommendation by Jamieson, 1991 and Singh, et al., 2004), d≥ 0.9 as very good, 0.80-0.89 as good, 0.65-0.79 as moderate good, 0.50-0.64 as moderate poor, 0.25-0.49 as poor, d<0.25 as very poor (Threshold based on AquaCrop version 5.0 model's evaluation, p45).

Table 3: Model evaluation statistics for Millet based on poor soil fertility, 1981/85-2010.

Statistics	**Dori (FAO VS. Simulated) Sahelian Zone**	**Tahoua (Agryhmet VS. Simulated) Sahelian Zone**	**Tillabery (Agryhmet VS. Simulated) Sahelian Zone**
	Millet Yield	Millet Yield	Millet Yield
d	0.758	0.740	0.731
RMSE, t ha^{-1}	0.131	0.063	0.071
NRMSE (%)	21.412	15.776	17.348
MAE, t ha^{-1}	0.113	0.042	0.0567
MBE, t ha^{-1}	-0.011	0.007	0.026

Note: NRMSE<10% as excellent, NRMSE 10-20 as Good, NRMSE 20-30% as Satisfactory, NRMSE>30%, as Unsatisfactory (Threshold based on the recommendation by Jamieson, 1991 and Singh, et al., 2004), d≥ 0.9 as very good, 0.80-0.89 as good, 0.65-0.79 as moderate good, 0.50-0.64 as moderate poor, 0.25-0.49 as poor, d<0.25 as very poor (Threshold based on AquaCrop version 5.0 model's evaluation, p45).

4.2. Precipitation and temperature change in the Niger River Basin

Table 4 summarizes the change in ensemble minimum and maximum temperatures at each study location between future climate and baseline. The ensemble changes are computed as averages across the nine GCM simulations for each of the six locations. The range of variation in individual models appear in Figure 5. The results show that all models are in agreement that the minimum and maximum temperatures in the Niger Basin will be higher in the future, relative to baseline. The result is consistent with the findings of numerous studies (IPCC, 2014, Sultan, *et al*., 2014) and GCM simulations which consistently find strong agreement in the sign of the change in temperature across West Africa. Second, the change in minimum temperatures will be higher than the change in the maximum. For rcp4.5 the expected change in minimum temperature will be 1°C, 2°C and 2.2°C respectively in southern Guinea, northern Guinea and the Sahel, compared to 1.2°C,1.8°C and 1.8°C for the maximum temperature change. For rcp8.5 the corresponding values are 1.4°C, 2.4°C and 2.6°C for minimum temperature and 1.4°C, 2.2 and 2.1 for maximum temperature. Again, these results are in accord with the findings presented in the IPCC (2014) report.

Figure 6 and Table 5 show the mean annual precipitation changes for each study location under scenarios rcp4.5 and rcp8.5 emission scenarios for the period, 2021/25-2050. The range of variation in individual models and the ensemble means appear in Figure 6 and Table 5. Unlike the results for temperature, there is no consensus on the sign of precipitation change across the models and locations. However, most of the models agree that the precipitation in the Niger Basin will be higher in the future (2021/25-2050) relative to baseline (1981/85-2010). The result is consistent with the findings of other studies (Nikulin, *et al*., 2012, Sultan, *et al*., 2014) and GCM simulations which consistently find disagreement in the sign of the change in precipitation across West Africa. For rcp4.5, the expected ensemble change in precipitation will be 4.5%, 11.3% and 8.3% respectively in Southern Guinea, Northern Guinea and the Sahel, compared to 4.4%, 21.0% and 11.5% under rcp8.5. The range of precipitation change across the nine models and six locations varies from -50% to 40%. Again, these results are in accord with the findings presented in the IPCC (2014) report, (Adejuwon, 2006 and Sultan, *et al*., 2014).

Table 4: Multi model ensemble temperature change relative to the baseline, 1976/80-2005

Agroecological zone	**Location**	**Tmin ensemble Change (°C)**		**Tmax ensemble Change (°C)**		**Period**
		RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**	
Southern Guinea	Makurdi	1.1	1.4	1.2	1.4	2025-2050
Northern Guinea	Samaru	2.5	2.9	1.8	2.2	2021-2050
	Ntarla	1.5	1.9	1.8	2.3	2025-2050
Sahelian Zone	Tillabery	1.7	2.1	1.8	2.2	2025-2050
	Tahoua	2.4	2.9	1.8	2.1	2021-2050
	Dori	2.4	2.9	1.8	2.1	2021-2050

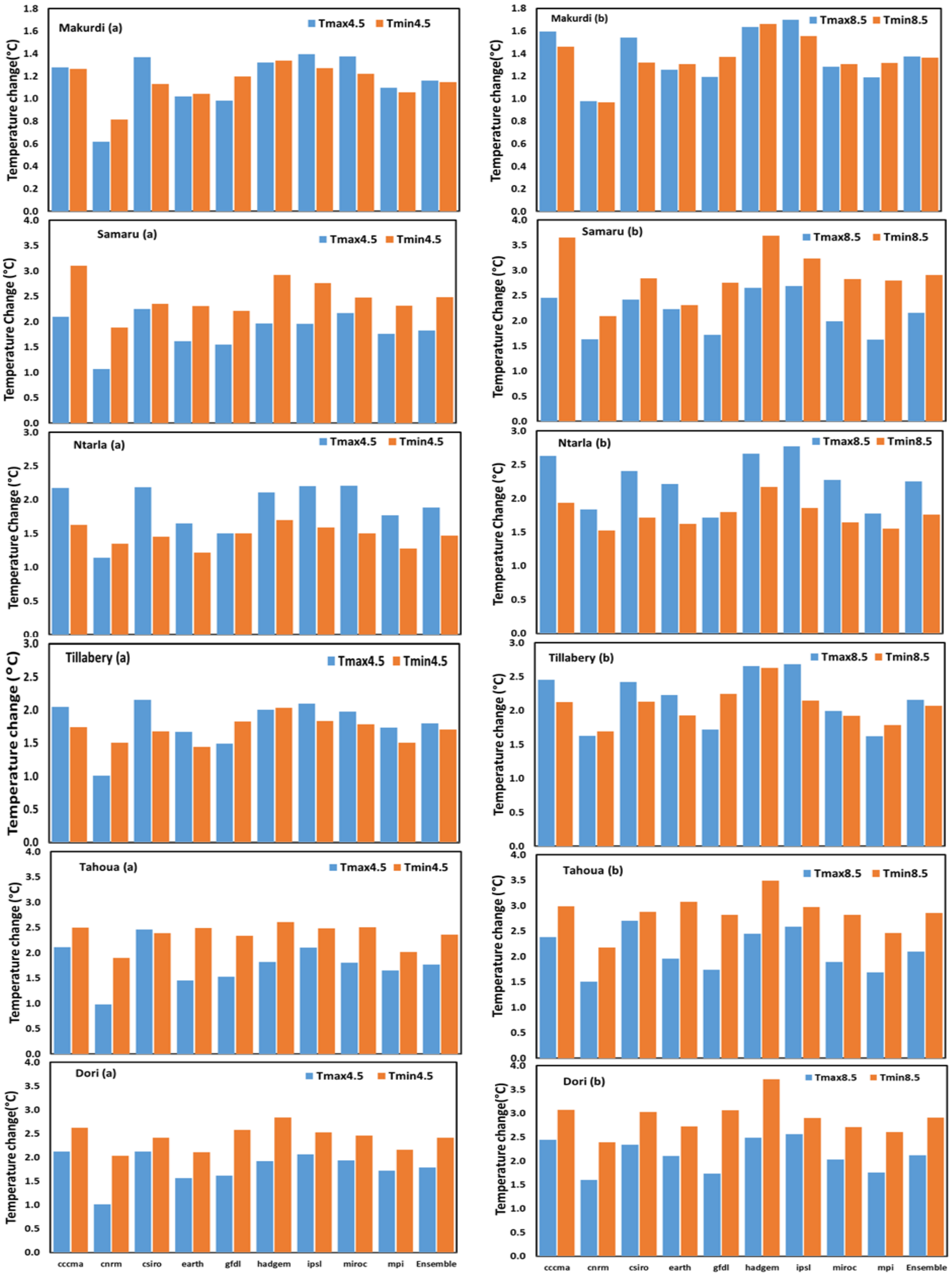


Figure 5: Mean temperature changes under the (a) rcp4.5 and (b) 8.5 scenarios for the future period, 2021-2050 relative to the baseline period, 1976-2005 across the nine GCM models.

Table 5: Multi model ensemble precipitation change relative to the baseline 1976/80-2005

Agroecological zone	**Location**	**PCP ensemble Change (%)**		**PCP Change (%) range by nine models**		**Period**
		RCP4.5	**RCP8.5**	**RCP4.5**	**RCP8.5**	
Southern Guinea	Makurdi	4.5	4.4	-7 to + 22	-8 to +28	2025-2050
Northern Guinea	Samaru	10.5	15.4	2 to 29	4 to 34	2021-2050
	Ntarla	12.0	26.5	3 to 28	2 to 33	2025-2050
Sahelian Zone	Tillabery	2.0	2.8	-52 to 33	-50 to 34	2025-2050
	Tahoua	12.5	18.7	6 to 31	3 to 40	2021-2050
	Dori	10.3	12.9	-12 to 20	-0.2 to 22	2021-2050

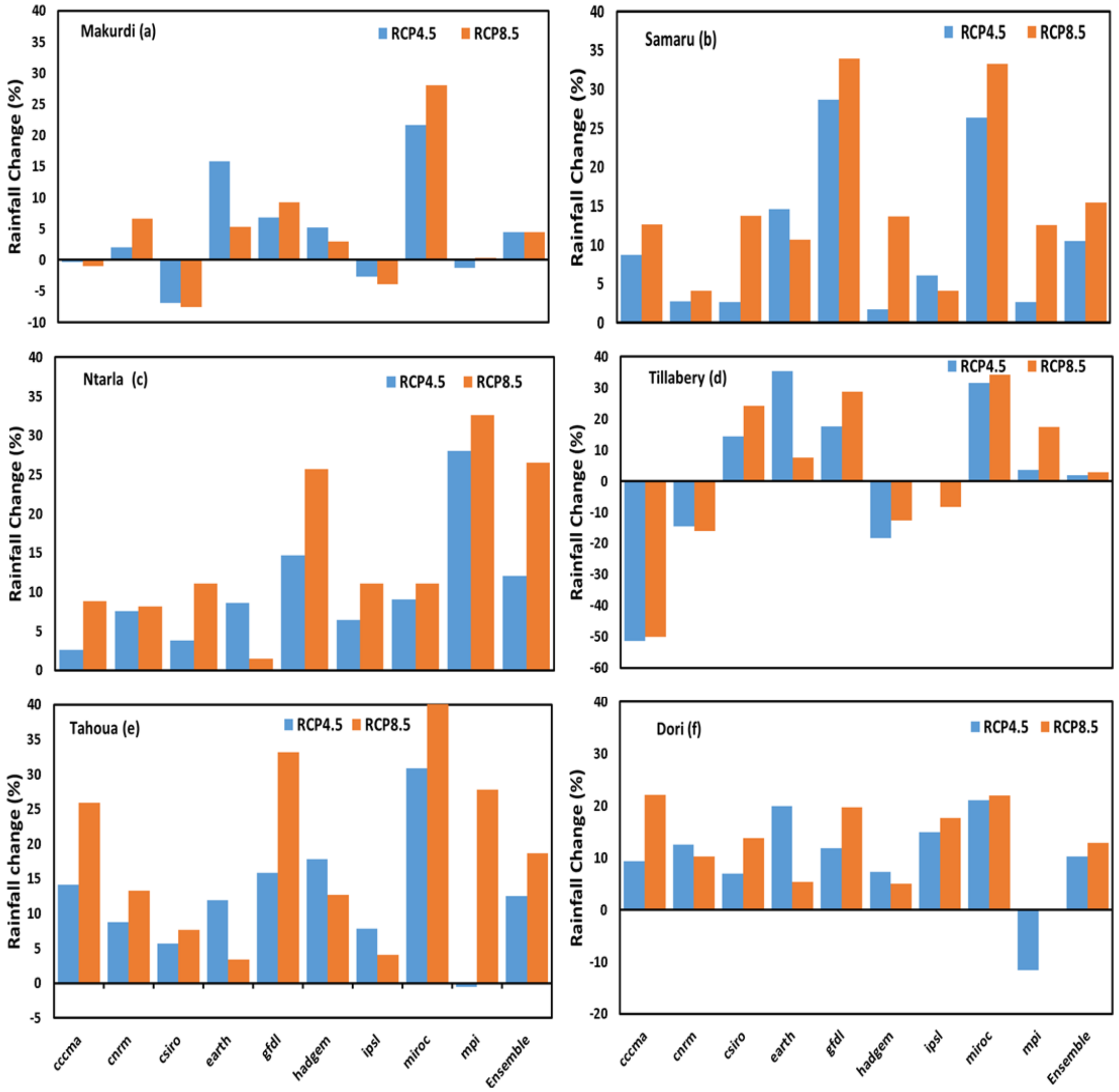


Figure 6: **Annual rainfall changes under the rcp4.5 and 8.5 scenarios for the future period, 2021/25-2050 relative to the baseline period, 1976-2005 across the nine GCM models**.

4.3 Assessing climate change impact and the adaptation options on cereal yields

4.3.1 Guinea agroecological zones (Southern and Northern Guinea)

a) **Maize**

Figures 7 and 8 present the simulated maize ensemble yield change for the future time period, 2025-2050 relative to the baseline period, 1985-2010, for Southern Guinea agro-ecological Zone (illustrated by Makurdi location) under rcp4.5 and rcp8.5 scenarios. The results revealed that under current farmers fertilization (0 N kg/ha, denoted as P), the yield for long duration cultivar (V1), and D1 planting date, showed a small but statistically significant ($P<0.001$) positive yield change of between 2-4% and 3-4% under the rcp4.5 and rcp8.5 scenarios respectively for the future period relative to baseline period. Changing the planting dates (to D2 and D3) and cultivar (to V2) significantly increased grain yield of maize between 4-5% (3-5% for cultivar change) and 4-6 % (4-5% for cultivar change) under rcp4.5 and rcp8.5 scenarios respectively, relative to the baseline period 1985-2010 and similar to the results reported by Adejuwon (2006). The results also showed that for both V1 and V2 cultivars, the planting dates of D2 and D3 are viable adaptation options for maize in Southern Guinea (Figures 7a,b; Table 6; and Supplementary Table S1). In fact, planting at D3 significantly ($P<0.001$) increased maize yield from 2.1% to 4% under rcp4.5 (see Figure 7a and 8, Table 6). This is because rainfall is well established at the later part of the rainy season in this zone and the rainy season remains unchanged (over 180 days) in this location. The increase in yield is not surprising, considering that the future precipitation will increase by 5% and the corresponding average temperature increase of 1.3 (34°C) is within the maximum temperature range (30-37°C) for maize growth (Washington and Hawcroft, 2012).

Figures 7a,b showed that increasing soil fertility levels consistently dwarf the negative climatic effect thereby increasing significantly ($P<0.001$) the average yield between 59% and 182% for moderate, near optimal, and optimal soil fertility (See Figures 7 and 8 and Table 6). These results are consistent with the findings of Butt *et al*., (2005); Rockstrom, *et al*., (2007) and Jalloh *et al*., (2013). The results also suggest that management factors such as soil fertility had a much larger effect on crop yield than the climatic change factors in the Southern Guinea agroecological zone. There is a significant ($P<0.05$) rcp positive effect on crop yield in this zone. The yields under rcp8.5 were significantly higher than the yields under rcp4.5.

		Maize	Climate Scenarios		Climate Scenarios		**Sorghum**	Climate Scenarios		Climate Scenarios	
Adaptation	Factor	Baseline	Rcp4.5	YΔ (%)	Rcp 8.5	YΔ (%)	Baseline	Rcp4.5	YΔ (%)	Rcp 8.5	YΔ (%)
Fert.	P	1.28	1.33	3.7	1.33	3.9	1.58	1.64	3.3	1.62	2.5
	M	*	*	*	2.03	58.8	*	*	*	2.56	61.9
	NP	*	*	*	2.82	120.0	*	*	*	3.60	127.4
	OP	*	*	*	3.62	182.9	*	*	*	4.81	203.6
Cult.	V1	1.28	1.32	3.1	1.33	3.9	1.57	1.62	3.2	1.60	2.0
	V2	1.28	1.34	4.7	1.34	4.7	1.60	1.65	3.3	1.65	3.0
Plant.D	D1	1.28	1.32	3.1	1.33	3.9	1.58	1.59	0.3	1.58	0.0[a]
	D2	1.28	1.33	3.9	1.33	3.9	1.58	1.65	4.2	1.63	3.2
	D3	1.28	1.34	4.7	1.33	3.9	1.58	1.67	5.5	1.65	4.3

Table 6: Southern Guinea Savanna (Makurdi) average simulated maize and sorghum grain yield change for the future period (2025-2050) relative to the current period (1985-2010)

Note: * indicate no scenarios investigated. All results are significant at $P< 0.05$, except [a]

Table 7: Northern Guinea Savanna (Samaru illustrated) average simulated maize and sorghum grain yield change for the future period (2021-2050) relative to the current period (1981-2010)

	Maize	Climate Scenarios		Climate Scenarios		**Sorghum**	Climate Scenarios		Climate Scenarios	
Factor	Baseline	Rcp4.5	YΔ (%)	Rcp8.5	YΔ (%)	Baseline	Rcp4.5	YΔ (%)	Rcp8.5	YΔ (%)
P	1.63	1.36	-16.3	1.33	-18.1	1.380	1.272	-7.8	1.252	-9.3
M	*	*	*	2.05	26.0	*	*	*	1.983	43.7
NP	*	*	*	2.84	74.6	*	*	*	2.774	101.1
OP	*	*	*	3.66	125.0	*	*	*	3.659	165.2
V1	1.63	1.35	-17.3	1.33	-18.2	1.362	1.264	-7.2	1.240	-9.0
V2	1.63	1.38	-15.4	1.34	-17.9	1.397	1.281	-8.3	1.264	-9.5
D1	1.63	1.36	-16.4	1.31	-19.6	1.380	1.251	-9.3	1.231	-10.8
D2	1.63	1.35	-17.1	1.33	-18.5	1.380	1.280	-7.2	1.252	-9.3
D3	1.63	1.38	-15.4	1.37	-16.0	1.380	1.285	-6.8	1.273	-7.7

Note: * indicate no scenarios investigated. All results are significant at $P<0.05$

However, the results presented in Figures 7c,d present a different picture for the Northern Guinea Zone. The maize ensemble yield change results in Figures 7c,d and 9 and Table 7 present a significantly negative yield loss in the future time period, 2021-2050, relative to the baseline period, 1981-2010 under current farmers' fertilization, planting date and cultivar (V1) under rcp4.5 and rcp8.5 scenarios. The results revealed that the future maize yield will significantly ($P<0.05$) decline by 18% and 20%, under rcp4.5 and rcp8.5 scenarios respectively relative to the baseline period, 1981-2010 (See Figures 7c and 9). The average yield decline for V1 cultivar varies between 17% and 19% respectively under rcp4.5 and rcp8.5 scenarios, while for V2 cultivar the decline varies between 15% and 19% respectively under rcp4.5 and rcp8.5 scenarios (see also Jones and Thornton, 2003, Schlenker and Lobell, 2010, Rouldier *et al.*, 2011). There is a significant ($P<0.001$) yield change for changing planting dates and cultivars in this location. The yield decline of 18.4% under D1 was significantly reversed to 17.3% and 16.1% under

D2 and D3 respectively for rcp4.5 and a yield decline of 18.4% was reversed to 14.4% under V2 (see Figures 7c,d). These results indicate that planting dates (D2 and D3) and cultivar (V2) are also viable and effective adaptation options in the Northern Guinea Zone (See Figures 7c,d, Table 7).

