Spatio-temporal effects of projected climate on future crop suitability over West Africa

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DECLARATION

I, **Temitope Samuel Egbebiyi,** hereby declare that this thesis is my own work (except where acknowledgements indicate otherwise) and that neither the whole work, nor any part of it has been, is being, or is to be submitted for another degree in this or any other university. I authorise the University to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

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ABSTRACT

Future climate is projected to deviate from present-day by unprecedented measure, hereafter climate departure, with direct consequences on food security. West Africa, one of the hotspots for climate departure globally, has suffered significantly from climate change impacts via extreme events with large impacts on food production. A better understanding of the impact of climate departure on crop growth suitability and planting season is still unknown and is highly needed in West Africa, owing to its high vulnerability and low adaptive capacity. This thesis developed a methodology aimed at defining the cropping system to investigate the projected timing of climate departures from historical variability and their impact on crop growth suitability over West Africa. For the study we used 4 statistically downscaled Global Climate Models, GCMs at station level for the period 1951-2100 under RCP8.5 across the three AgroEcological Zones (AEZs) of West Africa for eight crops, cassava, maize, mango, orange, pearl millet, plantain, pineapple and tomato. Climate variables minimum mean monthly temperature and total monthly precipitation were used as input crop suitability model, Ecocrop to develop a new approach to define and characterise cropping systems departure from their normal regime, called crop-climate departure (CCD), to better understand the timing of future changes in crop suitability. Also, the concept of CCD was defined, tested and applied in West Africa for five different crops types, using 10 GCMs downscaled by regional climate model, RCA4 as input into crop suitability model Ecocrop. The downscaled GCMs were also employed to examine the impact at the different global warming levels, 1.5, 2.0 and 3.0^{o}C on crop suitability over West Africa. Using the GCMs at station level, we develop the concept of crop-climate used in characterizing the suitability of different crop across the three AEZs of West Africa. The result highlights the constraint, a reduction in suitable area, of growing cassava and pineapple only in the Guinea zone by mid and end of century. In contrast, there is an observed and projected opportunity, increase in suitable areas, of growing maize in southern Sahel by the end of the century while mango remains suitable across the three West African AEZs. The application applying the concept crop-climate departure on different crop types showed in decrease suitable areas for most crops by the end of century with horticultural, cassava and cereals respectively are the crops mostly affected. The changes in crop-climate relationship suggests a future constraint in crop suitability could be detrimental to future food security over West Africa. Finally, our findings from the impact of different global warming levels, 1.5. 2.0 and 3.0^{o}C highlights the potential of sustained suitability for all the crops and improved food security under 1.5^{o}C global warming for all the six crops but a contrast under 3^{o}C over West Africa except for cowpea and groundnut. Our findings for cowpea and groundnut showed an increase suitable area into the southern Sahel with increasing global warming level. The study holds great value at regional scale where improved preparedness and regional cohesion could make the difference in making decision for a food secure Africa. Further studies to explore associated short and long-term adaptation options to changes in crop-climate relationship are recommended.

Dedication

To the Almighty God (the dependable father)

To Jesus Christ (the Alpha and Omega)

To the Holy Spirit, my companion and guardian all through this Journey

To my Darling wife, Oluwabukola and daughters, Praise and Peace

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List of Acronyms/Abbreviations

ACCESS—Alliance for Collaboration on Climate and Earth System Sciences

AEZs—AgroEcological Zones

AR – Assessment Report

CCCMA—Canadian Centre for Climate Modelling and Analysis

CD – Climate Departure

CCD – Crop Climate Departure

CIP—Climate Information Portal

CMIP5—Coupled Model Intercomparison Project (Phase 5)

CNRM—Centre National de Recherches Meteorolo-Giques

CRU – Climate Research Unit

CSAG—Climate System Analysis Group

FAO—Food and Agriculture Organization

GCMs—Global Climate Models

GDP – Gross Domestic Product

GFDL—Geophysical Fluid Dynamic Laboratory

GWLs – Global Warming Levels

INDC – Intended Nationally Determined Contributions

IPCC – Intergovernmental Panel on Climate Change

ITCZ – InterTropical Convergence Zone

ITD – InterTropical Discontinuity

MIRCA - Monthly Irrigated and Rainfed Crop Areas

NDC – Nationally Determined Contributions

NRF—National Research Foundation

PM – Planting Month

RCA – Rossby Centre’s regional Atmospheric model

RCMs -Regional Climate Models

RCPs – Representative Concentration Pathways

SIV – Suitability Index Value

SMHI – Swedish Meteorological and Hydrological Institute

SSA—Sub Saharan Africa

UNFCCC - United Nations Framework Convention on Climate Change

WAM – West African Monsoon

WFDEI - WATCH-Forcing-Data-ERA-Interim

CHAPTER 1

1. INTRODUCTION

1.1 Background

This chapter provides an overview of the major themes of this research. It describes the livelihoods, current and projected population and the state of food security over Sub-Saharan Africa (SSA). It further describes the impact of population growth and climate change on food security in SSA. It focuses on West African region, its climate, its agriculture as a major means of livelihoods and the impact that climate change has on agriculture. The chapter defines and explores the concept of climate departure and describes the climate crop relationship through the climate-crop threshold. Ultimately, the chapter provides motivation for the research on the timing of climate departure and its spatio-temporal impact on crop suitability over West Africa. It also contains the research question, aim and objectives of the research, the approach to achieve research objectives are briefly described. The chapter ends with an outline of the thesis structure.

1.2 Population Growth, Livelihoods and Food Security in SSA

The continuous increase in population growth remains a critical challenge influencing global change in the twenty-first century (Hertel, 2011, 2015). The global population, currently about 7.6 billion is projected to reach almost 10 billion by mid-century (Bloom, 2011; Population Reference Bureau, 2018). In SSA, a rapid increase in population growth is projected compared to other continents of the globe (Bloom, 2011). Currently about 950 million, about 13% of the global population, SSA population is projected to double by mid-century reaching around 2.2 billion people (Bloom, 2011; United Nations, 2013; OECD/FAO, 2016). The total population of the inhabitants of West Africa is estimated at approximately 250 million, growing at an average rate of 3% annually and expected to reach about 430 million by 2020 (Bloom, 2011). SSA is mostly rural, with about 60% of the population consisting of people living in rural areas, with main source of livelihoods highly dependent on rainfed agriculture (Bloom, 2011). The rural areas are characterized by low education status, low income, malnutrition, hunger, high population density, high poverty rate, and low agricultural productivity (Vermeulen, Campbell & Ingram, 2012). The area is densely populated and are projected to further increase. The projected population growth will also affect the agricultural land (Jayne, Chamberlin & Headey, 2014) as this is will put further pressures on the suitable agricultural land over the region. The reduction in cultivated land or farm size for subsistence farming will mainly affect the rural farmer through a decrease in agricultural production to meet their immediate needs (Kyalo Willy, Muyanga & Jayne, 2019). This will exacerbate the current high demand for food in the region further increasing lack of access to food and undernourishment in the region (OECD/FAO, 2016).

Food security remains a great challenge in SSA. A recent report by the Food and Agriculture Organization (FAO) showed that one out of every four persons in Africa, does not have access to a healthy diet (FAO, 2018) even as SSA continues to lag in the fight against access to food with the increasing rate of hunger and malnutrition. The report further showed that SSA has the highest number of food-insecure people, about 925 million, with about 800 million suffering from chronic hunger and undernourishment (FAO, 2018). The number of people who are food insecure is projected to further increase with the increasing population in the region as well as the prevalence of undernourishment in different parts of the region except for East Africa (UNDP, 2015; FAO, 2018). Although giant strides have been made in improving food security and reducing hunger over the last two decades in other regions of the world, Africa has the highest population with the prevalence of undernourishment in the world. Although much of the food produced is through subsistence farming, food security and ending hunger remains a major challenge and topical issue in SSA especially West Africa, the most populous region and one of the hotspots of climate change impact (IFAD and UNEP, 2013; Ricciardi et al., 2018).

1.3 An overview of the West African Region

West Africa comprises 16 developing countries (member state) which form the regional body called the, Economic Community of West African States (ECOWAS) (Figure 1.1). ECOWAS member states include Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Republic of Benin, Senegal, Sierra Leone and Togo (Figure 1.2). ECOWAS oversees the economic needs and integration of member states in the region. The West African region is situated north of the equator at longitudes 16°W and 15°E and latitudes 4-24°N. It extends from the Gulf of Guinea to Sahara Desert in the south and north respectively and in the east from Mount Cameroon to the Atlantic Ocean in the west. The landmass of the region is large area of over 6million square kilometres and about 20% of the African continent1. The total population of the inhabitants of West Africa is estimated at approximately 250 million, growing at an average rate of 3% annually and expected to reach about 430 mmillion by 2020 (Bloom, 2011).

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[1] http://global.britannica.com/place/western-Africa

Figure 1.1: Map of West Africa showing ECOWAS member states (green colour). The dotted lines represent the climatic transition zone[2].

1.3.1 The West African Climate

The climate of West Africa is influenced by two major air masses; a tropical maritime and a continental air mass (Nicholson, 2008, 2009). These strongly modulate variability in temperature and rainfall in the region (Abiodun et al., 2008; Nicholson, 2009). Both air masses meets over the ocean and land at a point called the InterTropical Convergence Zone (ITCZ) and the InterTropical Discontinuity (ITD) respectively (Figure 1) (Abiodun et al., 2008; Nicholson, 2008, 2009). The ITD oscillates from south to north over the region modulating the pressure system of the West African Monsoon which controls the moisture laden south-westerly wind and dry North-west trade winds that results in the wet and dry season over the region (Abiodun et al., 2008). The ITD at 7^{o}N gets to its southernmost

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[2] Map of west Africa accessed online 17 September, 2019 at https://saylordotorg.github.io/text_world-regional-geography-people-places-and-globalization/s10-03-west-africa.html

position in the Guinea zone in January and furthest north in August in the Sahel around 22°N (Nicholson, 2009).

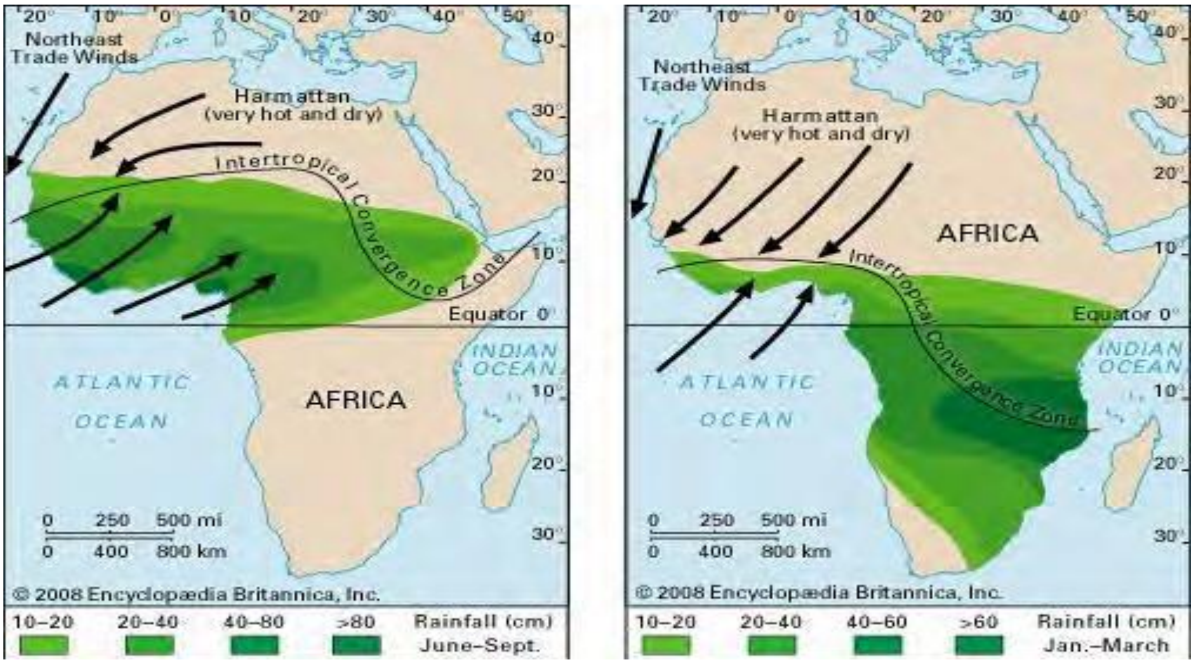

Figure 1.2: The West African Monsoon influence on wind and rainfall pattern in (a) June–September. and (b) January-March[3]

West African rainfall pattern is mainly controlled by the West African Monsoon (WAM), which is the main source of moisture. The West African climate is divided into three major ecological zones namely; Guinea (latitude 4-8°N), Savannah (latitude 8-12°N, 750-1250 mm/year) and Sahel (latitude12-16°N) (Omotosho & Abiodun, 2007; Abiodun et al., 2012). The Guinea zone, the south most boundaries to the Atlantic Ocean has mean annual precipitation above 2500 mm. The zone has a longer rainy season with a bi-modal rainy season between March-July and September-October respectively (Baidu et al., 2017). The region experiences a break in rain during this period in August, commonly referred to as the August break (Omotosho & Abiodun, 2007; Abiodun et al., 2008; Baidu et al., 2017). The Savannah zone is a semi-arid zone with mean annual rainfall between 750-1250 mm. The

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[3] Encyclopaedia Britannica accessed online 3 September 2019 at http://www.britannica.com/science/West-African-monsoon

northernmost part is the Sahel zone with mean annual precipitation of 750 mm comprising of Mauritania, Mali and Niger. This zone has a short and single rainy season between June-September. Overall, rainfall decreases northward from the coast, through the Guinea, Savanna an Sahel AEZs up to the Sahara of the region (Jalloh et al., 2013). Unlike rainfall temperature increases shows through a south to north gradient from the south coast. Annual maximum temperatures range is about 30–33°C along the gulf of Guinea in the south, 36–39°C in the Sahel and from 42–45°C near the desert in the north (Jalloh et al., 2013). The climate variability of the region is affected by topography; and its low adaptive capacity makes it highly vulnerable to climate change (Kirtman et al. et al., 2013; Riede et al., 2013).

1.3.2 Agriculture in West Africa

The socio-economic activities of West Africa are driven by and largely depend on agriculture (Omotosho & Abiodun, 2007; Diasso & Abiodun, 2017). Agriculture and other related activities employ over 60% of the labour force and about 65% employment rate are dependent on this activities (Serdeczny et al., 2017). Also, at about 5.9% annual rate growth in the last ten years, about 35% of the Gross Domestic Product (GDP) is from agriculture (Blein et al., 2008). Blein et al. (2008) also showed that agriculture accounts for about 16.3% (about USD 6billion) of the total exports of product and services and about 78% of food exports for the region. The report further revealed that agriculture alone provides about 80% of the regional food needs of the inhabitants through regional production (Blein et al., 2008).

West African agriculture is composed of various farming systems. This ranges from the root and tree crop systems in the south to the nomadic pastoralism in the north. Some of farming systems in the West Africa include Agro-pastoral, highland perennials, cereal-root crop mixed, large commercial and smallholder, root and tuber crop and humid lowland tree crop farming systems. The smallholder farming system constitute about 80% of all the farms in West Africa with a significant contribution to livelihoods and the economy (Williams et al., 2018). The Agro-pastoral farming system refers to the practice of agriculture that involves growing and cultivation of crops and raising of livestock. The Highland perennial system is based on perennial crops such as banana, plantain, coffee supplemented by cassava, sweet potato etc. Cereal-root crop described the cultivation of both cereal and root crops such as maize, millet, cassava, plantain etc. Tree crop farming system involves the cultivation of industrialised tree crops such as cocoa, coffee, rubber and oil palm while root and tuber crop farming system are based on the cultivation of root and tuber crops such as plantain, yam and cassava etc.

Different crops are grown in various parts of West Africa (Figure 1.3). Some of the major crops grown in the region are cassava, groundnut, millet, maize, sorghum, yam, plantain, cocoa, rice, and cowpea (Paeth, Capo-Chichi & Endlicher, 2008; Jarvis et al., 2012a; Nelson et al., 2014; Sultan & Gaetani, 2016). Millet and sorghum accounted for 64% of cereal production within the region in the year 2000, making them among the more important staple crops in West Africa. Cassava is also an important staple food crop in terms of production in West Africa owing to its high resilience to drought (Jarvis et al., 2012a; Srivastava et al., 2016; Sultan & Gaetani, 2016). This also applies to yam production, which accounts for about 91% of the world's production (Hijmans et al., 2001; FAOSTAT, 2014; Sultan & Gaetani, 2016). Maize provides about 20% of the calorie intake in West Africa and is adjudged the most important staple food overall in SSA (FAOSTAT, 2014; Sultan & Gaetani, 2016). Other crops such as cocoa and plantain, also contribute significantly to the economy of the region.

Figure1.3: Map showing different cultivated crops in West Africa[4]

1.4 Impacts of Climate Change on Agriculture in West Africa

Projected changes in the climate will significantly affect food security in SSA. The variability in climate will strongly affect rainfed agriculture, which is the main source of livelihoods in SSA (Niang et al., 2014). Variability and change in the West African climate, both spatial and temporal, remains a challenge to agricultural production, threatens food security and many socio-economic activities across the region (Abatan, 2011). Projected changes in climate show there will be increases in temperature and variability in rainfall resulting in water scarcity will increase over the regions (Gizaw & Gan, 2017). Niang et al. (2014) stated that the projected change in rainfall pattern will have a significant impact on the growing season, mainly on the onset, cessation and length of the growing season. This makes climate variability and changes the main driver of agricultural production and food

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[4] The World Bank Group brief accessed online 13 September, 2019 at https://www.worldbank.org/en/topic/agriculture/brief/the-west-africa-agricultural-productivity-program

security in SSA due to high sensitivity and exposure of rainfed agriculture to climate. Thus, variability in rainfall pattern through onset, length of growing season, cessation and temperature may lead to a significant change in agricultural production. For example, the decline in mean yield of cereal production is projected over SSA due to the impact of climate change (Schlenker & Lobell, 2010; Lobell, Schlenker & Costa-Roberts, 2011). Furthermore, Roudier et al. (2011) project a decrease of up to 20% in the production of staple crop over the different regions of SSA. In addition, climate change impacts through extreme events as been reported to leads to destruction of agricultural production and crop yield via soil erosion, decrease in rainfall and agricultural drought (see Grolle, 1997; Tarhule & Woo, 1997; Hountondji & Ozer, 2011; Paeth et al., 2011; République du Bénin, 2011; Sighomnou et al., 2013; World Meteorological Organization Report, 2015). However, despite the impact of climate change over the region, increasing warming may lead to deviation in historical climate variability has been projected globally and sub-Saharan West Africa as one of the hot spots (Mora et al., 2013). This projected further warming will exacerbate the challenge of food security in the region. Thus, it will be important to examine how this may affect agricultural production and food security over West Africa.

1.5 The Concept of Departure in Cropping system (Crop-climate Departure)

1.5.1 What is Climate Departure?

Future climate is projected to be unprecedented in comparison to the present-day climate over the next 50-100 years (Hawkins & Sutton, 2012; Mora et al., 2013). Many studies have shown with evidence an increasing trend in the earth warming beyond natural trends since mid-19th Century (Rosenzweig et al., 2007; Hansen et al., 2012, Screen & Simmonds, 2010; IPCC, 2013). An increase in global mean temperature of about 0.8^{o}C above pre-industrial period has already recorded while a further increase between 1.5 - 4^{o}C is projected in the near future (World Bank Report., 2010; IPCC, 2013). Some refer to such an unprecedented increase in global mean temperature as climate departure (see Mahlstein, Daniel & Solomon, 2013; Mora et al., 2013). Different definitions and terminologies have been used to describe climate departure in the literature. For example, Mahlstein, Daniel & Solomon (2013) as a change in the regional climate zones leading to a major alteration in the local climate due to global warming such as shift or change in the Köppen-Geiger climate classification over a location. Another study also described it as a shift in the present agro-ecological zone/classification due to the spatio-temporal changes in precipitation and temperature over a region in future climate (Kurukulasuriya & Mendelsohn, 2006; Travis, 2016). Further Mora et al. (2013) defined climate departure as when crossing a threshold that current climate extreme events becomes a normal event in the future climate. In addition, it is referred to as an abrupt shift in climate over a region due to the increasing global mean temperature (Drijfhout et al., 2015).

In addition, Figure1.4 further describes climate departure as defined by Mora et al. (2013) as a time when the climate of an area continuously moves outside the range of historical variability or the global mean temperature. From the above definitions, climate departure can simply be described as the transition of a climate regime (evident via a remarkable change in mean and variance) of an area from a past climate to new climate due to increasing greenhouse gas concentration. In this thesis the above definition of climate departure is extended into the agricultural context to arrive at the concept of crop-climate departure based on the crop-climate relationship.

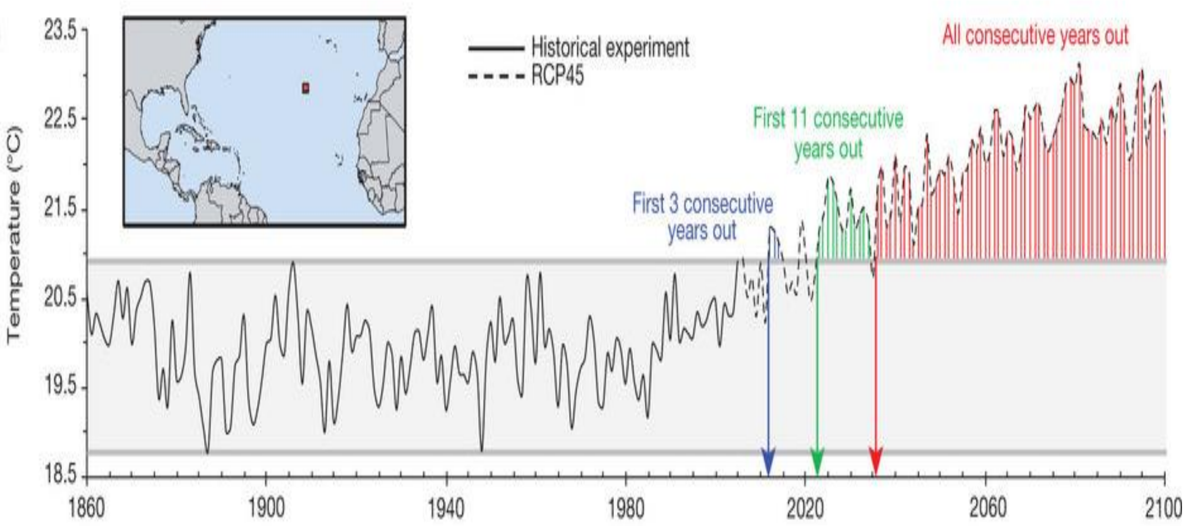

Figure 1.4: Mean annual temperatures of an example grid cell (small square on map) exceed historical climate bounds (grey area) for three consecutive years starting in 2012 (blue arrow) and for 11 consecutive years after 2023 (green arrow); after 2036 (red arrow) all subsequent years remained outside the bound (data from GFDL-ESM 2D) (Mora et al., 2013)

1.5.2 Crop-climate relationship

Agriculture (e.g. rainfed subsistence) is highly dependent on climate with increased limitation on the cropping mechanism and adaptation to its variability and change. This dependence often affects socio-economic development both at household (smallholder farmers) and national level. Crop growth and yield are determined by numerous factors including weather, climate, soil characteristics, management, pest/disease etc. Of all these factors, climate is recognised as the most determinant factor and remains the main driver of the agricultural system and crop growth, especially under rain fed agriculture (Ramirez-Villegas, Jarvis & Läderach, 2013). However, while some of these factors can be controlled, climate cannot. This is due to the increasing greenhouse gas emissions that has resulted in a projected unprecedented future climate with a deviation from the historical mean climate, called climate departure (Hawkins & Sutton, 2012; Mora et al., 2013) The projected climate departure raises concerns and the questions on the need to anticipate when, where and how climate departure may influence cropping system in a way that cannot be coped with or manage. This provides motivation to understand crop thresholds and the best possible conditions for a crop under a given climate.

1.5.3 Crop-climate Threshold

Crop response to the climatic environment (i.e. crop-climate threshold) determines the magnitude of impact on growth, development and yield (Porter & Semenov, 2005; Solomon et al., 2007). The extent of variations in crop yields largely depends on each crop and its environmental requirements (Porter & Semenov, 2005). Temperature and rainfall are important climate variables used in determining the nature of climate change and departure at different scales (sub-continental to global) (Cong & Brady, 2012; Mastrandrea et al., 2015). These two climate variables have a significant effect on crop growth suitability and yield (Abbate et al., 2004; Medori et al., 2012). While rainfall affects the crop growth and production in relation to its photosynthesis activities and leaf area, temperature affects the length of the crop growing season (Olesen & Bindi, 2002; Cantelaube & Terres, 2005) .

Identification of temperature thresholds is the basis for assessing extreme temperature-related risks on crop production (Luo, 2011), as crops are vulnerable when these thresholds are reached and exceeded (Challinor et al., 2005; Porter & Semenov, 2005; Thornton et al. 2011). Therefore, the impact on crop growth, development and yield when these climate thresholds are reached may be thought of as a crop-climate threshold. The crop-climate thresholds are crop dependant as each crop exists within particular environmental requirements (Solomon et al., 2007). For food security in a changing and shifting climate, it is highly pertinent to investigate and identify the crop-climate thresholds (crop suitability thresholds) for crop yield under future climate and also the timing of these changes (i.e. crop-climate departure), especially when dealing with vulnerable regions like West Africa with low adaptive capacity.

1.6 Motivation for study

Future climate change is projected to affect food security. Niang et al., (2014) in the fifth IPCC assessment report revealed that Africa, one of the most vulnerable continents owing to its low adaptive capacity, has suffered significantly from the changing climate with detrimental consequences on food production. Moreover, the future climate could further aggravate the current risks of the decrease in food production and introduce new ones (Mora et al., 2013). In addition, the impact of 1.5-2.0°C global warming is projected to be more pronounced in tropical region like West Africa owing to its with high exposure and low adaptive capacity to climate change impact (Schleussner et al., 2016). However, little understanding exists about the timing of crop-climate departure from historical trends and especially those instances that could affect crop growth suitability and planting season in West Africa in the future. There is a need to understand and predict the timing of crop-climate departure(s) from historical variability and further investigate its impact on crop suitability growth and planting season over West Africa. This will help in the urgency of implementing adaptation responses to the impacts of crop-climate departure on crop growth suitability and planting season in future climate over the region and to inform policymakers on the appropriate adaptation response.

1.7 Aim and objectives

1.7.1 Aim

This research investigates the time when crop-climate thresholds are reached in the future called crop-climate departure. Hereafter, the concept of crop-climate departure is applied to examine future changes in crop suitability and planting season over West Africa. Hence, the aim of this research is to investigate the spatio-temporal effects of projected climate on future crop suitability over West Africa.

1.7.2 Objectives

The aim of this research will be achieved through 3 sets of objectives. Therefore, the objectives of this research are to:

- define crop–climate departure in West Africa for improved understanding of the timing of future changes in crop suitability

- determine the projected impact of crop-climate departure on spatio-temporal characteristic of crop suitability and planting season over West Africa

- investigate the impact of the projected Global Warming Levels, GWLs (1.5, 2.0 and 3.0) on crop suitability and planting season over West Africa.

1.8 Research Questions

The objectives of this research shall be achieved through the following questions:

- What is crop-climate departure and how do we assess the impact on crop suitability changes over West Africa?

- What is the projected impact of crop-climate departure on spatio-temporal characteristic of crop suitability and planting season over West Africa?

- How will the projected Global Warming Levels, GWLs (1.5, 2.0 and 3.0) influence Crop suitability and Planting season over West Africa?

The concept of crop-climate departure is not trivial as it entails addressing the interaction between the climate and cropping system which may not be linear (Ramirez-Villegas, Jarvis & Läderach, 2013)**.** Crop-climate departure which involves the interaction between the climate system (climate departure) and changes in crop suitability threshold is not simply linear as crop departure is not necessarily dependent on climate departure alone.

This is because the process also involves other biophysical factors such as crop thresholds, soil, environmental factors other than climate alone. For example, a departure in climate regime is not necessarily related to a departure in cropping system. At the same time a cropping system could radically change as a response to a marginal climate change.

Consequently, to define the concept of crop-climate departure, appropriate methods and technique suitable for such interaction must be used. Thus, in this study, a combination of methodologies that involves both climate and crop model simulations were used. For instance, an index that gives an indication of the year when a climate variable exceeds the bounds of historical variability for a location was developed by Mora et al. (2013) to describe timing of projected climate departure globally. This has been used to define climate departure as unprecedented increase in global mean temperature and the identify the time of deviation from historical variability across the globe (see Mahlstein, Daniel & Solomon, 2013; Mora et al., 2013). Several crop models have been developed with varying strengths and limitations in their applications. The Ecocrop model developed by Hijmans (2001) has been widely used. Studies have shown the model to be reliable in identifying and understanding crop suitability spatial distribution.(see Ramirez-Villegas, Jarvis & Läderach, 2013). A good advantage of employing a combination of models is that such methods does not lie only in their individual capability but also in how their combination can be employed to define the concept of crop-climate departure. Thus, this research employs the combination of different methods in tackling the objectives of this study.

The use of this different time period for chapter 3 and 4 is to understand the impact of the concept of crop-climate departure across timescale, from near future to end of century over West Africa while in chapter 4 it was to evaluate the impact of the different global warming levels on the key crops over the region to aid adaptation. Furthermore, we used different time-horizon and global warmings levels in chapters 3 and 4 respectively to provide information on the impact of crop-climate departure (CCD) on crop suitability and planting season for planning and adaption strategies owing to the high exposure and low adaptive capacity of the region to increasing global warming. The same 10 CMIP5 GCMs ensemble models were used for the analyses of Chapters 3 & 4. We use RCA4 in the two studies being the only RCM in the CORDEX experiment that downscale the 10 CMIP5 GCMs. Statistical and trend analyses were also employed to examine the robustness and trend of change. Further details about the station and simulation data, Ecocrop and analysis are discussed in the data and methodology section of chapters 2-4 for each objective.

1.9 Thesis outline

The thesis is structured in five chapters but chapters 2-4 follows a journal article format. It is worth stating that the first and second chapter of the dissertation has been published and the fourth is under review. Each article includes an introduction where appropriate literature is discussed. For coherence, whenever a result is referred to in the previous chapter, it will be cited according to the article reference.

Though the chapters are individually written, they all feed into a broader scope of my research dissertation of defining and understanding the spatio-temporal characteristics of crop departure in projected climate in West Africa. Each article builds on the previous result in addressing these specific questions.

Chapter 1 provides background and an introduction of the study. It presents the structure, the aim and objectives of the thesis.

Chapter 2 defines the concept of crop-climate departure as a crop realisation of climate departure from historical variability. This chapter explores the definition of crop-climate departure and employs the concept to characterize the suitability of different crops across three weather stations which are a representation three AEZs of West Africa. This chapter addresses objective 1.

Chapter 3 assesses the future impact of climate departure from historical variability on crop suitability and planting month over West Africa. This chapter applies and employs the concept of crop-climate departure on five different crop types to highlights how climate departure might influence the suitability and planting date of the different crop. Recognising the consequent impact of climate departure over the region, the chapter highlights the sensitivity and trend of each crop type in terms of suitability and period of planting for the crops and its impact on socio-economy of the region and trade. This chapter addresses objective 2.