This is because the future growing cycle remains over 170 days for the location and planting late does not limit the crop based on growth cycle length. The high temperature increase is the main reason for the yield loss at this location. The adaptation results also revealed that increasing soil fertility from poor fertility to moderate, near optimal and optimal levels significantly reversed the negative yield change for both cultivars under rcp8.5 scenarios (See Figures 7c,d and Table 7 and Supplementary Table S2). This demonstrated that increasing soil fertility dwarfs the negative climatic effects thereby increasing significantly ($P<0.001$) the average yield respectively by over 26%, 75% and 125% for moderate fertility (M), near optimal fertility (np), and optimal fertility (op) under rcp8.5 emission scenarios. There is a significant ($P<0.05$) rcp negative effect in this zone. The yields under rcp8.5 were significantly lower than the yields under rcp4.5. We hypothesize that this happens because temperature under rcp8.5 are higher and this zone is already at the upper limit of temperature range for maize growth.

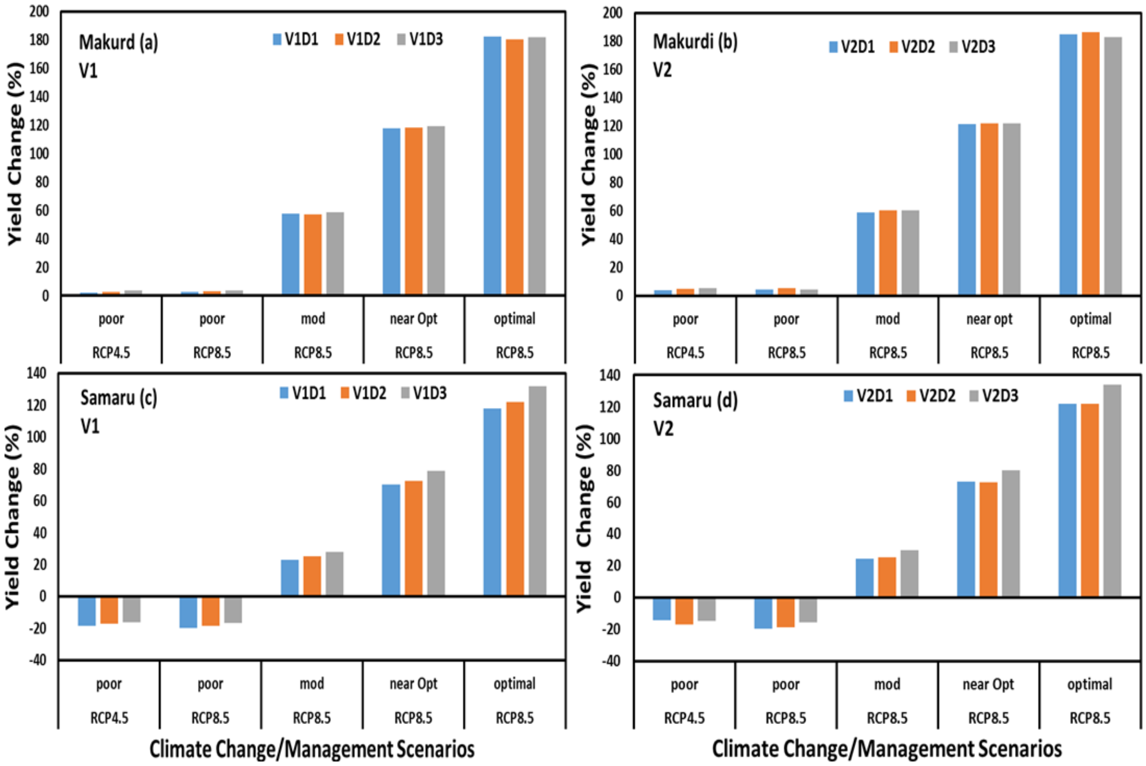


Figure 7: Maize yield ensemble (9 GCM models) change under the rcp4.5 and 8.5 scenarios for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010.

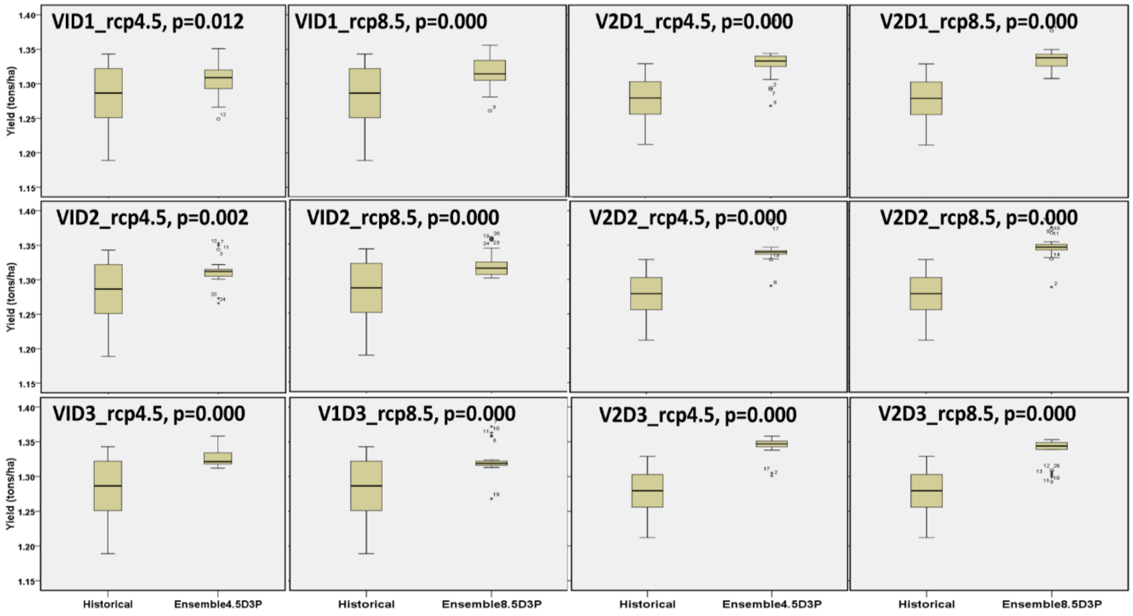


Figure 8: **Makurdi maize yield ensemble (9 GCM models) for poor soils under the rcp4.54.5 and 8.5 for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010**.

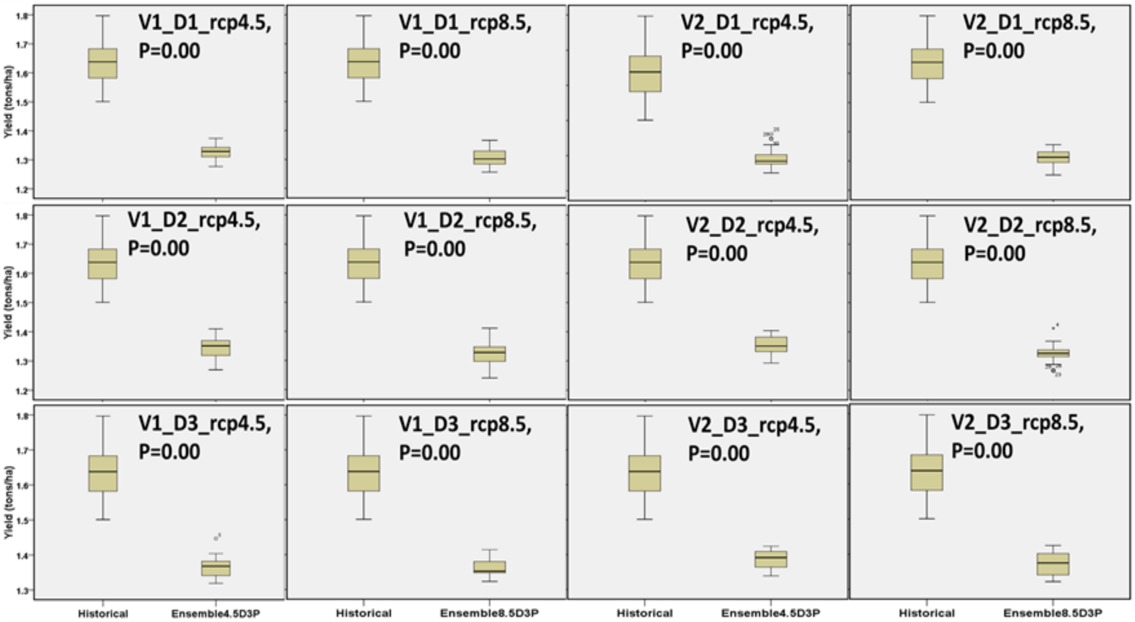


Figure 9: **Samaru maize yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010**.

b) **Sorghum**

There is little to no negative impact of climate change on sorghum yields in the Southern Guinea Zone (Figure 11 and Table 6). Still, changing planting date from D1 to D2 and D3 and cultivar from V1 to V2 moderately but significantly ($P<0.05$) increased sorghum grain yields at this location (Figures 10a,b, Table 6). The most dramatic yield change (60 to 208%) is achieved by increasing soil fertility from poor to optimal (Figures 10a,b, and Table 6).

In Northern Guinea Zone, sorghum yield changes are mostly negative (-2 to -10%) for the future time period under poor fertility level. For both cultivars the median yield decreased by between 2 and 8% and 3 and 10% under rcp4.5 and rcp8.5 scenarios respectively. There is no significant ($P>0.05$) difference in ensemble sorghum yield change between cultivars (V1 vs.V2). However, changing planting dates from D1 to D2 and D3 in this zone (Figures 10c-f and 12) significantly improved sorghum yields. There is a small but statistically insignificant difference in yield between D2 and D3 planting dates. Overall, the impact of climate change on sorghum yield is much smaller at the NTarla location compared to Samaru suggesting that even within the same ecological zone, crop response to climate change may vary (See Figure 12 and supplementary Figure S3). Increasing the soil fertility from poor to moderate improved yields from -10% to 44%. The yields increased further still to 165% at optimal fertilizer level (Figure 10e,f).

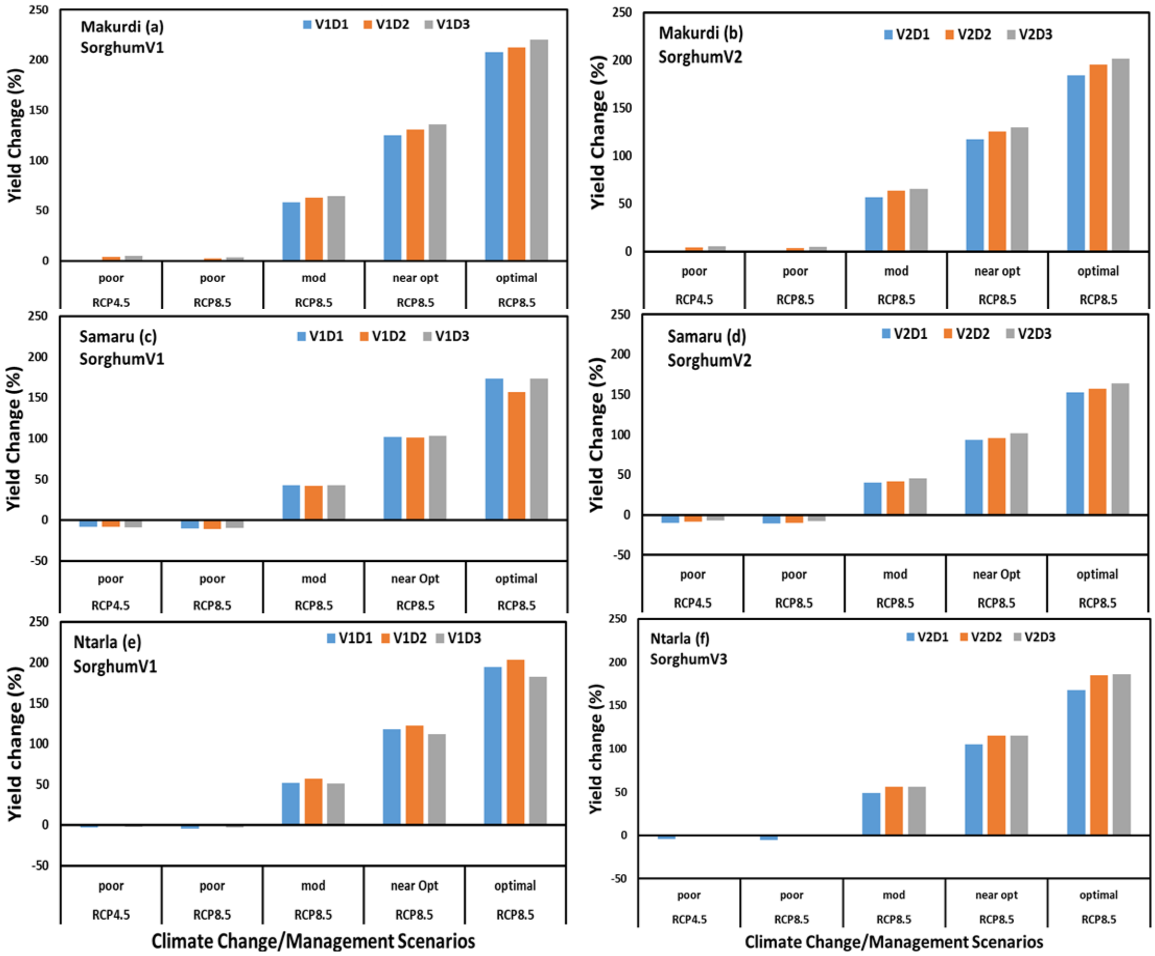


Figure 10: Sorghum yield ensemble (9 GCM models) change under the rcp4.5 and 8.5 scenarios for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010.

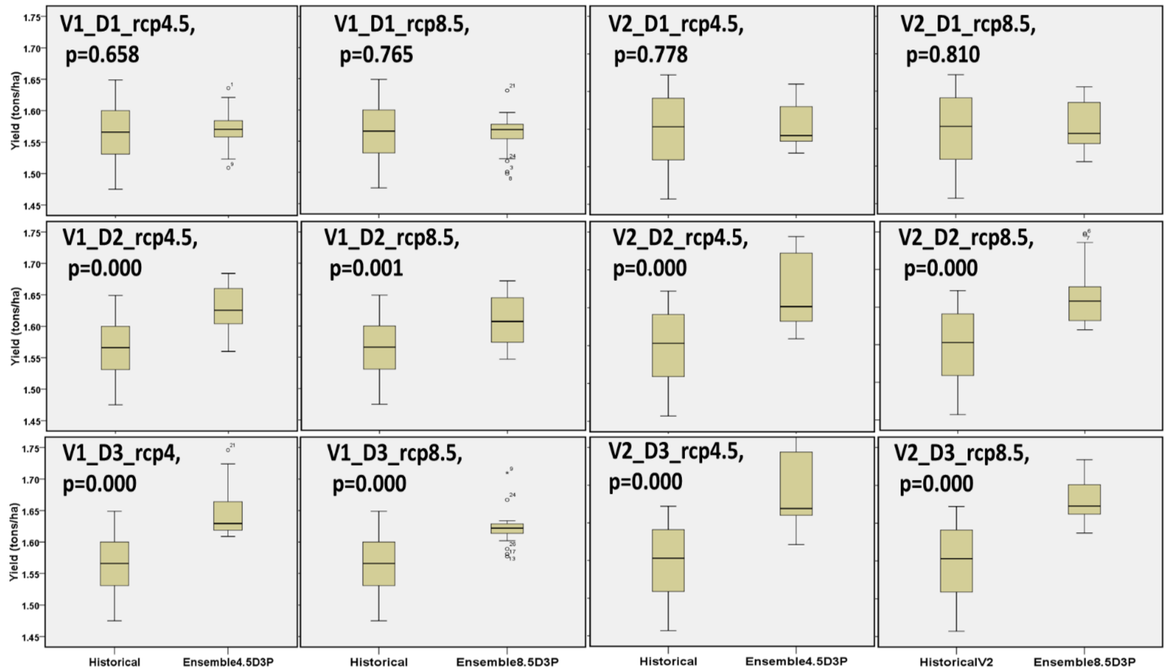


Figure 11: **Makurdi sorghum yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline periods, 1981/85-2010**.

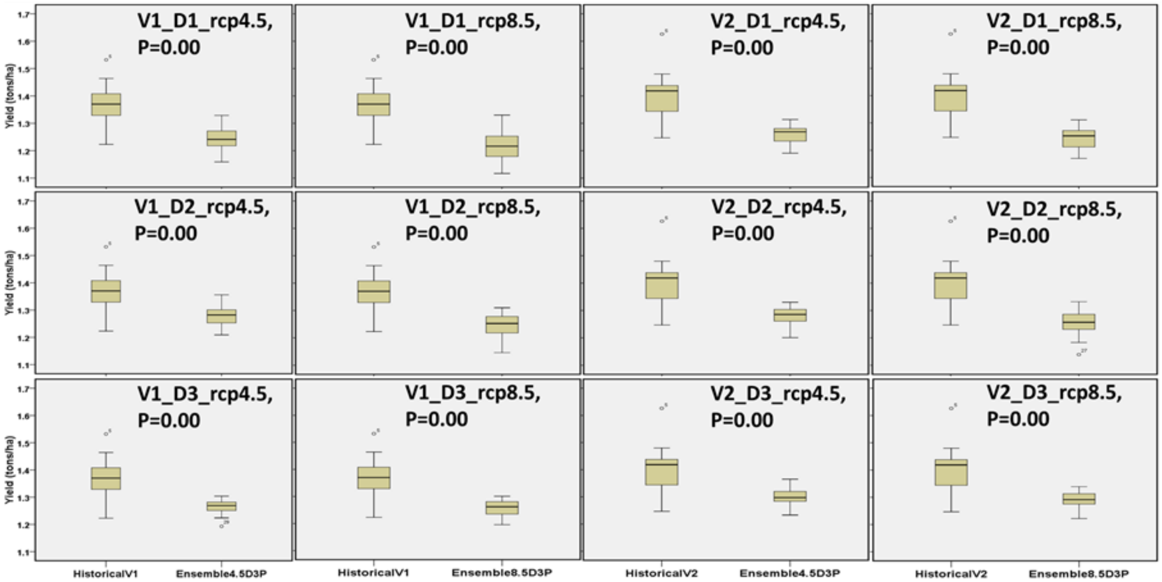


Figure 12: **Samaru sorghum yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline periods, 1981/85-2010**.

4.3.2 Sahelian agroecological zone

a) Millet

Figure 13 presents the simulated millet ensemble grain yield change for the Sahelian agro-ecological zone (Illustrated by Dori, Tahoua and Tillabery locations). The results show that projected temperature and precipitation changes have little to no impacts on millet yield in the Sahel except for Tillabery location (See Figures 14 and supplementary Figure S4 and S5). Even so, changing millet cultivar (to V2) will lead to a 5% improvement in millet for medium planting date under rcp4.5 (See Figures 13-14 and Supplementary Figure S5 and Table S3). Changing planting dates has only moderate impacts on yields except for D3, which results in a 20% yield loss due to the very short growing season in the Sahel (see also, Sultan *et al*., 2014; Traore *et al*., 2017). Finally, as with other crops in all zones, raising soil fertility from poor to moderate and optimal improves millet yields by 40% and 126% respectively under rcp8.5.

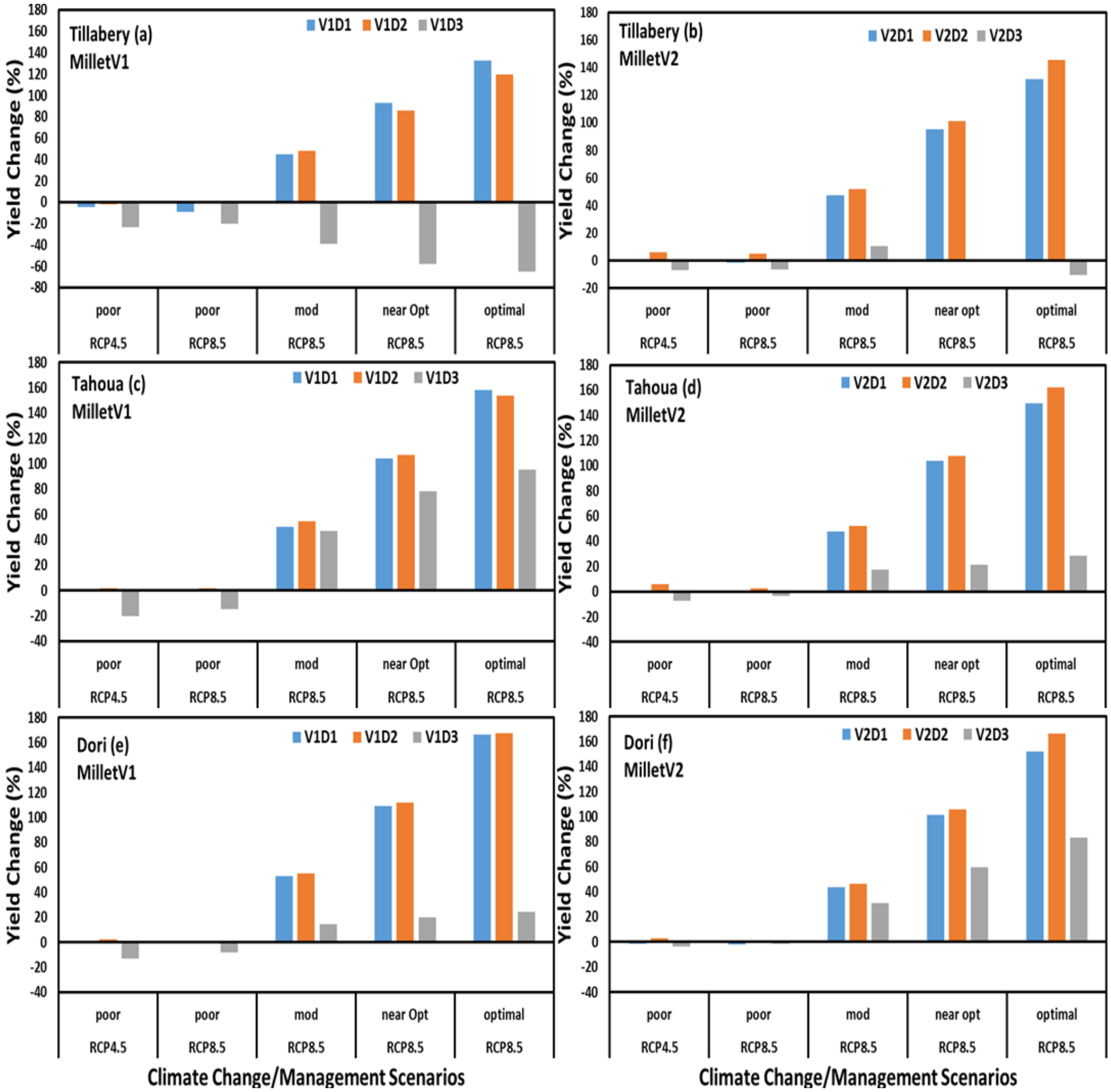


Figure 13: Millet yield ensemble (9 GCM models) change under the rcp4.5 and 8.5 scenarios for future period, 2021/25-2050, relative to the baseline period, 1981/85-2010

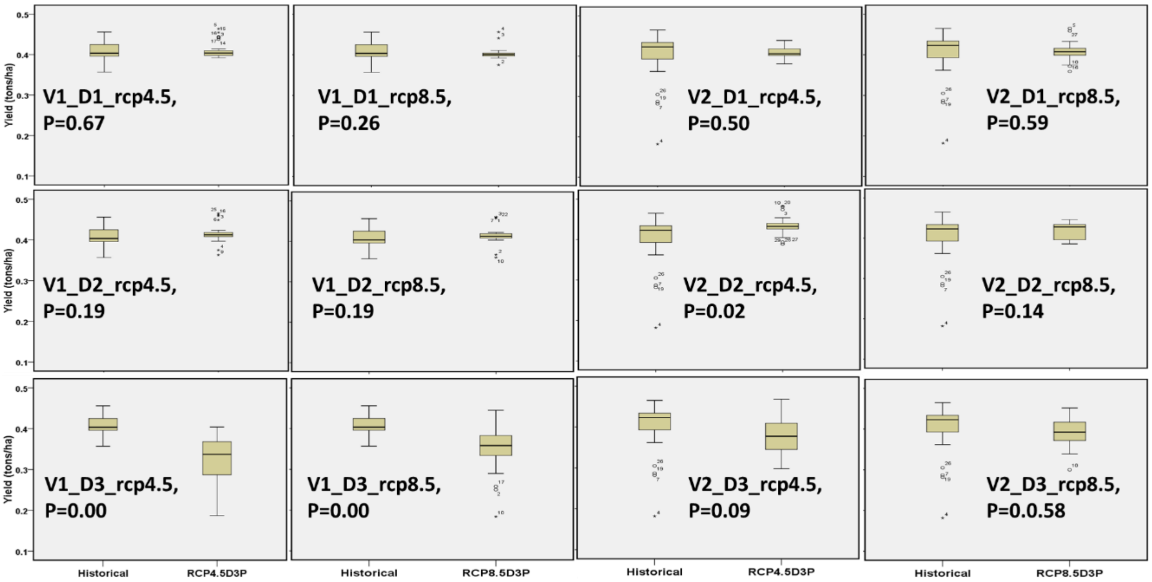


Figure 14: **Tahoua millet yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010**.

5. Conclusion

Analysis of climate change impacts consistently shows that cereal yields may decrease by as much as 10% by the middle of this century in semi-arid West Africa. Yet, few studies also suggest that much of the yield loss can be mitigated using adaptation measures. In this paper, we used an ensemble of nine bias-corrected GCMs downscaled with one regional climate model to assess cereal yield response to rcp4.5 and rcp8.5 scenarios at six locations in three agro-ecological zones in the Niger River Basin. We also used AquaCrop process-based crop model for yield prediction and investigated the effects of changing sowing dates, cultivar, and fertility treatment on yield change. The major findings are the following:

1. There is strong consensus among all models that mean surface temperature in the Niger Basin will increase by between 1.3°C, 2.3°C and 2.3°C in the Southern Guinea Zone and the Northern Guinea Zone and Sahel Zone respectively.

2. The average ensemble Basin rainfall shows an increase of about 5% for Southern Guinea Zone, 10-20% for Northern Guinea Zone, and 10-15% for the Sahelian zone although there is much less agreement among the models.

3. Climate change effects on maize and sorghum yield are mostly positive (2%-6% increase) in the Southern Guinea Zone whereas in the Northern Guinea Zone it is mostly negative (7-20% decrease). Despite increased rainfall, millet yield at the Sahelian Zone generally showed no change under current farmers' level of fertilization, except at Tillabery where a yield decrease of up to 10% occurred.

4. Changing planting dates and crop cultivar results in significant positive yield change in all the agroecological zones except for Sahelian zone where delaying planting to late planting date (D3) lead to crop failures.

5. Increasing soil fertility is the single most important adaptation farmers in the Niger Basin can make in response to climate change. For all crops and zones investigated, crop yields increased by 20%, 70%, and 180% for moderate fertility (M), near optimal fertility (np) and optimal fertility (op) under rcp8.5 scenarios for both cultivars, and planting dates.

6. Finally, the effects of climate change on crop yields are considerable and pose serious risks not just to farmers but regional food security, especially given rapidly growing population in West Africa which necessitates increasing food production several

folds. Ultimately, the solution lies in mitigating the causes of climate change. In the meantime, this study suggests that yield losses can be substantially alleviated through several adaptation measures, notably changing planting dates, changing crop cultivars and most importantly, increasing fertilizer use on farms. These changes are well within the ability of policy makers and a majority of smallholder farmers.

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Supplementary Figures

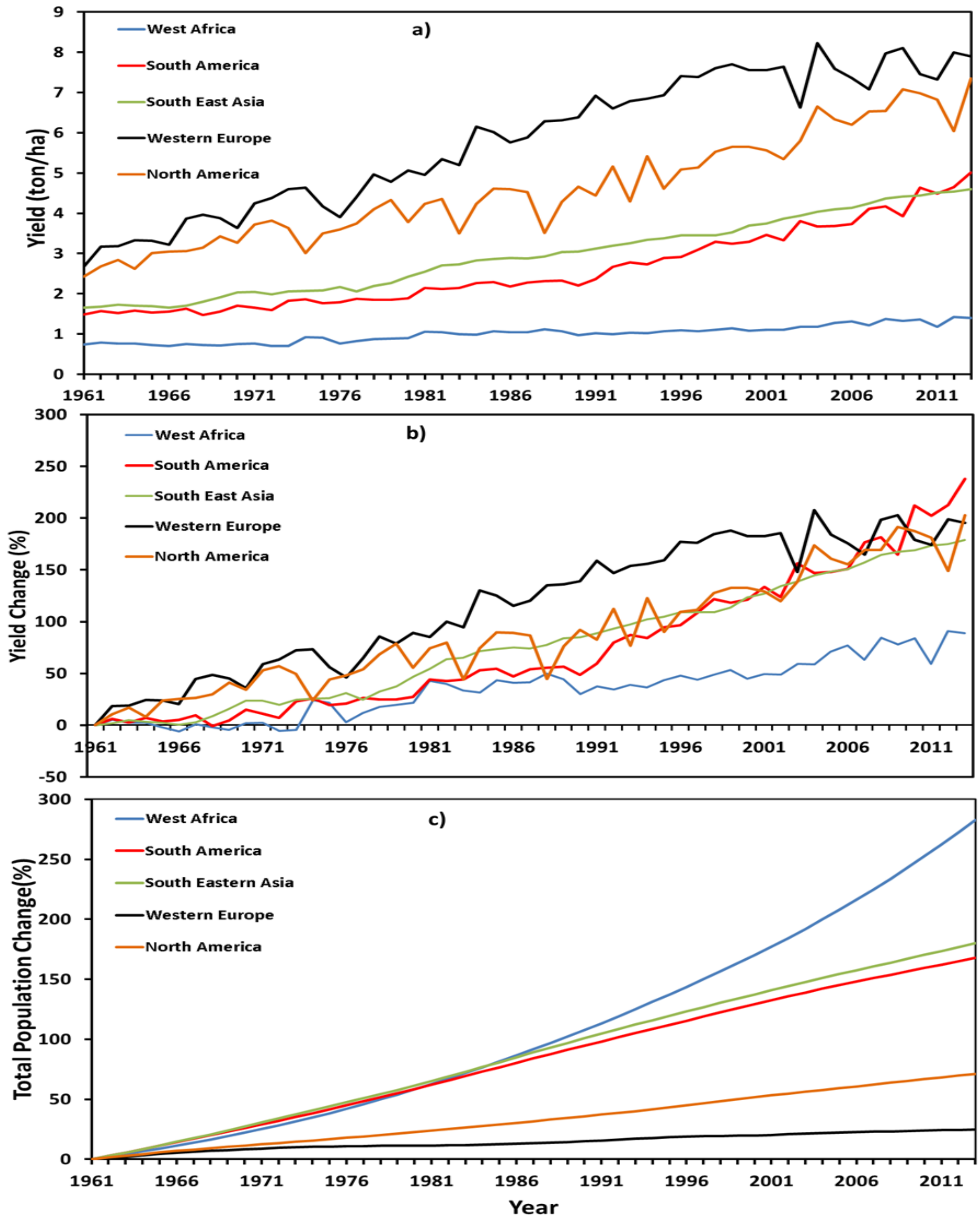

Figure S1: Cereals yield (a, b) and population(c) trend comparison. Source: FAOSTAT, 2017

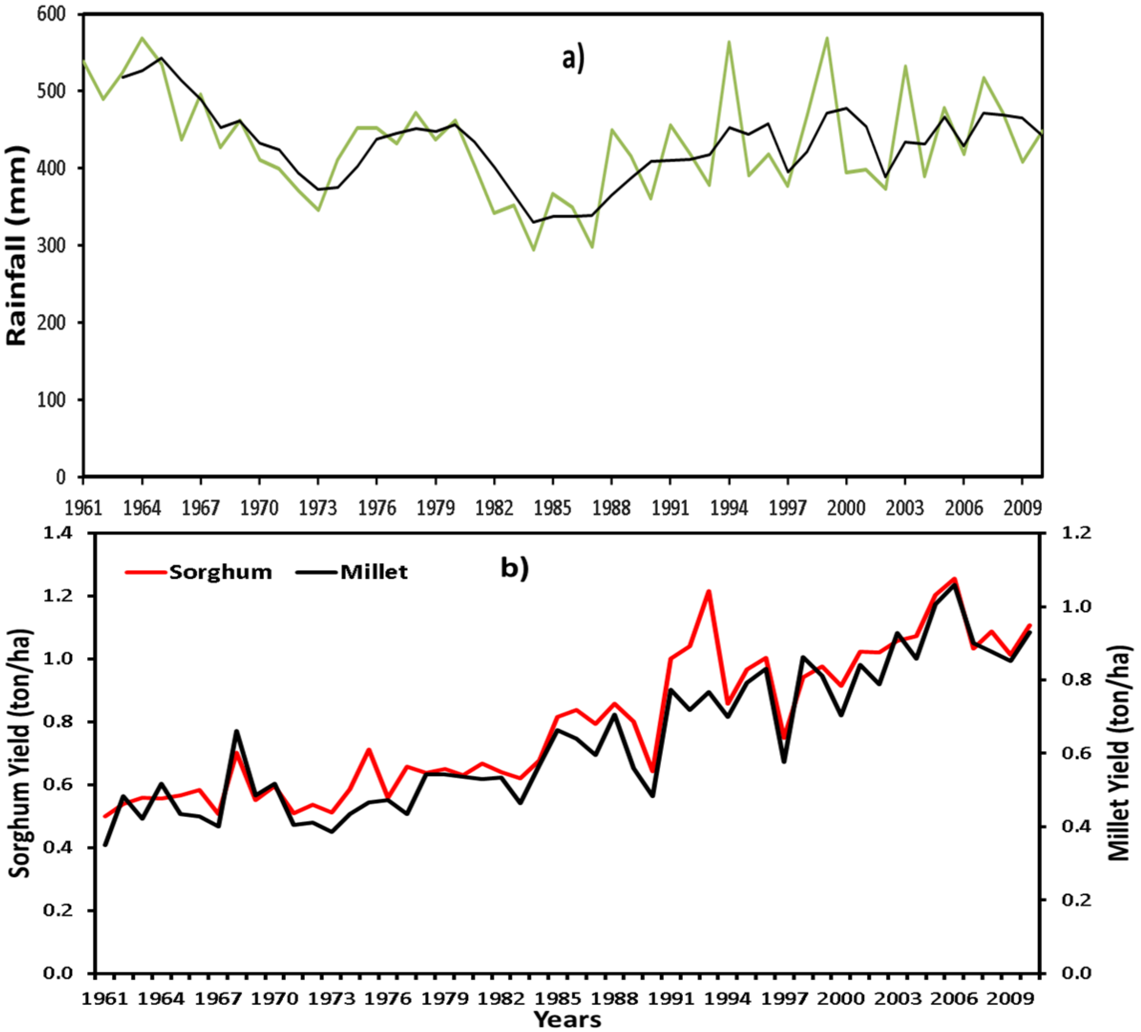

Figure S2: Decreasing rainfall (a) and increasing yields (b) at Dori in Burkina Faso

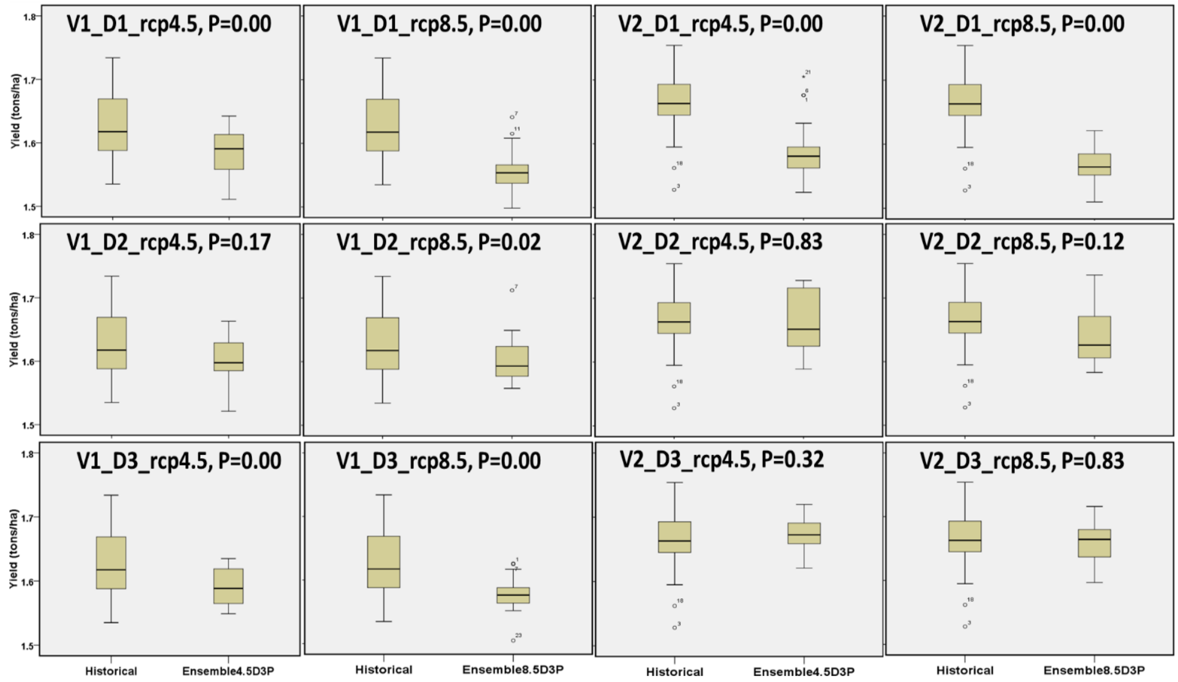

Figure S3: NTarla sorghum yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline periods, 1981/85-2010.