Chapter 4 describes projected changes in suitability and planting across three Global Warming Levels, GWL1.5^{o}C, GWL2.0^{o}C and GWL3.0^{o}C. The chapter highlights the importance of recognising and limiting global warming to less than 1.5^{o}C to improve food security over West Africa. This chapter, therefore, addresses objective 3.

Chapter 5 reflects on previous chapters and summarises the main findings. It then synthesises the research findings and constructs emerging conclusions about crop-climate departure. Finally, it proposes future work to further consolidate and advance knowledge in this study area.

This next chapter prepares the stage for the PhD study by defining the concept of crop-climate departure as a crop realisation of climate departure from historical variability. This chapter explores the definition of crop-climate departure and employs the concept to characterize the suitability of different crops across three weather stations which are a representation three AEZs of West Africa. This chapter addresses objective 1.

CHAPTER 2

Defining Crop–climate Departure in West Africa: Improved Understanding of the Timing of Future Changes in Crop Suitability

What is crop-climate departure and how do we assess the impact on crop suitability changes over West Africa?

Specific Questions

How do we define crop-climate departure?

How do we characterize crop departure using the concept of crop-climate departure?

What are the projected changes of crop suitability and planting across the three selected stations across the West African AgroEcological Zones?

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Abstract

The future climate is projected to change rapidly with potentially severe consequences for global food security. This study aims to improve the understanding of future changes in the suitability of crop growth conditions. It proposes a definition of crop realization, of the climate departure from recent historical variability, or crop–climate departure. Four statistically downscaled and bias-corrected Global Climate Models (GCMs): CCCMA, CNRM5, NOAA-GFDL, and MIROC5 performed simulations for the period 1960–2100 under the Representative Concentration Pathway RCP8.5 scenario to compute 20 year moving averages at 5-year increments. These were used to drive a crop suitability model, Ecocrop, for eight different crops across the three Food and Agriculture Organizations (FAO) AgroEcological Zones (AEZs) of West Africa (Guinea, Sahel, and Savanna). Simulations using historical climate data found that all crops except maize had a suitability index value (SIV) ≥ 0.50 outside the Sahel region, equivalent to conditions being suitable or strongly suitable. Simulations of future climate reveal that warming is projected to constrain crop growth suitability for cassava and pineapple in the Guinea zone. A potential for the northward expansion of maize is projected by the end of the century, suggesting a future opportunity for its growth in the southern Sahel zone. Crop growth conditions for mango and pearl millet remain suitable across all three AEZs. In general, crops in the Savanna AEZ are the most sensitive to the projected changes in climate. The changes in the crop–climate relationship suggests a future constraint in crop suitability, which could be detrimental to future food security in West Africa. Further studies to explore associated short- and long-term adaptation options are recommended.

Keywords: Climate-departure; Crop–climate departure; Crop suitability; Ecocrop; Food security; West Africa

2.1. Introduction

The livelihood and economies of most Sub Saharan African (SSA) countries are driven by rainfed agriculture (Omotosho & Abiodun, 2007; Roudier et al., 2011; Diasso & Abiodun, 2017). About 96% of agricultural lands in SSA are rainfed (World Bank Report., 2009; Roudier et al., 2011). Agriculture employs over 65% of the active labour force of the region, the majority of whom are practicing subsistence rainfed farming (Blein et al., 2008). The agricultural sector is also responsible for 75% of SSA domestic trade (McCarthy, J et al., 2001; World Bank Report., 2013). It adds significantly to the economy of the region by contributing up to 15%–20% to the Gross Domestic Product (GDP) (Benhin, 2008; World Bank Report., 2009; Schlenker & Lobell, 2010; Roudier et al., 2011). In 2000, about 80% of the cereals consumed in SSA were domestically produced locally (World Bank Report., 2009). However, West Africa has been identified as one of the most vulnerable regions of the world owing to its low adaptive capacity and a fast-growing population, with many citizens whom are faced with malnourishment (Slingo et al., 2005; Abatan, 2011; Roudier et al., 2011; Knox et al., 2012). An adverse change in the climate over West Africa, both spatially and temporally, coupled with inadequate institutional and economic capacity to cope or adapt to its impact could become a determinant threat to agricultural production. Thus, food security and socio-economic activities across the region may be affected (Grolle, 1997; Tarhule & Woo, 1997; Challinor et al., 2007; Paeth et al., 2011; Rippke et al., 2016).

Climate strongly affects rainfed agriculture with direct consequences on food security (Pretty, Morison & Hine, 2003; Hansen, Sato & Ruedy, 2012; Sultan & Gaetani, 2016). This has resulted in different studies focusing on the response of crops and agriculture to the impact of increased greenhouse gas emissions across different regions of SSA owing to malnutrition and the need to improve food security (Lobell et al., 2008; Roudier et al., 2011; Knox et al., 2012; Zinyengere, Crespo & Hachigonta, 2013; Sultan & Gaetani, 2016). Extreme changes in climate are projected to increase (IPCC, 2013), translating into increased occurrence of both droughts and floods, which already account for 70% of economic losses through soil erosion and drought in West Africa (World Bank Report., 2010; Egbebiyi, 2016). The fifth Intergovernmental Panel on Climate Change (IPCC) assessment reported a projected warming across the different seasons over SSA to be larger than the global annual mean temperature increase (IPCC, 2013). The projected warming (1.5–4°C by 2100) is likely to affect the agricultural sector by a reduction of up to 50% in crop yield and 90% in revenue across the region by the end of the century (IPCC, 2013; World Bank Report., 2013). However, this may be further aggravated in regions like West Africa where the climate is warming faster and may lead to a radical departure from the regions' historical variability (Challinor et al., 2013) .

The definition of departure varies across disciplines. Broadly, a departure refers to a deviation or variation from a norm, standard rule, or behavior. It can also mean starting out on a new course of action. In climate science, climate departure can be defined as a shift in the climate pattern of a region outside the range of historical variability and may be described in terms of mean local temperature exceeding historical highs (Hawkins & Sutton, 2012; Mora et al., 2013; Vermeulen et al., 2013). Mora et al. (Mora et al., 2013) described climate departure as the year in which the average temperature of the coldest year after 2005 was warmer than the historic hottest year at a given location. Here we have defined climate departure as a deviation from the historical mean and/or variance of the local climate of an area or region induced by global warming (McCarthy et al., 2002).

The projected global warming level and the timing over the continent may intensify the impact of climate change on crop suitability. Severe temperature fluctuations and other extreme weather conditions such as droughts and floods may also threaten crop suitability thresholds. They vary spatially, resulting in potential yield declines where crop growth conditions are currently suitable and possible yield increases in other areas (Porter & Semenov, 2005; Lobell, Schlenker & Costa-Roberts, 2011). Challinor et al. (Challinor et al., 2014), for instance, projected a future decline in crop yield of up to 5% for every degree of warming above the historical level in Africa.

Given the current state of climate departure research and the direct impact of climate on crop production systems (particularly rainfed), we are interested in the climate change induced crop realizations when climate departs from historical variability, which we term crop–climate departure. This study explores and proposes the information value of a comprehensive definition of crop–climate departure as "a departure from historical crop suitability threshold, whether in terms of variability, mean or both, due to warming of the climate over a location both in space and time resulting from climate change whether of radical climatic nature or not”. This is in the context of recent climate historical variability and future climate projections using three West African weather stations, within three Food and Agriculture Organizations (FAO) Agro-Ecological Zones (AEZs). Mora et al. (2013) suggests that West Africa will experience a climate departure with a mean temperature about two decades (2029) earlier than the global mean temperature (2047). Thus, we use the region as our proof of concept and to examine any likely large-scale crop suitability consequent changes the region may already be experiencing. Section 2 describes the data and methods used. Results from the study are outlined in section 3. The discussion of the results and concluding remarks and recommendations for future are in Sections 4 and 5, respectively.

2.2. Data and Methods

2.2.1. Study Area

The demonstration area for this work is West Africa (Figure 2.1), which has rainfed agriculture as its mainstay economy. It is located at latitude 4-20°N and 16°W-20°E. The region comprises of 15 countries namely Benin, Burkina Faso, Gambia, Ghana, Guinea Bissau, Guinea, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. It is divided into three AEZs: Guinea (4-8°N), Savanna [8-12°N], and the Sahel (12-20°N) (Abiodun et al., 2012; Egbebiyi, 2016). The temperature increases to the north of the region, while precipitation increases towards the south (Abiodun et al., 2012; Egbebiyi, 2016; Klutse et al., 2018). The Sahel zone is the warmest and driest, while the Guinea zone is the coolest and wettest of the three AEZs in West Africa. The climate of the region is mainly controlled by the West African Monsoon (WAM) which accounts for about 70% of the annual rainfall (Abiodun et al., 2012; Sultan & Gaetani, 2016). The WAM is an important and dynamic characteristic of the West African climate during the summer period (Janicot et al., 2011). It is produced from the reversal of the land and ocean differential heating and dictates the seasonal pattern of rainfall over West Africa between latitudes 9° and 20°N. The WAM is characterized by winds that blow south–westerly during the warmer months (June–September) and north-easterly during the cooler months (January–March) of the year (Janicot et al., 2011; Egbebiyi, 2016). It is the major system that influences the onset, variability, and pattern of rainfall over West Africa (Omotosho &

Abiodun, 2007; Nicholson, 2013). This affects rainfall producing systems with an impact on rainfed agriculture, which influences crop growth suitability and consequently food production in the region.

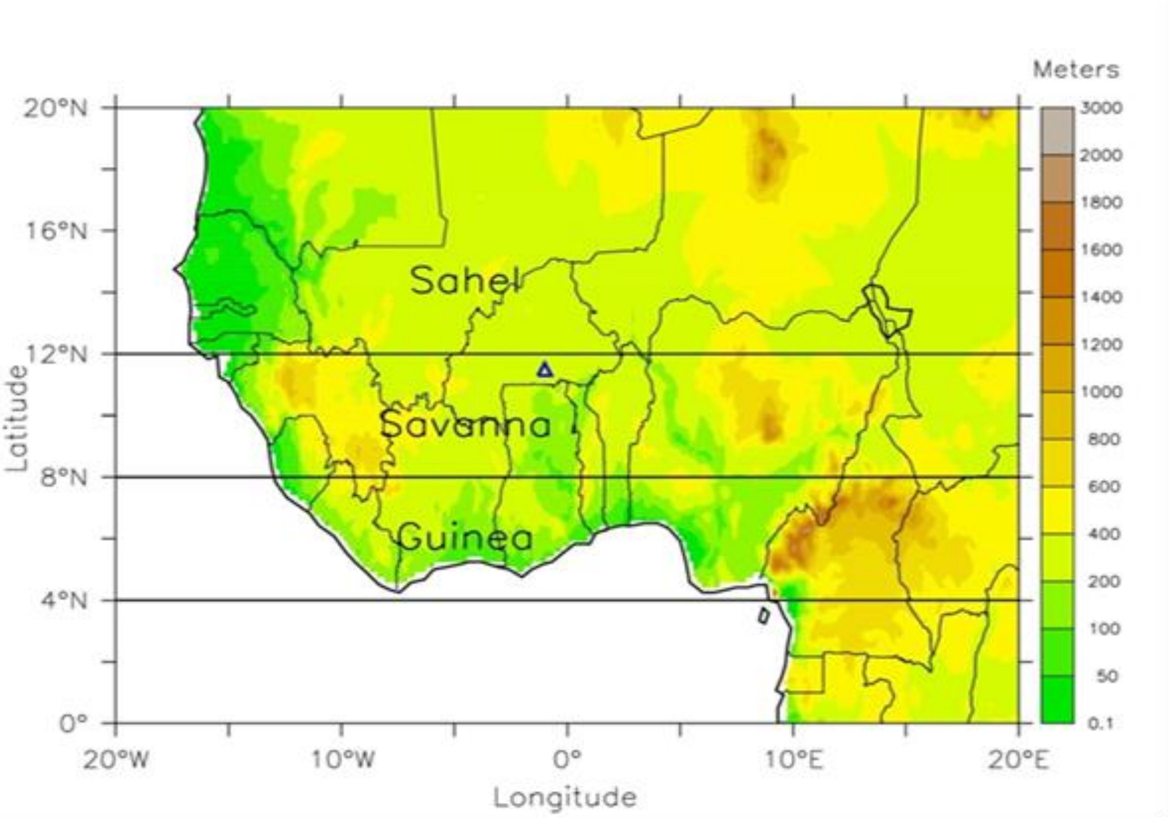

Figure 2.1: West African topography and the three main climatic zones from Food and Agriculture Organizations (FAO)- Agro-ecological zones (AEZs): the Guinea, Savanna, and Sahel zones (Abiodun et al., 2012; Egbebiyi, 2016).

2.2.2. Data

This study used three dataset types: observational weather station data, climate modelled data (statistically downscaled at the weather station level), and crop suitability data. The observed weather station data validated the mean monthly temperature and total monthly rainfall across the three AEZs. The crop suitability time series were simulated based on output from the Ecocrop suitability model (Hijmans et al., 2001) and the modelled climate data.

2.2.2.1. Climatic Variables

Temperatures (minimum and mean) and rainfall are important climate variables used in determining the impacts of climate change at subcontinental to global scales (Cong & Brady, 2012; Mastrandrea, Mach, Barros, Bilir, Dokken, Edenhofer, Field, Hiraishi, Kadner, Krug, Minx, Madruga, et al., 2015). These two climate variables also have a significant effect on crop yield (Medori et al., 2012). While rainfall affects the crop production in relation to its photosynthesis activities and leaf area, temperature affects the length of the crop growing season (Olesen & Bindi, 2002; Cantelaube & Terres, 2005). For this study, we used mean monthly minimum temperature (t-min) and mean monthly temperature (t-mean) and total monthly precipitation (prec.) of weather station data from Tabou, Ivory Coast; Sokode, Togo; Magaria, Niger. These weather stations each lie in three AEZs, Guinea, Savanna, and Sahel, respectively over West Africa. We only used one station for each AEZs based on the available data at the time of the analysis and being the most suitable for the study objective. For the study, we used four statistically downscaled and bias corrected Global Climate Models (GCMs) in our analysis (CCCMA, CNRM5, GFDL, and MIROC) under a high-end climate change emission scenario (no adaptation), RCP8.5 (See Table 2.1 for a description of the model). The GCMs were statistically downscaled using the Conditional Interpolation method as described in Hewitson and Crane (Hewitson & Crane, 2005). The Conditional Interpolation downscaling method calculates the local phase relationships (PMI) for each weather station and each synoptic state combination. The bias relationship (BSI) between the weather station and its surroundings is then calculated. The method estimates the spatial extent of precipitation accurately and derives spatially referenced values representative of the area average. Overall, the interpolation conditioned by the synoptic state appears to better estimate realistic gridded values appropriate for use with model simulation output. For the temperature variable, the conditional interpolation employs the information content of the source data coupled with additional assumptions that may be physically justified (such as lapse-rate effects). The climate data were sourced from the Climate Information Portal (CIP) of the Climate System Analysis Group (CSAG), University of Cape Town (http://www.csag.uct.ac.za/climate-services/cip/). Data from this portal are at the station scale and weather stations in each AEZ are representative of that area.

Table 2.1: List of statistically downscaled and bias corrected GCMs used in the study.

Modelling Institution	**Institute ID**	**Model Name**	**Resolution**
Canadian centre for climate modelling and analysis	CCCMA	CanESM2	2.8° x 2.8°
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifique	CNRMCERFACS	CNRM-CM5	1.4° x 1.4°
National Oceanic and Atmospheric Administration Geophysical Fluid Dynamic Laboratory	NOAAGDFL	GFDL_ESM2M	2.5° x2.0°
Japan agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4° x 1.4°

2.2.2.2. Crop Thresholds to Suitability

The results of field experiments apply globally. A database of crop thresholds that translate into climate suitability has been collected and used in many locations to describe the suitability range of many plant and crop species using prec., t-min, t-mean, and the length of the growing season (Hijmans et al., 2001; Ramirez-Villegas, Jarvis & Läderach, 2013). The climate threshold hosted by FAO dataset was extracted from the "dismo" package of the cran R software (Hijmans et al., 2017) (https://cran.r-project.org/web/packages/dismo/index.html). It was used in computing the climate suitability of each crop evaluated. It is acknowledged that thresholds will vary depending on finer resolution of the species (e.g. different varieties) or location (e.g. different soil, different rain distribution). However, the concept of crop suitability and the general validation of the thresholds makes this a useful tool to assess the impact of climate change and the emergence of novel regional climates on crop suitability over large areas examining the concept of crop–climate departure. The Ecocrop suitability model assessed four broad crop types and eight crops in total: cereals (pearl millet and maize); horticultural crops (tomato and pineapple); root and tuber crops (plantain and cassava) and fruit crops (mango and orange), using Ecocrop. The crop thresholds are listed in Table 2.2.

Table 2.2: Crop growth thresholds for eight crops as generated by the Ecocrop model.

Crop Name	Growing duration (days)	Temperature (°C)				Rainfall (mm)			
		Tmin	Topmin	Topmax	Tmax	Rmin	Ropmin	Ropmax	Rmax
Pearl millet	60–120	12	25	35	40	200	400	900	1700
Maize	65–365	10	18	33	47	400	600	1200	1800
Cassava	180–365	10	20	29	35	500	1000	1500	5000
Plantain	365	16	23	28	38	1000	1300	3000	5000
Pineapple	330–365	10	21	30	36	550	800	2500	3500
Tomato	70–150	7	20	27	35	400	600	1300	1800
Orange	180–365	13	20	38	38	450	1200	2000	2700
Mango	150–365	8	24	30	48	300	600	1500	2600

Where Tmin, Topmin, Topmax, and Tmax represents monthly minimum temperature, minimum optimum temperature, maximum optimum temperature, and maximum temperature, respectively; Rmin, Ropmin, Ropmax, and Rmax represents total monthly minimum rainfall, minimum optimum total monthly rainfall, maximum optimum total monthly rainfall, and maximum total monthly rainfall, respectively; optimum values represent the most suitable period for crop planting.

2.2.2.3. Model Description

The Ecocrop model is a crop suitability model. It uses a crop growth suitability threshold dataset hosted by the FAO (Hijmans et al., 2001). It is an empirical model originally developed by Hijmans et al. (Hijmans et al., 2001) and based on the FAO-Ecocrop database (Ramirez-Villegas, Jarvis & Läderach, 2013) (Figure 2.2). The computation of optimal, suboptimal, and non-optimal conditions based on these datasets allows for the simulation of the suitability of crops in response to 12-month climate via t-min, t-mean, and prec. (Hijmans et al., 2001) (Figure 2.2). The Ecocrop model evaluates the relative suitability of crops in response to a range of climates including rainfall, temperature, and the growing season for optimal crop growth. A suitability index is generated as follows: 0 < 0.25 (not suitable), 0.25 < 0.5 (marginally suitable), 0.5 < 0.75 (suitable), and 0.75 < (highly suitable) (Ramirez-Villegas, Jarvis & Läderach, 2013; Hunter & Crespo, 2018). The default Ecocrop parameters were assumed. Although those thresholds may vary with different geographical and/or climatic conditions, previous studies report a close correlation between the Ecocrop model and the climate change impact projections from other crop models (Ramirez-Villegas, Jarvis & Läderach, 2013; Vermeulen et al., 2013; Challinor et al., 2014; Rippke et al., 2016). A paucity of data over regions of interest like SSA limits the validation of these processes (White et al., 2011).

Nevertheless, the method contributes to the demand for regional scale assessment of crop response to future climate projections. The 12 coloured lines observed for the Ecocrop climate suitability simulations in Figure 2 (a) and (b) represents 12 months. Each describes the most suitable conditions for the crop under consideration in any given month. A highly seasonal crop (e.g. maize) has suitable growth conditions for a limited number of months. The conditions for non-seasonal crops are suitable throughout the year. Crops with a growing cycle longer than a year (e.g. pineapple and plantain) are represented by a single 12-month period.

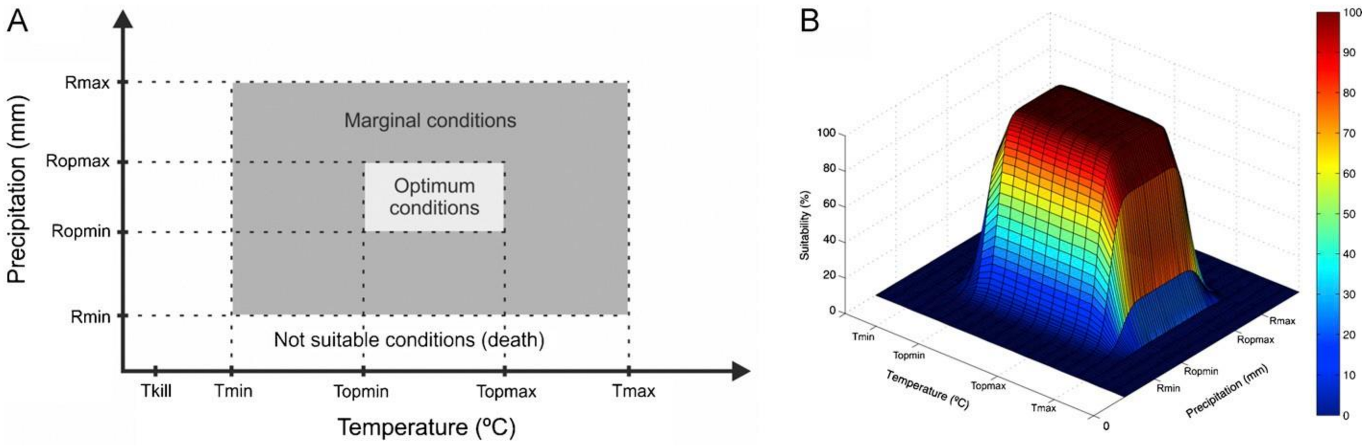

Figure 2.2: (a) two dimensional and (b) three dimensional diagram describing climate thresholds and its translation into crop suitability (Adapted from Ramirez-Villegas, Jarvis & Läderach, 2013)

2.2.3. Method

Four GCMs for the period 1960–2100 under the RCP8.5 scenario computed a 20-year moving average at 5-year time increments. It generated one mean 12-month value per 20-year window period for t-min, tmean, and prec. The mean 12-month climate value informed the crop suitability model, Ecocrop, for each GCM based on the methodologies described in Ramirez-Villegas, Jarvis, and Läderbach (Ramirez-Villegas, Jarvis & Läderach, 2013) for eight crops across the three AEZs of West Africa. The Ecocrop model simulated crop suitability indices characterized the crop–climate relationship and the impact global warming has on this relationship for each AEZ both spatially and temporally for each climate window. The suitability index scores were calculated for a range of climate variables for the period 1980–2000 using observed weather station data. This was used as a baseline to evaluate the downscaled GCM results spanning 1960–2100 at the three West African weather stations. It assessed the crop growth suitability in the zone for past climate conditions in reference to the published literature. Present day climate data was used as the preference for this zone owing to the constraint and paucity of weather station data and this data being the best available data to overlap with the Ecocrop model for the zone in the given study period.

2.3. Results

2.3.1. Evaluation of the GCMs in Simulating Rainfall and Temperature over West Africa

The downscaled climate data was firstly validated with the observed weather station data. Where missing records occurred, the corresponding month in the model's data were removed before computing the relationship between the datasets. Each GCM was correlated with the observed data for prec. and t-mean over the three weather stations, despite some discrepancy in precipitation over the Guinea zone (Figures 2.3 and 2.4). For temperature, the four models were correlated ($r \geq 0.6$) with the observed t-mean across the three AEZs of West Africa with the highest correlation ($r = 0.9$) over Magaria. The models were also correlated ($r \geq 0.6$) with the observed prec. in the Savanna and Sahel AEZs. A moderate correlation ($r \geq 0.3$) with observed weather station data was evident in the Guinea AEZ. This moderate correlation may be due to the low resolution of the GCMs in capturing the total monthly rainfall in the Guinea zone. However, the moderate correlation between the model and station over the Guinea AEZ does not undermine the large-scale vision of this study. The validated GCM data was then input into the Ecocrop model.

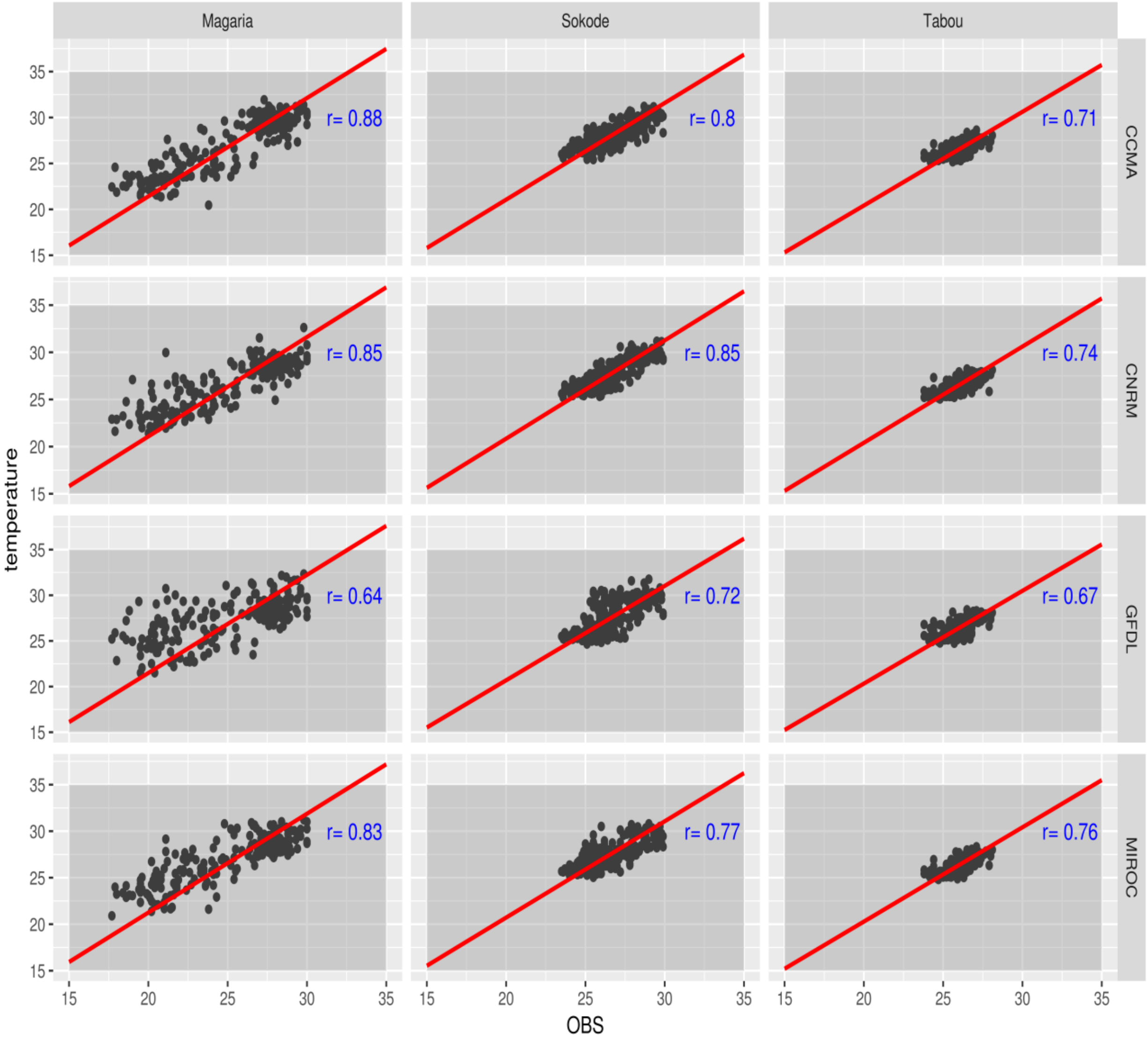

Figure 2.3: Mean monthly temperature (°C) as depicted by station observations and statistically downscaled CMIP5 GCMs (CCMA, CNRM5, GFDL, and MIROC) across the three agro ecological zones, Tabou, Sokode, and Magaria, of West Africa for the period 1980–2000. The top right corner r-values in each panel represent the correlations between the simulated and observed mean monthly temperature.

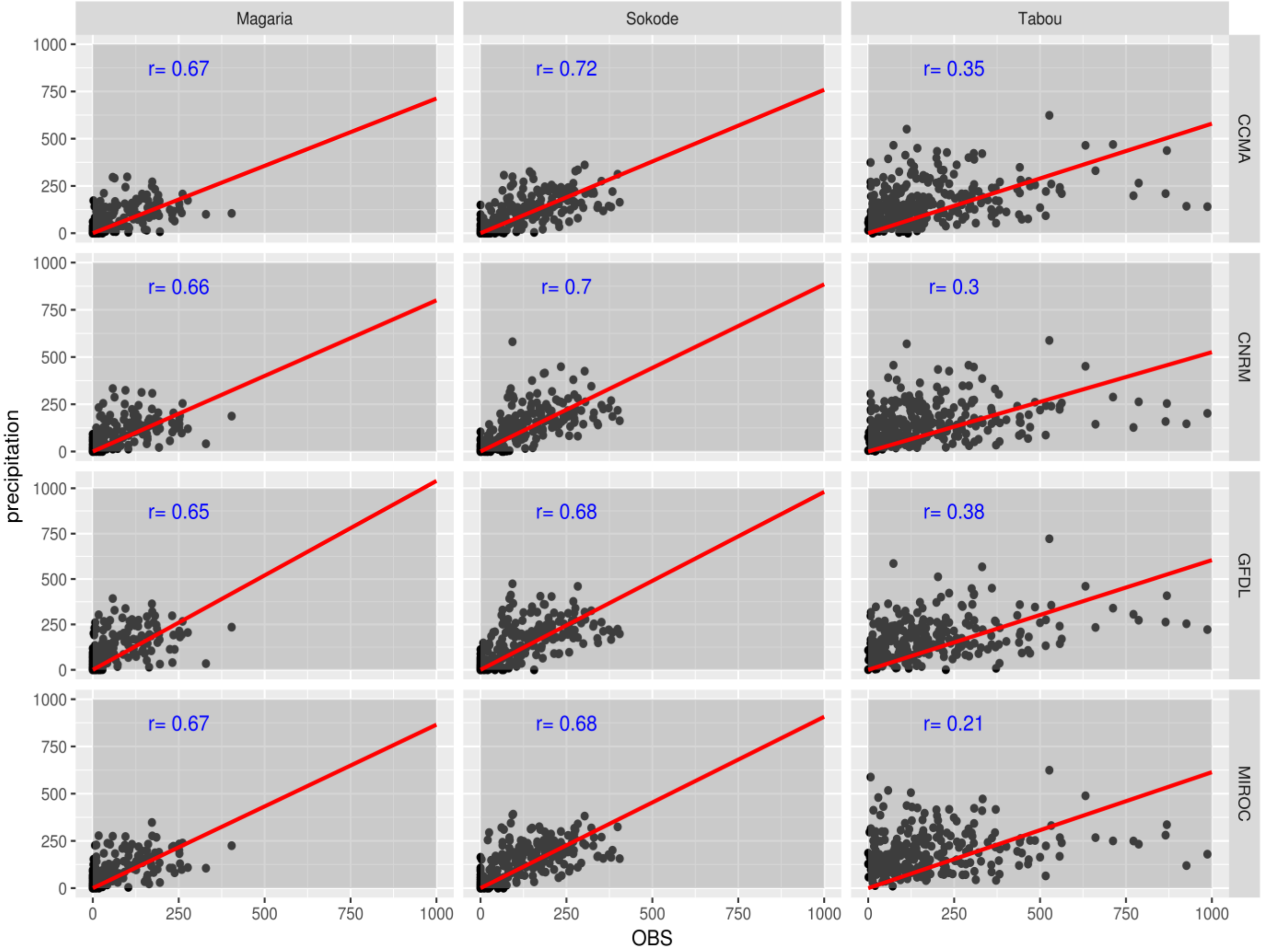

Figure 2.4: Total monthly rainfall (mm/month) as depicted by station observations and statistically downscaled CMIP5 GCMs (CCMA, CNRM5, GFDL, and MIROC) across the three agro ecological zones, Tabou, Sokode, and Magaria, of West Africa for the period 1980–2000. The top right corner r-values in each panel represent the correlations between the simulated and observed mean monthly temperature.

2.3.2. GCMs Representation of AEZs, Seasons, and Suitability over West Africa AEZs

A correlation exists between the Ecocrop suitability model simulated with climate inputs from four GCMs, CCMA, CNRM, GFDL, and MIROC (hereafter Eco-GCMs), although with minor variations in amplitude and time. However, it is worth stating that the variation in simulated suitability by the four GCMs may be attributed to the inter-annual variability of the GCMs or the GCMs parametrization scheme. Nevertheless, Eco-GCMs simulated crop suitability is similar across the three AEZs over West Africa for the eight crops considered in the study. For example, cassava shows a similar suitability pattern across the AEZs (Figure 2.5). It is unsuitable (Eco-CCMA and CNRM) to marginally suitable (Eco-GFDL and MIROC) for cassava crop growth in the Sahel AEZ. In the Savanna AEZ, it is currently highly suitable for cassava, but this is predicted to decline in the future to become marginally unsuitable. The Guinea AEZ suitability for cassava does not change. The variability in crop growth suitability curves may be attributed to the variation in yield and production of cassava across the region due to the impact of climate change, corroborating previous studies (Benhin, 2008; Paeth, Capo-Chichi & Endlicher, 2008).

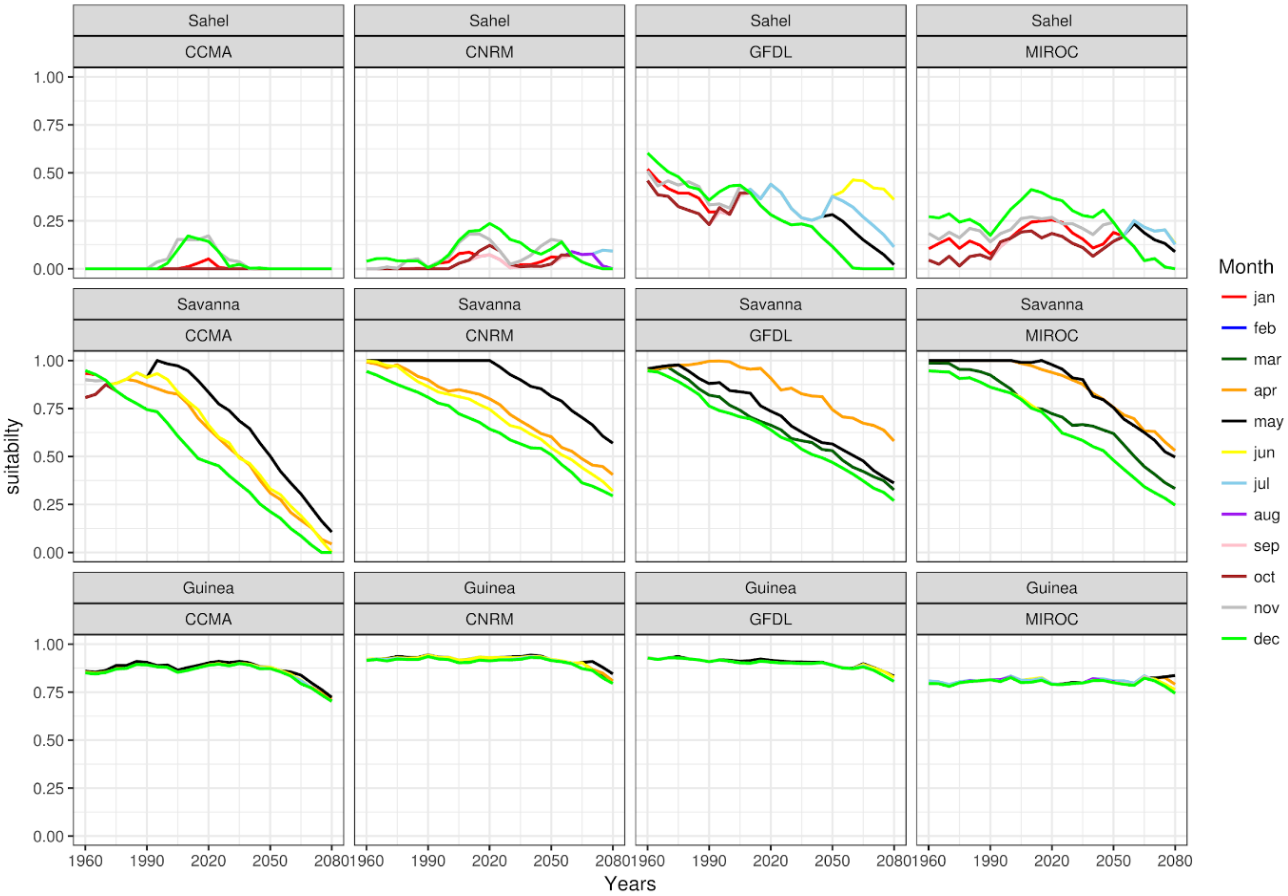

Figure 2.5: Cassava planting month suitability plots in the Guinea, Sahel, and Savanna as simulated by the four GCMs (CCMA, CNRM, GFDL, and MIROC) used as climate inputs into the Ecocrop suitability model.

Variability in the suitability of the month of planting for cassava crops in response to both AEZ and time increment is observed across the GCMs (Figure 2.5). The Guinea AEZ is currently the most suitable AEZ in which to grow cassava and is predicted to remain so. Suitable planting months in the Savanna AEZ as identified by all four models includes April–June and December, however a notable decline is observed, consistent for all four GCMs. Suitability declines from just below 1.0 to below 0.5 by 2050 in most cases. Conditions in the Sahel are presently and remain of low suitability. The simulation of the cassava crop growing season and period of planting across the three AEZs: Guinea (January–July and September–December), Savanna (April–November), and the Sahel (May/June–November) corroborates with previous findings with respect to the planting period and growing season in West Africa (Brown & de Beurs, 2008; Butt et al., 2011; Vrieling, De Leeuw & Said, 2013).

The concept of crop–climate departure allows for a consolidation of climate outputs from an ensemble of four GCMs into simulated crop suitability indices. Despite the marginal scale differences, the four GCMs consistently represent the unsuitability of cassava in the Sahel AEZ, its fast-declining suitability in the Savanna AEZ, as well as the high suitability of the Guinea AEZ. The cassava growing season is 12 months. Due to the predicted decline in the suitability of growth conditions, it is expected that it will become seasonal i.e. the suitability remains subject to appropriate seasonal planting, but conditions will then become unsuitable in the Savanna AEZ. Farmers will be required to adapt their practices in this AEZ. There is no reason at this stage to prefer one over the other GCMs, thus we use GCMs ensemble data as future climate scenario to simulate crop suitability in the subsequent sections of the paper plots of crop suitability from the Eco-GCMs. As seen from Figure 2.5, the ensemble suitability plots give a good representation of the Eco-GCMs model simulated suitability across the AEZs over West Africa. It shows the non-suitability of cassava in the Sahel, the fast-declining suitability and the observed seasonality in the Savanna AEZ, and high suitability in the Guinea zone. Thus, the crops ensemble suitability simulations are used in the results and discussion in the subsequent sections of this paper. A summary of the crop suitability index values is given in Table 2.3.

Table 2.3: Ecocrop simulated crop Suitability Index Value (SIV) for the eight (8) different crops across the three Agro-ecological zones (AEZs) of West Africa.

Years	**1960**			**1990**			**2020**			**2050**			**2080**		
Crops/AEZs	**GUI**	**SAV**	**SAH**	**GUI**	**SAV**	**SAH**	**GUI**	**SAV**	**SAH**	**GUI**	**SAV**	**SAH**	**GUI**	**SAV**	**SAH**
Cassava	>0.75	>0.75	<0.25	>0.75	>0.75	<0.25	>0.75	>0.50	<0.25	>0.75	≤0.50	<0.25	>0.75	<0.50	<0.25
Maize	≤0.50	≥0.50	<0.75	≤0.50	≥0.50	0.50–0.75	<0.50	>0.50	>0.50	<0.50	>0.50	>0.50	<0.50	>0.75	>0.75
Mango	0.50–0.75	1.00	≤0.75	0.50–0.75	1.00	≤0.75	0.50 – 0.75	>0.75	>0.75	0.50 – 0.75	>0.75	0.75	0.50 – 0.75	>0.75	0.75
Orange	>0.75	>0.75	<0.25	>0.75	>0.75	<0.25	>0.75	>0.75	>0.25	>0.75	0.50 – 0.75	<0.25	>0.75	0.50 – 0.75	<0.25
Pearl millet	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50
Pineapple	>0.75	>0.75	<0.5	>0.75	<0.50	<0.50	>0.75	>0.75	0.50	>0.75	0.50 – 0.75	<0.50	>0.75	<0.50	<0.50
Plantain	1.00	>0.75	0.00	1.00	>0.75	0.00	>0.75	<0.75	0.00	>0.75	<0.75	0.00	>0.75	<0.50	0.00
Tomato	>0.75	>0.25	<0.5	>0.75	>0.50	<0.5	>0.75	>0.50	<0.5	<0.75	<0.50	<0.25	<0.75	<0.50	<0.25

GUI – Guinea AEZ, SAV – Savanna AEZ, SAH – Sahel AEZ

Ecocrop suitability Index: 0.0–0.25—Unsuitable/No suitability, 0.25–0.50—Marginally suitable, 0.50–0.75—Suitable, 0.75–1.00—Highly suitable

2.3.3. Crop Suitability Response with Past Climate

Past climatic conditions (1960–2010) indicate that a crop growth suitability gradient existed from south to north across the three AEZs for each crop type considered. A Suitability Index Value (SIV) (0.75–1.00) is observed for each crop type in the Guinea and Savanna zones throughout the year (Figure 2.6 and 2.7). An exception is the cereal crop maize. Maize is marginally suitable (0.25–0.50) in the Guinea AEZ, suitable (0.50–0.75) for planting in May, September, and December in the Savanna AEZ, and January–February in the Sahel AEZ. The suitability increases (0.75–1.00) in 2050 (Figure 6). In the Sahel AEZ, other cereals and mango are suitable (above 0.50). Crop growth suitability increased for pineapple crops in this AEZ.

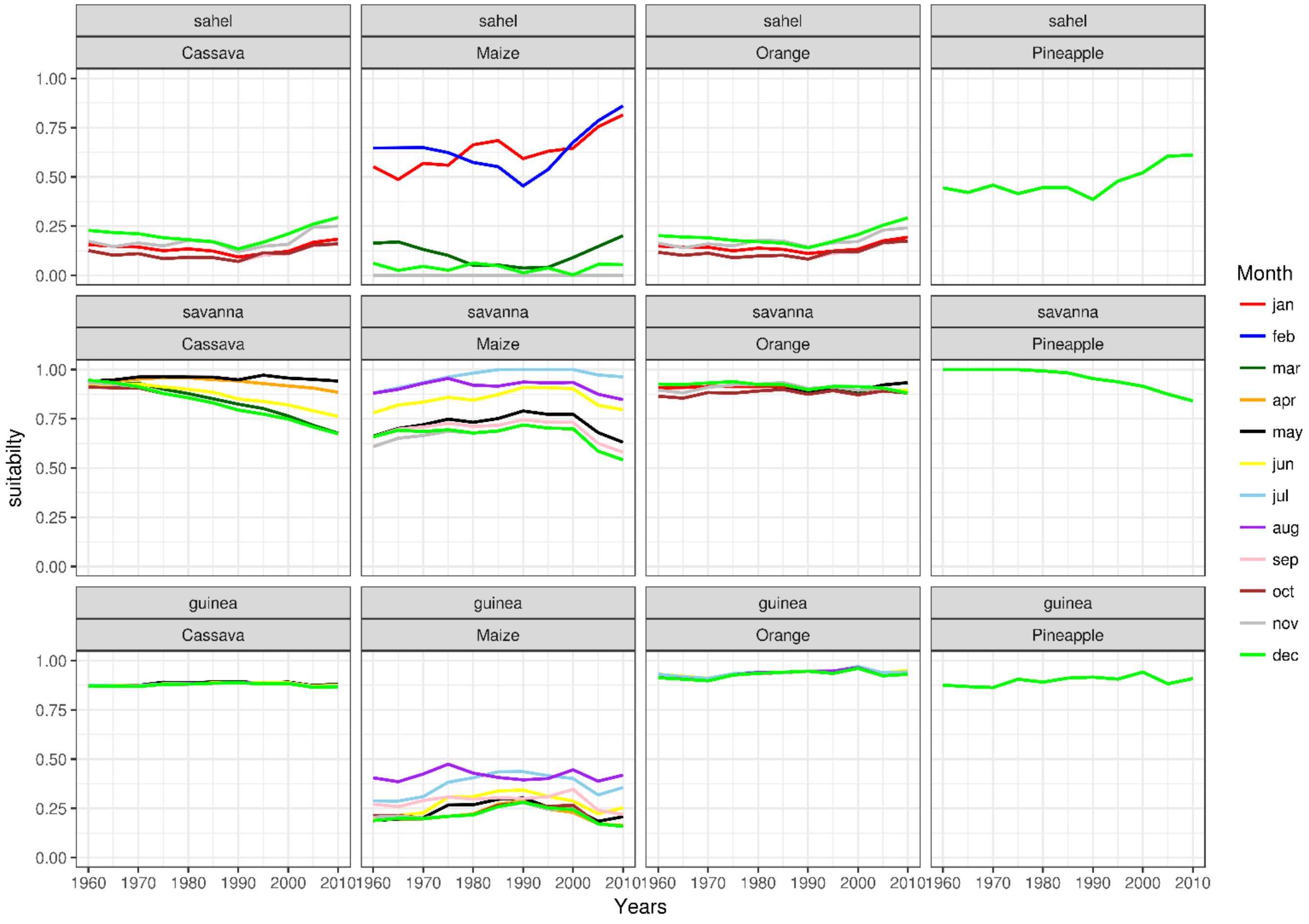

Figure 2.6: Ensemble crop suitability plots in the past climate (1960–2010) for cassava, maize, orange, and pineapple.

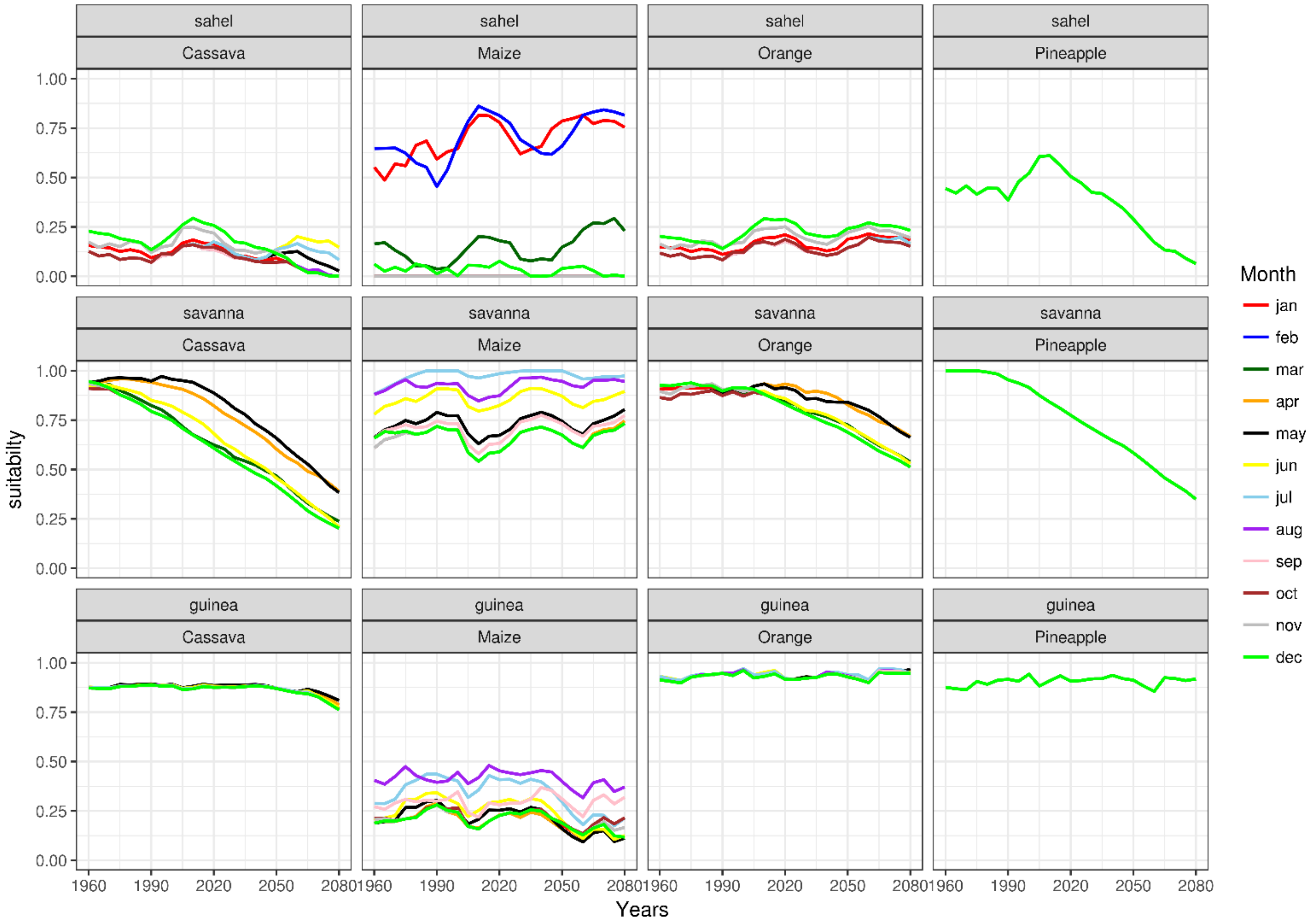

Figure 2.7: Projected model ensemble suitability over West Africa between 1960–2100 for cassava, maize, orange, and pineapple.

The Ecocrop simulations of crop growth suitability for the period 1960–2010 and the crop types evaluated corroborate previous findings with respect to the type of crops actually grown in the region. Cereals and root and tuber crops were the principal agricultural commodities in the region during this period (Dixon, Gulliver & Gibbon., 2001; Alliance for Green Revolution in Africa (AGRA), 2014). Cassava and maize crops demonstrated modest yield increases of 6.3 to 10.3 and 1.1 to 1.8 tons ha^{-1}, respectively in the last 40 years (Bationo et al., 2006; Alliance for Green Revolution in Africa (AGRA), 2014). The historical suitability of growth conditions for maize across the region (although marginal in the Guinea zone) highlights its importance as a staple crop here, accounting for almost 20% of the calorie intake for the population of West Africa (FAOSTAT, 2014; Sultan &

Gaetani, 2016). The large area grown and high yield of pearl millet between 1960 and 2010 can be linked to the high suitability indices across the AEZs of West Africa over this period, contributing considerably to the livelihoods and economies of the countries in this region (Mason, Maman & Palé, 2015; Singh et al., 2017). Increased productivity has also been witnessed in crops such as orange, mango, pineapple, and tomatoes in the last 40 years, again correlating with the high crop growth suitability indices identified for these crops (Barrett & Browne, 1996; TAKANE, 2004). Given the importance of these crops in the regional economy, a key question is, how is the projected change in climate predicted to impact on the crop growth suitability of these key crops in West Africa?

2.3.4. Projected Changes in Crop Suitability and Time of Planting over West Africa

The projected increase in global temperature is predicted to have a varied impact on crop growth suitability in West Africa (Figures 2.8 and 2.9). The Guinea AEZ remains largely unchanged with respect to crop growth suitability, evidently a more resilient area. Drastic declines are predicted for multiple crops in the Savanna AEZ including for cassava, orange, and pineapple. The main staple crop, maize, remains stable with an SIV of 0.5–1.0. It is interesting to note that the SIV for maize in the Sahel AEZ is projected to increase, shifting from suitable in 2020 to highly suitable by 2050 (Figure 2.7). Conditions for pearl millet will remain highly suitable (Figure 2.9), although the SIV for mango will decline post 2020.

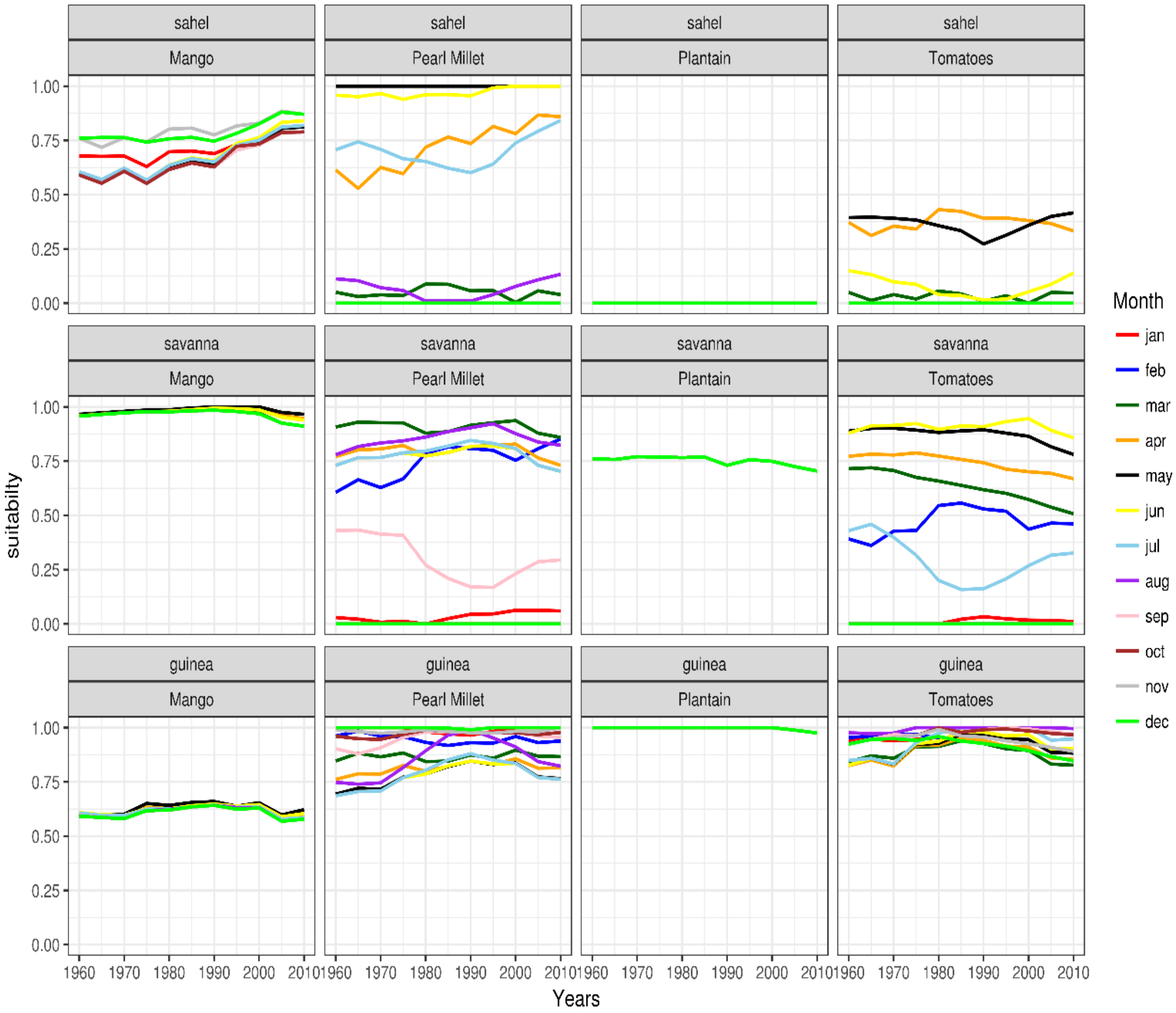

Figure 2.8: Ensemble crop suitability plots in the past climate (1960–2010) for mango, pearl millet, plantain, and tomatoes.

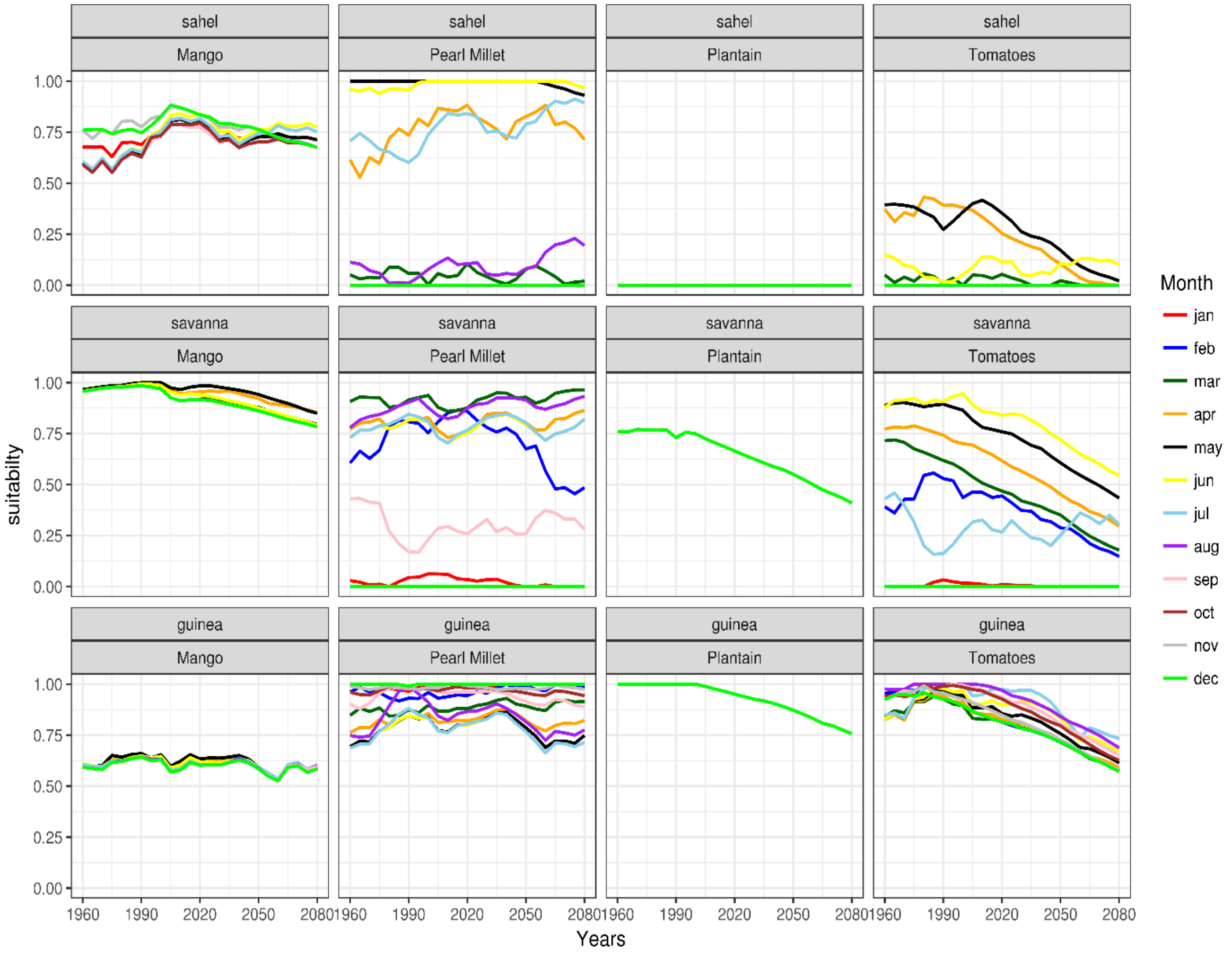

Figure 2.9: Projected model ensemble suitability over West Africa between 1960–2100 for mango, pearl millet, plantain, and tomatoes.

The impact of future warming will affect crop seasonality, i.e. the suitability of the time of planting. For root and tuber crops and cassava, in the months of April and May, they will become marginally suitable for cultivation by mid-century in the Savanna AEZ. Conditions will be unsuitable if planted in March, June, or December, which are currently optimal seasons. No change is predicted for cereal crops mango or orange.

2.4. Discussion

2.4.1. From Climate Departure to Crop–climate Departure

The impact of global warming on the crop–climate relationship in the three AEZs of West Africa varies depending on the crop grown. The combination of a changing climate and crop growth suitability thresholds results in a projected deviation for the SIV from historical data. This may be a predicted increase in SIV, as observed for maize, or a decline as noted for crops such as cassava. A further variable is the AEZ itself. The predicted increase in SIV for maize in the Sahel zone by 2100 results from the projected increase in temperature and precipitation in this location. The decline in SIV forecast for cassava and pineapple in the Savanna AEZ decreases the suitability of the SSA region for these crops, spatially constraining suitable areas to the Guinea AEZ by 2100. The warming climate also influences the suitability of the month of planting of many crops. A potential cause for concern is the timing of crop–climate departure in the Savanna AEZ, which is already evident in root and tuber, cassava, and pineapple crops, and projected for orange crops by 2100. The diversity of crops grown in this AEZ may be diminished in the future.

The projected shifts in suitability and the variation of suitability between different crops and AEZ due to global warming highlights the importance of local climatic conditions in determining the extent of crop growth, development, and yield in response to climate suitability thresholds (Porter & Semenov, 2005; Solomon et al., 2007). The above characteristics observed from the crop–climate relationship of different crops in the three AEZs of West Africa supports our proposed crop–climate departure definition of "a departure/shift from a historical crop suitability threshold, whether in terms of variability, mean or both, resulting from climate change whether of radical climatic nature or not due to warming of the climate over a location both in space and time". This definition can be used to inform adaptation responses to impacts resulting from climate change that will influence crop suitability, especially in a vulnerable region with low adaptive capacity like West Africa. Cultivating crops with high suitability as projected by the models such as cassava in the Guinea and maize in the southern Sahel may be the best solution. However, with improved/hybrid seedlings of the crop projected to decline that can withstand the variability in climate, this improved suitability may be considered another option.