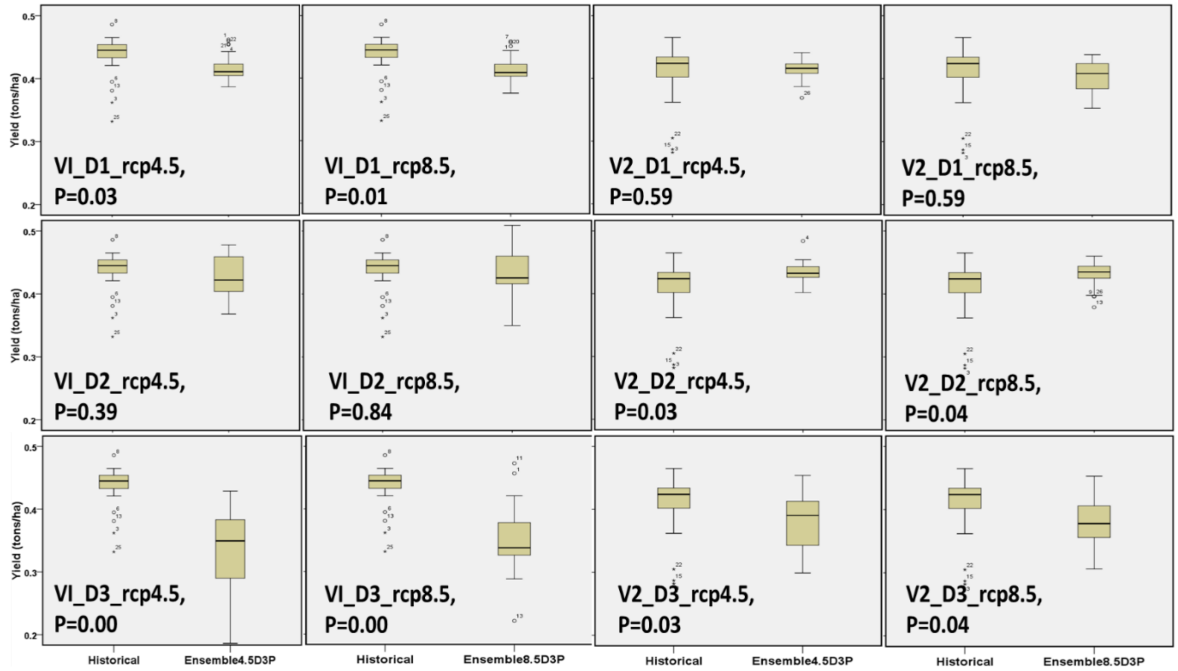

Figure S4: Tillabery millet yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010.

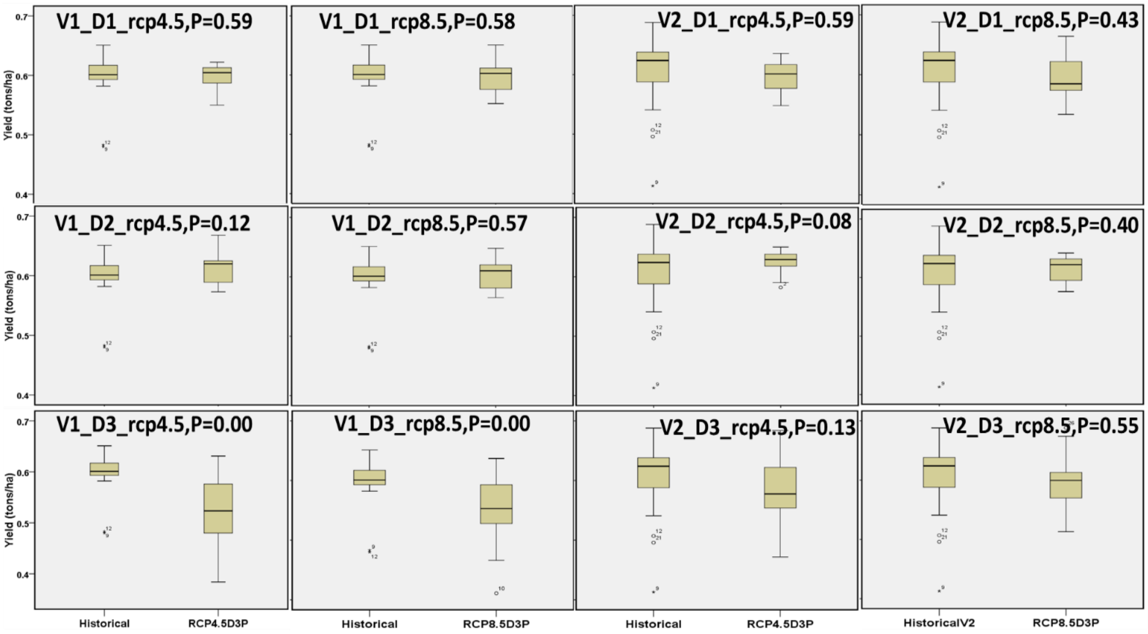

Figure S5: Dori millet yield ensemble (9 GCM models) for poor soils under the rcp4.5 and 8.5 for future period, 2021/25-2050 relative to the baseline period, 1981/85-2010.

Supplementary Tables.

Table S1: Southern Guinea Savanna (Makurdi) average simulated maize and sorghum grain yield change for the future period (2025-2050) relative to the current period (1985-2010)

Scenarios	**Yield(tons/ha) Maize V1**	**YΔ (%)**	**Yield(tons/ha) MaizeV2**	**YΔ (%)**	**Yield(tons/ha) SorghumV1**	**YΔ (%)**	**Yield(tons/ha) SorghumV2**	**YΔ (%)**
Histv1D1p	1.281	0	1.278	0	1.565	0	1.602	0
Rcp4.5V1D1P	1.307	2.1	1.329	4.0	1.572	0.4[a]	1.605	0.2[a]
RCP4.5V1D2P	1.313	2.5	1.340	4.9	1.630	4.1	1.668	4.2
RCP4.5V1D3P	1.329	3.7	1.344	5.1	1.647	5.2	1.693	5.7
RCP8.5V1D1P	1.317	3.3	1.335	4.4	1.562	-0.2[a]	1.604	0.2[a]
RCP8.5V1D2P	1.320	3.0	1.347	5.4	1.605	2.6	1.663	3.8
RCP8.5V1D3P	1.323	3.3	1.337	4.6	1.623	3.7	1.681	5.0
RCP8.5V1D1M	2.017	57.5	2.033	59.0	2.478	58.3	2.511	56.8
RCP8.5V1D2M	2.015	57.3	2.050	60.4	2.550	62.9	2.621	63.7
RCP8.5V1D3M	2.029	58.4	2.049	60.3	2.575	64.6	2.648	65.3
RCP8.5V1D1NP	2.791	117.9	2.832	121.6	3.522	125.0	3.481	117.4
RCP8.5V1D2NP	2.796	118.3	2.839	122.1	3.609	130.6	3.613	125.6
RCP8.5V1D3NP	2.804	118.9	2.834	121.7	3.690	135.8	3.685	130.1
RCP8.5V1D1OP	3.613	182.1	3.645	185.2	4.815	207.7	4.554	184.4
RCP8.5V1D2OP	3.590	180.3	3.660	186.4	4.892	212.6	4.735	195.7
RCP8.5V1D3OP	3.601	181.2	3.615	182.9	5.012	220.3	4.833	201.8

Note: All are significant at 0.05 except those specified as [a]

Table S2: Northern Guinea Savanna (Samaru illustrated) average simulated maize and sorghum grain yield change for the future period (2021-2050) relative to the current period (1981-2010)

Scenarios	Yield(tons/ha) MaizeV1	YΔ (%)	Yield(tons/ha) MaizeV2	YΔ (%)	Yield(tons/ha) Sorghum V1	YΔ (%)	Yield(tons/ha) SorghumV2	YΔ (%)
Histv1D1p	1.628	0	1.628	0	1.360	0	1.397	0
Rcp4.5V1D1P	1.325	-18.6	1.393	-14.4	1.246	-8.4	1.257	-10.0
RCP4.5V1D2P	1.341	-17.6	1.348	-17.2	1.278	-6.0	1.276	-8.6
RCP4.5V1D3P	1.364	-16.2	1.385	-14.9	1.267	-6.9	1.303	-6.7
RCP8.5V1D1P	1.302	-20.0	1.303	-19.9	1.208	-11.2	1.239	-11.3
RCP8.5V1D2P	1.319	-19.0	1.321	-18.9	1.238	-8.9	1.253	-10.2
RCP8.5V1D3P	1.360	-16.5	1.368	-15.9	1.257	-7.6	1.287	-7.8
RCP8.5V1D1M	1.993	22.4	2.014	23.7	1.924	41.5	1.945	39.3
RCP8.5V1D2M	2.026	24.5	2.032	24.8	1.974	45.1	1.972	41.2
RCP8.5V1D3M	2.082	27.9	2.103	29.2	1.990	46.4	2.033	45.6
RCP8.5V1D1NP	2.758	69.4	2.801	72.0	2.724	100.3	2.682	92.0
RCP8.5V1D2NP	2.790	71.4	2.797	71.8	2.792	105.3	2.723	95.0
RCP8.5V1D3NP	2.908	78.6	2.921	79.4	2.835	108.4	2.812	101.3
RCP8.5V1D1OP	3.525	116.5	3.592	120.6	3.687	171.1	3.517	151.8
RCP8.5V1D2OP	3.595	120.8	3.597	121.0	3.577	163.0	3.577	156.1
RCP8.5V1D3OP	3.764	131.2	3.801	133.5	3.821	181.0	3.684	163.8

Note: All are significant at 0.05 level

Table S3: Sahelian zone (Dori and Tahoua illustrated) average simulated millet grain yield

Dori/Scenarios	**Yield(tons/ha) V1**	**YΔ (%)**	**Yield(tons/ha) V2**	**YΔ (%)**	**Tahoua/ Scenarios**	**Yield (tons/ha) V1**	**YΔ (%)**	**Yield(tons/ha) V2**	**YΔ (%)**
Histv1D1p	0.601	0	0.604	0	Histv1D1p	0.412	0	0.402	0
Rcp4.5V1 D1P	0.597	-0.7ab	0.598	-1.0ab	Rcp4.5V1 D1P	0.411	-0.1ab	0.410	2.0ab
RCP4.5V1 D2P	0.614	2.2ab	0.624	3.4	RCP4.5V1 D2P	0.417	1.2ab	0.432	7.5
RCP4.5V1 D3P	0.524	-12.9	0.582	-3.6ab	RCP4.5V1 D3P	0.333	-19.2	0.379	-5.8ab
RCP8.5V1 D1P	0.596	-0.8ab	0.594	-1.6ab	RCP8.5V1 D1P	0.400	-2.8ab	0.409	1.7ab
RCP8.5V1 D2P	0.606	0.8ab	0.614	1.6ab	RCP8.5V1 D2P	0.415	0.7ab	0.420	4.5ab
RCP8.5V1 D3P	0.553	-7.9	0.596	-1.3ab	RCP8.5V1 D3P	0.353	-14.1	0.395	-1.8ab
RCP8.5V1 D1M	0.922	53.4	0.871	44.2	RCP8.5V1 D1M	0.612	48.7	0.602	49.7
RCP8.5V1 D2M	0.933	55.3	0.887	46.9	RCP8.5V1 D2M	0.633	53.7	0.620	54.3
RCP8.5V1 D3M	0.687	14.4	0.793	31.3	RCP8.5V1 D3M	0.603	46.5	0.480	19.4
RCP8.5V1 D1NP	1.259	109.5	1.219	101.9	RCP8.5V1 D1NP	0.832	102.2	0.831	106.7
RCP8.5V1 D2NP	1.275	112.1	1.246	106.3	RCP8.5V1 D2NP	0.855	107.9	0.846	110.5
RCP8.5V1 D3NP	0.721	20.0	0.968	60.2	RCP8.5V1 D3NP	0.739	79.6	0.495	23.1
RCP8.5V1 D1OP	1.601	166.4	1.524	152.4	RCP8.5V1 D1OP	1.048	154.8	1.017	153.1
RCP8.5V1 D2OP	1.607	167.3	1.610	166.6	RCP8.5V1 D2OP	1.062	158.1	1.069	165.9
RCP8.5V1 D3OP	0.746	24.1	1.109	83.6	RCP8.5V1 D3OP	0.824	100.3	0.495	23.1

Note: ab indicates not Significant at 0.05

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Chapter 4

Projected changes in intra-seasonal rainfall characteristics in the Niger River Basin, West Africa

Projected changes in intra-seasonal rainfall characteristics in the Niger River Basin, West Africa

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Abstract: The magnitude and timing of seasonal rainfall is vitally important to the health and vitality of key agro-ecological and social-economic systems of the Niger River Basin. Given this unique context, knowledge concerning how climate change is likely to impact future rainfall characteristics and patterns is critically needed for adaptation and mitigation planning. Using nine ensemble bias-corrected climate model projection results under rcp4.5 and rcp8.5 emissions scenario at mid future time period, 2021/25-2050 from CORDEX dataset, this study provide a comprehensive analysis of the projected changes in rainfall characteristics in three agro-ecological Zones of the Niger River Basin. The results show an increase of the average rainfall of about 5%, 10-20% and 10-15% for the Southern Guinea, Northern Guinea and Sahelian Zones respectively. On the other hand, the future mean rainfall intensities are largely significant and the frequency of rainfall at the low, heavy and extreme rainfall events in the future decrease in most of the locations in the Niger River Basin. The results showed an increase in the frequency of the moderate rainfall events in all locations in the basin. However, Samaru, at the Northern Guinea, and Tahoua, at the Sahel locations show an increase in the frequency of the heavy and extreme rainfall events in the future. The results reveal a shift in the future onset/cessation and a decline in duration of the rainy season in the Basin. These results further revealed a delay of onset and a late cessation of rains and a significant decline in the duration of the growing season in all locations except for Samaru in the Basin. Finally, this study projected that the change in the future rainfall characteristics as a result of climate change poses serious risks for food security of the region and therefore demands adequate change in the cropping pattern and management to adapt to these changes.

Keywords: Climate Change; Rainfall; Rainfall characteristics; cereal yield; Niger River Basin; West Africa.

1. Introduction

The magnitude, timing, and distribution of intra-seasonal or within season rainfall is vitally important to agro-ecological and social-economic systems in the Niger River Basin of West Africa and, indeed, most of Sub Saharan Africa (SSA) (Tarhule and Woo, 1997; Andersen, *et al*., 2005; Wani, *et al*., 2009). Rainfed agriculture, for example, employs approximately 65% of the labor force, accounts for about 95% of cultivated area, and contributes between 30% and 70% of the region's Gross Domestic Product (GDP) (World Bank, 2008; Tarhule, *et al*., 2009; Wani, *et al*., 2009; Blanc, 2012). As a result of such high dependence, deviations from the norm or expected amounts and patterns of rainfall have frequently led to devastating droughts and famines, such as the infamous Sahel droughts of 1970-73, 1983-85, and 2011, with tragic loss of lives (Van Apeldorn, 1981; Tarhule and Woo, 1997; Boyd *et al*., 2013), social dislocations (Van Apeldorn, 1981; Anyadike, 1987, Watts, 1987 and 1989), and loss of livestock (U.S. Humanitarian policy studies, 1974, p.66; Watts, 1989). Deviations in rainfall also have adverse impacts on the economies and GDP of the countries of the region (Benson and Clay, 1994), and therefore, the stability of governments (Watts, 1989; Boyd, *et al*., 2013).

Hence, knowledge concerning expected change in future rainfall characteristics and pattern is critically needed for adaptation and mitigation planning (Sylla, *et al*., 2013; Klutse, *et al*., 2015; Guan, *et al*., 2015). Owing to a variety of reasons, however, including data constraints, the majority of studies on West Africa to date have focused on changes in the mean annual rainfall (e.g. Afiesimama, *et al*., 2006; Sylla, *et al*., 2009, 2010; Nikulin, *et al*., 2012; Biasutti, 2013; Sultan, *et al*., 2013, and Gbobaniyi, *et al*., 2015).

Relatively fewer studies have investigated changes in intra-seasonal rainfall characteristics, including, for example, the number, frequency, and intensity of rain events (Owosu and Klutse, 2013; Sylla, *et al*., 2013; Klutse, *et al*., 2015; Guan, *et al*., 2015). While total seasonal rainfall is undoubtedly important for various purposes, including water resources management, for other activities, such as crop production, the timing, spacing, and overall quality of the rainy season are far more critical. Encouragingly, a number of studies have begun to take advantage of the improving granularity of projected climate data over West Africa to investigate and quantify these dynamics. Klutse *et al*. (2015), analyzed statistics for simulated daily rainfall characteristics over West Africa produced by ten regional climate models (RCMs) within the framework of the Coordinated Regional Climate Downscaling Experiments (CORDEX; http://www.cordex.org/). The results showed that while individual RCMs exhibited a wide range of differences associated with higher-order statistics (frequency, intensity of precipitation and extreme daily events), through error cancellation, the multi-model ensemble mean of the indices provides a good agreement with the observations. Mariotti *et al*. (2014), analyzed an ensemble of regional climate projections over the CORDEX African domain, with RegCM4 model driven by the Hadley Centre Global Environment Model (HadGEM) and Max-Planck-Institute (MPI) global models for RCP8.5 emission scenario for 1976-2005 and 2070-2099 time periods. Their study focused on the seasonal and intra-seasonal monsoon characteristics, including seasonal totals, onset and cessation and intra-seasonal variability of the monsoon season. They observed a delayed onset and early retreat of the monsoon along with increased intensity of precipitation over the West Africa sub region, implying a shortening of the growing season.

In this study, we make use of the same CORDEX dataset to further analyze projected changes in intra-seasonal rainfall characteristics in the Niger River Basin (NRB). Distinct from prior studies which focused on the region at large, the present study is site specific, providing finer detail, and therefore more actionable information, about the risks and changes that stakeholders at the specific locations will have to respond to. Additionally, we investigate these field-scale dynamics for three agro-ecological zones, providing a basis for comparison and analysis of spatial differences. We recognize that the results of site-specific analyses are inherently less robust and less spatially representative than regional-scale studies. On the other hand, local stakeholders have to respond to changes at the scale at which they operate, not to regional averages which may be robust in a statistical sense but not necessarily representative of the local scale.

The rest of the paper is organized in the following manner. Section two provides a brief description of the study area, conceptual framework, data and methods; results and discussions appear in section three; finally, major findings and conclusions are presented in section four**.**

2. Study Area, Data and method

2.1. Study area

This study is focused on six locations within the Niger River Basin (Figure 1), distributed in three agro-ecological zones, namely: semi-arid (Sahelian) zone (represented by study sites at Dori, Tahoua and Tillabery); the southern Guinea zone (represented by Makurdi); and the northern Guinea zones (represented by Samaru and NTarla). Farthest north is the semi-arid Sahel. Here, annual rainfall declines from 750 mm in the south to 250 mm in the northern limit of the zone, concentrated in a single-peaked rainy season spanning four to five months (i.e. May/June to September/October). The zonal mean annual rainfall is about 500 mm (1981-2010), allowing a growing period of 90 to 120 days. Below the Sahel is the northern Guinea zone, which also experiences a unimodal rainfall season. In this zone, the annual rainfall declines from 1400 mm in the south to 750 mm in its northern limit with zonal mean average of 1050 mm (1981-2011). The rainy season is longer (five to six months), allowing a growing period of 150 to 180 days. In the southern Guinea zone, rainfall reaches 1600 mm distributed across seven months, allowing a growing period of 150 to 210 days.