2.4.2. Crop–climate Departure and the Spatio-Temporal Variability of Crop-Suitability in West Africa

The temporal and spatial targeting of adaptation measures under an increasing global temperature will be crucial in maintaining and improving food security in the future. Identifying the timing and location of changes in crop growth suitability due to climate change can play a potentially key role in addressing the challenge of food production (Challinor et al., 2014; Rippke et al., 2016). This is particularly relevant for the crops of vital importance in the West African region assessed here. The projected decrease in growth suitability conditions for cassava crops in the Savanna AEZ between 2020 and 2050, for example, depends on the time of planting or season. This projected departure is critical for the Savanna region as it may impact negatively on both the economy and livelihoods within the region. The improved understanding of crop–climate departure timing may permit timely adaptation plans such as modification to crop management regimes that account for this change in crop seasonality. If this were to be included in combination with increased use of key varietal traits, e.g. drought resistance, it will greatly assist in improving the adaptive capacity of such crops and mitigating the future impacts of a warmer climate to increase the resilience of current cropping systems within the region (Wheeler & von Braun, 2013; Rippke et al., 2016). Improvements to the underlying knowledge base can therefore potentially improve both crop yield and crop quality.

In AEZs where the continued growing of given crop types is no longer possible, a further adaptation strategy is a shift to other more resilient crop species (Ramirez-Villegas & Thornton, 2015), or the substitution of existing crops with crops not previously grown within a given AEZ. Maize, for example, is projected to increase in yield by up to 7% in comparison to non-adapted crops under future climate change scenarios in SSA (Challinor et al., 2014). An increase in the planting area of crops such as maize further northwards into the southern Sahel AEZ due to the projected rainfall increase in this AEZ (Porter & Semenov, 2005), or a shift of cassava or pineapple cropping into the Guinea AEZ due to reduced rainfall and the crops ability to withstand drought (Porter & Semenov, 2005; Jarvis et al., 2012b; Wheeler & von Braun, 2013; Rippke et al., 2016) represent further opportunities. A spatio-temporal projection of potential crop growth suitability can help provide information on future opportunities and constraints that will arise from shifts in the location of suitable crop lands within each AEZ (Wheeler & von Braun, 2013). Adaptation measures may then be prioritized for individual countries in response to the predicted changes (Porter & Semenov, 2005; Lobell, Schlenker & Costa-Roberts, 2011), resulting in the maximum utilization of suitable areas for specific crop types, which will greatly assist in mitigating the future impacts from a warmer climate.

2.5. Summary and Conclusion

In order to improve the understanding of climatic impacts on agriculture, we conceptualized and explored the notion of crop–climate departure from historical variability in West Africa. We used four downscaled CMIP5 GCMs (CCMA CNRM5, GFDL, and MIROC) for the period 1960–2100 under RCP8.5 emission scenario and a crop suitability model, Ecocrop, across three weather stations representative of the Guinea, Savanna, and Sahel AEZs. In summary, all four GCMs correlate with observed weather station data in their simulation of monthly mean temperature and total monthly rainfall in the Savanna and Sahel zones, but moderately over the Guinea zone. It is recommended that future simulations acquire data from additional weather stations and utilize additional CMIP5 GCMs such as CSIRO, ICHEC, HADGEM, IPSL, MPI etc. In terms of crop rotations, the current climate is suitable for maize in the Savanna and Sahel AEZs, while future projections predict a potential for the expansion of maize further into the Sahel zone. The Guinea zone remains less suitable for maize but provides the correct climate both currently and in the future for crops such as cassava and pineapple. The predicted range for pearl millet and mango will remain stable in all three AEZs. Importantly, the Savanna AEZ, given its current cropping regime, is the most sensitive to climate change and shows the least resilience of the three AEZs considered. Climate change adaptation strategies will require prioritization in this zone. The climate-departure concept has been used to characterize crop–climate relationships i.e. crop–climate departure with increased warming and how it can, with appropriately planned adaptation and mitigation strategies, increase food security in the future.

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This next chapter assesses the impact of crop departure from historical variability on crop suitability and planting month over West Africa. This chapter applies and employs the concept of crop-climate departure on five different crop types to highlights its influence on the spatial variability of crop suitability and planting date of the different crops in projected climate. Recognising the consequent impact of crop-climate departure over the region, the chapter highlights the sensitivity and trend of each crop type in terms of suitability and period of planting for the crops and its impact on socio-economy of the region and trade. This chapter addresses objective 2 of the theses.

CHAPTER 3

Assessing Future Spatio-Temporal Changes in Crop Suitability and Planting Season over West Africa: Using the Concept of Crop-Climate Departure

What is the projected impact of crop-climate departure on spatio-temporal characteristic of crop suitability and planting season over West Africa?

Specific Questions

How will crop-climate departure influence crop suitability over West Africa?

How will the planting season for different crop types be affected over West Africa under crop-climate departure?

What will be the trend of change in projected crop suitability and planting season over West Africa by the end of century?

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Abstract

The changing climate is posing significant threats to agriculture, the most vulnerable sector, and the main source of livelihood in West Africa. This study assesses the impact of the climate-departure on the crop suitability and planting month over West Africa. We used 10 CMIP5 Global climate models bias-corrected simulations downscaled by the CORDEX regional climate model, RCA4 to drive the crop suitability model, Ecocrop. We applied the concept of the crop-climate departure (CCD) to evaluate future changes in the crop suitability and planting month for five crop types, cereals, legumes, fruits, root and tuber and horticulture over the historical and future months. Our result shows a reduction (negative linear correlation) and an expansion (positive linear correlation) in the suitable area and crop suitability index value in the Guinea-Savanna and Sahel (southern Sahel) zone, respectively. The horticulture crop was the most negatively affected with a decrease in the suitable area while cereals and legumes benefited from the expansion in suitable areas into the Sahel zone. In general, CCD would likely lead to a delay in the planting season by 2–4 months except for the orange and early planting dates by about 2–3 months for cassava. No projected changes in the planting month are observed for the plantain and pineapple which are annual crops. The study is relevant for a short and long-term adaptation option and planning for future changes in the crop suitability and planting month to improve food security in the region.

Keywords: crop-climate departure; Ecocrop; crop suitability; planting month; CORDEX; West Africa

3.1 Introduction

The West African region has been identified as one of the hotspots with high susceptibility and vulnerability to the impact of climate change and global warming (IPCC, 2013). For example, the global climate is projected to be above 1.5 °C above the pre-industrial level in the next decade (Kirtman et al. et al., 2013). An increase in temperature between 3 °C and 6 °C coupled with a rise in the rainfall variability is projected into the future over West Africa from the AR5 report (Riede et al., 2013). Most countries in West Africa heavily rely on agriculture, which is predominantly rainfed, as an important and significant contributor to their economies. It accounts for over 16% of the Gross Domestic Product (GDP) of the region's economy and employs over 60% of the labour force (Benhin, 2008; Schlenker & Lobell, 2010; Roudier et al., 2011). Additionally, West Africa has accounted for about 60% of the total value of the agricultural production in the continent for about 24 years (OECD/FAO, 2016). However, the region has been identified as a hotspot to climate change impacts in the recent time owing to its reducing yields in the total agricultural production since 2007 in comparison to other sub-regions on the continent (OECD/FAO, 2016). Current trends show that there may be further decreases in yields especially in the face of increasing warming and droughts which may lead to food insecurity over the region (Nelson et al., 2009, 2014; Ray & Foley, 2013).

Findings from the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5) shows widespread impacts from the changing climate to the historical month across all continents (Field et al., 2014). The report reveals a high exposure to climatic events and a low adaptive capacity of the African continent makes it one of the most vulnerable regions of the world. Agriculture is the main economic sector in Africa and has been described as the most vulnerable sector to the climate change impact with a great threat to the farming systems, crop production and food security at any level (Challinor et al., 2007; Rurinda et al., 2014; OECD/FAO, 2016; Williams et al., 2018). For example, past studies (e.g. Ramírez-Villegas et al., 2011; Jalloh et al., 2013; Sultan et al., 2014; Parkes et al., 2018) have shown the impact of climate change on crop production and yield in Africa and West Africa in particular using different crop models. Sultan et al. (Sultan et al., 2014) showed the decrease in the mean yield of sorghum cultivars due to the impact of climate change resulting from variation in the rainfall pattern and increasing temperature. Jalloh et al. (Jalloh et al., 2013) revealed that the impact of climate change will badly affect the production of major staple crops in West Africa particularly sorghum and groundnut in the Sahel. Moreover, Roudier et al. (Roudier et al., 2011) combining the result of 16 published studies, showed that the projected impact of climate change on the crop yield over most African countries is negative (about 11%) with variations among crops, regions and modelling uncertainties posing the challenge for robust assessment of future yields at the regional scale. Further changes in the climate are expected in Africa over the next decades (IPCC, 2013), as projections suggest a threat to food security due to the likely increase in climate variability over the next decades in Sub-Saharan Africa (SSA) (OECD/FAO, 2016). As a result, impacts from the changing climate varies from subsectors among regions and different countries in SSA including West Africa but may be more detrimental to the West African region owing to its high susceptibility and low adaptive capacity with further warming (Adger, 2003; Williams et al., 2018).

The increase in global warming will lead to a new climate regime with a deviation from historical variability with a variation in the timing of emergence for different regions of the world called the climate departure (Hawkins & Sutton, 2012; Mora et al., 2013). For instance, Mora et al. (2013) found that the mean temperature over West Africa will move outside the bounds of historical variability about two decades earlier before the global mean temperature thus making the region a hotspot of climate departure due to the impact of the global warming. On this premise and its direct consequence on rainfed crop production in West Africa, Egbebiyi et al. (2019) explored the climate change induced crop realizations of the climate departing from historical variability, developed and proposed the concept called the crop-climate departure (CCD) in the context of recent climate historical variability and future climate projections. The study defines CCD “as a departure from historical crop suitability threshold, whether in terms of variability, mean or both, over a location both in space and in time resulting from climate change (whether radical climatic change or not)” (Egbebiyi, Crespo & Lennard, 2019). This concept was used to characterize crop suitability across the three agro-ecological zones (AEZs) of West Africa. However, the CCD concept was only tested and applied using three weather stations, within the three AEZs of West Africa. Although these stations are a representation of the three AEZs, nevertheless these cannot be generalized for the entire region, hence there is a need to examine how CCD at different climate windows, near the future (2031–2050) till end of the century (2081–2100) will affect crop suitability over the region using the concept of CCD.

Based on our definition and understanding on CCD, the aim of this present study is to examine the impact of CCD from the historical variability on future changes in crop suitability and month of planting over the entire West African region. Section 2 describes the data and methods used. Results from the study are outlined in Section 3. The discussion of the results and concluding remarks and recommendations for the future are in Sections 4 and 5, respectively.

3.2. Data and Methodology

3.2.1. Study Area

The West African (shown in Figure 1) region comprises of 15 countries namely Benin, Burkina Faso, Gambia, Ghana, Guinea Bissau, Guinea, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. It is geographically located at latitude 4–20 °N and 16 °W–20 °E and has rainfed agriculture as its mainstay economy. The region can be divided into three Food and Agriculture Organization (FAO) agro ecological zones (AEZs) namely, Guinea (4–8 °N), Savanna (8–12 °N) and the Sahel (12–20 °N) (Abiodun et al., 2012; Egbebiyi, 2016). The region also has some localized highlands (Cameroon Mountains, Jos Plateau, and Guinea Highlands) which influence its climate. The climate of the region is mainly controlled by the West African Monsoon (WAM) which accounts for about 70% of the annual rainfall (Abiodun et al., 2012; Sultan & Gaetani, 2016). WAM is an important and dynamic characteristic of the West African climate during the summer month (Janicot et al., 2011).WAM is produced from the reversal of the land and ocean differential heating and dictates the seasonal pattern of rainfall over West Africa between latitudes 9° and 20 °N. It is characterized by winds that blow south-westerly during warmer months (June–September) and north-easterly during cooler months (January–March) of the year (Janicot et al., 2011; Egbebiyi, 2016). It is the major system that influences the onset, variability and pattern of rainfall over West Africa (Omotosho & Abiodun, 2007; Nicholson, 2013). It alternates between wet (April–October) and dry seasons (November–March) as the rainfall belt follows the migration of Inter-Tropical Discontinuity (ITD) (Klutse et al., 2018) and thus affects the rainfall producing systems with an impact on the rainfed agriculture and influences crops suitability and food production in the region.

3.2.2. Data

3.2.2.1. Historical and Future Climate Datasets

For this study, three datasets were used as observations of the present-day climate and the locations where crops are grown as observed from the crop suitability model, Ecocrop output, and modelled simulations of the present and projected crop suitability driven by the observed and projected climate data. The observation dataset was the 0.5° × 0.5° resolution monthly precipitation and minimum and mean temperature gridded dataset for the month of 1901 to 2016 obtained from the Climate Research Unit (CRU TS4.01 version, land only) University of East Anglia (Harris et al., 2014). This was used to evaluate the available bias corrected RCMs forced by the 10 CMIP5 global climate models. The bias-corrected climate data were obtained from the Swedish Meteorological and Hydrological Institute, Linköping, Sweden. The modelled climate data were used as inputs into the crop suitability model, Ecocrop (Hijmans et al., 2001). For this study, five different crop types namely; cereals (maize, pearl millet and sorghum), root and tuber (cassava, plantain and yam), legumes (cowpea and groundnut), horticulture (pineapple and tomato) and fruit (mango and orange) were selected based on the FAO 2016 statistics and their economic importance in the region. These different datasets are defined in the sub-sections below.

Temperatures and rainfall are important climate variables used in determining the impacts of climate change at different scales (Cong & Brady, 2012; Mastrandrea, Mach, Barros, Bilir, Dokken, Edenhofer, Field, Hiraishi, Kadner, Krug, Minx, Pichs-Madruga, et al., 2015). These two climate variables have a significant effect on crop yield (Abbate et al., 2004; Medori et al., 2012). While rainfall affects crop production in relation to the photosynthesis and leaf area, the temperature affects the length of the growing season (Olesen & Bindi, 2002; Cantelaube & Terres, 2005). For this study, we used the bias-corrected mean monthly minimum temperature (tmin), mean monthly temperature (tmean) and total monthly precipitation (prec). Data from 10 CMIP5 GCMs downscaled by SMHI-RCA4 are used as input into the crop suitability model (Table 1). We used the RCP8.5 emission scenario for the analysis to investigate the impact of CCD from the historical variability on the crop growth suitability and month of planting over West Africa. We used RCP8.5 because it seems the most realistic emission scenario as seen from the greenhouse gas emission trajectories in comparison to other scenarios and also has the largest simulation ensemble members (Abiodun et al., 2018).

Table 3.1:List of dynamically downscaled Global Climate Models (GCMs) used in the study.

Modelling Institution	Institute ID	Model Name	Resolution
Canadian centre for climate modelling and analysis	CCCMA	CanESM2	2.8° × 2.8°
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifiqu	CNRMCERFACS	CNRM-CM5	1.4° × 1.4°
Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0	1.875° × 1.875°
NOAA geophysical fluid dynamic laboratory	NOAAGDFL	GFDL_ESM2M	2.5° × 2.0°
UK Met Office Hadley centre	MOHC	HadGEM2-ES	1.9° × 1.3°
EC-EARTH consortium	EC-EARTH	ICHEC	1.25° × 1.25°
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR	1.25° × 1.25°
Japan agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4° × 1.4°
Max Planck institute for meteorology	MPI	MPI-ESM-LR	1.9° × 1.9°
Norwegian climate centre	NCC	NorESM1-R	2.5° × 1.9°

3.2.2.2. Ecocrop—A Crop Suitability Model

The Ecocrop model is a crop suitability model. It uses a crop growth suitability threshold dataset hosted by the FAO (Hijmans et al., 2001). It is a simple mechanistic and empirical model originally developed by Hijmans et al. (Hijmans et al., 2001) and based on the FAO-Ecocrop database (Ramirez-Villegas, Jarvis & Läderach, 2013). It is designed at a monthly scale with the ability to analyse the crop suitability in relation to the climate conditions over a geographical location (Hijmans et al., 2001; Ramirez-Villegas, Jarvis & Läderach, 2013). Ecocrop employs environmental ranges of a crop coupled with numerical assessment of the environmental condition to determine the potential suitable climatic condition for a crop. The suitability rating can be linked to the agricultural yield which is partly dependent on the strength of the climate signal in the agricultural yield (Ramírez-Villegas et al., 2011) The computation of optimal, suboptimal and non-optimal conditions based on these datasets allows for the simulation of the suitability of crops in response to the 12-month climate via t-min, t-mean and prec. (Hijmans et al., 2001). The Ecocrop model evaluates the relative suitability of crops in response to a range of climates including rainfall, temperature and the growing season for optimal crop growth. A suitability index is generated as follows: 0 < 0.20 (not suitable), 0.20 < 0.4 (very marginally suitable), 0.4 < 0.6 (marginally suitable), 0.6 < 0.8 (suitable), and 0.8 < 1.0 (highly suitable) (Ramirez-Villegas, Jarvis & Läderach, 2013; Hunter & Crespo, 2018). The default Ecocrop parameters were assumed. Although those thresholds may vary with different geographical and/or climatic conditions, previous studies have reported a close correlation between the Ecocrop model and the climate change impact projections from other crop models (Ramirez-Villegas, Jarvis & Läderach, 2013; Vermeulen et al., 2013; Challinor et al., 2014; Rippke et al., 2016). A paucity of data over regions of interest like SSA limits the validation of these processes (White et al., 2011). Nevertheless, the method contributes to the demand for the regional scale assessment of the crop response to future climate projections.

3.2.3. Methods

10 CMIP 5 GCMs datasets downscaled by CORDEX RCM, RCA4, were analyzed to assess the impacts of CCD from the historical variability on crop suitability and planting season over West Africa for five different crop types, cereal (maize, pearl millet and sorghum), fruit (mango and orange), horticulture (pineapple and tomato), legume (cowpea and groundnut) and root and tuber (cassava, plantain and yam). The RCA4 simulation output for the monthly minimum and mean temperature and total monthly precipitation was used as input into Ecocrop, a crop suitability model. Using a 20-year moving average at five-year time steps, we computed the Suitability Index Value (SIV) for each crop across the 10 downscaled

GCMs over West Africa. The Ecocrop suitability output were then used to assess the impact of global warming through CCD from the historical variability on the crop suitability and planting season over a month 1951–2100. Across the agro-ecological zones (AEZs) of West Africa. After the simulation, we computed the mean of the best three consecutive suitability index and best three months of planting window within the growing season across each grid point over the region for the historical and future month. Before examining the RCM-projected changes in the future crop suitability and planting season, we evaluated the capability of the models in simulating the crop suitability spatial distribution and planting date/season during the reference month (1981–2000).

A statistical tool, Theil-Sen estimator or Sen's slope was used to calculate the trend of change across the three windows compared to the historical month (Theil, 1950; Sen, 1968). This was used to assess the trend of change in crop suitability and month of planting at each global warming levels for each crop. Theil-Sen slope estimator is non-parametric, compatible with the Mann-Kendall test and applied in estimating the magnitude of trend. It is more robust and can detect significant trends (Ohlson & Kim, 2015). Previous studies (Wilcox, 1998; Peng, Wang & Wang, 2008) have used the method in calculating trends.

3.2.3.1. Simulation Approach and Analysis of suitability

Past studies (e.g. Gbobaniyi et al., 2014; Egbebiyi, 2016; Klutse et al., 2016; Abiodun et al., 2017) have evaluated the performance of the RCA4 historical data against the CRU dataset in the past climate. Their results showed that there is a good agreement with a strong correlation ($r \geq 0.6$) between the CRU dataset and RCA4 monthly simulated past climate data for both the temperature and precipitation over West Africa. For example, the model replicates the CRU north-south temperature gradient that concurs with previous findings by (Gbobaniyi et al., 2014). Additionally, the RCA4 simulated total monthly rainfall realistically captures the essential features namely, both the zonal pattern and meridional gradient and the rainfall maxima over high topography (i.e. Cameroon Mountains and

Guinean Highlands) as observed in CRU which agrees with previous findings by (Egbebiyi, 2016; Klutse et al., 2016; Abiodun et al., 2017). The performance of RCA4 in simulating the essential features of West African climate variables, temperature and rainfall, and doubles as the needed input variables for the crop suitability model, Ecocrop makes it suitable and gives confidence in the use of the RCA4 for the crop suitability simulation over the region.

In addition, we compare the Ecocrop simulation over the region with the MIRCA2000 annual harvested area around year 2000 from the global monthly gridded data as described by (Portmann et al., 2010) for six crops, cassava, maize, groundnut, sorghum, millet and plantain available in the MIRCA2000 dataset. The MIRCA2000 dataset provides monthly irrigated and rainfed crops area for 26 crop classes for each month of the year around year 2000 with a spatial resolution about 9.2 km. We compare the spatial agreement between the Ecocrop simulation and MIRCA2000 by using an overlap in the spatial agreement between the two datasets. Although, we admit the short time length of the MIRCA dataset however, it is a useful gridded dataset that has been used to provide information on the crop harvested area across different regions of the world (Portmann et al., 2010) and will be useful to evaluate the simulated Ecocrop spatial suitability distribution at present due to the paucity of the suitability dataset across the globe. To see the overlap and area of agreement in the spatial suitability output of the two datasets, we set the MIRCA2000 annual harvested area dataset as one (1) and the Ecocrop simulated suitable area suitability index value from 0.2 (SIV ≥ 0.2) as two (2). Where the two datasets agree as three (3). The output shows a good agreement between the Ecocrop and MIRCA2000 data for the examined crops with a strong spatial correlation ($r > 0.7$) (Figure 2). This gives some level of confidence in the use and performance of the Ecocrop simulation over the region.

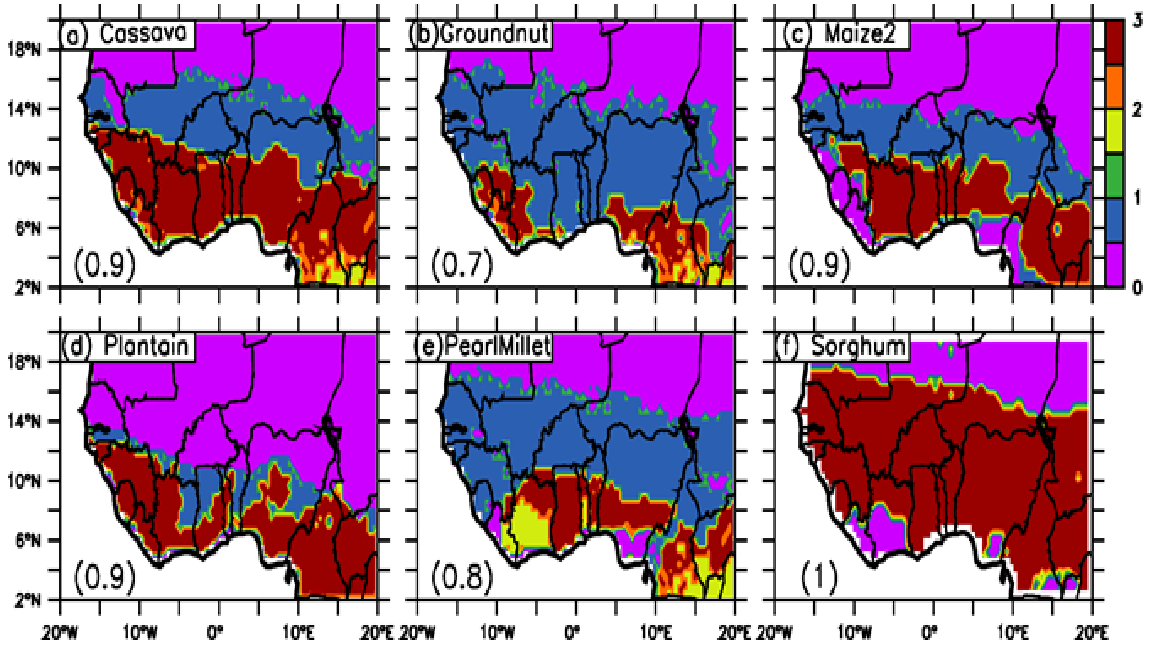

Figure 3.1: A simulated spatial distribution of the crop harvested area and suitability over West Africa for the year 2000 as simulated by the MIRCA2000 dataset and Ecocrop, respectively. The blue area (represented by 1) are the crop harvested area around the year 2000 as simulated by the MIRCA2000 dataset while the yellow colour represents the suitability index value above0.2 (SIV ≥ 0.2) which is represented by two. The red colour represents the area where the two datasets agree as denoted by three. The number at the left-hand corner represents the spatial correlation (r ≥ 0.7) value between the two datasets. The red colour depicts in Fig. 3.1a-3.1f depicts harvested and suitable areas as simulated by MIRCA2000 and Ecocrop from cassava to sorghum respectively. The blue colour depicts MIRCA2000 simulated harvested area only for each crop while yellow means Ecocrop simulated suitable areas for cultivation of each crop in year 2000. The purple colour,0 depicts non harvested and unsuitable areas as simulated by both MIRCA2000 and Ecocrop for each of the crops around the year 2000.

To assess the impact of CCD from the historical variability on the crop suitability over West Africa, we computed the monthly climatological mean for a 20-year running month, at every five-year timestep for the t-min, t-mean and prec. from 1951–2100. For example, the first 20-year mean computed was 1951–1970, the second 20-year mean was 1956–1975, etc., until the last month 2081–2100. The resulting 12-month values per the 20-year month window was used as an input climatology into the Ecocrop suitability model as developed by the Food and Agriculture Organization, FAO (Hijmans et al., 2001) to simulate crop suitability for each downscaled GCM based on the methodologies described in (Ramirez-Villegas, Jarvis & Läderach, 2013). Ecocrop calculates the crop suitability values in the response climate variables such as a monthly rainfall and temperature datasets and generates an output with a suitability index score from zero (unsuitable) to one (optimal/excellent suitability). It should be noted that this study did not undertake any additional ground-truthing or calibration of the range of climate parameters preferred for either crop, therefore the default EcoCrop parameters were assumed. Suitability index scores were calculated for the range of climate variables reported for the historical baseline (1981–2000) future months, near future (2031–2050), mid-century (2051–2070) and end of century (2081–2100) for the downscaled 10 CMIP5 GCMs that participated in the CORDEX experiment.

3.2.3.2. Assessing the Robustness of Climate Change

We use two conditions (model agreement and statistical significance) to evaluate the robustness of the projected climate change for the three future months. For the model agreement, at least 80% of the simulation must agree on the sign of change. For the statistical significance, at least 80% of the simulations must indicate that the influence of the climate change is statistically significant, at 95% confidence level using a *t* test with regards to the baseline years, 1981–2000. When these two conditions are met then we consider the climate change signal to be significant. Previous studies have all used the methods to test and indicate the robustness of the climate change signals (Abiodun et al., 2018; Klutse et al., 2018; Maúre et al., 2018; Nikulin et al., 2018).

3.3 Result

3.3.1. Crop Suitability in the Historical Climate over West Africa

The RCA4 simulated crop suitability from the observed climatology inputs (RCA4-Ecocrop) shows a decreasing mean suitability from south to north over West Africa (north-south suitability gradient). The spatial suitability representation reveals unsuitable or very marginal suitability to the north in the Sahel from lat. 14°N with a low Suitability Index Value (SIV) value between 0.0–0.4 and a higher suitability to the south in the Guinea-Savanna AEZ with a high SIV (0.6–1.0) sandwiched by an ash/silver suitability line called the Marginal Suitability Line (MSL) with an SIV between 0.41–0.59. In general, the MSL are observed around lat.14 °N in the Sahel AEZ (northern Sahel) for the simulation across the region except for the one observed around lat. 12 °N, the boundary between the Sahel and Savanna AEZ. The RCA4 simulation of all crop types examined, legumes (cowpea and groundnut), root and tuber (cassava, plantain, Yam, white yam), cereals (maize, pearl millet and sorghum) and fruit and horticultural crops (mango, orange, pineapple and tomato) shows that all the crops are very suitable to the south of the MSL but with no or low suitability to the north (Figure 3.2–3.5, column 1).

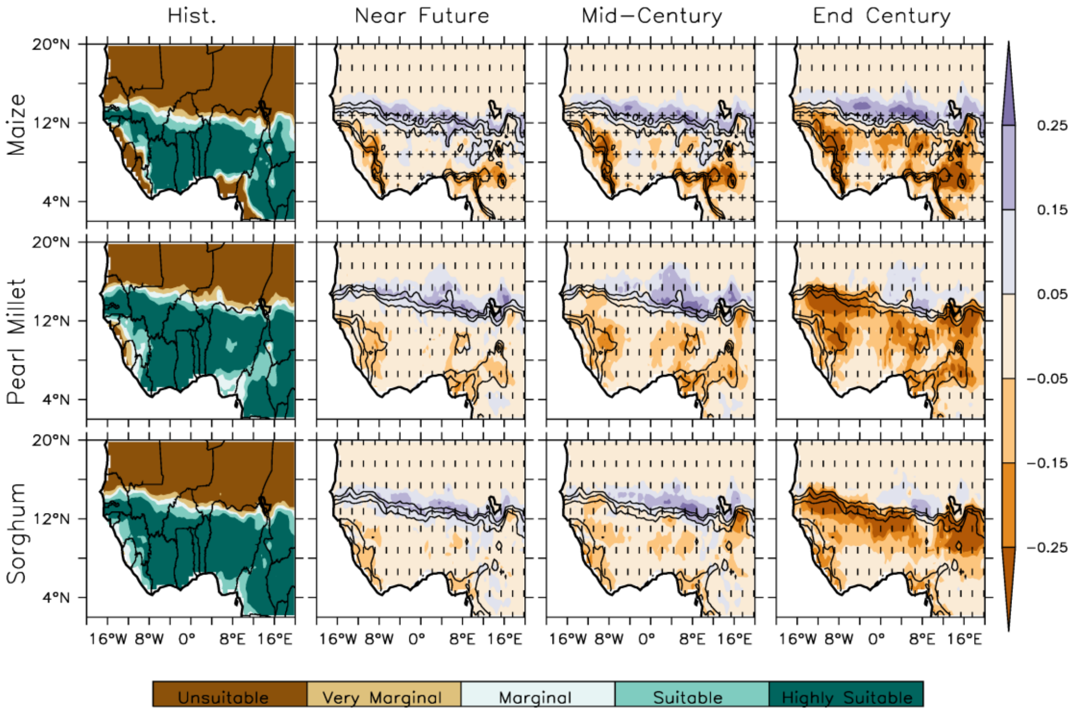

*Figure 3.2**:** Simulated spatial suitability distribution cereal crops, (maize, pearl millet and sorghum) over West Africa for the historical period (1981–2000) (column 1) and the projected change in the crop suitability for the near future month (2031–2050), mid-century (2051–2070) and end of century (2081–2100) (column 2–4, respectively). The vertical strip (|) indicates where at least 80% of the model simulations agrees on the projected sign of change while the horizontal strip (-) indicates where at least 80% of the model simulations agree that the projected change is statistically significant at 99% confidence level. The cross (+) indicates where the two conditions are met, meaning that the change is robust.*

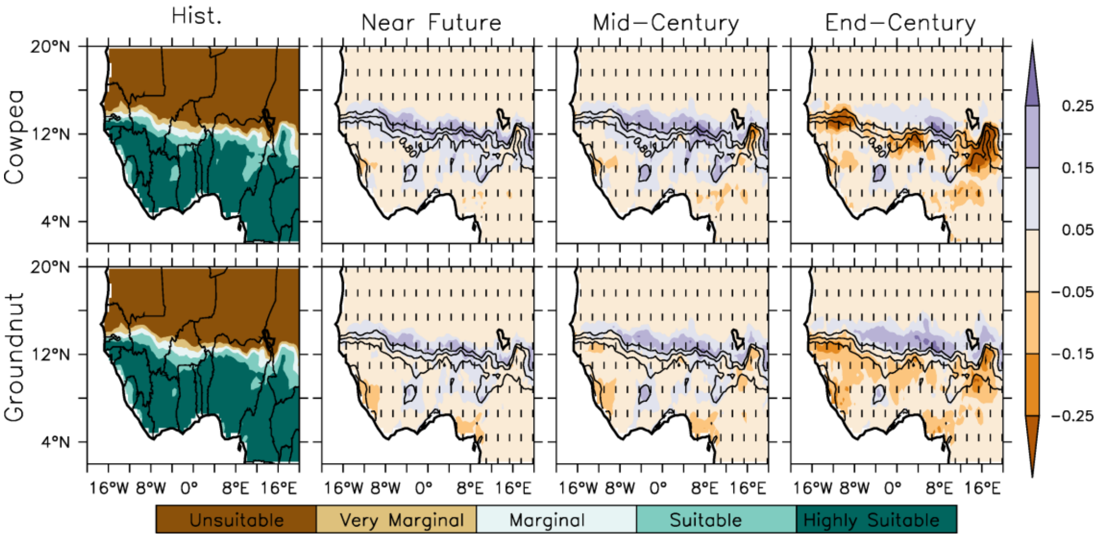

Figure 3.3: Same as Figure 3.2 but for the legume crops, cowpea and groundnut.