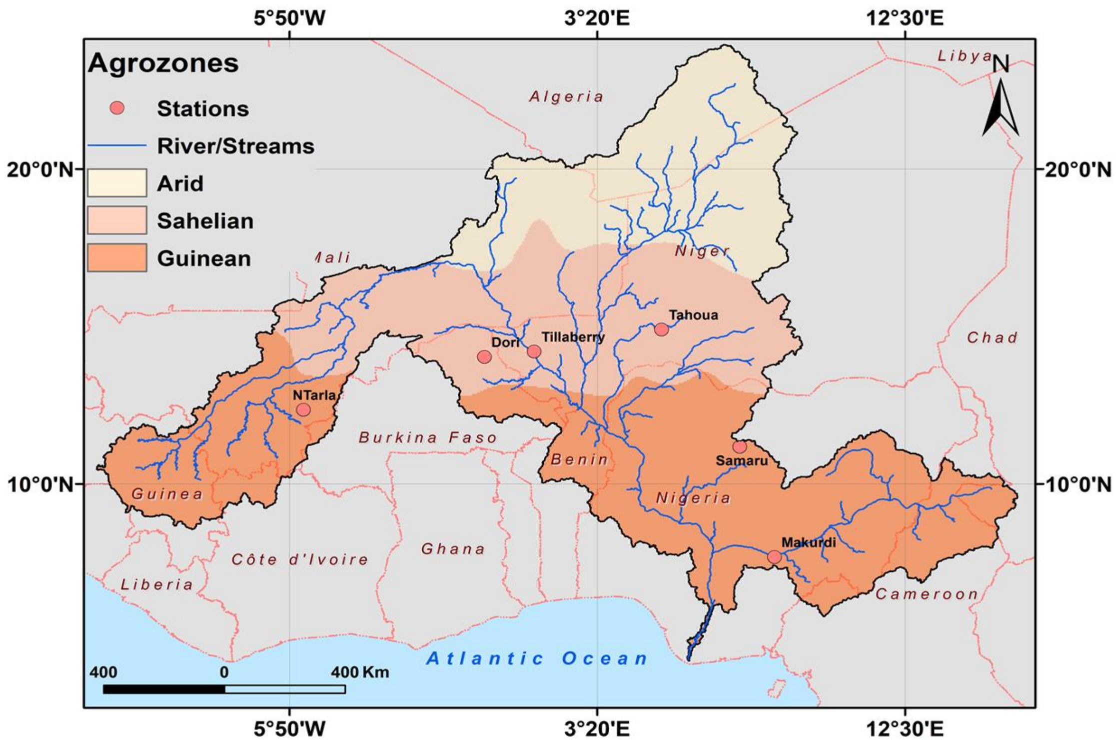


Figure 1: The Location of the Niger Basin in West Africa showing study locations (red dots) and agro-ecological zones.

2.2. Conceptual framework and data

Figure 2 and Table 1 illustrate several conceptual scenarios of how a location might experience changes in intra-seasonal rainfall. Each scenario has implications for different sectors and activities. For example, a seasonal rainfall shift (scenario 1) could cause a change in traditional sowing and harvesting dates, possibly conflicting with, or displacing the timing of, other non-agricultural activities during the year. Similarly, a delay in the onset and early cessation (scenarios 3 and 4) will shorten the growing period, increasing the risk of crop failures or reduced yields, especially for long duration cultivars. The apparent simplistic and orderly scenarios shown in Table 1 are for purposes of illustration and clarity of presentation only. In practice, rainfall changes may involve complex combinations of several scenarios contemporaneously.

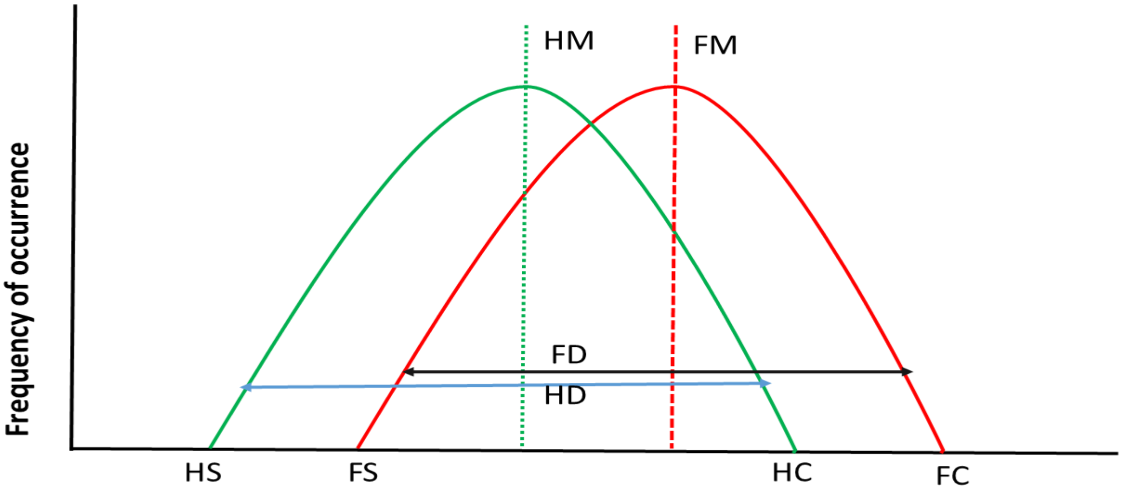
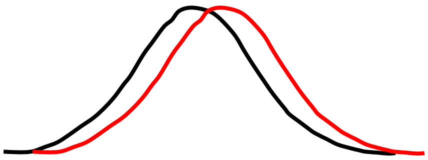
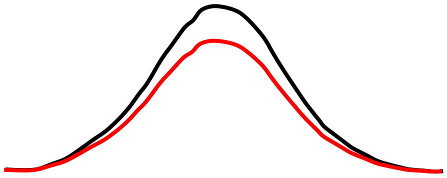
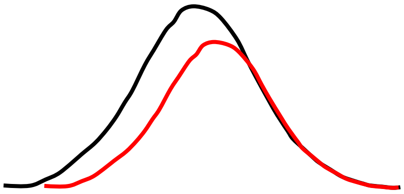
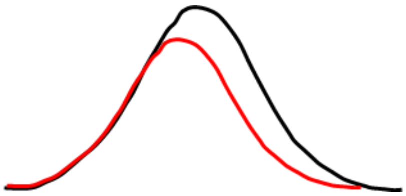
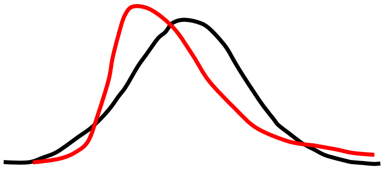


Figure 2: Schematic of the possible changes in rainfall characteristics at a given location between the current or historical (H) period and a hypothetical future (F) period (HS= historical onset, HM= Historical mean of onset/Cessation, HC= Historical cessation, HD= Historical duration, FS= Future onset, FM= Future mean of onset/cessation, FC= Future cessation, and FD= Future duration). Given no change in the timing of the mean rainfall between the historical, HS, and future, FM, rainfall periods, HS –FM=0. If the timing of the mean is delayed, HS – FS will be negative. Similarly, if the timing of the mean occurs earlier, HS-FS will be positive. The other variables are read similarly.

Table 1: The conceptual framework

Type of change/scenarios	Manifestation	Practical implication
1. Seasonal rainfall shift (no change in amount, duration or frequency of rainfall)	 Shifts may occur in the timing of the mean rainfall; onset date; or cessation.	From an agricultural perspective, the entire traditional agricultural season will need to shift backwards (i.e. later in the year), possibly conflicting with, or displacing, other non-agricultural activities.
2.Change in the amount of total seasonal rainfall (no change in season length)	 Change in the seasonal amount of rainfall (HM-FM) but no change in onset and cessation dates.	In this scenario, the timing of the onset and cessation of the rainy season remain unchanged and therefore the length of the agricultural season remains the same. Yet, the amount of total seasonal rainfall is reduced, implying

		possibly fewer rain events and/or reduced amount of rain per rain event.
3.Delayed onset leading to reduced length of season (no change in cessation)	(a)  Change in onset (HS-FS <0) (b)  Change in cessation (HC-FC > 0)	A change (i.e. early or delayed) onset of the rainy season with no corresponding change in cessation will lead to a shorter/longer cropping season overall, necessitating changes in the traditional sowing date of crops. Furthermore, unless the intensity of rain events increases this scenario also leads to reduced total seasonal rainfall and possibly, greater risk of crop failure. Similar dynamics apply if the changes occur at

		the end (cessation) of the rainy season with no corresponding change in the onset (scenario 3b)..
4.Changes in onset, cessation and distribution of rainfall	 Change in the pattern and distribution of seasonal rainfall. For this illustration the onset of rains is delayed, the within season distribution of rains is altered and the cessation of rains has also changed.	In this scenario, the timing of the onset and cessation of the rainy season has changed and therefore the length of the cropping season changes. The shift in the average onset and an early cessation could lead to a shorter growing season.

2.3. Data

The historical daily rainfall data were obtained from the National Meteorological Agencies of Nigeria (for Makurdi and Samaru), Burkina Faso (Dori), Republic of Niger (Tahoua and Tillabery) and Mali (NTarla). To evaluate possible changes in rainfall characteristics, we relied on climate projections data from CORDEX, Africa (http://www.cordex.org/community/domain-africa-cordex.html**)**. The datasets are available at 0.5 x 0.5 degree resolution for West Africa. Daily bias corrected data for rainfall were readily available for all six study locations for the period 2021/25-2050 for two representative concentration pathways (rcp4.5 and rcp8.5) and nine climate models. Akumaga, *et al*. (2017), provide a succinct description of the bias correction method employed. The selected models have all been shown to have skill in reproducing the current mean climatology (Hernandez-Diaz, *et al*., 2012; Nikulin, *et al*., 2012; Gbobaniyi, *et al*., 2014; Diallo, *et al*., 2014) and key features of the present-day precipitation over West Africa, including onset, cessation, intensity and frequency of rainfall events for the West Africa region (e.g. Owosu and Klutse., 2013; Sylla, *et al*., 2013; Mariotti, *et al*., 2014; Klutse, *et al*., 2015; Guan, *et al*., 2015). In this study, we utilized the t-test for difference of means (assuming unequal variance) as well as the F-test two sample for variances to evaluate how well the simulated model ensembles reproduced the observed rainfall characteristics of interest for the historical period (1976/80-2005). Note, for the cases where the variances are not statistically different, the T-test for means, assuming equal variance, is used; for those situations where the F-test is significantly different, the T-test assuming unequal difference is used. Then we analyzed the projected changes in rainfall characteristics in the mid-term (2021/25-2050) at a field scale within three agro-ecological zones of the Niger River Basin.

2.2.1. Onset, cessation and duration of the rainy season

Researchers have employed numerous different criteria to define the agriculturally meaningful onset, cessation and duration of the rainy season in west Africa (see, e.g. Benoit, 1977; Kowal and Kassam, 1978; Stern, *et al*., 1982; Sivakumar, 1988; Ati et al., 2002, Liebman et al., 2012; Dunning et al., 2016). For this study, we adopted the criteria of Stern et al., (1982) and Sivakumar (1988) based on the recommendation of AGRHYMET (2000). Accordingly, the date of onset is defined as that date from January 1, onward, when rainfall accumulated over a maximum of three consecutive days is at least 20 mm and when no dry spell within the next 30 days exceeds 10 days. The date of cessation of rains is taken as that date after September 1 following which no rain occurs over a period of 20 days. The duration of the rainy season is the difference between cessation and the onset of rains.

2.2.2. Daily rainfall frequency and intensity analysis

To investigate possible changes in daily rainfall intensity, three intensity categories were prescribed and analyzed: namely, light rainfall (< 10 mm/day), moderate (10.1 mm - 25 mm), heavy (25.1 mm – 65 mm) and extreme (> 65 mm). These categories have previously been shown to be meaningful for crop production in West Africa (see Kowal and Kassam, 1978; Olaniran, 1988). For each category, we tested for differences in the amount and frequency of rain events in the CORDEX future and observational data using box plots and the T-test for means.

For each study location, the ensemble time series of the total rainfall, onset, cessation, duration, frequency and intensity were derived for the future time period. The ensemble mean was obtained by taking the average of the nine climate models after calculating the indices investigated for each of the individual climate models. To determine changes in the projected rainfall, the projected rainfall characteristics were compared with the baseline conditions using box-and-whisker plots.

3. Results and Discussion

3.1. Evaluation of the simulated rainfall for the historical period

Table 2 summarizes results of the F-test for variance and T-test for means (assuming unequal variance) for each pair of observational and simulated rainfall characteristics for the historical period. Figures 3-5 shows illustrative box-and-whisker plots of the comparison of the CORDEX multi-models ensemble and observed intra-seasonal rainfall variables at the study locations. For reasons of space, the complete set of evaluation plots appear at supplementary Figures S1-S2.

Table 2: Evaluation summary statistics for average annual rainfall, onset, cessation and duration of the growing season, 1976/80-2005. Note, these are P-values at 0.05 significance level.

Agro-zone	Location	F-test for variance								T-test for Difference of Means							
		Ann	Onset	End	Dur	Rainfall Intensity				Ann	Onset	End	Dur	Rainfall Intensity			
						Low	Mod	Heavy	Ext					Low	Mod	Heavy	Ext
Southern Guinea	Makurdi	0.000	0.069	0.000	0.006	0.498	0.490	0.478	0.023	0.978	0.101	0.776	0.724	0.856	0.950	0.840	0.230
Northern Guinea	Samaru	0.000	0.005	0.031	0.049	0.485	0.473	0.496	0.158	0.597	0.839	0.060	0.672	0.851	0.889	0.918	0.745
Sahel	Tahoua	0.000	0.000	0.278	0.004	0.489	0.469	0.448	0.135	0.944	0.877	0.110	0.127	0.994	0.936	0.913	0.683
	Dori	0.000	0.000	0.313	0.000	0.448	0.469	0.483	0.043	0.646	0.127	0.337	0.655	0.755	0.944	0.864	0.264

Table 2 results show that the variance of the observational data is statistically different ($P>0.05$) from the variance of the simulated ensemble for annual total rainfall, onset and duration of season for the historical period. Also, the variance of the observed cessation date is statistically different ($P>0.05$) from the simulated ensemble variance at the Southern and Northern Guinea locations but not at the Sahelian locations. Finally, the variance of the observed rainfall intensity categories is not statistically different ($P<0.05$) from the variance of the ensemble categories for all locations.

The results of the T-test for means show that the means of the observational data are not statistically different ($P>0.05$) from the ensemble mean rainfall for all variables and all locations except for the Makurdi location were the onset is significantly different ($P>0.05$) from the observed and the extreme rainfall intensity events at the Makurdi and Dori locations (See Table 2). The boxplots qualitatively show comparisons for other statistics between observed and simulated rainfall variables (Figures 4 and 5).

Despite some differences for the onset at Makurdi location and cessation at Tahoua and Dori locations, these results generally reveal that our ensemble model performed reasonably well in reproducing the key features of rainfall in this region and, therefore, can be used to analyze the projected changes in rainfall characteristics in the region (See also Table 3 and 4)..

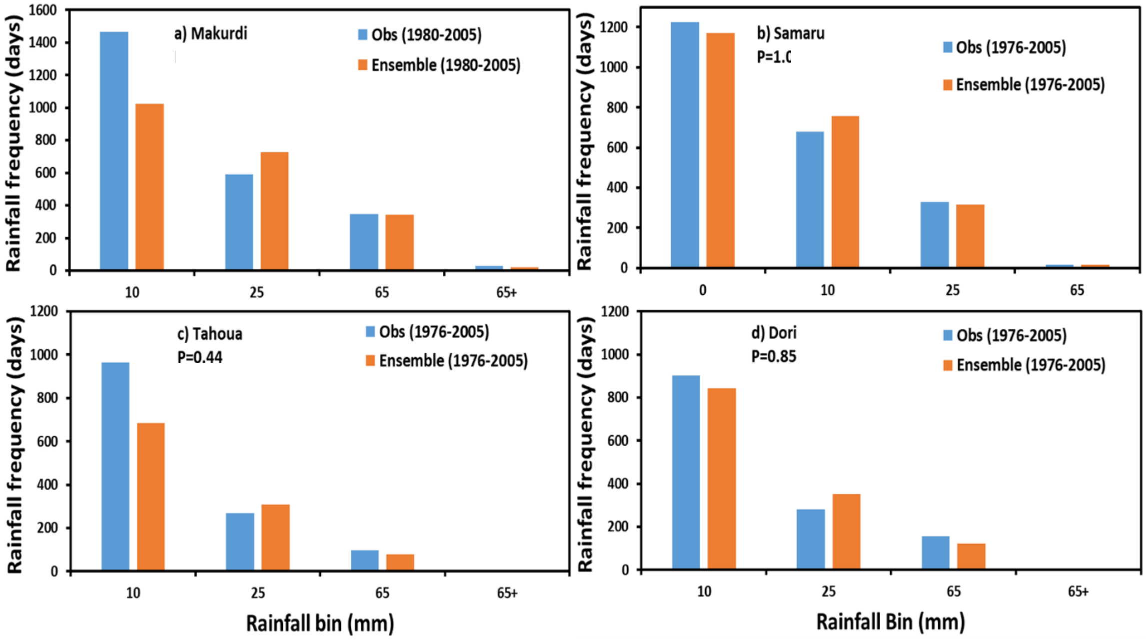


Figure 3: **A comparison of the CORDEX multi-models ensemble and observed frequency of rainfall at different intensities (low, moderate, heavy and extreme) over the Southern (Makurdi) and Northern (Samaru) Guinea agro-ecological zones and the Sahelian (Tahoua and Dori) agro-ecological zones for the historical period, 1976/80-2005**.

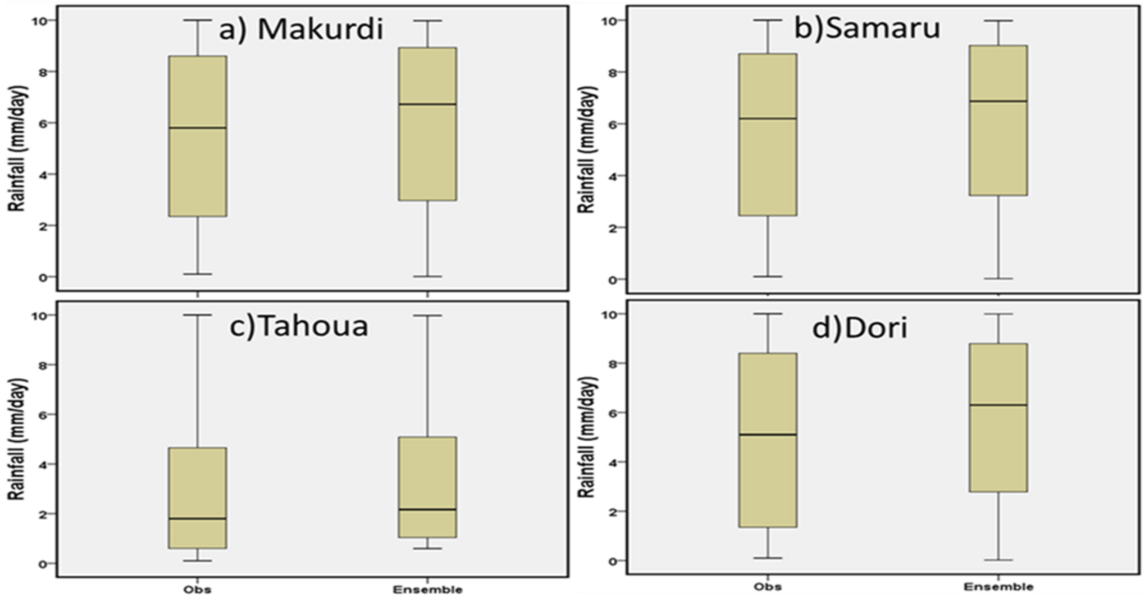


Figure 4: A comparison of the CORDEX multi-models ensemble and observed mean daily low rainfall intensity (>0 to <=10mm) over the Southern (Makurdi) and Northern (Samaru) Guinea agro-ecological zones and the Sahelian (Tahoua and Dori) agro-ecological zones for the historical period, 1976/80-2005.