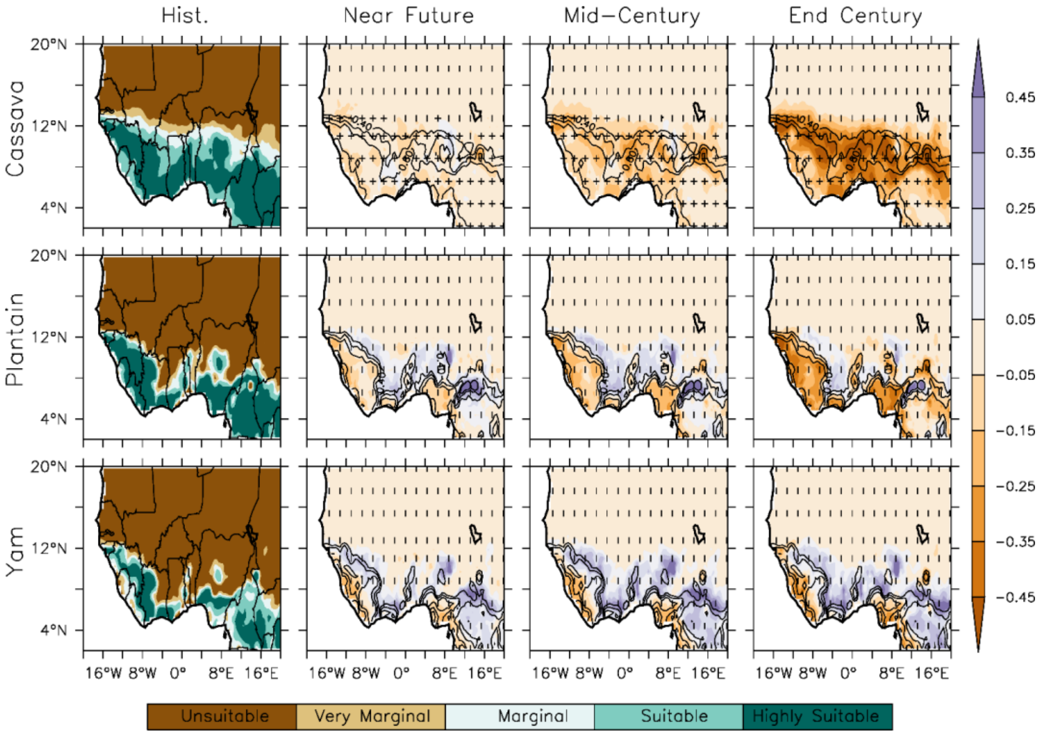

Figure 3.4: Same as Figure 3.2 but for the root and tuber crops (cassava, plantain and yam)

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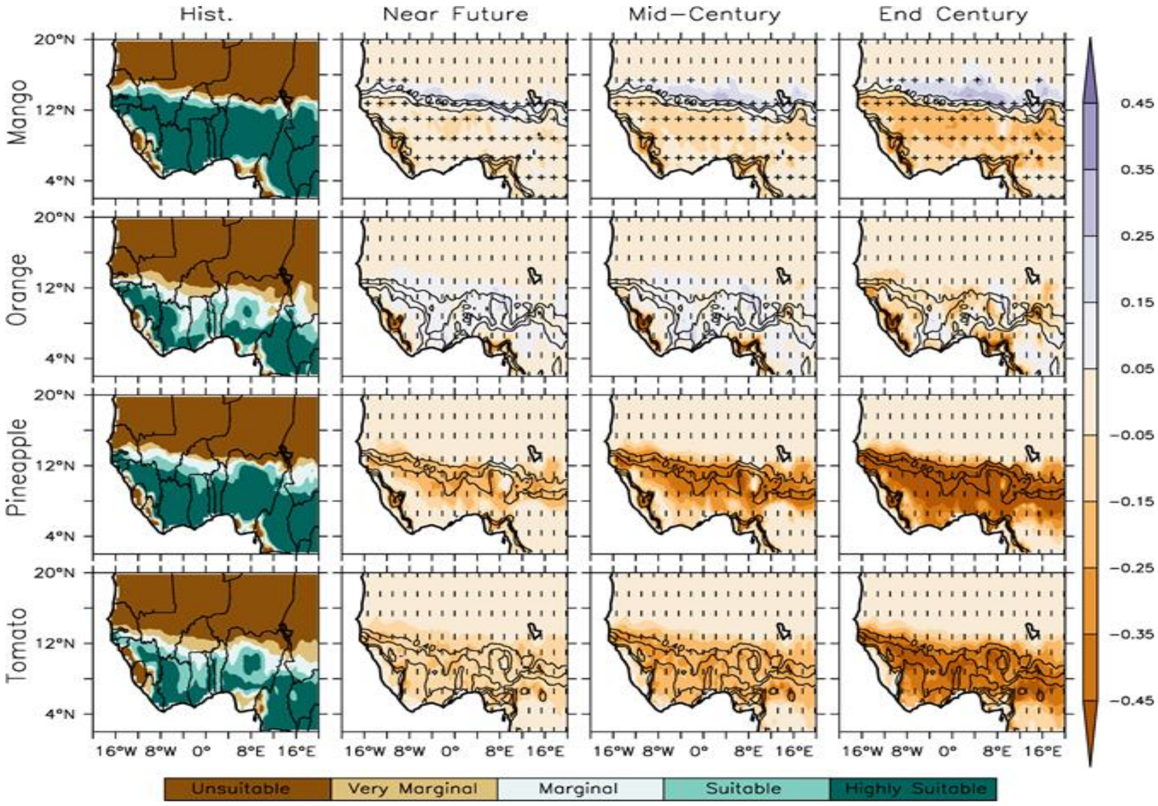

*Figure 3.5**:** Same as Figure 3.2 but for the fruit crops (mango and orange) and horticultural crops (pineapple and tomato).*

Along the coastal areas, legumes and root and tuber crops are suitable along the south-west coast of Senegal to the south-west coast of Cameroon. High SIV are observed for the root and tuber crops, plantain and Yam in the north central part of Nigeria in the Savanna. It is worth mentioning because the surrounding areas are observed to be unsuitable for the cultivation of both crops. For cereals, pearl millet is suitable along the west coast of Senegal and from the south coast Ivory Coast to the south-west coast of Cameroon. Maize is suitable from the south coast of Ivory Coast to the south-west coast of Nigeria. Fruit and horticultural crops are all suitable along the south coast of the Ivory Coast to the south-west coast of Nigeria. Mango and pineapple are suitable along the west coast of Senegal to Gambia while orange and tomato are only suitable along the west coast of Gambia.

RCA4 was also used in simulating the best planting months (PM) from the range of month in a planting window within the Length of Growing Season (LGS) over West Africa for the historical climate (Figure 3.6–3.9, column 1). LGS provides information on the start and end of the growing season and can also assist in the simulation process of identifying the best PM within a possible planting window in a growing season over a given location. The simulated planting month represents the first month of the best three months of the planting window. For example, a simulation of April means April–June is the three best PM and varies with crop types across the three AEZs of the region. For the legumes, our simulation shows January–July as the planting windows for cowpea and groundnut over the region (Figure 3.7, column 1). Jan (January–March) and Feb (February–April) as the best PM for cowpea and groundnut, respectively in the central Guinea and Savanna AEZs except over Sierra Leone, Liberia and the south coast of Nigeria. The month of Feb (Feb-April) was simulated as the best three planting months in the western and eastern Savanna-Sahel AEZs for cowpea, while it was Mar (March–May) over the same area and month for the groundnut. Along the coastal areas, July is simulated as the PM along the southwest coast from southern Sierra Leone to Liberia and the south coast of Nigeria and April along the southwest coast of northern Sierra Leone. For the groundnut, April is the PM along the west coast of Guinea, while May is the PM along the west coast of Sierra Leone and northern Liberia. August and March are the PM at the south coast of Liberia and Nigeria, respectively. The months of December and January are the PMs along the south coast of Ivory Coast to Ghana for the cowpea and groundnut, respectively.

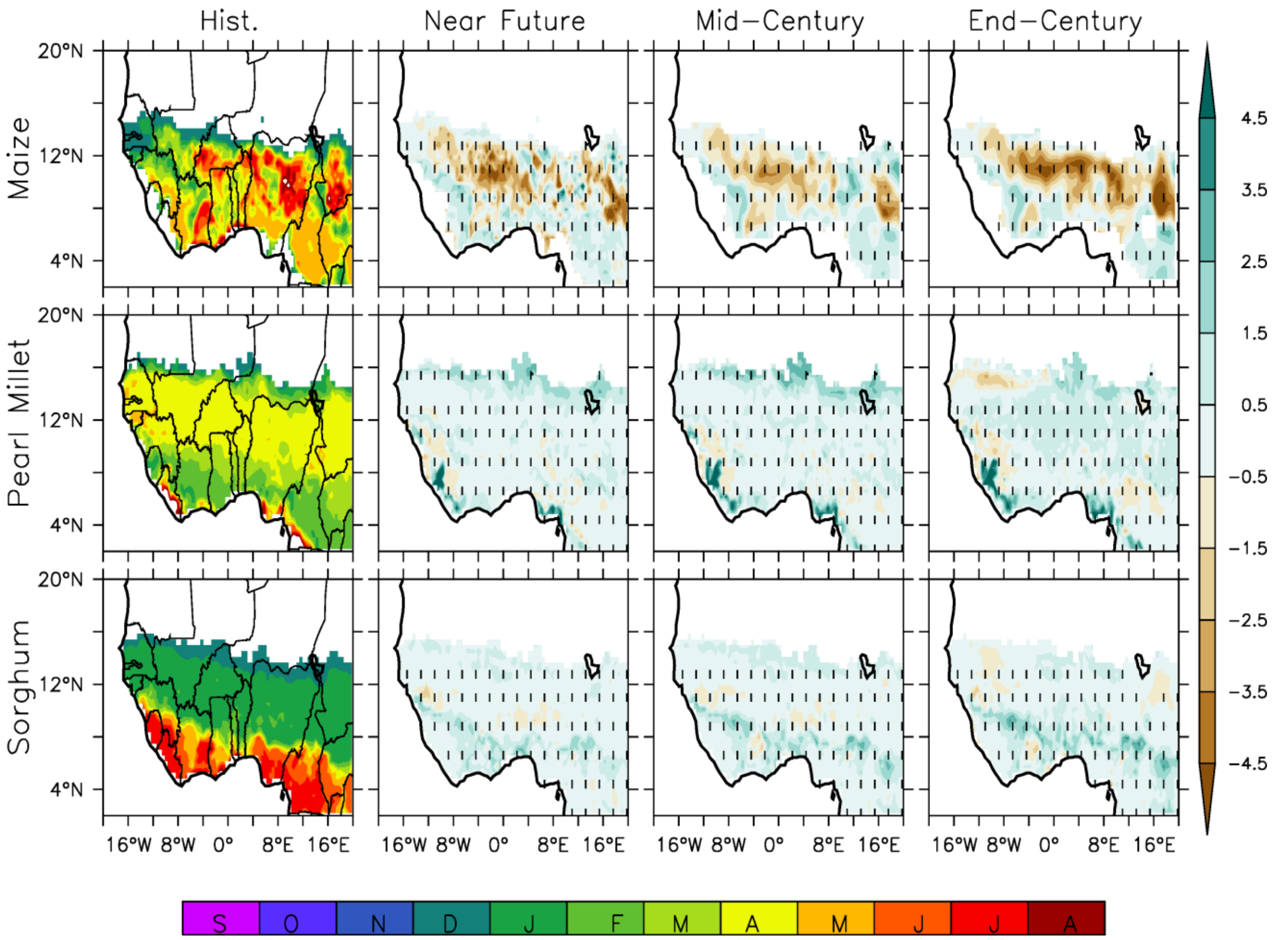

Figure 3.6: Simulated month of planting for cereals, maize, pearl millet and sorghum over West Africa for the historical month (1981–2000) (column 1) and the projected change in the crop planting month for the near future month (2031–2050), mid-century (2051–2070) and end of century (2081–2100) (column 2–4 respectively). The planting is simulated from September to August. The vertical strip (|) indicates where at least 80% of the model simulations agrees on the projected sign of change while the horizontal strip (-) indicates where at least 80% of the model simulations agree that the projected change is statistically significant at 99% confidence level. The cross (+) indicates where the two conditions are met, meaning that the change is robust.

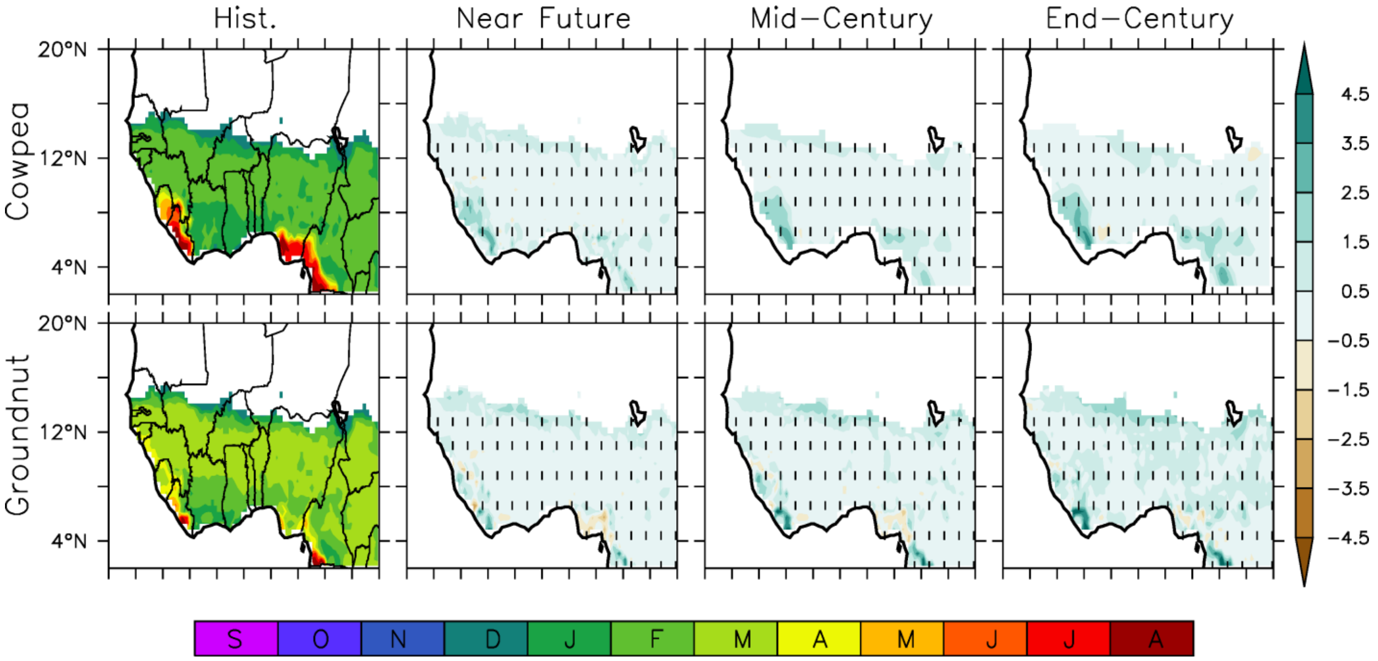

Figure 3.7: Same as Figure 3.6 but for the legumes, cowpea and groundnut.

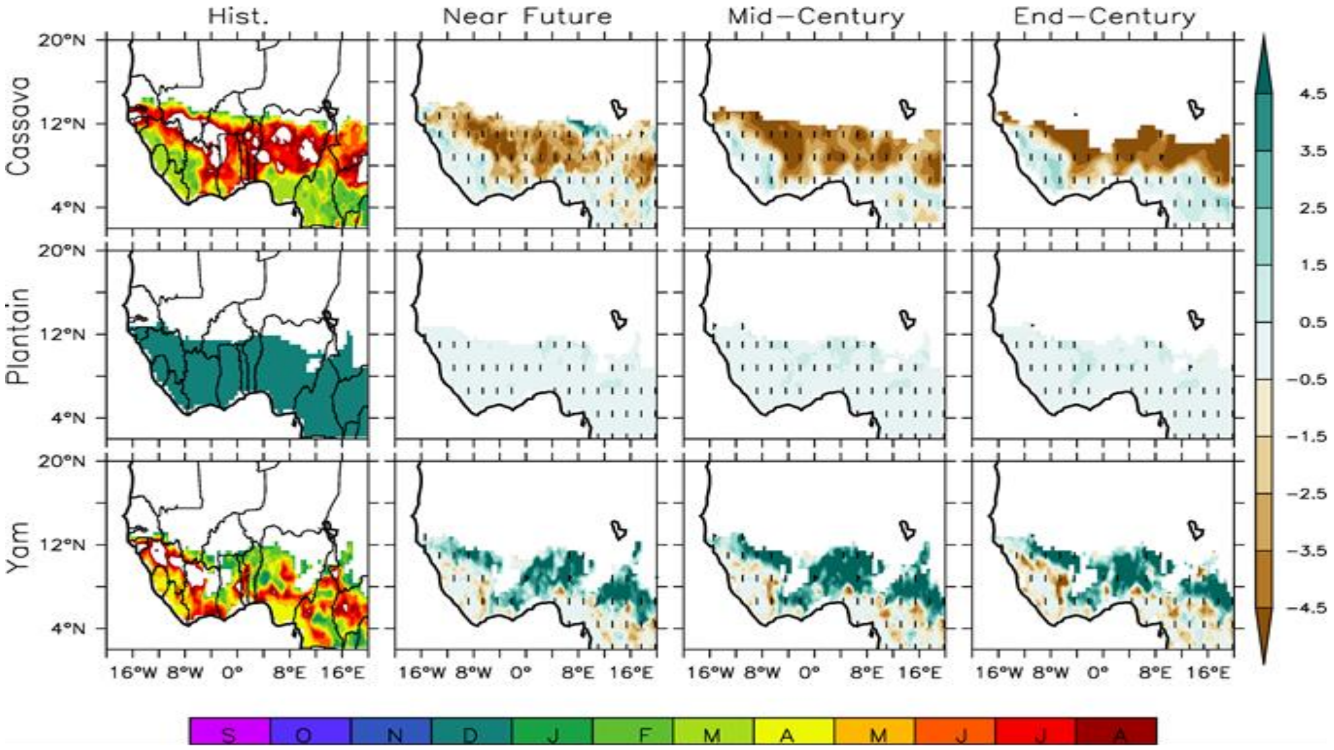

Figure 3.8: Same as Figure 3.6 but for the root and tubers (cassava, plantain and yam)

Plantain is an annual crop that can be planted at any month of the year however it is better when planted during the rainy season (Figure 3.8). Our finding agrees with previous work that plantain can be planted at any time of the year Swennen (1990). The study showed the average air temperature should be about 30°C and rainfall should be well distributed across the year with at least 100 mm per month. The simulated PM is an overlay of the simulation of other months in the year as the crop may be planted in the suitable zones, Guinea and Savanna at any month/month of the year. For cassava, our simulation shows March (March–May) as the best PM generally over the region (Guinea-Savanna AEZs) except along the south-east coast of Ivory Coast to Ghana with PM in July, northern Guinea to Gambia and south east Senegal and from the boundary of Benin Republic to north west Nigeria in April. The Ecocrop simulation for Yam shows June as the best PM in the central Guinea zone from the south-east Ghana to the south-east of Nigeria and in the north central part of Nigeria as well as Togo in the central Savanna zone. The month of February is observed as the best PM from the south-east Mali to the north-western part of Nigeria in the Savanna. Over the coastal area, April is observed as the PM along the south west coast from Sierra Leone to Liberia and the south coast of Nigeria and June along the west coast of Guinea and from the south coast of Ivory Coast to the south-west coast of Ghana in the past climate.

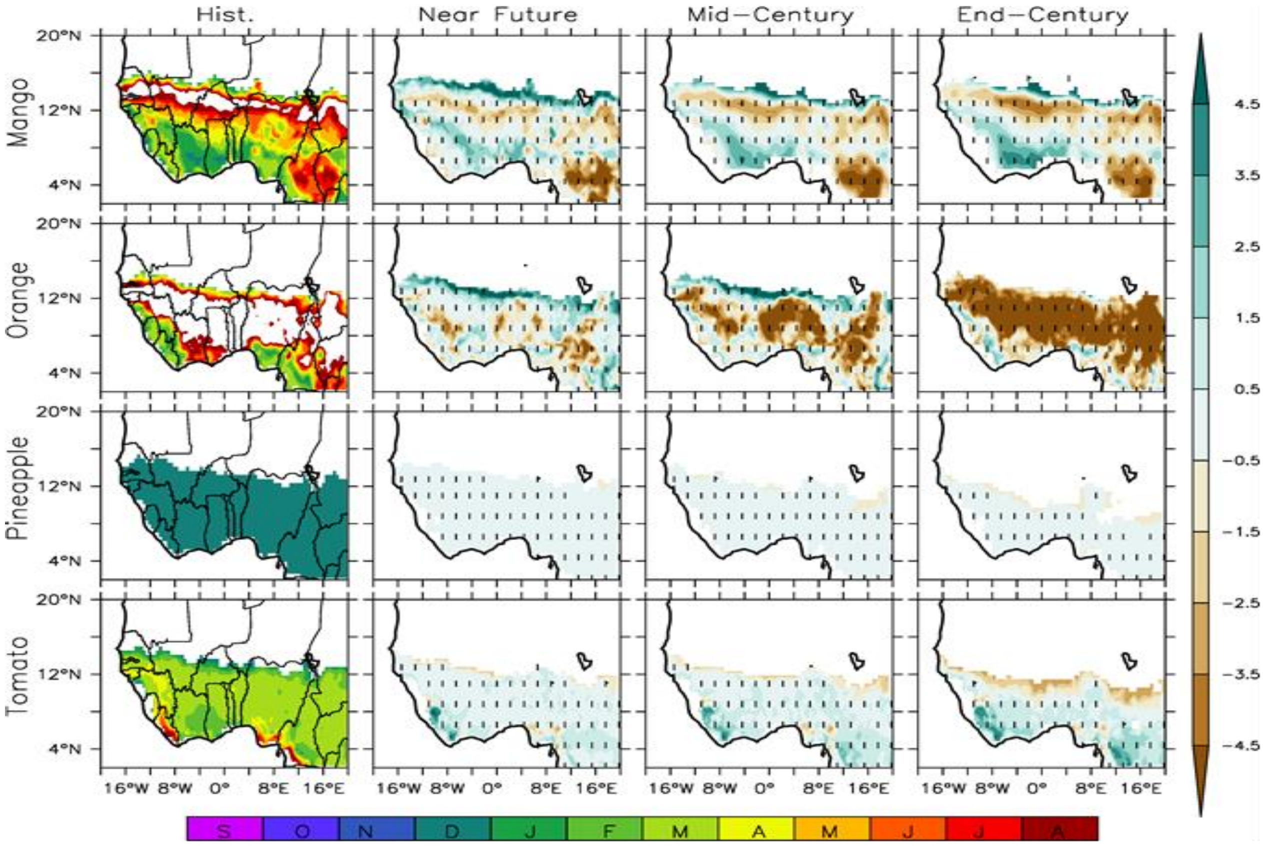

Figure 3.9: Same as Figure 3.6 but for the fruit and horticultural crops.

Our simulation for cereal crops shows February as the PM for pearl millet in Guinea, March and April are the best PMs in the south Savanna and northern savanna and Sahel AEZs, respectively although with exception. For example, in central savanna, from the northern Benin Republic to the north-western Nigeria for millet, the PM is April while in the north-eastern Nigeria in the Sahel it is March compared to April in the Sahel zone. However, for the pearl millet, the PM is April in the western Sahel along the south-west coast of Senegal, June along the west coast of Guinea and January along the south coast of Ivory Coast to the south-west coast of Nigeria. For maize, the PM is simulated to be in May (May–July) in the Guinea and southern Savanna zone of West Africa while it is in December (December–February) in the northern Savanna into the Sahel zone. For sorghum, June is simulated as the PM over Sierra Leone to Liberia and its coastal areas as well as the south coast of Ivory coast and Nigeria while it is May in the central south of Ivory coast and southern Ghana. The crop is simulated to be best cultivated in January in the Savanna-Sahel zones and best in December in the northern Sahel.

The Ecocrop simulation of the best PM for the horticultural crops (Figure 3.9) in the past climate shows tomato is mainly planted in March over the regions except from the south-east Ivory coast to south-west Ghana and around 14 °N in the Sahel where the best PM in February, along the west and south coast of Liberia and Nigeria, respectively where the best PM is July. Pineapple is an annual crop and it shows similar characteristics as plantain as mentioned above, which can be planted at any month of the year. For the fruit crop, orange shows February as the best PM over Sierra Leone to Liberia and along the west coast from Guinea to Liberia and the south coast of Nigeria. June is observed as the best PM in the south of Ivory coast to Ghana and Nigeria as well as the south coast of the Ivory and Ghana. June is also simulated as the best PM from Guinea Bissau to north-east Nigeria around lat 14 °N in the Sahel. The Ecocrop simulation for mango in the past climate shows February as the PM from the Guinea to southern savanna AEZ, April, May in the northern savanna AEZ and June as the best PM in the southern Sahel AEZ. Along the coastal areas, March is simulated and observed as the best PM from the west coast of Guinea to Liberia and south coast of Nigeria but February over the south coast of Ivory coast and Ghana.

Nevertheless, the evaluation demonstrates that RCA4-Ecocrop captures the spatial variation in suitability of different crops across the three AEZs of West Africa in the present-day climate and can serve as a baseline for evaluating the changes in crop suitability under global warming at different time windows over the region. The model also captures the spatial distribution of the best planting month within a growing season for crops over the region which varies with different months of the year.

3.3.2. Projected Changes in t-min, t-mean and precip over West Africa

An increasing clear trend of warming is projected across West Africa in the future, with predictions of increases of the t-min and t-mean of approximately 1–4.5°C (Figure 3.10, Row 2 and 3 respectively). The minimum and mean monthly temperature (t-min and t-mean) is predicted to increase by 1.5–2°C in the Guinea-Savanna of the regions, about 2–2.5°C in the Sahel and increases of about 1 °C predicted for the south-west coastal area in the near future month (2031–2050). By mid- century, the t-mean is projected to increase by 2.5°C and 3.0°C over the Guinea-Savanna and Sahel, respectively and 3.0°C increase over the Guinea and 3.5°C over the Savanna-Sahel for t-min. At the end of the century, a 4.0°C temperature increase is projected over the Guinea-Savanna zone except the western area and 3.5°C increase over the Sahel for t-mean. The projected change in the minimum temperature by the end of the century showed a different pattern over the region as the Guinea zone, southern Guinea-coastal area, is warmer than the Sahel. The projection shows an increase up to 4.5°C in the southern Guinea (coastal area) and 4°C inland. A similar characteristic is also observed over the Sahel as the southern Sahel (12–14 °N) is projected as warmer (4.0°C) than north of 14 °N (3.5°C) in the Sahel zone. The savanna zone is however different to the Guinea and Sahel as the temperature increases northward over the zone, i.e., southern Savanna (3.5°C) is lower to the northern Savanna (4.0°C) except for the western part of the Savanna zone, which is much cooler than the rest with an increase of 2.5°C. Our findings are consistent with that of Klutse et al. (2018).

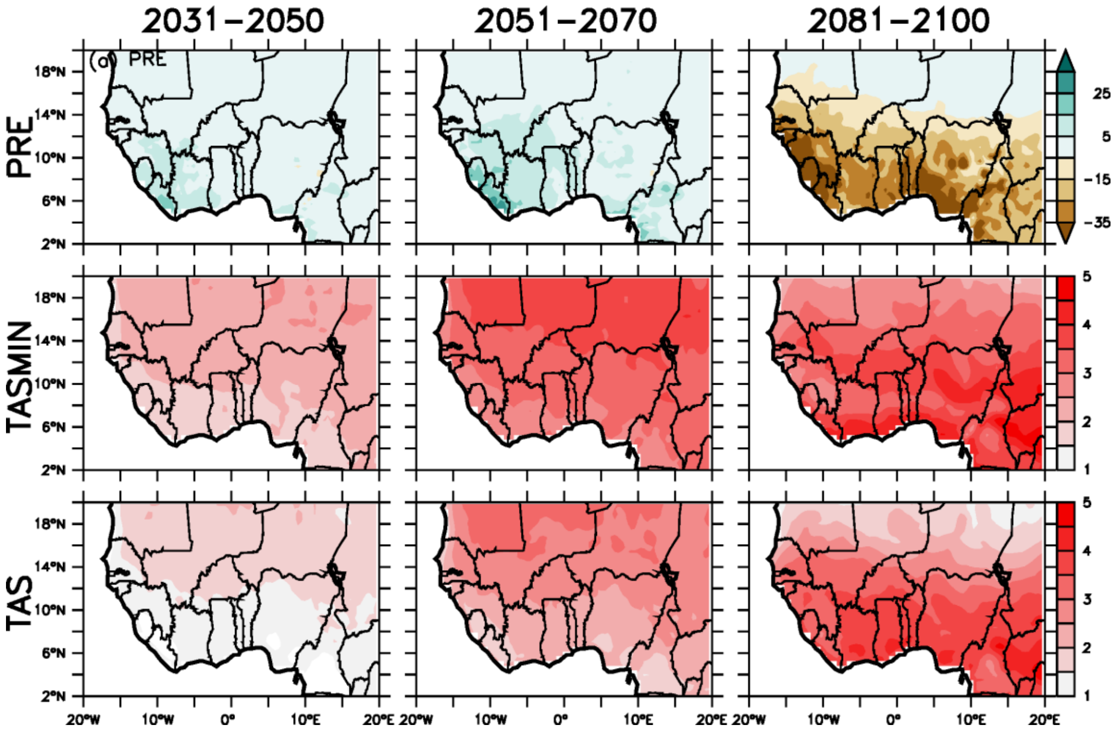

Figure 3.10: Projected changes in the total monthly rainfall (PRE), minimum (TASMIN) and mean (TAS) monthly temperature over West Africa as simulated by RCA4 for the near future month (2031–2050), mid-century (2051–2070) and the end of the century (2081–2100).

With respect to the predicted effects of climate change on rainfall, it is not a major change in the mean monthly precipitation that is projected over the region except in the south-west Guinea zone extending to the southern Guinea in the Savanna and the south coast of Nigeria (Figure 3.10, Row 1). The projected increase of about 10 mm extends from the south-west coastal area of Sierra-Leone to Liberia to the south-west coast of Ghana and south coast Nigeria in the near future (2031–2050) compared to the historical climate. By mid-century (2051–2070), the projected change of about 10 mm is expected in the western part of the region from the Guinea zone to the southern Sahel zone and the north-central part of Nigeria. Over the coastal area, an increase up to 25 mm is projected along the south-west coast of Sierra-Leone to Liberia and 10 mm over the south coast of Nigeria. The projection shows that no change is expected in the eastern part of the region by the mid-century. In contrast, by the end of the century, the projected change in the rainfall will be characterized by a decrease in the monthly precipitation across the entire region compared to the baseline. A gradient decrease in the rainfall is projected from south to north with a reduction up to 35 mm over the Guinea-Savanna and about 25 mm over the Sahel. Over the coastal area, a decrease above 35 mm is projected along the west coast of Gambia to northern Liberia and south coast of Nigeria. Our findings are in agreement with (Klutse et al., 2018).

3.3.3. Impact of CCD on Future Crop Suitability over West Africa

Projected changes in the future crop suitability for all crop types varies across the three future climate windows, from the near future period (2031–2051) to the end of the century (2081–2100) (Figures 3.2–3.5, column 2–4). The variation in the impact for the crops may be linked to the difference in crops response to the different climate window as described in Table 2 below for the three-climate window/period. For the near future, our simulation projects a general no change in the suitability for cereals south of 12 °N except the south coast of Nigeria (Figure 3.2, column 1). However, projected decrease of about 0.1 SIV is expected in the south coast of Nigeria for all the cereal crop, over Guinea for pearl millet, from Sierra Leone to Liberia for sorghum and from eastern Guinea to Liberia in the western Guinea-Savanna zone. In contrast, an increase in SIV up to 0.2 is expected in the southern Sahel zone for cereals. No suitability change is projected for legumes (Figure 4, column 2) except an increase in SIV of about 0.1 in the southern Sahel (12–14 °N) and up to 0.2 in the central savanna zone (Figure 3.3). On the other hand, a projected decrease of 0.1 in SIV is expected along the west coast of Sierra Leone and the south coast of Nigeria for groundnut. The projected increase in SIV provides an increase in the suitable area for the cultivation of both crops. This is so because a 0.2 increase in SIV for the marginally suitable (SIV, 0.4–0.6) areas in the southern Sahel results in the area becoming suitable (SIV, 0.6–0.8) for both crops. The projected decrease in the SIV values along the coastal areas and over Sierra Leone also does not affect the area negatively as the area remains suitable for these crops.

For the root and tuber crop (Figure 3.4, column 2), a projected decrease of about 0.1 SIV is expected for cassava and up to 0.2 in southern Nigeria and along the west coast of Guinea to Liberia for plantain and yam extending to south of Ivory Coast for plantain. A similar magnitude decrease is also expected in the western Guinea-Savanna zone from Guinea to the western Ivory Coast. For the horticulture and fruit crops (Figure 3.5, column 1), a 0.1 projected decrease in SIV is expected south of 12 °N and the savanna zone for tomato and pineapple, respectively while up to 0.2 SIV decrease is expected in the south coast of Nigeria for mango and orange. However, a projected increase up to 0.2 SIV is expected in the southern Sahel for mango. The projected suitability changes are robust (i.e., at least 80% of the simulation that the climate change is statistically significant at 95% confidence level) for cassava, maize and mango in the near future month (2031–2050) while the changes are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change).

Table 3.2: Projected changes in crop suitability over West African AEZs at different future window periods.

Crops	**Near Future (2031–2050)**			**Mid-Century (2051–2070)**			**End-Century (2081–2100)**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Cassava	No change remains suitable	No change remains suitable	No change remains unsuitable	A 0.2 SIV decrease but still suitable	A 0.2 SIV decrease but still suitable	Same as near future period	About 0.4 SIV decrease still suitable	About 0.4 SIV decrease but still suitable	Same as near future period
Plantain	About 0.1 SIV decrease but still suitable	A 0.1 & 0.2 SIV decrease and increase in west and central respectively	No change unsuitable	About 0.2 decrease in SIV but still suitable	A 0.2 SIV decrease and increase in west and central respectively	No change remains unsuitable	About 0.4 SIV decrease may become marginally suitable	About 0.4 and 0.2 SIV decrease to the west and central respectively	No change remains unsuitable
Yam	Suitable except in coastal area	Suitable in the west & central Savana	No change, unsuitable	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period
Maize	No change remains unsuitable	Suitable, but not along the west coast of Guinea to Sierra Leone	A 0.2 SIV increase with, suitability in the southern Sahel	No change remains unsuitable	About 0.1 SIV decrease but still suitable	Same as near future period	No change remains unsuitable	About 0.2 decrease in SIV but still suitable	Same as near future period but SIV increase up to 0.3
Pearl millet	No change, very marginal suitability south coast of Nigeria and north Liberia	No change but about 0.1 SIV decrease in eastern Guinea	A 0.2 SIV increase make northern Sahel suitable	Same as near future period	Same as near future period	Same as near future period	Same as near future period	About 0.3 decrease in SIV but still suitable	A 0.4 SIV decrease in west Sahel but still suitable
Sorghum	No change in suitability	No change in suitability	A 0.2 SIV increase make northern Sahel suitable	No change in suitability	About 0.1 decrease in SIV but still suitable	About 0.1 SIV increase makes Sahel suitable	About 0.1 decrease in SIV but still suitable	About 0.2 SIV decrease west respectively	Above 0.2 SIV decrease but still suitable

Table 3.3: Projected changes in crop suitability over West African AEZs at different future window periods (Contd.).

Crops	**Near Future (2031–2050)**			**Mid-Century (2051–2070)**			**End-Century (2081–2100)**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Mango	No change in suitability	No change in suitability	No change in suitability	About 0.1 decrease in SIV but still suitable	About 0.1 decrease in SIV but still suitable	About 0.1 increase in SIV but still unsuitable	About 0.2 SIV decrease but still suitable	About 0.2 SIV increase but still unsuitable	About 0.2 SIV increase but still unsuitable
Orange	About 0.1 SIV increase	About 0.1 SIV increase	No change in suitability	Same as near future period	Same as near future period	Same as near future period	About 0.2 SIV decrease but still suitable	About 0.2 SIV decrease but still suitable	Same as near future period
Pineapple	No change in suitability	About 0.2 SIV decrease but still suitable	No change in suitability	About 0.1 decrease but still suitable	About 0.3 decrease but still suitable	Same as near future period	About 0.4 decrease but still suitable	About 0.4 SIV decrease but still suitable	Same as near future period
Tomato	About 0.1 decrease but still suitable	About 0.1 decrease but still suitable	No change in suitability	About 0.3 decrease but still suitable	About 0.3 SIV decrease but still suitable	Same as near future period	About 0.4 decrease but still suitable	About 0.4 SIV decrease but still suitable	Same as near future period
Cowpea	No change in suitability	No change in suitability	A 0.2 SIV increase make southern Sahel suitable	Same as near future period	Same as near future period	Same as near future period	Same as near future period	About 0.1 decrease in SIV but still suitable	Same as near future period
Groundnut	No change in suitability	No change in suitability	A 0.2 SIV increase makes southern Sahel suitable	Same as near future period	Same as near future period	Same as near future period	Same as near future period	About 0.1 decrease in SIV but still suitable	Same as near future period

The Ecocrop suitability simulation by mid-century (2051–2070) shows a projected increase in the magnitude of change of SIV and spatial suitability distribution of suitable areas compared to the past climate for the different crop types. The projected spatial suitability distribution for mid-century shows a similar spatial pattern as the near future period (2031–2050) with an increase in the suitability spatial extent and the magnitude of change in SIV. For cereals (Figure 3.2, column 3), the projected change is like the spatial suitability pattern as the near future period except for the spatial extension in the suitable area further north in the central Sahel zone for pearl millet. In contrast, a decrease in the suitable area in the western Nigeria for pearl millet and north-west Nigeria for maize and sorghum. The legume (Figure 3.3, column 3) crops show a similar projected suitability spatial pattern as the near future period except a projected decrease in SIV of about 0.1 and 0.2 of the suitable area is expected in the south-west Chad Republic in the eastern Sahel zone for the groundnut and cowpea, respectively. For the root and tubers (Figure 3.4 column 3), a decrease of about 0.2 SIV is projected for both the plantain and yam but with a similar spatial suitability pattern as shown for the near future period. However, for cassava about 0.2 decrease SIV is projected over the guinea-Savanna zone but the area remains suitable. For the fruit and horticulture crops (Figure 3.5, column 3), there are no changes in the projected spatial suitability pattern as observed in the near future period by mid-century. However, there is an increase in the magnitude of change of SIV from 0.1 to 0.2 and 0.2 to 0.3 for the tomato and pineapple, respectively. All the projected suitability changes are statistically significant at 95% confidence level for cassava, maize and mango and are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change) by mid-century (2051–2070).

The projected increase in global warming will lead to increasing the magnitude in the projected change for the crop SIV and spatial suitability distribution across different crop types by the end of the century (2081–2100). Cereal (Figure 3.2, column 4) as projected will be severely affected as more areas becomes less suitable by the end of the century. For legume (Figure 3.3, column 4), the Savanna zone will be less suitable with a decrease of about 0.1 in SIV while a decrease of about 0.2 SIV is expected along the eastern Sahel zone for groundnut as well as the south coast of Nigeria. Cowpea as projected will be more affected with a decrease of about 0.2 SIV in the northern savanna in the southern Chad Republic and Nigeria with its boundary with south-east Niger Republic in the Sahel and south-west Mali in the western Sahel zones. A decrease up to 0.2 in SIV is expected in the southern Sahel for cereal except maize with an increase of about 0.2 in the central southern Sahel zone. The root and tubers (Figure 3.4, column 4), show a similar spatial pattern for the decrease in the suitable area as the near future period and mid-century but with an increase in the SIV magnitude of about 0.2, 0.3 and 0.4 for yam, plantain and cassava, respectively. The fruit and horticulture crops (Figure 3.5, column 4) shows further reduction in the suitable area compared to the near future period with an increase up to 0.4 SIV for the horticulture crop. The Guinea-Savanna will become less suitable with a decrease of 0.1 and 0.2 SIV for orange and mango, respectively. All the projected suitability changes are statistically significant at 95% confidence level for cassava, maize and mango and are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change) by the end of the century (2081–2100).

3.3.4. Impact of CCD on Crop Planting Month over West Africa

At all the three future climate windows, the Ecocrop projected change on the planting month varies for different crop types across the different AEZs of West Africa (Figures 3.6–3.9). The impact of CCD resulted in an early or late/delay in the PM for different crops and increases in magnitude across the three zones as described in Table 3 below. It is worth stating that the change in PM describes a change in the best three planting months under the three future windows.

In the near future, cereals crops, pearl millet and sorghum are projected to experience a one-month delay over the region and up to 0.2 along the west coast of Sierra Leone to Liberia and the south coast of Nigeria (Figure 3.6, column 2). In contrast, a two-month delayed planting is expected over the Savanna-Sahel zone for maize. For the legumes crops, cowpea and groundnut (Figure 3.7 column 2, see Table 3.3) no projected change in the PM compared to the past climate is expected over the regions except about one-month delay (i.e., from June to July) in planting over Sierra-Leone and Liberia in the Guinea zone and the southern Sahel zone from Senegal to Chad Republic compared to the planting month (June) over the area. For the root and tuber (Figure 3.8 column 2), about three to four months early (February/March) the planting is projected for cassava in the near future as compared to June/July, the PM from the historical climate across the region except the north-east Nigeria and the coastal areas (Figure 3.8, Table 3.3). No change in the PM is expected in the near future over the coastal areas but about three months delay in planting is projected in the north-eastern part of Nigeria. No change in the PM is projected for plantain, an annual crop which can be planted anytime of the year while a 3–4 months delay is expected for yam except in western Guinea-Savanna and the south coast of Nigeria. For fruits and horticulture (Figure 3.9, column 2), no projected change in the planting month is expected for tomato and pineapple except a two-month delay over Liberia. Early planting between one to two months is expected in the Guinea-Savanna zone and about three-months delay in the planting of orange in the southern Sahel zone. About two-months and up to four-months delay in planting is projected for mango in the Guinea-Savanna zone and the northern Sahel zone, respectively while a two-month early planting of the crop is expected in the southern Sahel zone. The projected change is consistent for all crops as 80% of the simulation agree to the sign of change.

Table 3.4:Projected changes in time of planting (crop planting months) over West African AEZs at different global warming levels.

Crops	**Near Future (2031–2050)**			**Mid-Century (2051–2070)**			**End-Century (2081–2100)**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Cassava	Delayed planting for one month	Early planting by four months	Not applicable	Same as near future period	Same as near future period but for more area	No planting date	Same as near future period	Same as near future period	No planting date
Plantain	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Yam	On month delayed planting	No change in planting date	No change in planting date	Same as near future period	Same as near future period	No change in planting date	Same as near future period	Same as near future period	No change in planting date
Maize	Three months delayed planting	Four months early and delayed planting in east and west respectively	No change in planting date	Same as near future period	Same as near future period	No change in planting date	Same as near future period	Same as near future period	No change in planting date
Pearl millet	One-month delayed planting	Two months delayed planting	Two months delayed planting	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period
Sorghum	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Mango	Delayed planting for two months	Early planting by four months	One-month delay in southern Sahel zone	Same as near future period	Same as near future period but for more area	No planting, date	Same as near future period	Same as near future period	No planting date
Orange	One-month delayed planting	No change in planting date	No change in planting date	Same as near future period	Same as near future period	No change in planting date	Same as near future period	Same as near future period	No change in planting date

Table 3.5:Projected changes in time of planting (crop planting months) over West African AEZs at different global warming levels (Contd.).

Crops	**Near Future (2031–2050)**			**Mid-Century (2051–2070)**			**End-Century (2081–2100)**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Pineapple	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Tomato	One-month delayed planting	No change in planting date	No change in planting date	Same as near future period	Same as near future period	No change in planting date	Two months delayed planting	One-month early planting	No change in planting date
Cowpea	One-month delayed planting	Two months delayed planting	Two months delayed planting	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period
Groundnut	No change in planting date	No change in planting date	No change in planting date	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period	Same as near future period

By mid (2051–2070) and end of the century (2081–2100), most crop types show a similar spatial pattern in the planting month as observed in the near future but with an increase in the magnitude of the delay or early planting period (Figure 3.6–3.9, column 3–4). For example, cereal crops show a similar spatial pattern as projected for the near future for sorghum and pearl millet by mid-century (Figure 3.6, column 3) and the end of the century (Figure 3.6, column 4) except over Liberia and south coast of Nigeria for pearl millet. These areas are expected to experience a 2–3-month delay in planting. Legume crops, cowpea and groundnut show similar characteristics of no projected change in the PM as the near future period but for an increase in the magnitude a delay period in the south coast of Nigeria and southern Liberia. A delay in planting from one to two months is expected from Sierra-Leone to Liberia and over the south coast of Nigeria for cowpea by mid-century (Figure 3.7, column 3) and up to three months by the end of century (Figure 3.7, column 4). A two-month delay in the PM is projected over southern Liberia and a one-month delay in the southern Sahel zone by mid and end of the century (Figure 3.7, column 3–4).

For the root and tuber crops (Figure 3.8, column 3–4), about a four-month delay in planting is projected over the Savanna zone except the western area of the zone and in the central Guinea zone by mid-century for yam (Figure 3.8, column 3). A similar pattern is projected by the end of the century for crop (Figure 3.8, column 4). No change in the planting period is projected for plantain because it is annual crop over these two periods. For cassava a month delay planting by mid-century and up to two-months by the end of the century is projected in the western Guinea-Savanna zone while an early planting is expected in other parts of the Savanna zone and north of the Guinea zone over the two-climate change period. For the fruit and horticulture crops, there is no change in the PM for pineapple being an annual crop. A one-month PM delay is projected for tomato over the region and up to two-months over Liberia by mid and end of the century. However, a projected two-month early planting is expected by the end of the century in the southern Sahel zone. For fruit crops, a four-month early planting compared to the historical climate is projected in the Guinea-Savanna zone with a delay of about three-months in the south Sahel by mid-century. By the end of the century, an early planting of about four-month early compared to the historical climate is projected over the region for orange. Similarly, a two-month early planting is projected for mango in the southern Sahel zone for mid and up to three-months by the end of the century. In contrast, a delay in planting of about two-three months is expected over the Guinea-Savanna zone and up to four-months in the northern Sahel zone. All the projected changes are consistent for all crops as 80% of the simulation agree to the sign of change over the two climate periods.

3.3.5. Trends in Projected Crop Suitability and Crop Planting over West Africa

We used the Theil-Sen slope to evaluate the trend in the projected suitability and month of planting for the crop types for the near future, mid and end of the century over West Africa (Tables 3.4 and 3.5). The trend describes the rate of increase and decrease of the suitable area and SIV with increasing warming over the three-window month. In general, the trends are all positive and the number represents the magnitude of the trend between the projected change in suitability and past climate. All the crop types show an increasing trend in the projected change in the crop suitability compared to the past climate from the near future to the end of the century when compared to the past climate except for yam (Table 3.4). The projected change in the suitability index value of suitable areas for tomato showed the highest magnitude in trend value from 1.219 in the near future month to 1.997 by the end of the century. Compared to other crops, our analysis showed that there was a decrease in trend magnitude (from 0.873 in the near future to 0.779 by end of the century) for yam in the projected suitability change with increasing warming across each time of month from the near future to the end of century over West Africa. Additionally, there was decrease in the magnitude of the trend value between the near future and mid-century suitability projected change for orange but later increased at end of the century. Moreover, there was no magnitude change in trend value for the projected change in the suitability of cowpea for the near future month and mid-century but there was increase in the trend of the projected change for the crop by the end of the century. All the trends are significant at 95% level.

Table 3.6: Trends in the projected change in suitability over West Africa for the near future, mid and end of the century periods for different crops.

Crops/Period	2031-2050	2051-2070	2081-2100
Cassava	1.053	1.141	1.497
Cowpea	1.000	1.000	1.002
Groundnut	1.000	1.001	1.030
Maize	1.007	1.021	1.082
Mango	1.013	1.046	1.137
Orange	0.981	0.974	1.089
Pearl millet	1.007	1.022	1.057
Pineapple	1.061	1.216	1.580
Plantain	1.017	1.025	1.215
Sorghum	1.007	1.018	1.032
Tomato	1.219	1.421	1.997
Yam	0.873	0.784	0.779

Our Theil-Sen slope trend analysis also shows positive trend values in PM for all the crops. In general, there is an observed decrease in the magnitude of trend value for projected changes in the planting month compared to the past climate for the different crop types except for orange (Table 3.5). For Orange, an increase in trend value is projected for the planting month with increasing warming levels crops. Our trend analysis test show there was no change in the trend value for the projected change in planting month for plantain, pineapple (1.000) and for sorghum for the near future and mid-century month (1.000). All trends are significant at 95% level.

3.4. Discussion

3.4.1. Crop Type Sensitivity to CCD and Impact on Food Security

Horticulture, cereals, root and tubers (hereafter HCRT) crops, respectively will be the most impacted by the climate change/departure impact from the historical variability in West Africa. All the five different crop types show a different response to the impact of the global warming induced CCD across the examined three-window month, near the future to the end of the century in West Africa. The variability in the response of the different crop types to CCD is very cardinal to the agricultural production and food security in the region. HCRT are the most negatively affected with decreasing suitability across the three AEZs of West Africa due to the impact of the climate change compared to the legumes and fruit crops. In terms of sensitivity, the HCRT crop suitability show a negative linear relationship with increasing global warming over the region except for cereals with a positive linear relationship in the southern Sahel zone. The negative linear relationship is observed notably over the Guinea-Savanna zone for the HCRT resulting in a decrease in the crop suitable area with increasing warming across the three months examined. The projected negative linear relationship due to an increase in global warming may result in a decrease in the yield of these crop types over West Africa due to a decrease in the crop suitable land (Roudier et al., 2011; Ahmed et al., 2015). For example, previous studies (e.g. Lobell et al., 2008; Sultan et al., 2014) have revealed that the impact of climate change will result in a decrease in the yield of cereals by 20% in the near future month over West Africa.

Table 3.7:Trends in the projected change in the month of planting over West Africa for the near future, mid and end of the century periods for the different crops.

Crops/Period	**2031-2050**	**2051-2070**	**2081-2100**
Cassava	1.125	1.171	0.974
Cowpea	0.972	0.957	0.887
Groundnut	0.969	0.952	0.857
Maize	1.000	0.990	0.950
Mango	1.000	0.976	0.909
Orange	1.000	1.111	1.930
Pearl millet	0.980	0.959	0.912
Pineapple	1.000	1.000	1.000
Plantain	1.000	1.000	1.000
Sorghum	1.000	1.000	0.944
Tomato	0.938	0.900	0.851
Yam	1.000	0.924	0.909

Additionally, the result is in line with the findings of (Jarvis et al., 2012b) that there will be a decline in the suitability and suitable cultivated areas for cassava due to a result of the temperature increases but the crop will remain suitable over the region. In addition, our result also agrees with Malhotra (2017) findings that increasing warming will lead to a decrease in the availability of the suitable land for the cultivation of horticulture with a direct implication on the horticultural production. This agrees with Williams et al. (2018) that the variability in the climate will lead to a reduction in the yield quantity of pineapple in Ghana which is one of the key producers of pineapple, which may be linked to the decrease in the suitable areas and SIV as projected in this study.

The projected impacts of CCD on crop suitability will further compound the challenge of food security in West Africa. This is in line with past findings that climate variability and change in the coming decades will further threaten food security in sub-Saharan Africa notably West Africa, a region that plays a major role in the agricultural production (IPCC, 2013; OECD/FAO, 2016). West Africa for about 24 years mainly accounts for about 60% of the total value of agricultural outputs within Africa (OECD/FAO, 2016). However, the story has not been the same since 2007 due to instability in the agricultural production over the region and this has been a source of concern (OECD/FAO, 2016). As a result, the projected decrease in crop suitability due to a reduction in the suitable area for crop cultivation coupled with the projected delay in the month of planting will both strongly have a negative impact on the crop yield and agricultural production. This may further plunge the plan for food security in the region into a mirage.

3.4.2. Impact of CCD on Spatial Suitability Distribution

The impact of CCD will lead to a projected variability in the spatial suitability distribution across the three AEZs in the three future months and different crop types. The magnitude of deviation due to the increase in warming may influence the suitability over the zones as well as crop sensitivity to the projected change in the climate. The crop growth and yield are directly proportional to the climate-crop threshold i.e., climate suitability/threshold (Luo, 2011). It is important to note that each crop has their climatic or suitability threshold for healthy growth, development and optimal yield and that future changes/departure in the climate generally has a reaching impact on the yield of the crop. This is further buttressed by our finding that CCD may lead to future constraint in the available cultivated area in the Guinea and southern Savanna zones of West Africa. On the other hand, it tends to provide an opportunity in the northern Savanna extending to the southern Sahel.

The projected spatial constraint in the suitability and cultivated area will strongly affect the crop production and yield over West Africa. The Guinea-Savanna zone provides and significantly contributes to the agricultural production over the region and a large proportion in the continent (OECD/FAO, 2016). For example, about four of the five different crop types (except the legumes) examined in the study is and will be significantly affected with the projected decrease in SIV and reduction in the cultivated area of the crops. This projected decrease in SIV and the reduction in the spatial distribution of suitable areas for cultivation of major crops such as cassava and the horticulture crops such as pineapple pose a great challenge to the economy of most countries and further raises the challenge of food security in the region. The challenge of food security due to projected decrease in suitable area for cultivation may compound the climatic stress over the region. This is because the projected limited available land for cultivation are not enough to meet the present food demand and increase in food production may become a mirage with the projected increase in the population over the region by mid-century, 2050 (UNDP, 2015; FAO, 2018).

On the other hand, crop suitability due to CCD from historical variability is projected will lead to an increase in SIV and suitable area notably in the Southern Sahel. The increase in suitable areas provides an opportunity for more suitable areas in the region for the cultivation of cereals, legumes and mango in the southern Sahel zone (12–14 °N), plantain and yam in the Savanna zone as well as the legume crops in the central savanna zone of West Africa. The projected increase into the Sahel agrees with the previous finding for maize in the Sahel zone with CCD. This shows that the crop spatial suitability distribution and productivity are highly sensitive to variations in the climate such that a departure of the future African climate from the recent range of historical variability will have the most devastating effect on agriculture over the continent (Lobell & Gourdji, 2012; Taylor et al., 2012; Zhang & Cai, 2013).

3.4.3. Implication for Socio-Economic Development and Strategy Policy

The above result provides a basis for developing the policy and strategy to reduce future crop loss due to a lack of suitable land and risks of food security over West Africa. At the same time, it advocates for a more proactive response to increase resilience and adaptive options via the urgency and timing of adaptation. For instance, the analysis of crop suitability indicates that a greater proportion of suitable land areas in the West African region may become less suitable or unsuitable in the future from CCD due to global warming, which may enhance a decrease in the crop yield and agricultural production of some crop. On the other hand, the analysis showed an expansion of the suitable area into the Sahel for the cereal and legume crops with CCD, which provide future opportunities for more suitable areas for the cultivation of one of the most staple crops, maize. This will have both positive and negative impacts on regional development and economic activities (e.g. regional trade and international relation in terms of exports and importing goods). The impact of CCD through an expansion in suitable area may lead to an improved yield or production for some crops like maize in the region for countries. This increase in production may lead to an increase in socio-economic activity and regional/ international trade between countries with expansion in cultivated area (exportation leading to an increase in revenue) and those with decrease in suitability of cultivated area and need to meet the their food demand as observed across the three AEZs of West Africa. This implies shift in crop suitability may lead to regional tradeoffs in crops among countries i.e. the land lost to cassava in a country may be that gained for groundnut in the other thereby influencing soico-economic activity within the region. However, the projected change in suitability also suggests that a well-planned land use change (through the urgency of adaptation to the CCD) could help reduce the impacts of CCD on the crop yield and food security in the region. Hence, there is a need for the formulation of a strategic policy that can accommodate or encourage such a land-use change. A strategic policy is also required more importantly for the new opportunities such as an expansion into the Sahel for maize and the other crops that may arise out of the impact of CCD over the region. Hence, the results can guide policymakers on how to prioritize their adaptation plan in terms of the urgency of response and redefine mitigation measures to the future impact of CCD on the crop suitability and planting season over West Africa.

3.5. Summary and Conclusions

In investigating the impact of CCD on the crop suitability and planting month over the entire West African region, we analyzed 10 CMIP 5 GCM datasets downscaled by CORDEX RCM, RCA4 for five different crop types, cereal (maize, pearl millet and sorghum), fruit (mango and orange), horticulture (pineapple and tomato), legume (cowpea and groundnut) and root and tuber (cassava, plantain and yam). The summary from our study are as follows:

The projected changes in the temperature may lead to an increase between 1–4.5 °C for the minimum and mean temperature over West Africa from the near future to the end of the century. A change of about 10 mm in rainfall is projected over the western Guinea-Savanna zone and no major changes in other parts of the region and up to 25 mm along the coastal areas (west coast of Sierra-Leone to south-west Ghana and the south coast of Nigeria) for the near future and mid-century. A projected decrease up to 25 mm is expected over the region and up to 35 mm over the coastal area (from the west coast of Gambia to north Liberia) by the end of the century.

Addressing our main objective, the Ecocrop simulated spatial suitability distribution of the crops shows higher suitability are to the south of 14 °N while a lower suitability is to the north. The marginal suitability line (around 12–14 °N) shows the transition between the higher and lower suitability of the crop. Results show that the horticulture crops, pineapple and tomato, respectively are the most negatively affected by the impact of CCD from the historical variability over the region. There is a projected constraint showing a negative linear correlation with increasing warming in the cultivation of most different crop types except for cowpea in the Guinea-Savanna AEZs (south of 14 °N) by the end of the century due to an increasing reduction in the suitable area and crops suitability index value due to the climate departure although most of the crop remains suitable. The impact of CCD will provide opportunities for more suitable areas in the southern Sahel zone for cereals, mango and legumes crops showing a positive linear correlation with increasing warming thus creating more land for cultivation, which can in turn increase the yield and production of the crops. Generally, a projected delay of 1–4 months is expected for most of the crop types with CCD except for orange and cassava as well as maize in the Savanna zone. No projected changes are observed for plantain and pineapple, mainly because they are annual crops.

Statistically, we demonstrated that over 80% of the simulations agree with the sign of the projected change for all the crop types due to the CCD and the changes are statistically significant at 95% confidence interval for maize, cassava and mango. Additionally, we showed there is an increasing trend in the projected crop suitability for all crops except yam with a decreasing trend as seen from the trend magnitude due to CCD from the historical variability while a decreasing trend is projected for the future change in the month of planting of the crops. All trends values are positive

Despite our analysis, the results of this study can be improved and applied to reduce the future impact of crop suitability and risks of food security over West Africa in many ways. For instance, future studies may investigate the impact of CCD on the crop suitability and planting season over the region using more RCMs with different forcing GCMs other than only RCA4. This may help resolve the challenge of uncertainty in the future simulation of the crop suitability and planting season. In addition, the results of the study will be more robust and improve our knowledge on the impact of CCD and its influence on the crop suitability and planting season over West Africa. Further studies on how to reduce the uncertainty will improve the credibility and application of the results. Nevertheless, the present work shows the impact of CCD on the crop suitability and planting season using GCMs downscaled with RCMs. This establishes a premise for future work in advancing our knowledge into how CCD influences the crop suitability and planting season in West Africa.

In conclusion, the application of the concept of CCD in this study has demonstrated future changes in how the crop suitability and planting season can be analyzed. The application of CCD established the impact of climate change on crop suitability over West Africa and further identified spatial variability in the future suitability showing that horticulture, cereal, root and tubers crops will be most negatively affected by the impact of CCD in West Africa. It also identifies the three best planting months in a growing season and the changes in the planting time is about four-month delay in the planting season for most crops but early planting for cassava, orange and maize but only in the savanna zone. The application of CCD aims to underpin future works to advance the study of future changes in crop suitability and planting in any region of the world. This type of analysis is important for adaptation options and planning for future changes in the crop suitability and planting period to improve food security.

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The next chapter investigates how different Global Warming Levels, GWL1.5^{o}C, GWL2.0^{o}C and GWL3.0^{o}C will influence the projected changes in suitability and planting over West Africa in the future climate. The chapter highlights the importance of recognising and limiting global warming to less than 1.5^{o}C to improve food security over West Africa. This chapter, therefore, addresses objective 3.