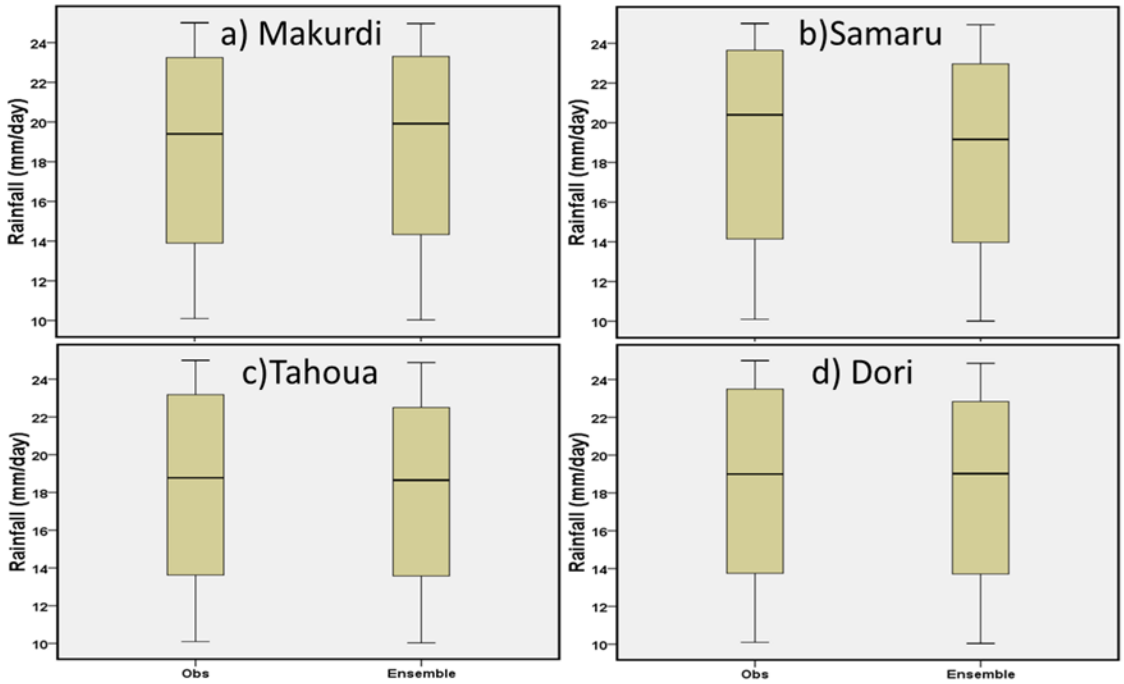


Figure 5: A comparison of the CORDEX multi-models ensemble and observed mean daily moderate rainfall intensity (>10 to <=25mm) over the Southern (Makurdi) and Northern (Samaru) Guinea agro-ecological zones and the Sahelian (Tahoua and Dori) agro-ecological zones for the historical period, 1976/80-2005.

Table 3: The Southern Guinea (Makurdi illustrated), Northern Guinea (Samaru), and the Sahelian (Dori and Tahoua) observed vs. simulated onset, cessation and duration of rainfall for the baseline (1976/80-2005). Note, the ensemble model means are all not statistically different with the observed at 0.05 confidence level.

Southern Guinea (Makurdi)	**Mean Onset (Julian days)**	**Deviation %(days)**	**Mean cessation (Julian days)**	**Deviation %(days)**	**Mean Duration (days)**	**Deviation %(days)**
Obs	117	0	320	0	203	0
Ensemble	126	8 (9 days)	323	1 (3 days)	197	-3 (6 days)
Northern Guinea (Samaru)	**Mean Onset (Julian days)**	**Deviation %(days)**	**Mean cessation (Julian days)**	**Deviation %(days)**	**Mean Duration (days)**	**Deviation %(days)**

Obs	138	0	307	0	171	0
Ensemble	140	6(2 days)	317	-3 (10 days)	177	5 (9 days)
Sahelian (Tahoua)	**Mean Onset (Julian days)**	**Deviation %(days)**	**Mean cessation (Julian days)**	**Deviation %(days)**	**Mean Duration (days)**	**Deviation %(days)**
Obs	190	0	297	0	107	0
ensemble	189	-1 (1 day)	303	2 (6 days)	114	7 (7 days)
Sahelian (Dori)	**Mean Onset (Julian days)**	**Deviation %(days)**	**Mean cessation (Julian days)**	**Deviation %(days)**	**Mean Duration (days)**	**Deviation %(days)**
Obs	178	0	299	0	121	0
ensemble	185	4 (7 days)	308	3 (9 days)	123	2 (2days)

Table 4: The historical observed and ensemble model average annual rainfall for some locations in the Niger River Basin.

Agro-ecological Zone	**Location**	**Average rainfall (mm)**		**Period**
		Obs	**ensemble**	
Southern Guinea	Makurdi	1168	1167	1980-2005
Northern Guinea	Samaru	983	1001	1976-2005
Sahelian Zone	Tahoua	355	354	1976-2005
	Dori	455	466	1976-2005

Note, the ensemble model means are all not statistically different with the observed at 0.05 significant level.

3.2. Future rainfall characteristics in the Niger River Basin

3.2.1. Seasonal rainfall patterns

Figure 6 and Tables 5 and 6 show the summary statistics and mean seasonal precipitation changes for both rcp4.5 and rcp8.5 emission scenarios for the period (2021/2025-250) relative to the baseline period (1976/80-2005) for each of the study locations. The results reveal that there is a significant increase ($P<0.001$) in the future annual season rainfall for Northern and Sahelian locations for both rcp4.5 and rcp8.5 scenarios but insignificant increase ($P>0.05$) in the Southern Guinea zone (Makurdi) and Tillabery for the Sahel location. The variances of the observed annual rainfall is statistically different ($P<0.001$) from the future simulated ensemble variance at all locations. Our results further revealed that even within the same ecological zone, there is a striking local difference in precipitation change which might have implications for climate change agricultural adaptation within an ecological zone. The boxplots also reveal that the observed seasonal rainfall has a much larger range/variability than the projected rainfall. In fact, the entire box plots for rcp.5 and rcp8.5 fit within a very narrow range of the observed data. For example, in Figure 6, the lowest simulated value for NTarla is about the same or higher than the median of the observed values. These results of a positive mean precipitation change are consistent with the findings of numerous studies in the region (Adejuwon, 2006; IPCC, 2014, Sultan, *et al*., 2014; Guan, *et al*., 2015).

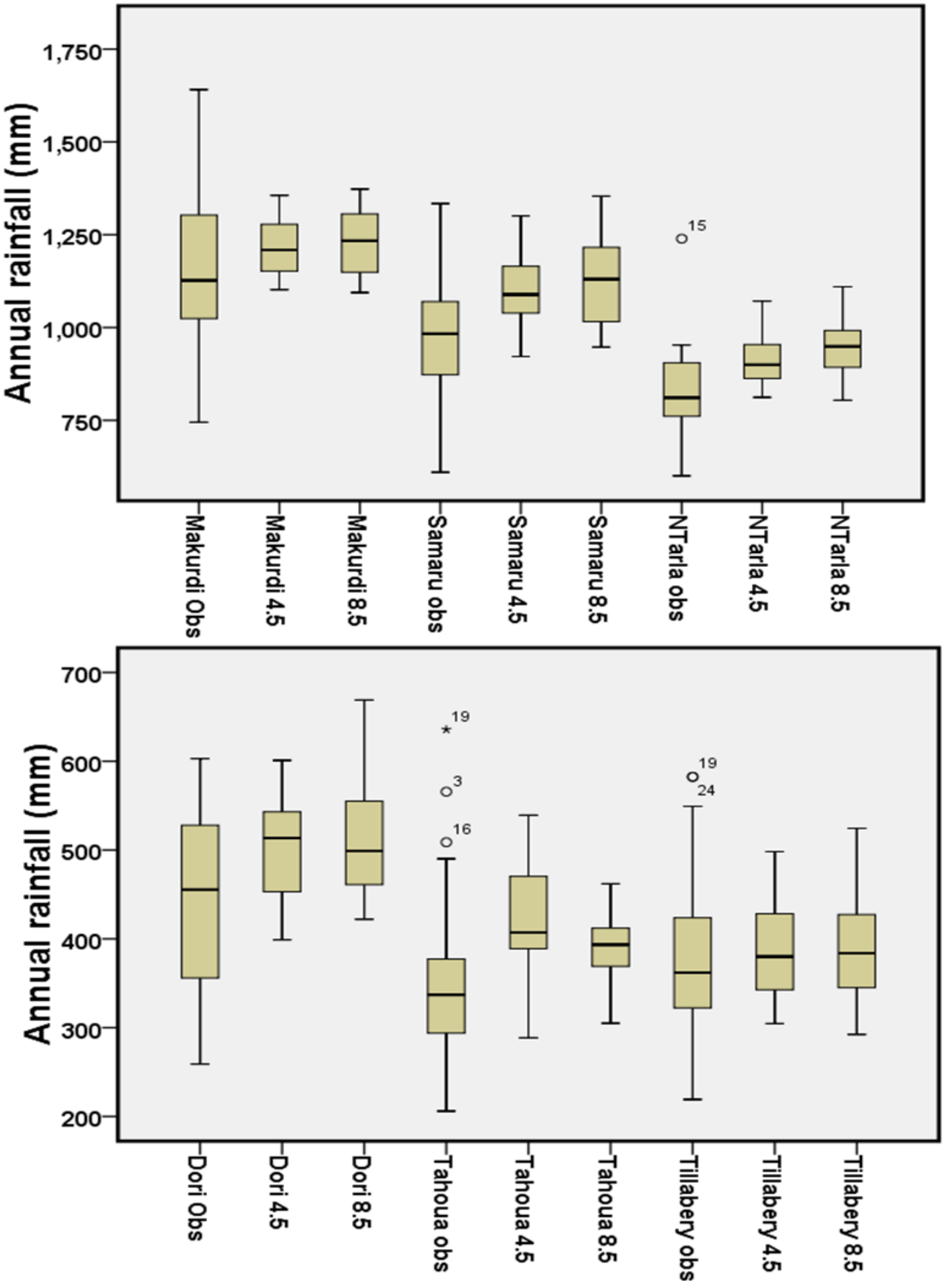


Figure 6: The Guinean (Makurdi, Samaru and NTarla) and Sahelian (Tahoua, Tillabery and Dori) agro-ecological zones average ensemble annual rainfall under the rcp4.5 and 8.5 scenarios for the future period, 2021/25-2050 relative to the baseline period, 1976/80-2005. Note, all are statistically significant at 0.05.

Table 5: Change in the seasonal rainfall for the Niger River Basin for the future period (2021/25-2050) relative to the historical period (1976/80-2005)

Agro-ecological Zone	**Location**	**Average rainfall (mm)**			**PCP ensemble Change (%)**		**Period**
		Obs	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**	
Southern Guinea	Makurdi	1168	1219	1222	4.5*	4.4*	2025-2050
Northern Guinea	Samaru	983	1086	1134	10.5	15.4	2021-2050
	NTarla	826	912	952	12.0	26.5	2025-2050
Sahelian Zone	Tillabery	381	389	392	2.0*	2.8*	2025-2050
	Tahoua	355	399	421	12.5	18.7	2021-2050
	Dori	455	501	513	10.3	12.9	2021-2050

Note, all are statistically significant at 0.05 except *.

Table 6: The summary statistics of the intra-seasonal rainfall characteristic in the Niger River Basin for the future period (2021/25-2050) relative to the historical period (1976/80-2005). Note, these are P-values and values in parenthesis are for rcp8.5 while others are for rcp4.5.

Agro-zone	Location	F-test for variance								T-test for Difference of Means							
		Ann	Onset	End	Dur	Rainfall Intensity				Ann	Onset	End	Dur	Rainfall Intensity			
						Low	Mod	Heavy	Ext					Low	Mod	Heavy	Ext
Southern Guinea	**Makurdi**	0.000 (0.000)	0.023(0.077)	0.004(0.057)	0.387 (0.180)	0.000 (0.000)	0.111 (0.060)	0.126(0.038)	0.000(0.000)	0.258 (0.273)	0.000 (0.001)	0.000(0.000)	0.0289(0.444)	0.000(0.000)	0.000 (0.000)	0.000(0.000)	0.000(0.000)
Northern Guinea	**Samaru**	0.001 (0.016)	0.245(0.215)	0.271(o.241)	0.439 (0.139)	0.000 (0.003)	0.198 (0.152)	0.000(0.001)	0.003(0.011)	0.004 (0.000)	0.048 (0.081)	0.000(0.000)	0.744(0.306)	0.000(0.000)	0.002 (0.005)	0.000(0.000)	0.013(0.014)
	NTarla	0.001 (0.011)	0.012(0.004)	0.002(0.171)	0.014 (0.008)	0.173 (0.077)	0.101 (0.090)	0.052(0.106)	0.016(0.008)	0.003 (0.003)	0.000 (0.001)	0.000(0.000)	0.000(0.002)	0.000(0.000)	0.355 (0.618)	0.685(0.950)	0.000(0.000)
Sahel	**Tahoua**	0.000 (0.002)	0.307(0.245)	0.376(0.231)	0.121 (0.417)	0.422 (0.420)	0.196 (0.137)	0.003(0.42)	0.059(0.135)	0.037 (0.003)	0.000 (0.000)	0.000(0.003)	0.142(0.033)	0.000(0.000)	0.003 (0.002)	0.054(0.002)	0.386(0.391)
	Tillabery	0.003 (0.008)	0.127(0.135)	0.278(0.080)	0.150 (0.354)	0.132 (0.016)	0.431 (0.300)	0.164(0.105)	0.000(0.249)	0.732 (0.638)	0.001 (0.000)	0.653(0.505)	0.003(0.000)	0.000(0.000)	0.018 (0.019)	0.014(0.002)	0.004(0.073)
	Dori	0.002 (0.002)	0.294(0.053)	0.107(0.019)	0.193 (0.138)	0.000 (0.000)	0.245 (0.082)	0.220(0.171)	0.015(0.061)	0.051 (0.020)	0.000 (0.001)	0.000(0.000)	0.006(0.149)	0.000(.000)	0.039 (0.030)	0.036(0.033)	0.041(0.171)

3.2.2. Projected change in intensity and frequency of average daily rainfall events in the Niger River Basin.

Tables 6 presents the summary statistics of the rainfall intensities in the Niger River Basin. The results reveal a significant ($P<0.05$) positive mean change in the future rainfall intensities for Southern and Northern Guinea zones and the Sahelian zones for rcp4.5 and rcp8.5 scenarios. However, there is no change in the future mean rainfall amount for the moderate and heavy intensities for the NTarla location, and extreme rainfall intensity for the Tahoua and Dori locations. The variances of the observed rainfall intensities are largely not statistically different ($P>0.05$) from the future simulated ensemble variances at all locations. However, there is a significant difference ($P<0.001$) for the low and extreme intensities for Makurdi location, heavy and extreme intensities at NTarla location, heavy intensity for Tahoua and low intensity at rcp4.5 at Tillabery and Dori locations.

Figure 7 shows the distributions of the mean frequency of the different categories of the intensity of rainfall events in the Southern (Makurdi) and Northern (Samaru and NTarla) Guinea agro-ecological zones. The results show that in the Southern Guinea Zone, there is a decrease (34-35%) in the frequency of the low intensity rainfall events (>0-10mm), an increase (15%) in moderate rainfall events (>10-25mm), an increase (9-10%) in the heavy intensity rainfall events (>25-65mm) and a decrease (1-10%) in the frequency of the extreme rainfall events (>65mm) for the future period (2025-2050) relative to the baseline (1980-2005) for both rcp4.5 and rcp8.5 scenarios (See Figure 7a). Note, the model underestimated the historical observed rainfall frequency at the low intensity category so the result should be interpreted cautiously for this category of intensity at this location. In the Northern Guinea Zone, there are mixed results for the two locations analyzed. The results show that, at the Samaru location, the frequency of rainfall decreased (16-17%) only for the low intensity rainfall events (>0-10mm) for both rcp4.5 and rcp8.5 scenarios in the future period (2021-2050) relative to the baseline (1976-2005) (See Figure 7b). The results produce an increase (14-15%) in the frequency of the moderate intensity rainfall events (>10-25mm), (12-20%) in the heavy intensity rainfall events (>25-65mm), and (26-51%) in the extreme intensity rainfall events (>65mm) for the location under the rcp4.5 and rcp8.5 scenarios (See Figure 7b). The NTarla location shows contrasting results where there is an increase (8%) in the frequency of the low intensity rainfall events, a decrease (15-20%) in the heavy intensity rainfall events (>25-65mm) and a decrease (25-36%) in the frequency of the extreme intensity rainfall events (>65mm) for the future relative to the baseline under the rcp4.5 and rcp8.5 scenarios (See Figure 7c). The increase (52-59%) also happened at the moderate rainfall events for the location. These contrasting results present a complex situation for agricultural policy making for climate change adaptation, which means that even within the same zone, climate change can present a unique situation that demands a local adaptation policy to climate change. On the other hand, we hypothesized that the projected increase in the frequency of the heavy and extreme rainfall events at the Samaru location may cause flooding at the root and result in the reduction of the cereals yields in the region.