CHAPTER 4

Investigating the potential impact of 1.5, 2 & 3^{o}C global warming levels on crop suitability and planting season over West Africa

How will the projected Global Warming Levels, GWLs (1.5, 2.0 and 3.0) influence Crop suitability and Planting season over West Africa?

Specific Questions:

- What is the impact projected GWL1.5, 2.0, 3.0 on crop suitability and planting season in West Africa?
- How will the inability to meet the NDC plan and increase up to 3^{o}C affect crop suitability over West Africa?
- What is the projected trend in crop suitability and planting season under the projected three GWLs?

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Abstract

West African rainfed agriculture is highly vulnerable to climate variability and change. Global warming is projected to result in higher regional warming and have a strong impact on agriculture. This study specifically examines the impact of global warming levels (GWLs) of 1.5, 2 and 3°C under RCP8.5 relative to 1971-2000 on crop suitability over West Africa. We used 10 Coupled Model Intercomparison Project Phase5 Global Climate Models (CMIP5 GCMs) downscaled by Coordinated Regional Downscaling Experiment (CORDEX) Rossby Centre’s regional Atmospheric model version 4, RCA4, to drive EcoCrop, a crop suitability model, for pearl millet, cassava, groundnut, cowpea, maize and plantain. The results show Ecocrop simulated crop suitability spatial representation with marginal cropping suitability line occurring at approximately 14°N for all crops except for plantain (12°N). Higher and lower suitability are observed to the south and north of the 1971-2000 marginal suitability line respectively. The model also simulates the best three planting months with the growing season from September-August over the past climate. Projected changes in suitability under the three GWLs suggest a spatial suitability expansion for legume and cereal crops, notably in the central southern Sahel zone; root and tuber and plantain in the central Guinea-Savanna zone. In contrast, projected decreases in the suitability index are predicted south of 14°N for cereals, root and tuber crops; nevertheless, the areas remain suitable for the crops. Planting month delays of from 1-4 months is projected over the region under the three GWLs for legumes, pearl millet and plantain. For cassava and maize, two months’ delay in planting are projected in the south, notably over the Guinea and central Savanna zone with earlier planting of about four months in the north in the Savanna-Sahel zones. The effect of GWL2.0 and GWL3.0 warming in comparison to GWL1.5°C are most dramatic on cereals and root and tuber crops, especially cassava. All the projected changes are statistically significant at 99% confidence level. There is also an increasing trend in the projected crop suitability change across the three warming levels except for cowpea. This study has implications for improving the resilience of crop production to climate changes, and more broadly, for food security in West Africa.

Keywords: Global warming levels, crop suitability, planting season, CORDEX, West Africa

4.1. Introduction

Rainfed agriculture is crucial to the economy and livelihood of the inhabitants of West Africa (Omotosho & Abiodun, 2007; Roudier et al., 2011; Diasso & Abiodun, 2017) . The agricultural sector employs more than 65% of the active labour force in the region, with the majority practising subsistence rain-fed farming (Benhin, 2008; Schlenker & Lobell, 2010; Roudier et al., 2011). The sector is also responsible for 75% of Sub-Saharan Africa (SSA) domestic trade (McCarthy, J et al., 2001; World Bank Report., 2013) and contributes significantly to the economy via a Gross Domestic Product (GDP) of up to 20% (World Bank Report., 2009; Schlenker & Lobell, 2010; Roudier et al., 2011). Like other regions of Africa, West Africa has suffered devastating effects in the last few decades from climate change impacts via rainfall, variability and droughts due to global warming (Sarr, 2012; Diasso & Abiodun, 2017). Thus, further warming over the region could worsen the current climatic stress on agricultural production, the main source of livelihood of the inhabitants.

Global mean surface temperature has increased by approximately 1^{o}C above pre-industrial levels and is likely to rise to 1.3-4.8^{o}C by 2081-2100 (IPCC, 2013, 2018). It is projected that the average temperature increase will be more intense in Africa than the rest of the globe (Solomon et al., 2007; Sarr, 2012). For the West African region, observed temperatures have increased between 0.2 and 0.8 since the end of 1970s a trend which is stronger with minimum temperature and faster than global warming (Sarr, 2012). There has been about 3-4^{o}C increase in mean temperatures since the 1980s and this increasing trend is projected to continue rising well into the end of century under greenhouse gas emission scenarios (A2 and B2) (Sarr, 2012). This trend is significant and much higher than the global warming trend (Sarr, 2012). Furthermore, other studies have revealed that an increase in global warming will result in the deviation of the mean temperature from the historical variability leading to new climate regime over the continent, particularly West Africa (Hawkins & Sutton, 2012; Mora et al., 2013). This deviation from historical variability was reaffirmed by Mora et al. (2013) which went a step further to show that the mean temperature over West Africa will move outside the bounds of historical variability in the next two decades earlier before the global mean temperature thus making the region a hotspot of the impact of global warming. In addition, a World Bank report revealed that 2-4^{o}C of warming poses a threat to agriculture and food security in sub-Saharan

Africa (World Bank Report., 2013). This projected warming is expected to affect the agricultural sector by a reduction of up to 50% in crop yield and 90% in revenue by the end of the century (IPCC, 2013; World Bank Report., 2013). Thus, knowing what the projected impacts of 1.5-3^{o}C warming above pre-industrial level on crop growth suitability over West Africa is of great importance.

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement aims to limit global average temperature rise to 'well below 2^{o}C above pre-industrial levels' and to 'pursue efforts' to limit it to 1.5^{o}C (UNFCCC, 2015) and the scientific community has since explored methods to help achieving this goal (IPCC, 2018). The signing of this Agreement was hinged on the submission of the Intended Nationally Determined Contributions (INDC) documents by each member country stating their plan for addressing climate change beyond 2020 by limiting global mean temperature below 2^{o}C (Rogelj et al., 2016). The INDC document, now Nationally Determined Contribution (NDC), after the Paris Agreement, addresses issues such as avoiding, adapting to, coping with climate change challenge (Rogelj et al., 2016; Hof et al., 2017). Although, the aim of the Paris Agreement, as expressed in the NDCs is to limit global warming to 1.5^{o}C and well below 2.0^{o}C, they are inadequate to do so. Furthermore, the trends in CO_2 emission indicates an urgent decline in global emission is crucial to the possibility of reducing warming below 2^{o}C (Luderer et al., 2013; Rogelj et al., 2013) while about two-third of the available resource to keep warming to below 2°C have already been emitted (Meinshausen et al., 2009; IPCC, 2014). Thus, the NDCs would likely mean that global temperatures may increase by 3^{o}C or more; below the necessary emission reduction consistent with 2^{o}C and 1.5^{o}C climate target (Rogelj et al., 2016; Hof et al., 2017). The impact of 1.5-2^{o}C warming is projected to be more pronounced in regions with low adaptive capacity and high exposure, such as West Africa (Mitchell et al., 2016; Rogelj et al., 2016; Schleussner et al., 2016). For example, in a tropical region like West Africa, holding temperature below 1.5^{o}C has a positive impact of limiting local yield reduction in wheat and maize (Schleussner et al., 2016). However, no previous studies have examined how the impact of these three different global warming levels, suggested by the IPCC tied to policy aspirations and goals, will affect crop mean suitability growth and planting months within a growing season in this region. In addition, no study has examined how the impact of the inability to meet the NDC plan and the potential of reaching a projected temperature increase up to 3^{o}C

(Mora et al., 2013; Rogelj et al., 2016) will affect crop suitability and agriculture over West Africa.

Given the global level significance of this threshold, and its particularly high exposure, the aim of this study is to examine the potential implications of the global warming levels (GWLs) 1.5, 2.0 and 3.0^{o}C on crop suitability and month of planting in West Africa. We examined how the differences between GWL1.5, 2.0 and 3.0^{o}C could influence crop growth suitability over West Africa to assess the benefit of limiting global warming. This information is important for developing timely adaptation strategies to improve crop yield and food security in the region. Section 2 describes the study area, the climate variables and crop data; it also gives an overview of the crop suitability model, Ecocrop used for the study. Section 3 describes Ecocrop suitability results for the historical climate, GWLs1.5, 2.0 and 3.0^{o}C and the difference between them. In section 4, the results from the study are discussed in relation to improving food security and adaptation strategies over West Africa. The concluding remarks are given in section 5.

4.2. Data and Methods

4.2.1 Study Domain

The study area is West Africa, which has rainfed agriculture as its mainstay economy. It ranges from latitude 2-20^{o}N and 20^{o}W to 20^{o}E (Figure 1). The region is divided into three agro-ecological zones namely, Guinea (4 - 8^{o}N), Savanna (8 - 12^{o}N) and the Sahel (12 - 20^{o}N) (Abiodun et al., 2012; Egbebiyi, 2016). The temperature gradient over the region increases to the north, while precipitation increases to the south in the region. The West Africa Monsoon (WAM) is the major system influencing the rainfall pattern in West Africa (Omotosho & Abiodun, 2007; Nicholson, 2013). The region provides a large amount of agricultural resources. However, due to its variability in rainfall patterns and low adaptive capacity, this region faces substantial risk from climate change.

Different parts of West Africa cultivate and grows different crops which contributes to the economy of the region. Major crops grown in the region include yam, plantain, banana, cassava, cocoa, rice, wheat, cowpea, groundnut, millet, maize, sorghum (Paeth, Capo-Chichi &

Endlicher, 2008; Jarvis et al., 2012b; Nelson et al., 2014; Sultan & Gaetani, 2016). For example, yam production in the region constitute about 91% of the global production. In Sub Saharan Africa (SSA), cassava remains the most important staple food crop in the region in terms of production due to its high resilience to drought (Jarvis et al., 2012b; Srivastava et al., 2016; Sultan & Gaetani, 2016). Sorghum and millet also account for about 64% of the cereal production in West Africa (FAOSTAT, 2014; Sultan & Gaetani, 2016). Maize adjudged to be the most important staple food in SSA provides about 20% of the calorie intake in the West African region (FAOSTAT, 2014; Sultan & Gaetani, 2016). Cash crops such as cocoa, oil palm and other crops such as plantain also contribute significantly to the region's economy.

4.2.2 Data

4.2.2.1 Historical and future climate datasets

For this study, three datasets were used: observations of present-day climate and the locations where crops are grown as observed from crop suitability model; Ecocrop output; modelled simulations of present and projected crop suitability driven by observed and projected climate data. The observation dataset was the 0.5^{o} x 0.5^{o} resolution monthly precipitation and temperature gridded dataset for the period of 1901 to 2016 obtained from the Climate Research Unit (CRU TS4.01, land only) University of East Anglia (Harris et al., 2014). This was used to evaluate the available bias corrected RCMs forced by 10 Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). The regional climate simulation was obtained from the Swedish Meteorological and Hydrological Institute, Linköping, Sweden Rossby Centre's regional atmospheric model (SMHI-RCA4, hereafter RCA4) (Samuelsson et al., 2011). The modelled climate data were used as inputs into the crop suitability model, Ecocrop (Hijmans et al., 2001). Six crops millet and maize (Cereals); cassava and plantain (Root and Tuber); cowpea and groundnut (legumes) were selected based on their economic importance in the region. The different datasets are defined in the following sub-sections.

Climate variables such as temperatures and rainfall are important climate variables used in determining the impacts of climate change at different scales (Cong & Brady, 2012; Mastrandrea et al., 2015) and have significant effect on crop yield (Abbate et al., 2004; Medori et al., 2012). While rainfall affects crop production in relation to photosynthesis and leaf area, temperature affects the length of the growing season (Olesen & Bindi, 2002; Cantelaube & Terres, 2005). For this study, we used the bias-corrected mean monthly minimum temperature (tmin), mean monthly temperature (tmean) and total monthly precipitation (prec). Data from 10 CMIP5 GCMs downscaled by RCA4 under RCP8.5 was used as input into crop suitability model (see Table 3.1) to present the influence GWL1.5, GWL2.0, & GWL3.0 on crop growth suitability over West Africa. RCP8.5 was used because it matches the current emission path in CO_2 increase and covers the range of three temperatures over the largest number of simulation ensemble members (Abiodun et al., 2018).

4.2.2.2 Ecocrop dataset

As a result of field experiments run across the world a database of crop thresholds has been developed. These crop thresholds describe the monthly suitability range of plant species against total monthly rainfall (prec.), monthly minimum temperature (tmin), mean temperature (tmean) and maximum temperature (tmax) over the length of its growing season (Dixon, Gulliver & Gibbon., 2001). The computation of optimal to non-optimal conditions based on this data, allows for the simulation of monthly crop suitability in response to monthly climatic variables. Ecocrop suitability model computes the relative suitability of a crop in response climate variables such as rainfall, temperature and length of growing season thus generating a suitability index score from 0 (unsuitable/non-optimal) to 1 (highly suitable/optimal) (Hijmans et al., 2001). See description of the suitability index in Table 4.1. Such division has been used in previous studies (e.g. Ramirez-Villegas & Thornton, 2015; Hunter & Crespo, 2018; Egbebiyi et al., 2019).

Table 4.1: A description of Ecocrop suitability index value (Adapted from Egbebiyi et al. 2019)

Suitability Index Value	Category/Description
0.0-0.2	Unsuitable
0.21-0.40	Very Marginally suitable
0.41-0.60	Marginally suitable
0.61-0.80	Suitable
0.81-1.00	Highly suitable

Although we understand that those thresholds will vary depending on crop varieties and location, the concept and the general validation of the thresholds makes it a suitable tool to assess different crop's suitability over large areas. Previous studies have reported a good agreement between climate change impacts projections from Ecocrop model and other crop models (Ramirez-Villegas, Jarvis & Läderach, 2013; Vermeulen et al., 2013; Challinor et al., 2014; Rippke et al., 2016). It should be noted that this study did not undertake any additional ground-truthing or calibration of the range of climate parameters preferred for the crops, and therefore the default EcoCrop parameters were assumed to be suitable. We therefore used this approach to evaluate crop suitability during the historical period and under different GWLs.

4.2.3 Simulation approach

We calculated the time of reaching 1.5, 2.0 and 3°C temperature warming over West Africa under RCP8.5 emission and a baseline period of 1971-2000 using the method of Deque *et al.* (2017) and Nikulin *et al*. (2018). A thirty-year running average was used to calculate the mid-year in which each global warming level (GWL) is reached relative to the pre-industrial baseline period of 1861-1890. The time of reaching GWL1.5, 2 and 3°C are projected as 2025, 2038, 2048 respectively (Nikulin et al., 2018). All the extracted and downscaled CMIP5 datasets by RCA4 were bias corrected with the observation based reference data WATCH-Forcing-Data-ERA-Interim (WFDEI) (Weedon et al., 2014). dataset. This is crucial because regional climate models often deviate from the observed climatological data hence the need for bias correction before the data is used for climate change impacts assessment such as hydrological modelling and agricultural impacts studies (Chen, Brissette & Lucas-Picher, 2015; Vrac, Noël & Vautard, 2016; Famien et al., 2018). We evaluated the bias corrected RCA4 historical data against CRU dataset. The results showed that there is a good agreement between observation dataset (CRU) and the bias corrected RCA4 monthly simulated past climate data for both temperature and precipitation over West Africa.

RCA4 bias corrected output has a strong correlation ($r \geq 0.8$ and $r \geq 0.6$) with the CRU datasets for temperature and total monthly rainfall datasets respectively. For example, the model replicates the CRU north-south temperature gradient, concurring with past studies (Gbobaniyi et al., 2014). RCA4 simulated total monthly rainfall realistically captures the essential features namely, both the zonal pattern and meridional gradient and the rainfall maxima over high topography (i.e. Cameroon Mountains and Guinean Highlands) as observed in CRU. This is in agreement with previous findings (e.g. Egbebiyi, 2016; Klutse et al., 2016; Abiodun et al., 2017). The performance of RCA4 in simulating the essential features of West African climate variables, temperature and rainfall, makes it suitable and gives confidence in the use of RCA4 for crop suitability simulation over the region. Also, the use of Ecocrop was based on past finding by Egbebiyi et al. (2019) that there is a good agreement between Ecocrop and MIRCA2000 dataset, a global monthly gridded data of annual harvested area around year 2000 (Portmann et al., 2010) for different crops. The study showed a strong spatial correlation ($r > 0.7$) for the examined crops in this study between Ecocrop and MIRCA2000 simulation. This gives some level of confidence in the use and performance of the Ecocrop simulation over the region.

The influence of GWL1.5, 2.0 and 3.0 on crop suitability and month of planting was assessed based on the methodologies described in Ramirez-Villegas et al. (2013). The resulting tmin, tmean and prec values from the 10 downscaled GCMs over the 30-year window at the time of reaching 1.5, 2 and 3^{o}C GWLs were calculated and used as input data into Ecocrop to compute the suitability index for each crop over West Africa. The results were then used to assess how each GWL will impact crop suitability across the Agro-Ecological Zones (AEZs) of West Africa. After the simulation, we computed the mean of the best three consecutive suitability index and planting window within the growing season across each grid point over the region for the historical and future analysis for the three GWL. This was done to remove the influence of unsuitable and marginally suitable months from the averaged suitability spatial distribution within a growing season and varies for each crop. The contour lines represent the regions with marginal to highly suitable mean crop suitability over West Africa over the historical period.

4.2.4 Assessing the robustness of climate change

We assessed the robustness of the projected climate change via the three GWLs based on two conditions. Firstly, at least 80% of the simulation must agree on the sign of change. Secondly, at least 80% of the simulations must indicate that influence of climate change is statistically significant, at 99% confidence level using a *t* test with regards to the baseline period, 1971-2000. When these two conditions are met then we consider the climate change signal to be significant. Previous studies (Abiodun et al., 2018; Klutse et al., 2018; Maúre et al., 2018; Nikulin et al., 2018) have all used the methods to test and indicate the robustness of climate change signals. We also assess the trend of change in crop suitability and month of planting at each global warming levels for each crop using Theil-Sen estimator or Sen's slope (Theil, 1950; Sen, 1968). The Theil-Sen slope estimator is non-parametric and applied in the estimation of magnitude of trend. It is more robust in estimating trends and can detect significant trends than the linear trend (Ohlson & Kim, 2015). Previous studies (Wilcox, 1998; Peng, Wang & Wang, 2008) have used the method in calculating trends.

4.3 Results

4.3.1 Simulated Crop Suitability in the Historical Climate over West Africa.

RCA4 simulated crop suitability from observed climatology inputs (CRU-Ecocrop) shows a decreasing mean suitability from south to north of West Africa (north-south suitability gradient) (Figs. 4.1 & 4.2, column 1). The spatial suitability representation reveals unsuitable or very marginal suitability to the north in the Sahel from latitude 14^{o}N with a low Suitability Index Value (SIV) value between 0.0 - 0.4. and higher suitability to the south in the Guinea-

Savanna AEZ with a high SIV (0.6 - 1.0) sandwiched by an ash/silver suitability line called the Marginal Suitability Line (MSL) with SIV between 0.41 - 0.59. In general, MSL are observed around latitude 14^{o}N in the Sahel AEZ (northern Sahel) for the simulation across the region except for the one observed around latitude 12^{o}N the boundary between the Sahel and Savanna AEZ. Ecocrop simulation of the crop types examined, legumes (cowpea and groundnut), root and tuber (cassava and plantain) and cereals (maize and pearl millet) are very suitable to the south of the MSL with no or low suitability to the north. Along the coastal areas, legumes and root and tuber crops are suitable along the south-west coast of Senegal to the south-west coast of Cameroon. For cereals, pearl millet is suitable along the west coast of Senegal and from the south coast Ivory Coast to the south coast of south-west coast of Cameroon while maize is suitable from the south coast of Ivory Coast to the south-west coast of Nigeria.

Ecocrop was also used in simulating the best planting months (PM) from range of month in a planting window within the Length of Growing Season (LGS) over West Africa for the historical climate (Figs. 4.3 & 4.4, column 1). LGS provides information on the start and end of growing season and can also assist in the simulation process of identifying the best PM within a possible planting window in a growing season over given location. The simulated planting month represent the first month of the best three month of the planting window and varies with crop types across the three AEZs of the region i.e. a simulation of April means April-June is the three best PM. For the legumes, our simulation shows January-July as the planting windows for legume crops, cowpea and groundnut over the region but January (January-March) and February (February-April) as the three-best PM for cowpea and groundnut respectively for large part of the region in the central Guinea and Savanna AEZs except over Sierra Leone, Liberia and south coast of Nigeria. The month of February (February-April) was simulated as the best three-month planting period in western and eastern Savanna-Sahel AEZs for cowpea while it was March (March-May) over the same area and period for groundnut. Along the coastal areas, July is simulated as the PM along the southwest coast from southern Sierra Leone to Liberia and the south coast of Nigeria and April along the southwest coast of northern Sierra Leone. For Groundnut April, is PM along the west coast of Guinea, May along the west coast of Sierra Leone and northern Liberia. August and March at south coast of Liberia and Nigeria respectively. December and January are the PMs along the south coast of Ivory Coast to Ghana for cowpea and groundnut respectively.

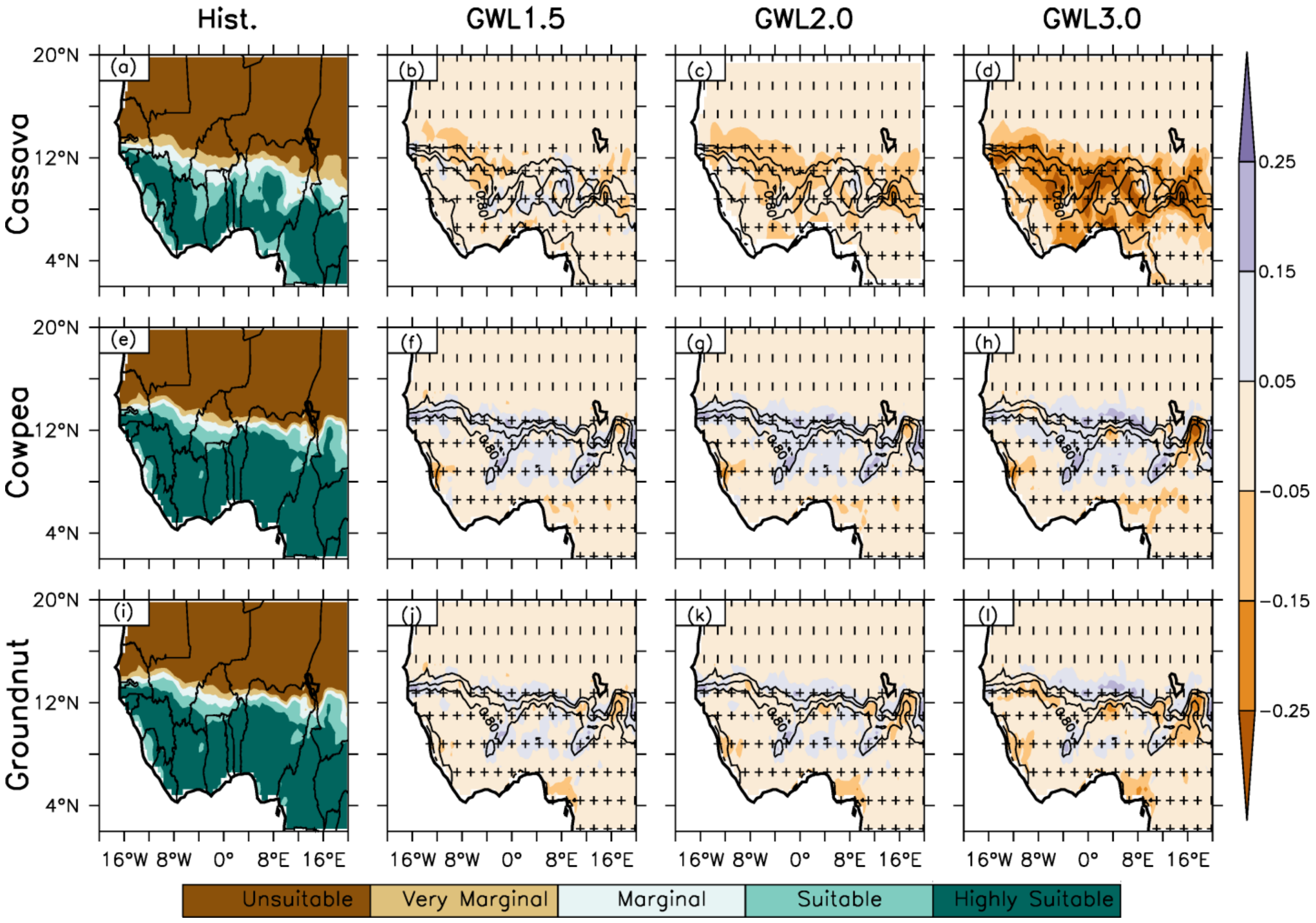

Figure 4.1:Spatial distribution of crop suitability as simulated by Ecocrop over West Africa for Hist. (column 1, left axis) and of change in crop suitability (right axis) at different global warming levels (GWL1.5, GWL2.0, GWL3.0) under RCP8.5 scenario (column 2-4) for cassava, cowpea and groundnut The white areas along the coast have no data. areas. (0.0> not suitable >0.2> very marginal >0.4> marginal >0.6> suitable >0.8> highly suitable). The contour lines represent crop suitability in the historical climate. The vertical strip (|) indicates where at least 80% of the simulations agree on the sign of the changes, while horizontal strip (−) indicates where at least 80% of the simulations agree that the projected change is statistically significant (at 99% confidence level). The cross (+) shows where both conditions are satisfied; hence, the change is robust

Root and tuber crops, plantain is an annual crop that can be planted in any month of the year (Figs. 4.3 & 4.4, column 1). The simulated PM is an overlay of the simulation of other months in the year as the crop may be planted in the suitable zones, Guinea and Savanna at any month/period of the year. For cassava, our simulation shows March (March-May) as the best PM generally over the region (Guinea-Savanna AEZs) except along the south-east coast of Ivory Coast to Ghana with PM in August, northern Guinea to Gambia and south east Senegal as well as the boundary of Benin Republic to north west Nigeria with PM in April. Our simulation for cereals shows Feb as PM for millet in the Guinea and March, April in the Savanna and Sahel AEZs respectively although there are exceptions. For example, in the central Savanna, from northern Benin Republic to north-western Nigeria, pearl millet PM is April while in the north-eastern Nigeria in the Sahel it is March compared to April in the Sahel zone. However, pearl millet PM is April in western Sahel along the south-west coast of Senegal, June along the west coast of Guinea and January along the south coast of Ivory Coast to the south-west coast of Nigeria. Maize PM is simulated to be in May (May-July) in the Guinea and southern Savanna zone while it is in December (December-February) in the northern Savanna into the Sahel zone.

These evaluations demonstrate that the (RCA4-Ecocrop) captures the variation in suitability with different crops across the three AEZs of West Africa in the present-day climate and can serve as a baseline for evaluating the changes in crop suitability under global warming levels of 1.5 to 3^{o}C over the region. The model also captures the growing season of crops over the region which varies with different months of the year.

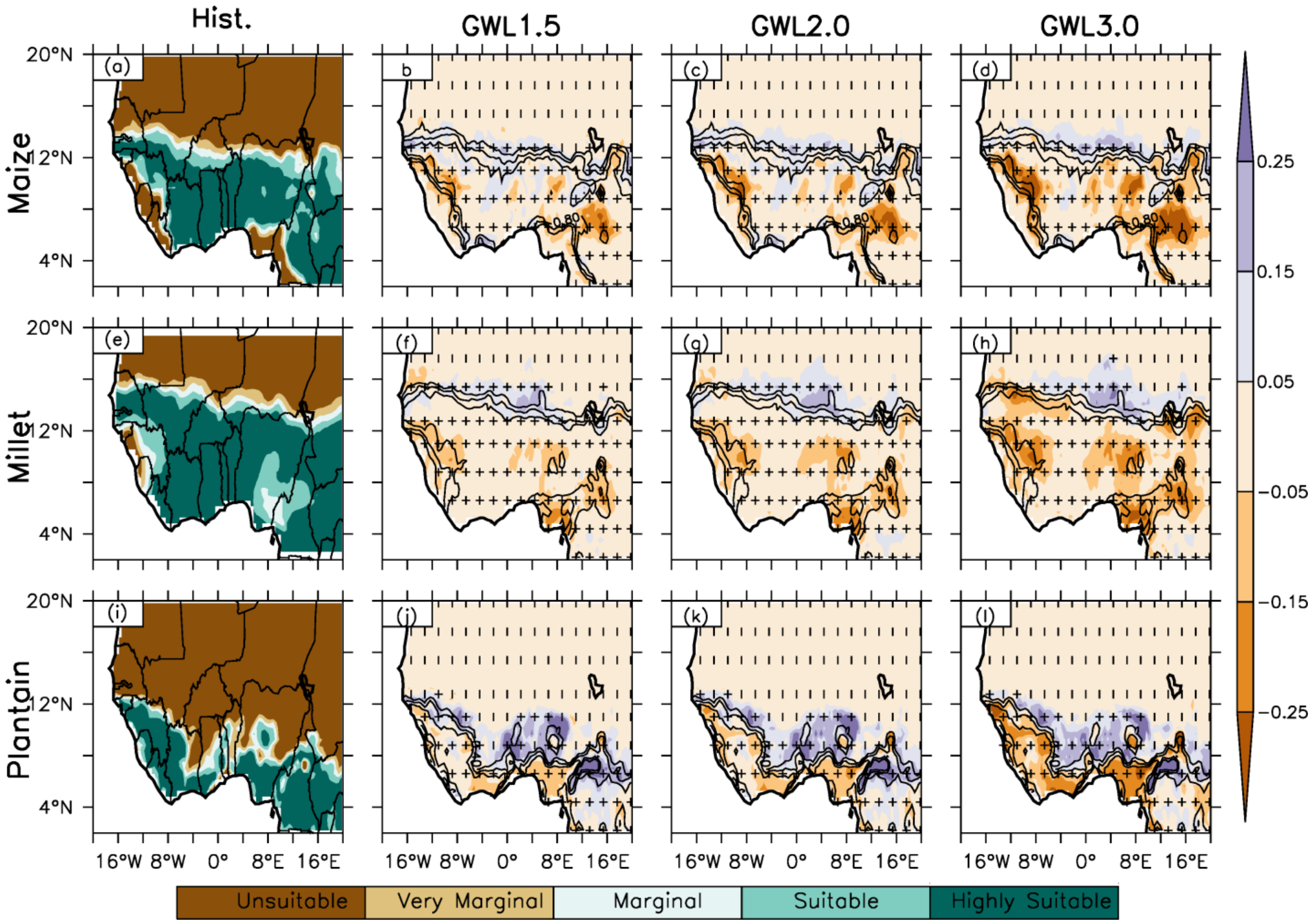

Figure 4.2: Spatial distribution of crop suitability as simulated by Ecocrop over West Africa for Hist. (column 1, left axis) and of change in crop suitability (right axis) at different global warming levels (GWL1.5, GWL2.0, GWL3.0) under RCP8.5 scenario (column 2-4) for maize, pearl millet and plantain. The white areas along the coast have no data. areas. (0.0> not suitable >0.2> very marginal >0.4> marginal >0.6> suitable >0.8> highly suitable). The contour lines represent crop suitability in the historical climate. The vertical strip (|) indicates where at least 80% of the simulations agree on the sign of the changes, while horizontal strip (−) indicates where at least 80% of the simulations agree that the projected change is statistically significant (at 99% confidence level). The cross (+) shows where both conditions are satisfied; hence, the change is robust.