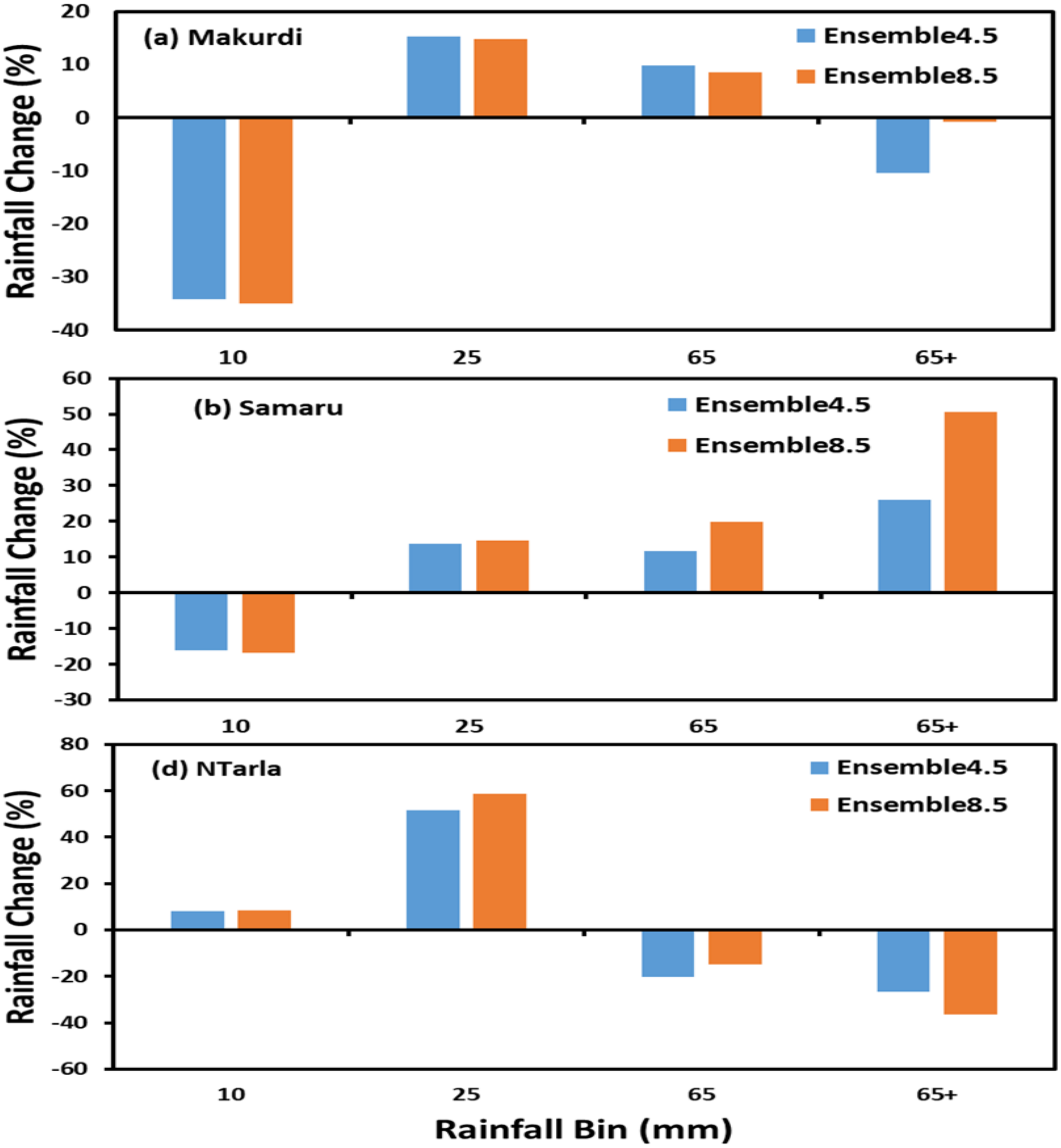


Figure 7: Southern (Makurdi) and Northern (Samaru and NTarla) Guinea average ensemble change in the frequency of the rainfall events at different intensities for the future (2021/25-2050) relative to the baseline (1976/80-2005).

Figure 8 shows the distribution of the mean ensemble frequency of different categories of intensity of rainfall events at the Sahelian Agro-ecological Zones. The results show a decline (10-28%) in the frequency of low intensity rainfall events (>0-10mm) and increase (23-40%) in the moderate intensity rainfall events (>10-25mm) respectively in the future period (2021/2025-2050) relative to the baseline (1976/1980-2005) under the rcp4.5 and rcp8.5 scenarios (See Figure 10). The results also show a decrease (6-13%) and 1-53%) in the frequency of the heavy (>25-65mm) and extreme (>65mm) rainfall events respectively. However, for the Tahoua location, there is an increase (6-13% and 33-44%) of the frequency of the heavy (>25-65mm) and extreme intensity rainfall events (>65+mm) respectively for the future period (2021-2050) relative to the baseline (1976-2005). In all locations within the Sahelian Zone, the frequency of the low and moderate intensity rainfall events decreased (increased) in the future period relative to the baseline period. This increase in the moderate rainfall events significantly contributed to the positive change of future annual rainfall in the Sahel Agro-ecological Zone. The decrease in the low, heavy and extreme rainfall events may cause crop water stress and reduce yield in this zone. Note, at the Tahoua location, the model underestimated the frequency of the low intensity rainfall events so the results should be interpreted cautiously.

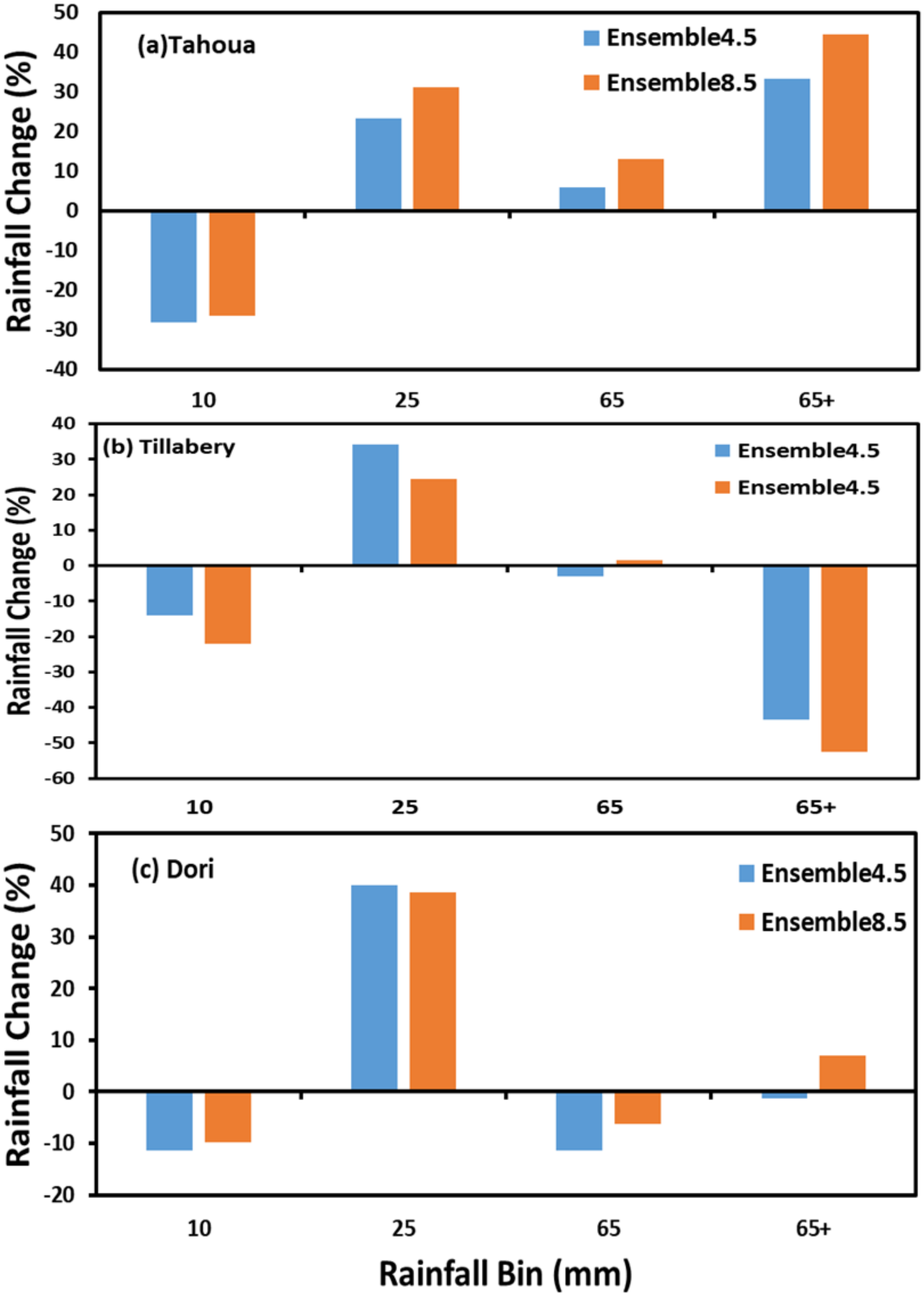


Figure 8: Sahelian average ensemble change in the frequency of rainfall at different intensities of rainfall events for the future (2021/25-2050) relative to the baseline (1976/80-2005)

3.3. Onset/cessation and duration of the rainy seasons in the Niger River Basin

Figures 9-11 and Tables 6-8 present the summary statistics and results of the mean/earliest/latest dates of onset and cessation of future rains in the Niger River Basin. The results reveal a significant change in the future onset, cessation and duration for Southern and Northern Guinea zones and the Sahelian zones for rcp4.5 and rcp8.5 scenarios. However, there is no change in the cessation of the future rain for the Tillabery location and duration for the Samaru location. The variance of the observed annual rainfall is statistically different from the future simulated ensemble variance at all locations. Also, the results show that the variance of the ensemble simulated future onset, cessation and duration of the rains are generally not statistically different from the observational for Southern and Northern Guinea zones and the Sahelian zone. However, there is a significant different for the onset and cessation at Samaru location, and a significant different at NTarla location for both the onset, cessation and the duration of rains.

Detailed analysis of our results reveals that there is a delay in onset (shift) of 31 days (26%) and 21 days (18%) under rcp4.5 and rcp8.5 respectively for the Makurdi (Southern Guinea) location (Figures 9a and Table 7 and Scenario 3), a delay in onset of 10 days (7%) and 8 days (6%) for Samaru and 28 days (20%) and 21 days (14%) for NTarla under rcp4.5 and rcp8.5 respectively (Figures 9 b and c and Table 7 and scenario 3). The Sahelian onset mean shift (delay) is between 17-20 days (10-19%) for rcp4.5 and 3-10 days (3-6%) under rcp8.5 scenarios (Figure 9 d-f and Table 8).

There is a late cessation of 15 days (5%) for both rcp4.5 and rcp8.5 for Makurdi location (Southern Guinea) (See Figure 10a and Table 7 and scenario 4) and a late cessation of

13 Days (4%) for both rcp4.5 and rcp8.5 for Samaru and a late cessation of 21 days (7%) and 17 days (6%) under rcp4.5 and rcp8.5 respectively for NTarla (Northern Guinea) (See Figure 10b and Table 7 and scenario 4). A late cessation of 11 days (4%) and 9 days (3%) is also observed at Tahoua under rcp4.5 and rcp8.5 respectively, 17 days (6%) and 13 days (4%) for Dori under rcp4.5 and rcp8.5 respectively both at the Sahelian locations (See Figure 10 e-f and Table 8 and scenario 4). The results show a reduction in duration of the growing season in all locations (Figure 11). A decline of 16 days (-8%) and 5 days (-3%) for rcp4.5 and rcp8.5 for Makurdi (Southern Guinea) (See Figure 11a) and a decline in duration of 25 days (-14%) and 21 days (-12%) under rcp4.5 and rcp8.5 respectively for the Northern Guinea (See Figure 11b and c). And lastly a decline in the duration of 8 days (-9%) and 14 days (-13%) for Tahoua and 17 days (-14%) and 10 days (-8 %) for Dori under rcp4.5 and rcp8.5 respectively and both at the Sahelian locations (See Figure 11 d-f). These result indicates that farmers in the Niger River Basin will need to delay planting and also plant medium duration crops in the future in order to adapt to the future change in the onset/cessation and duration of the growing season. Our results further reveal that the hypothetical scenarios 2 (change in the amount of total rainfall), scenario 3 (Delay onset) and scenario 4 (Changes in onset, cessation) are the dominant scenarios at play in this region in the future.

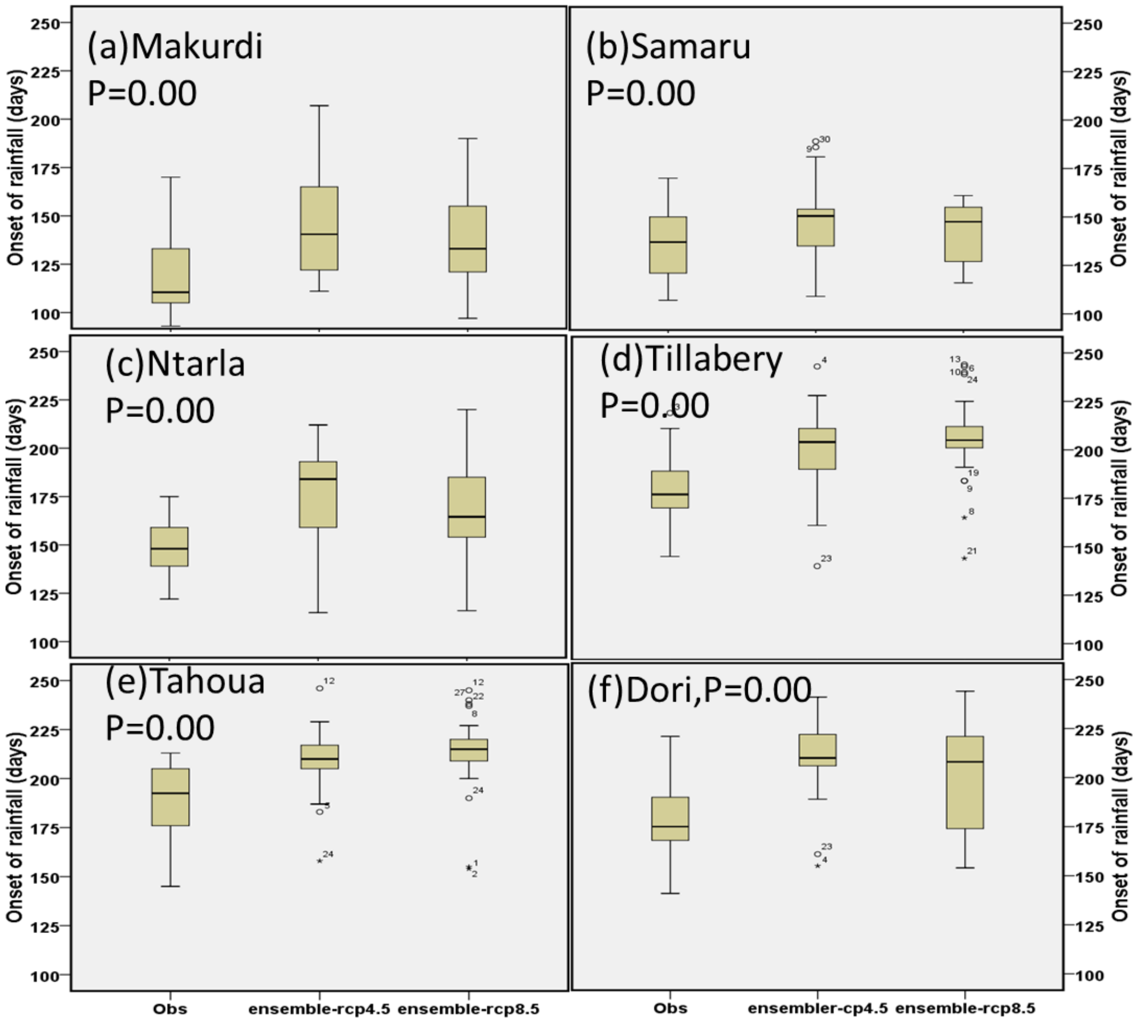


Figure 9: Southern (Makurdi) and Northern (Samaru and NTarla) Guinea and Sahelian (Tahoua, Tillabery and Dori) average ensemble change in rainfall onset for the future period (2021/25-2050) relative to the baseline (1976/80-2005). All in Julian days.

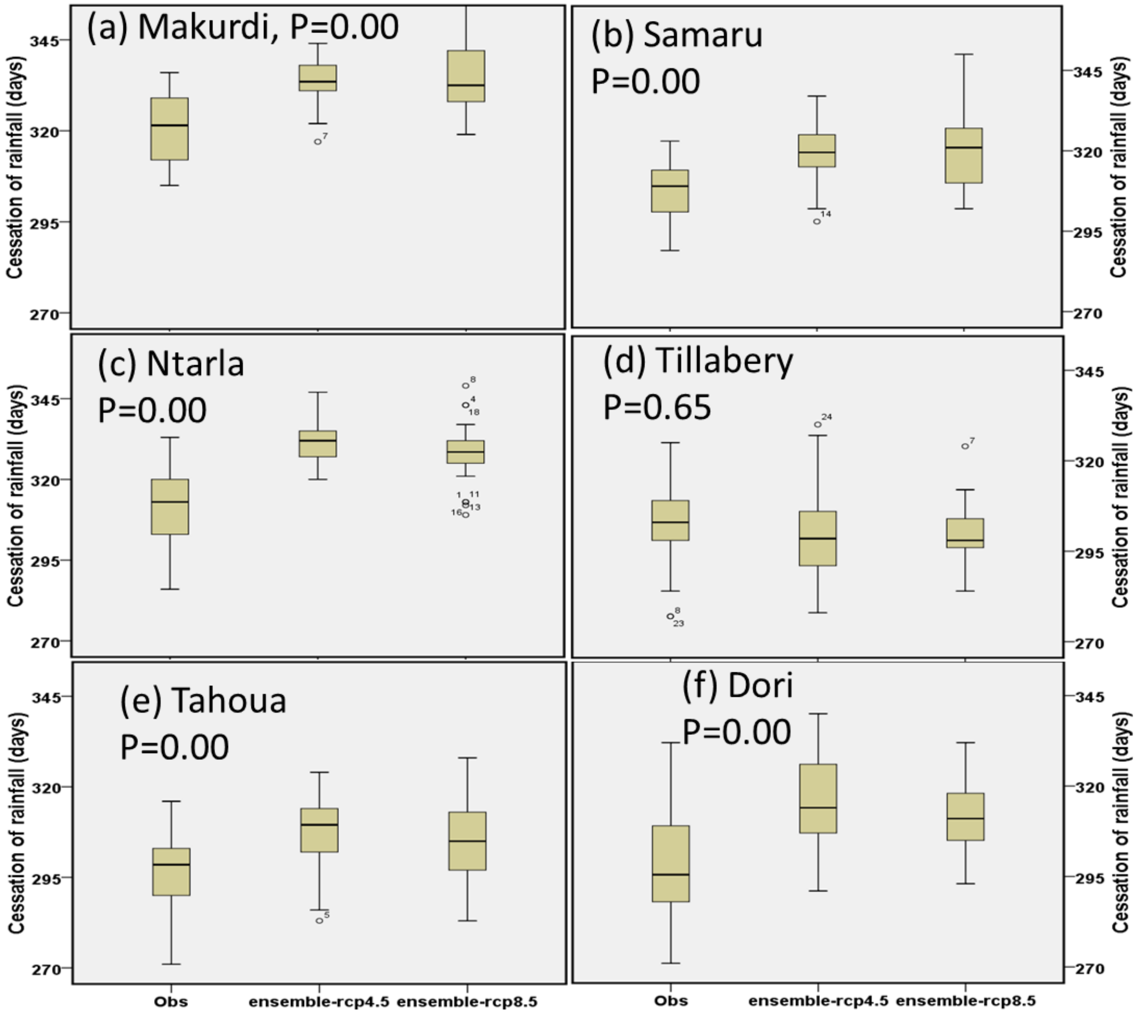


Figure 10: Southern (Makurdi) and Northern (Samaru and NTarla) Guinea and Sahelian (Tahoua, Tillabery and Dori) average ensemble change in rainfall cessation for the future period (2021/25-2050) relative to the baseline (1976/80-2005). All in Julian days.

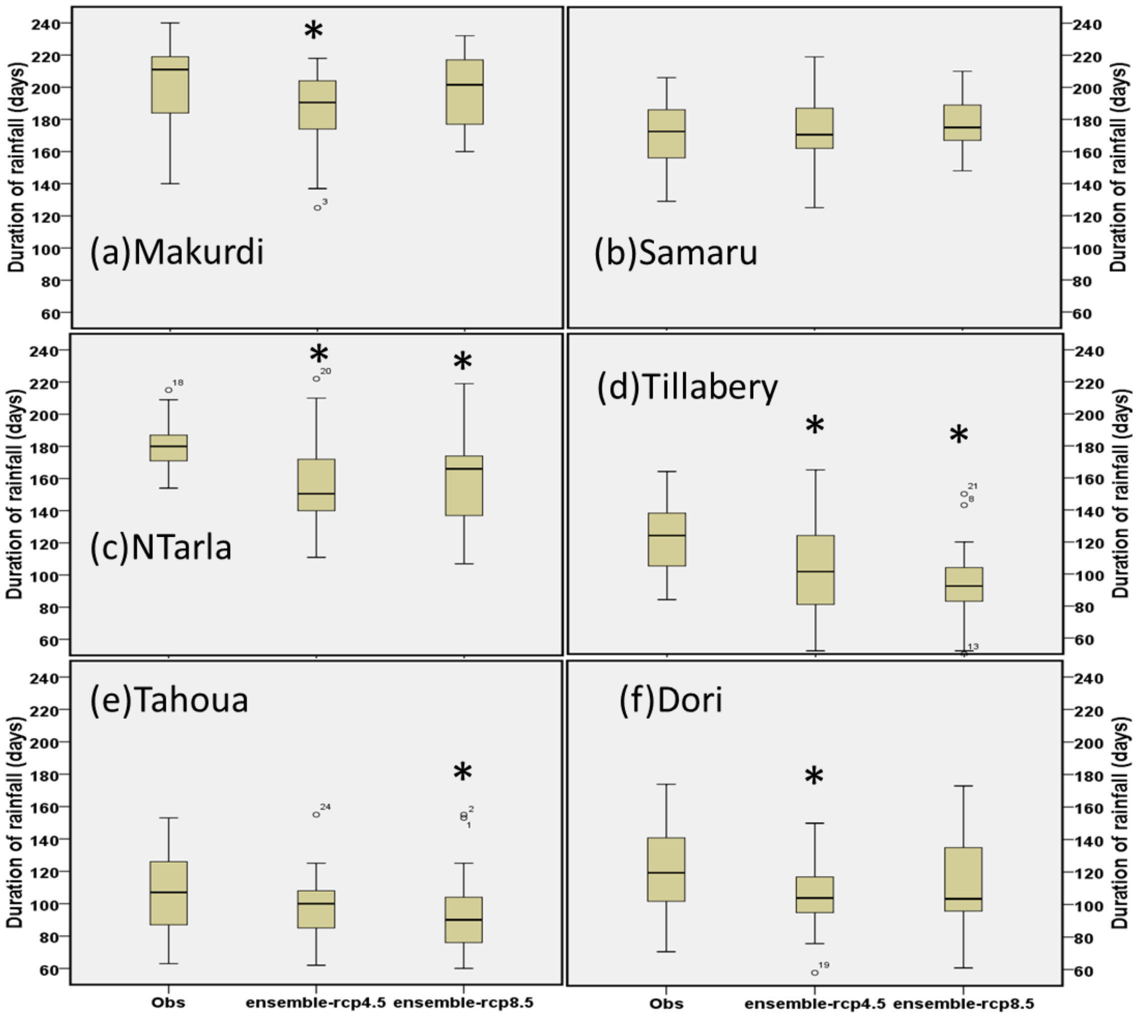


Figure 11: Southern (Makurdi) and Northern (Samaru and NTarla) Guinea and Sahelian (Tahoua, Tillabery and Dori) average ensemble change in the duration of the growing season for the future period (2021/25-2050) relative to the baseline (1976/80-2005). Note, * indicates a significant change (P<0.05).

Table 7: Southern and Northern Guinea average ensemble change in the rainfall characteristic for the future period (2021/25-2050) relative to the baseline (1976/80-2005).

Southern Guinea (Makurdi)	**Mean Onset (days)**	**Change (%)**	**Mean cessation (days)**	**Change (%)**	**Earliest onset (days)**	**Earliest cessation (days)**	**Latest onset (days)**	**Latest cessation**
Obs	117	0	320	0	93	264	170	336
Ensemble4.5	147	26	334	4	111	317	207	361
Ensemble8.5	138	18	335	5	87	319	190	361
Northern Guinea (Samaru)	**Mean Onset (Julian days)**	**Change (%)**	**Mean cessation (Julian days)**	**Change (%)**	**Earliest onset (Julian days)**	**Earliest cessation (Julian days)**	**Latest onset (Julian days)**	**Latest cessation (Julian days)**
Obs	136	0	307	0	107	289	170	323
Ensemble4.5	146	7	319	4	109	298	189	337
Ensemble8.5	143	6	320	4	116	302	161	350

Table 8: Sahelian average ensemble change in the rainfall characteristic for the future period (2021-2050) relative to the baseline (1976-2005).

Sahel (Tahoua)	**Mean onset (Julian days)**	**Change (%)**	**Mean cessation (Julian days)**	**Change (%)**	**Earliest onset (Julian days)**	**Earliest cessation (Julian days)**	**Latest onset (Julian days)**	**Latest cessation (Julian days)**
Obs	190	0	297	0	145	271	213	316
Ensemble 4.5	209	10	307	4	158	283	246	324
Ensemble 8.5	213	12	306	3	154	283	245	328

Sahel (Dori)	**Mean Onset (Julian days)**	**Change (%)**	**Mean cessation (Julian days)**	**Change (%)**	**Earliest onset (Julian days)**	**Earliest cessation (Julian days)**	**Latest onset (days)**	**Latest cessation (Julian days)**
Obs	178	0	299	0	141	271	221	332
Ensemble 4.5	210	19	315	6	155	291	241	340
Ensemble 8.5	201	13	312	4	154	293	244	332

4. Conclusion

In this paper, we used an ensemble of nine bias-corrected GCMs downscaled with one regional climate model to assess change in the future rainfall characteristics based on the major agro-ecological zones in the Niger River Basin. The major findings are the following:

1. The evaluation of the multi-model ensemble results show that the mean of the observational data is not statistically different from the ensemble mean for all variables and all locations except for the Makurdi location were the onset is significantly different from the observed and the extreme rainfall intensity events at the Makurdi and Dori locations. The average ensemble rainfall shows an insignificant increase of 5% and 4% under rcp4.5 and rcp8.5 respectively for the Southern Guinea zone, but a significant increase of 11% and 27% under rcp4.5 and rcp8.5 respectively for the Northern Guinea zone, and 8% and 12% under rcp4.5 and rcp8.5 respectively for the Sahelian zone although there is much less agreement among the models for all locations in the basin. These results prove otherwise the postulated scenario 2 of the likely decline in the seasonal amount of rainfall in the region.

2. The results reveal a significant mean change in the future rainfall intensities for Southern and Northern Guinea zones and the Sahelian zones for rcp4.5 and rcp8.5 scenarios. There is a decrease in the frequency of the low, heavy and extreme rainfall events in the future in four out of the six locations in the Niger River Basin. The results show an increase in the frequency of the moderate rainfall events in all locations in the basin. However, Samaru, at the Northern Guinea, and Tahoua, at the Sahel locations show an increase in the frequency of the heavy and extreme rainfall events in the future, and these results are consistent with rainfall projection in the region.

3. The results reveal a delay in the future onset/cessation and a decline in the duration of the rainy season in this region, and these results are consistent with other studies in the region (IPCC, 2014). There will be a delay of onset and a late cessation of rains and a significant decline in the duration of the growing season in all locations except for Samaru in the Northern Guinea Zone of the Niger River Basin.

4. Finally, we concluded that this change in future rainfall characteristics as a result of climate change poses serious risks not just to farmers but to the regional food security and, therefore, demands adequate crop management to adapt to these changes.

Supplementary Figures

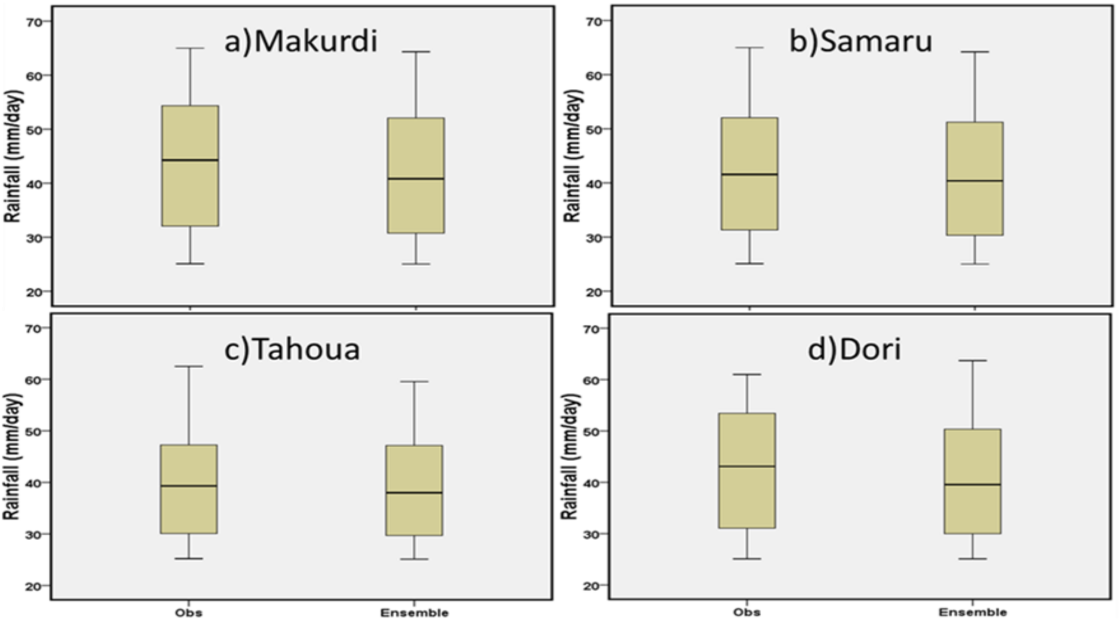


Figure S1: **A comparison of the CORDEX multi-models ensemble and observed mean daily heavy rainfall intensity (>25 to <=65mm) over the Southern (Makurdi) and Northern (Samaru) Guinea agro-ecological zones and the Sahelian (Tahoua and Dori) agro-ecological zones for the historical period, 1976/80-2005.**

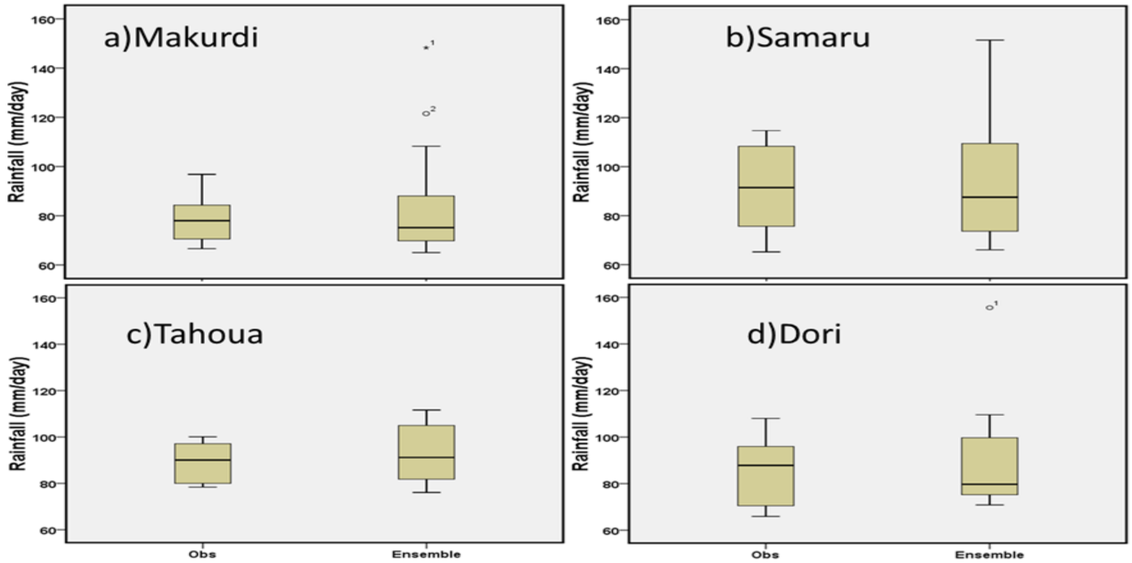


Figure S2: **A comparison of the CORDEX multi-models ensemble and observed mean daily heavy rainfall intensity (>65mm) over the Southern (Makurdi) and Northern (Samaru) Guinea agro-ecological zones and the Sahelian (Tahoua and Dori) agro-ecological zones for the historical period, 1976/80-2005.**

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Chapter 5

General summary and conclusions

5.1. Synopsis

During the past half century, food productivity in Sub-Saharan Africa (SSA) has lagged the rest of the world while population growth has outpaced the rest of the world. These contrasting trends portend serious risk for the food security of the region. The projected global climate models indicate that temperature will increase by more than 2°C in the mid-century while precipitation will increase by more than 10% in the region. To arrest or mitigate this situation, concerted action is needed, including improved decision-making informed by scientific evidence. Toward that goal, this dissertation used the AquaCrop model to evaluate the impact of climate change on major cereal yields and adaptation options in the Niger River Basin. The study also analyzed the projected changes in the intra-seasonal rainfall characteristics in the region.

This research is also timely because it responds to increased public awareness and concerns about the impacts of climate change on agricultural productivity. The potential impact of global climate change on agricultural productivity has been discussed at the West Africa and Sub Saharan Africa scale in several scientific media. However, agricultural adaptation to climate change is rarely discussed at the field or basin level and within the agro-ecological zones in this region. Therefore, it is important that resource managers and farmers have a holistic understanding of the issues from a practical standpoint and at a local level. A study of this nature provides both the necessary background information and the results that both users and policy makers can utilize to evaluate strategy and management decisions in the agricultural sector.

This study calibrated and validated AquaCrop on various cereal crops in the Niger River Basin for the first time (Chapter 2). The model is capable of producing robust and accurate results given relatively few input variables, making it uniquely suited to data-scarce regions like SSA. The results show that the model reasonably simulated cereal yields at different nitrogen fertility levels in this region. The observed and simulated yields were evaluated to be satisfactory. The evaluation results show that the normalized root mean square error (NRMSE) for grain yields were between 8%-17% for poor, about half, moderate fertilizer levels and near optimal fertilizer levels which indicate excellent to good results while the NRMSE for biomass yields were around 19% for poor, 24% for about half, 20% for moderate fertilizer levels and 26% for near optimal fertilizer levels which indicate good to satisfactory results. While encouraging, simulated yields systematically over-estimate observed yields, likely because AquaCrop is designed to simulate potential or achievable yields. Overall, however, the agreement between simulated and observed yields is consistent with those reported elsewhere and suggest that the model can be utilized as a tool in the study and modeling of crop productivity in this region.

In the second study, reported in chapter three, the impact of climate change on cereal yields and adaptation options in the Niger River Basin in three agro-ecological zones was assessed using AquaCrop process-based model and CORDEX nine ensemble climate models with one regional model for the mid-term (2021/25-2050) relative to the baseline period (1981/85-20100. The results show a strong consensus among all models that mean surface temperature in the Niger Basin will increase by 1.3°C, 2.3°C and 2.3°C in the Southern Guinea Zone, Northern Guinea Zone and Sahelian zone respectively. The average ensemble rainfall shows an increase of about 5% for the Southern Guinea Zone, 10-20% for the Northern Guinea Zone, and 10-15% for the Sahelian zone although there is much less agreement among the models. The results also show that climate change effects on maize and sorghum yields are mostly positive (2%-6% increase) in the Southern Guinea Zone whereas in the Northern Guinea Zone it is mostly negative (7-20% decrease). Despite an increase in rainfall, millet yield at the Sahelian Zone generally showed no change under current farmers' level of fertilization, except at Tillabery where a yield decrease of up to 10% occurred.

The adaptation options of changing planting dates (D2 and D3) and crop cultivar (V1 and V2) results in significant positive yield change in all the agro-ecological zones except for the Sahelian zone where delaying planting to late planting date caused crop failures.

In all the adaptation options evaluated, increasing soil fertility is the single most important adaptation that farmers in the Niger Basin can make in response to climate change. For all crops and zones investigated, crop yields increased by 20%, 70%, and 180% for moderate fertility (M), near optimal fertility (np) and optimal fertility (op) under rcp8.5 climate scenarios for both cultivars, and planting dates.

Finally, the effects of climate change on crop yields are considerable and pose serious risks not just to farmers but regional food security, especially given the rapidly growing population in West Africa which necessitates increasing food production several folds. Ultimately, the solution lies in mitigating the causes of climate change. In the meantime, this study suggests that yield losses can be substantially alleviated through several adaptation measures, notably changing planting dates, changing crop cultivars and most importantly, increasing fertilizer use on farms. These changes are well within the ability of policy makers and a majority of smallholder farmers.

Using the same CORDEX datasets, the last study (chapter four) carried out the analysis of the projected change in intra-seasonal rainfall characteristics for three agro-ecological zones in the Niger River Basin. The results of the study indicate that the future ensemble average seasonal rainfall will increase generally in the basin ranging from 5-20%. The results also show a decrease in the frequency of the low, heavy and extreme rainfall events in the future in most of the locations in the Niger River Basin. There is an increase in the frequency of the moderate rainfall events in all locations in the basin. However, Samaru, at the Northern Guinea, and Tahoua, at the Sahel locations show an increase in the frequency of the heavy and extreme rainfall events in the future. The results further reveal a shift in the future onset/cessation and a decline in duration of the rainy season in this region. There will be a delay of onset and a late cessation of rains and a significant decline in the duration of the growing season in all locations except for Samaru in the Northern Guinea Zone of the Niger River Basin. We therefore, hypothesized that this change in future rainfall characteristics, as a result of climate change, may poses serious risks not just to farmers but to the regional food security and therefore demands adequate change in the cropping pattern and management to adapt to these changes.

5.2. Implication for agricultural production and future research.

The overarching goal of this research was to provide information about the future impact of climate change to cereal productivity and the adaptation options available for policy makers and smallholder farmers in the Niger River Basin. The information contained in chapter 2 through 4 accomplishes this goal. The validation of AquaCrop model in this region gives policy makers and farmers a tool in making an informed decision on the environmental factors affecting crop yields way ahead of time (discussed in chapter 2). Therefore, this research has a significant implication for agricultural management in that it paves the way for proactive planning regarding the future projected climate changes and impending impacts on the food security of the region. Similarly, the increased understanding of the climate change agricultural adaptation options in the Niger River Basin and the future precipitation dynamics can actually help to reverse the yield losses due to climate change with adaptation measures that appear within the reach of a majority of small farmers in the region (discussed in chapter 3 and 4). Thus, farmers and policy makers in West Africa have viable options to produce sustainable food for the future and climate change is not a death sentence. We recommend that further research should use an ensemble of crop and climate models to assess the projected impact of climate change and adaptation options at each grid cell in the Basin for various crops to obtain more robust results.

In conclusion, the major contributions of this study are summarized as follows:

1. From an academic perspective, this study validates AquaCrop model in the major agro-ecological zones in the study area for the first time; thereby, helping the research community to gain improved understanding of the climate-environmental-cereals yield nexus in the region. The study contributes to the growing literature on the model's efficacy in simulating crop yield in different bio-ecological systems. Researchers and scientists will also be able to use the calibrated/validated AquaCrop model to investigate the impacts of climate change on crops within the region's agro-ecological zone.
2. The study also fills a critical gap regarding the understanding of climate change agricultural adaptation in semi-arid West Africa, particularly, the role of management strategies in mitigating climate change impacts. By evaluating the efficacy of several adaptation scenarios to future climate change, this study provides critical information for a proactive approach to agricultural adaptation options for smallholder farmers in this region.
3. This study also provides information on the projected change in intra-seasonal rainfall characteristics on a finer detail, and therefore more actionable information about the specific risks and changes that stakeholders at the specific location will need for climate change agricultural adaptation.
4. The results of this study provide an actionable decision support system that demonstrates how to evaluate strategies for improving cereals yield while mitigating and managing climate risks.