4.3.2 Projected Changes in crop suitability under different GWLs over West Africa.

At all warming levels, Ecocrop projects a similar spatial suitability distribution pattern in crop suitability over West Africa (Fig. 4.1 and 4.2, column 1). For instance, projected spatial suitability distribution under the three warming levels show a similar decreasing pattern suitability index value (SIV) from south to north over West Africa with high and low suitability to south and north respectively. For all the GWLs, there is no projected latitudinal shift from 14^{o}N (north of the Sahel AEZ) and 12^{o}N (north of the Savanna AEZ) in the marginal suitability area as observed in the historical climate (See Appendix A). The projected spatial suitability distribution under all the GWLs show higher SIV (0.6-1.0) remains in the Guinea-Savanna zone which is south of the marginal suitability while low SIV (0.0-0.4) are to the north of the MSL as observed in the historical climate. Similarly, projected suitability pattern remains similar along the coastal areas under the three global warming levels as for the historical climate.

Ecocrop projected change in suitability varies for different crop types at all warming levels. However, the magnitude of the projected change varies over the region and increase with increasing GWLs (Figs. 4.1 & 4.2, column 2 and Table 4.2). The change in SIV means an increase or decrease in the suitability index value of crop of one AEZ and GWL. For example, a 0.1 SIV increase for a crop with SIV 0.4 (in the past climate) under GWL2.0 means an increase in SIV 0.5 and change from very marginal suitable area to being marginally suitable under GWL2.0. At GWL1.5 (Figs. 4.1 & 4.2, column 2 and Table 4.2), for legume crops cowpea and groundnut, projected suitability change is notably over the central Savanna AEZ (from the northeast Ivory Coast to northeast Nigeria) extending to the southern Sahel with a magnitude increase of 0.1 except over the south-western area of Chad Republic, which is east of southern Sahel. The projected change shows the suitability of legumes from very marginal to being marginally suitable in the southern Sahel. Generally, no change in suitability is projected over the Guinea AEZ and over the western and eastern Savanna except in the coastal areas. No change in suitability is also projected north of 14°N under GWL1.5. However, some areas with pockets of projected suitability decrease (SIV = -0.1 under GWL1.5) are observed in the southern part of Nigeria and south-western part of Sierra Leone for cowpea. Along the coastal area projected decrease in suitability are projected along the south-west coast of Sierra Leone and the south coast of Nigeria for cowpea and groundnut respectively. Cereals, maize and pearl millet, a projected increase about 0.2 in SIV is expected in the central Sahel under GWL1.5 for pearl millet while a 0.1 suitability increase in is expected over the Sahel while for maize around 12-14^{o}N and central Savanna. However, despite the projected suitability increase in the Sahel, the cereal crops will only be marginally suitable for cultivation except over the

Savanna AEZ. Also, pockets of suitability increase are projected in north eastern part of Nigeria, south of Burkina Faso in central Savanna and along the south coast of Ivory Coast in the Guinea for maize. In contrast, south of 14°N no change in suitability under GWL1.5 is projected but with some exceptions along the coast areas of Guinea and Nigeria in Savanna and Guinea AEZs. Over the coastal areas, decreases in suitability about -0.2 are projected in the south coast of Nigeria and along the west coast of Guinea and Sierra Leone. A decrease of similar magnitude is also projected in north east boundary of Nigeria and Cameroon and in the central and north-western parts of Nigeria in the Guinea and Savanna AEZ respectively for both crops. Under GWL1.5, for root and tubers, suitability increases about 0.1 is projected over the central Savanna while a similar magnitude decrease is projected west and eastern Savanna for cassava. Plantain projected decrease in suitability (about -0.1) in the Guinea zone except along the southeast boundary between Nigeria and Cameroon with a projected suitability increase about 0.2 as in the central Savanna. The projected change under GWL1.5 is robust, in that at least 80% of the simulation agree with sign of change and the projected change in suitability are statistically significant (at 99% confidence level) for all the crop types.

Table 4.2: Projected changes in crop suitability over West African AEZs at different global warming levels

Crops	**GWL1.5**			**GWL2.0**			**GWL3.0**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Cassava	No change remains suitable	No change, remains suitable	No change, very marginally suitable	A 0.1 SIV decrease, remains suitable	A 0.1 SIV decrease, still suitable	A 0.1 SIV decrease becomes unsuitable	A 0.2 SIV decrease but still suitable	A 0.2 SIV decrease but still suitable	Above 0.2 SIV decrease becomes unsuitable
Cowpea	No change, highly suitable	A 0.1 SIV increase, highly suitable	A 0.1 SIV increase in the southern Sahel, marginally suitable	No change, highly suitable	Same as GWL1.5	Same as GWL1.5	No change in suitability	Same as in GWL1.5	Same as in GWL1.5
Groundnut	No change in suitability	No change in suitability	Same as Cowpea	Same as in GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as in GWL1.5	Same as GWL1.5	Same as GWL1.5
Maize	Suitable except the coastal areas of Nigeria and Liberia	Very suitable except Sierra Leone and west coast of Guinea	A 0.1 SIV increase now suitable in the south Sahel	Same as in GWL1.5	About 0.1 SIV decrease but still suitable	Same as GWL1.5	No change in suitability	About 0.2 decrease in SIV but still suitable	Same as GWL1.5
Pearl millet	Very suitable except the south coast of Nigeria	No change in SIV	No change but about 0.1 SIV increase in central Sahel	No change with about 0.1 SIV decrease east Guinea	About 0.1 decrease in SIV but still suitable	Same as GWL1.5	Same as GWL2.0	About 0.2 decrease in SIV but still suitable	A 0.2 SIV decrease & increase in western and central Sahel respectively
Plantain	A 0.1 SIV decrease but still suitable	A 0.2 SIV increase, now suitable in the savanna zone	No change in suitability remains unsuitable	Same as GWL1.5	Same as GWL1.5	Remains Unsuitable	A 0.1 SIV decrease but still suitable	Same as GWL1.5	Remains unsuitable

Under GWL2.0, the impact of the warming on crop suitability shows a similar spatial suitability pattern as GWL1.5 over West Africa but with an intensification of GWL1.5 effect across the different crop types over the region (Figure 4.1 & 4.2, column 3 and Table 4.2). The intensity of change at GWL2.0 warming in comparison to GWL1.5 are most drastic on cereals and root and tuber crops compared to the legumes both in magnitude of change and projected spatial suitability distribution. The meridional (N-S) movement via projected increase (expansion) and decrease (contraction) in magnitude and spatial suitability distribution at different GWLs shows contraction are mainly to the south (around 14°N, marginal suitability line from the historical climate and 0.4 contour line, 0.4 marginal suitability line) and expansion to the north for the root and tuber and cereal crops except maize. As seen from Figure 4.1, cassava remains the most impacted crop in the region due to 0.5°C increase warming that further reduces areas suitable for cultivation of the crop over West Africa. A reduction in suitable areas is also projected for groundnut and maize south of 14°N although majorly with maize and in the eastern Sahel for cowpea in south western area of Chad. On the other hand, the 2°C warming may also lead to an expansion in suitability over the region. A projected spatial increase through an expansion of suitable areas for crop types except cassava is expected at GWL2.0. The projected suitability increase has similar spatial pattern as GWL1.5 but with an increased magnitude of change in the suitability index value. All the projected change at GWL2.0 is robust (i.e. statistically significant at 99% confidence level and 80% of the model agree to the sign of suitability change). The increase in the reduction of suitable areas over the regions notably with cereals and root and tuber crops at GWL2.0 suggests keeping global warming to 1.5°C may limit decrease in projected SIV and spatial suitability of affected area within the natural variability of the reference/historical climate.

The impact of increase in global warming beyond GWL1.5 and GWL2.0, will be more drastic on cereals and root and tubers under GWL3.0 over West Africa (Figure 4.1 and 4.2, column 4, see also Table 4.2). Under GWL3.0, the spatial suitability distribution over the region under shows a similar spatial suitability distribution pattern over the region as the historical climate with higher suitability to the south of MSL around 14°N and low suitability to the north of the region. Projected change in SIV and suitable areas show an increase in the intensity of change with increased warming compared to GWL1.5 and GWL2.0 especially the cereal and root tuber crops. For example, projected decrease of 0.1 and up to 0.3 of SIV is projected for cassava along the coastal areas and further inland respectively across the three AEZs. The projected SIV decrease for cassava under GWL3.0 will result in decrease in suitable areas from the northern Savanna to south of the Sahel around 14^{o}N except along the coasts in the Savanna. The projected decrease in suitability over these areas shows the northern Sahel and Savanna will become unsuitable and marginally suitable respectively for the cultivation of cassava under GWL3.0 except in the southern Savanna and Guinea zone compared to the historical period thus showing a constraint in growing the crop only in the southern area of the region. The other root and tuber crop, plantain will also experience decrease up to 0.3 SIV over the Guinea zone and along the western area of the Savanna however, the crop remain suitable over the area. On the other hand, an increase in SIV above 0.2 is expected from the western to eastern Savanna except over the north-central area of Nigeria. The projected SIV increase also means an increase in the suitable area for the cultivation of plantain with increased suitability from being marginally suitable to suitable. This projected expansion in suitable areas for plantain thus provides an opportunity of more area for cultivation of the crop. As seen in Figure 3 and described in Table 1, both maize and pearl millet under GWL3.0 remains suitable over the Guinea and Savanna zone despite the projected decrease in SIV. However, the good news is the spatial increase in suitable area for the crop in central Sahel as compared to being marginally suitable in the past climate thus expanding northward in suitable areas which may improve the production of the crop. There are no much changes in the SIV and suitable areas for the cultivation of Legume crops, cowpea and groundnut, under GWL3.0.

Conversely under GWL3.0, projected decrease in SIV due to an increased warming will lead to a further decrease in suitable areas compared to the past climate. This is particularly expected over the Guinea and Savanna zones for roots and tuber ad cereal crop type due to a decrease in magnitude of SIV and spatial contraction in suitable areas of these crop type. Also, the projected changes under GWL2.0 and GWL3.0 are robust (i.e. are statistically significant at 99% confidence level) for all the crop types. In addition, as mentioned with GWL impact warming above, a projected spatial suitability change may not change the crops suitability spatial distribution status (e.g. from unsuitable to suitable or may remain marginal or highly suitable) due to an increase warming over West Africa. For example, despite the projected decrease in suitability index magnitude for cassava across West Africa, the crop will remain very suitable south of 14^{o}N under GWL2.0 and GWL3.0 warming over the region. On the other hand, despite the projected increase in suitability for groundnut, cowpea and maize north of 14N over west Africa, these crops still retain the unsuitable to marginally suitable characteristics in the Sahel zone.

4.3.3 Impact of different GWLs on crop planting period/month over West Africa

For all global warming levels, Ecocrop projected change in the planting period/month varies for different crop types across the different AEZs of West Africa (Figs. 4.3 and 4.4, column 2-4 and Table 4.3). The increased warming resulted in early or late/delay in PM for different crops and increases in magnitude with increasing warming level. It is worth stating that the change in PM describe a change in the best three planting months under the three GWLs. For example, under GWL1.5 no change in PM is projected for legume crops except over the Sahel (around 13^{o}N) and along the coastal area (Figs. 4.3, column 2-4, Table 4.3). A one-month delay in the PM (Feb to March) is projected in the Sahel for both Cowpea and Groundnut compared to the past climate. Along the coastal area, about two-month delay in the PM is projected along the south-west coast from Sierra-Leone to Liberia and up to 2-3 months extending to the south coast of Ivory Coast for Cowpea. A similar magnitude of delay in PM as Cowpea is projected for Groundnut along the south-west coast from Sierra Leone to Liberia except in the north-east of Sierra Leone. Under GWL1.5, early planting of about one-month PM (i.e. from February to January) is projected in the south-east of Nigeria for Cowpea as compared to the past climate while Groundnut, a similar one-month early planting (February-January) is projected in the north-east of Sierra Leone. Also, a two-month early planting along the south coast of Nigeria is predicted under GWL1.5 (i.e. February to December of the preceding year). This means there is a shift in the PM from February-April in the past climate into December-February under GWL1.5.

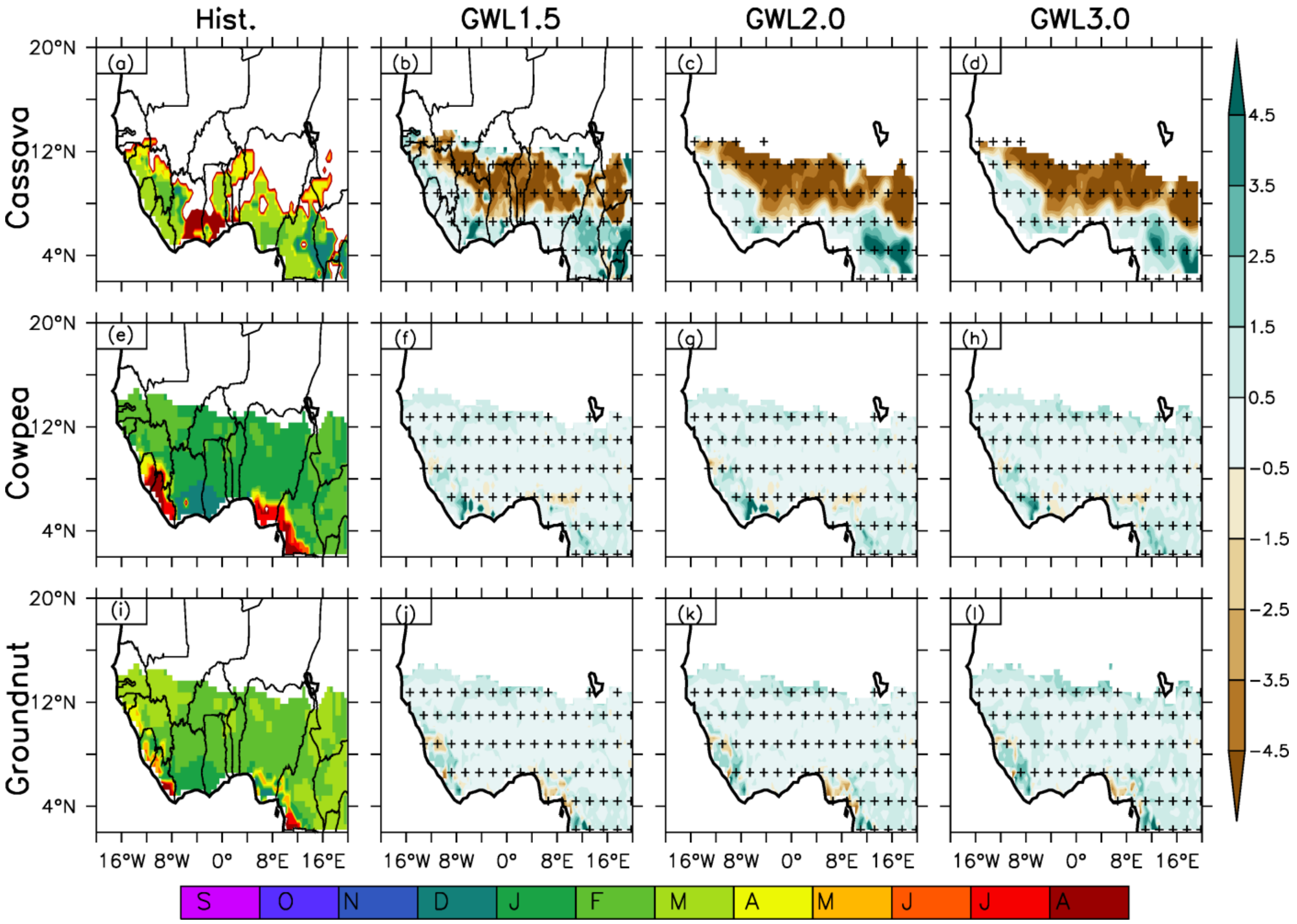

Figure 4.3: Spatial distribution of crop suitability as simulated by Ecocrop over West Africa for Hist. (column 1, left axis) and of change in crop suitability (right axis) at different global warming levels (GWL1.5, GWL2.0, GWL3.0) under RCP8.5 scenario (column 2-4) for maize, pearl millet and plantain. The colour in the historical month represents the first month of the best three consecutive months (e.g. a simulated planting month showing September means September-November planting period). The green and brown colour shows projected delay and early shift in the planting month from the historical climate. The white areas along the coast have no data. (0.0> not suitable >0.2> very marginal >0.4> marginal >0.6> suitable >0.8> highly suitable). The contour lines represent crop suitability in the historical climate. The vertical strip (|) indicates where at least 80% of the simulations agree on the sign of the changes, while horizontal strip (−) indicates where at least 80% of the simulations agree that the projected change is statistically significant (at 99% confidence level). The cross (+) shows where both conditions are satisfied; hence, the change is robust

For cereal crops (Fig. 4.4, column 2-4, Table 4.3), a general delay in the PM is projected across the region under GWL1.5 except over Sierra Leone and its boundary south-east boundary with Liberia and north-east boundary with Guinea. This is observed over the central Guinea-

Savanna zone in Nigeria except the south coast for millet and in the western and eastern Savanna for maize. Projected delays in the PM for millet is about two months across region and may be about four months in the central Sahel zone, south of Sierra Leone and south coast of Nigeria under GWL1.5. Delay about two months in the PM is projected for maize from Ivory Coast to central Cameroon in the Guinea zone, while the delay in PM is projected to be above four months from the central part of Nigeria extending to its boundary in the north with Niger Republic in the central Savanna-Sahel AEZ and in the south of Chad Republic in the south-eastern Sahel. Conversely, under GWL1.5, an early planting about 2-3 months (i.e. from December during the past climate to September) is projected from the east of Guinea extending to western Nigeria in the Savanna-Sahel AEZs and along the north boundary of Cameroon and South of Chad Republic in the eastern part of the Savanna AEZs for maize. For Millet, early planting about 1-2 months (from February to December) is projected in the Savanna zone from Sierra Leone and its boundary south-east boundary with Liberia and north-east boundary with Guinea and also from the southern to north-central part of Nigeria in central Guinea-Savanna zone except the south coast in the coastal area.

Projected changes in root and tuber crops follow similar pattern under the three GWLs although with different magnitudes at different warming level and crop (Figs. 4.3 and 4.4, column 2-4, Table 4.2). For example, about 2 months delay in planting of cassava in the Guinea zone and the western Savanna zone under the three global warming levels. The projected change means a change in the planting date of cassava from March to May along the west coast of Guinea (western Savanna) to the south-west coast of Liberia and from the south coast of Nigeria to the southern Cameroon (Guinea zone). Along coastal area, the projected change in PM is from June to August from the south coast of Ivory Coast to Ghana in the Guinea Zone. Additionally, under GWL1.5 a delay in PM of similar magnitude is predicted in the north-east Nigeria, along the south-west coast from Senegal to Guinea and from the south-east Mali to central region of Burkina Faso in the Sahel. On the other hand, an early planting is projected for cassava in the central Savanna zone from the south east Mali to the south of Chad Republic in the eastern Savanna zone except in the north-east Nigeria in the eastern Savanna under GWL1.5. The projected change in PM is about 4 months early (April to December), compared to the past climate in the Savanna zone. For plantain, no change in PM is projected under GWL1.5. The no change in the month of planting may be linked to it be an annual crop which can be planted at any month in the year.

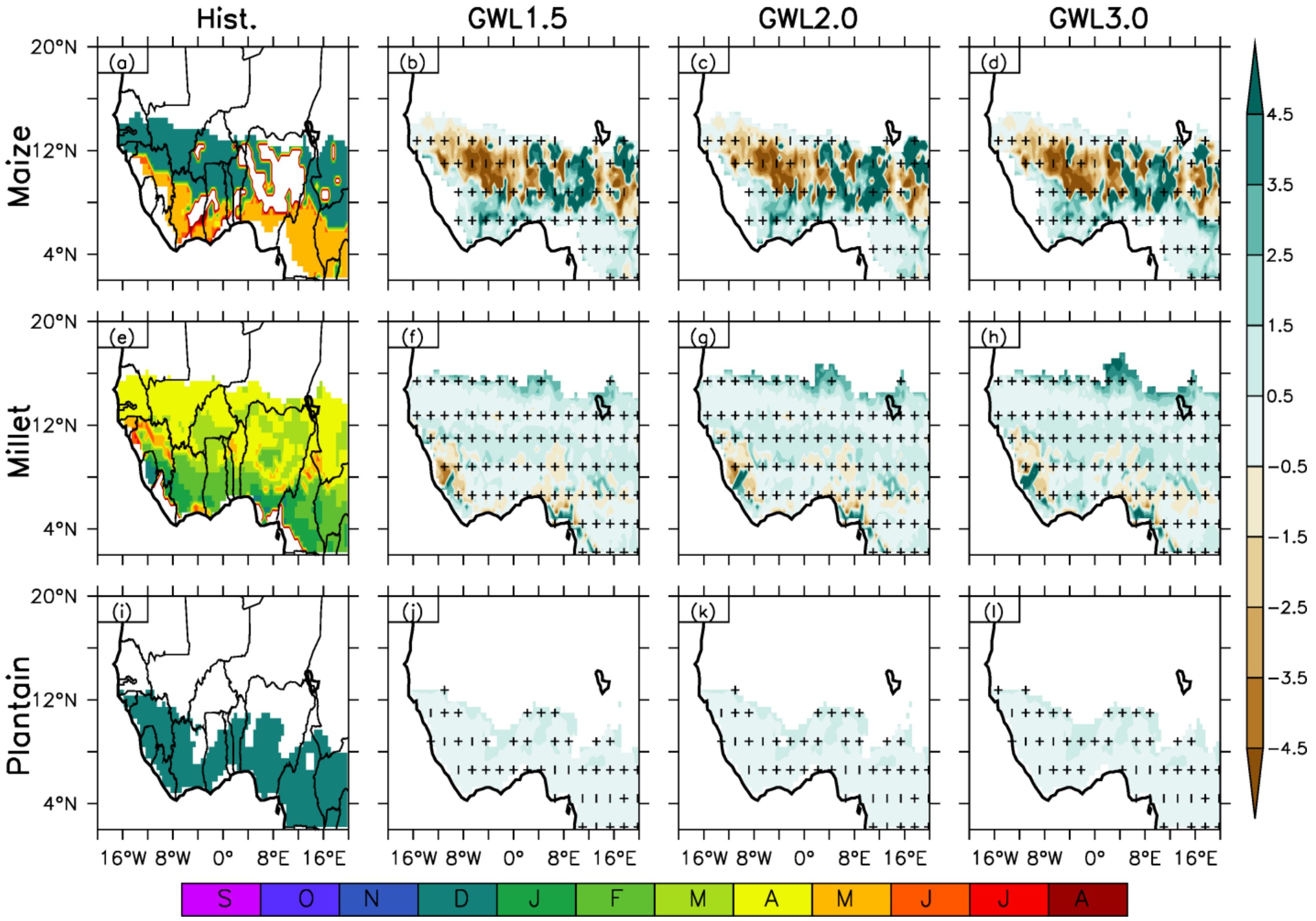

Figure 4.4: Spatial distribution of the best three planting month as simulated by Ecocrop over West Africa for Hist. (column 1) and (column 2-4) at different global warming levels (GWL1.5, GWL2.0, GWL3.0) under RCP8.5 for maize, pearl millet and plantain. The colour in the historical month represents the first month of the best three consecutive months (e.g. a simulated planting month showing September means September-November planting period). The green and brown colour shows projected delay and early shift in the planting month from the historical climate. The vertical strip (|) indicates where at least 80% of the simulations agree on the sign of the changes, while horizontal strip (−) indicates where at least 80% of the simulations agree that the projected change is statistically significant (at 99% confidence level). The cross (+) shows where both conditions are satisfied; hence, the change is robust

At GWL2.0, projected change in crop PM show a similar spatial characteristic in projected crop PM change across the three AEZs and crop types as simulated under GWL1.5 except with few discrepancies in some areas or crop types (Figs. 4.3 & 4.4, column 3, Table 4.3). Legume crops projected change in PM under GWL2.0 show similar spatial pattern for both delay and early in PM across the region as GWL1.5 except for Groundnut in the south coast of Nigeria. An additional 0.5^{o}C of warming is projected to potentially lead to an early planting of Groundnut in south coast of Nigeria about 2-3 months, PM December, under GWL2.0 compared to PM in February in past climate i.e. a change in PM from February to December of the preceding year. For cereals, projected change in PM similar spatial pattern for both maize and pearl millet under GWL2.0 as projected under GWL1.5 except for an increase in magnitude in the projected PM in the central Sahel under GWL2.0 for Pearl millet. A 2-month late/delayed planting is projected in southern Niger Republic in the central Sahel zone under GWL2.0. The projected delay means a change in the PM from April (April-June) in the past climate to June (June-August) under GWL2.0 as compared to the one-month delay under GWL1.5 over the area. This suggest limiting the global warming to 1.5^{o}C may help maintain the in planting and cultivation period over this area within the natural variability of the reference climate. Projected PM under GWL2.0 shows a delay about 1-2months to the south in the Guinea zone and along the west coast from Guinea to south coast of Nigeria for cassava. An early planting of the crop is projected in the north from the southern Senegal in western Sahel Zone to the south of Chad Republic in the eastern Savanna zone. The projected change in PM is about 4 months early (April to December) compared to the past climate in the Savanna zone. Under GWL2.0, no projected change is predicted for Plantain as stated under GWL1.5. All the above projected changes in PM under GWL2.0 are robust for all the crop types.

Table 4.3: Projected changes in time of planting (crop planting months) over West African AEZs at different global warming levels

Crops	**GWL1.5**			**GWL2.0**			**GWL3.0**		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Cassava	Delayed planting for two months	Early planting by four months	One-month delay in southern Sahel zone	Same as GWL1.5	Same as GWL1.5 but for more area	No change in planting, date	Same as GWL1.5	Same as GWL1.5	No planting date
Cowpea	One-month delayed planting	No change in planting date	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Groundnut	One-month delayed planting	No change in planting date	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Maize	Three months delayed planting	Two-three months early & delay planting except central area	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Pearl millet	One-month delayed planting	Two months delayed planting	Two months delayed planting	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5
Plantain	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date

An additional 0.5ºC of warming is projected to potentially lead to an early planting of Groundnut in south coast of Nigeria about 2-3 months, PM December, under GWL2.0 compared to PM in February in past climate i.e. a change in PM from February to December of the preceding year. For cereals, projected change in PM similar spatial pattern for both maize and pearl millet under GWL2.0 as projected under GWL1.5 except for an increase in magnitude in the projected PM in the central Sahel under GWL2.0 for Pearl millet. A 2-month late/delayed planting is projected in southern Niger Republic in the central Sahel zone under GWL2.0. The projected delay means a change in the PM from April (April-June) in the past climate to June (June-August) under GWL2.0 as compared to the one-month delay under GWL1.5 over the area. This suggest limiting the global warming to 1.5ºC may help maintain the in planting and cultivation period over this area within the natural variability of the reference climate. Projected PM under GWL2.0 shows a delay about 1-2months to the south in the Guinea zone and along the west coast from Guinea to south coast of Nigeria for cassava. An early planting of the crop is projected in the north from the southern Senegal in western Sahel Zone to the south of Chad Republic in the eastern Savanna zone. The projected change in PM is about 4 months early (April to December) compared to the past climate in the Savanna zone. Under GWL2.0, no projected change is predicted for Plantain as stated under GWL1.5. All the above projected changes in PM under GWL2.0 are robust for all the crop types.

The projected change in planting month under GWL3.0 show a similar spatial characteristic as that of GWL1.5 and GWL2.0 except for pearl millet over the Sahel zone (Figs. 4.3 & 4.4 column 4, Table 4.3). The increase in warming do not really influence the month of planting under GWL3.0 differently from other warming levels. The main difference in PM under GWL3.0 compared to other GWL1.5 & 2.0 is observed in central Sahel zone for cereal crop, pearl millet. Pearl millet is projected will experience a delayed planting about four months compared to the historical climate.

The effect of GWL2 & 3 warming in comparison to GWL1.5 are most drastic on millet and plantain. This is so because the major meridional (N-S) movement via expansion and contraction in suitability due to the increased warming are more observed with the two crops but more with millet. Cassava remains to be the most impacted crop in the region as a 2ºC temperature warming leads to more contracted area in the cultivation of the crop over West

Africa. A reduction in suitable areas are also projected for groundnut and maize south of 14^{o}N although majorly with maize and in the eastern Sahel for cowpea in south western area of Chad. On the other hand, the 2^{o}C warming may also lead to an expansion in suitability over the region. An intensification of a projected meridional expansion of suitable areas for cowpea, groundnut, maize, millet and plantain in comparison to the 1.5^{o}C warming is expected coupled with a zonal expansion (E-W spatial movement) in suitability are projected in the Sahel. In addition, as mentioned in the 1.5-degree impact warming above, a projected spatial suitability change may not change the crops suitability spatial distribution status (e.g. from unsuitable to suitable or may remain marginal or highly suitable) due to an increase warming over West Africa. For example, despite the projected decrease in suitability index magnitude for cassava across West Africa, the crop will remain very suitable south of 14^{o}N under GWL2.0 and GWL3.0 warming over the region. On the other hand, despite the projected increase in suitability for groundnut, cowpea and maize north of 14N over West Africa, these crops still retain the unsuitable to marginally suitable characteristics in the Sahel zone.

4.3.4 Trends in projected change in crop suitability and month of planting under different warming levels

We use the Theil-Sen estimator to assess the trends in crops suitability growth for each crop across the three warming levels over West Africa (Table 4.5). The trend describes the rate of increase and decrease of the suitable area and SIV with increasing global warming levels. In general, the trends are positive, and the number represents the magnitude of the trend between the projected change in suitability and past climate.

Our result shows that there is an increasing trend in crop suitability with increasing warming levels across all the crop types except legumes. Cassava has the highest trend values with an increasing trend value above 0.100 between GWL2.0 and GWL3.0 compared to the 0.028 for GWL2.0 and GWL1.5. The increase in trend value for cassava shows how the crop has been greatly affected by the increasing warming especially under GWL3.0 compared to other crops which has resulted in the loss of suitable areas in cultivating the cassava over the northern Savanna zone to the southern Sahel zone of West Africa. In general, our finding shows the trend value for each crop with each global warming level are almost three-four times the trend value between GWL1.5 and GWL3.0 except cowpea which is farfetched from that projected trend value for GWL1.5 and GWL2.0 is about an average 0.05 except for cassava with almost 0.03 trend increase.

This result further confirms the reason we need to strive to ensure we limit global warming to 1.5°C and to call our scientist and policymakers to the devasting impact of warming of 3°C on the different crops when compared to GWL2.0. This is in line with Rogelj et al. (2013) that although the NDCs leads to significant reduction in emission, however their impact is below the necessary emission reduction consistent with 2°C and 1.5°C climate target. For the Legume crops, there was no change in trend value for cowpea and groundnut for all the warmings levels from GWL1.5 to GWL2.0 respectively while an increase in trend value is expected for groundnut at GWL 3.0 over West Africa.

Table 4.4: Trends in projected changes of crop suitability over West Africa at different warming levels

Crop	GWL1.5	GWL2.0	GWL3.0
Cassava	1.026	1.054	1.157
Cowpea	1.000	1.000	1.000
Groundnut	1.000	1.000	1.004
Maize	1.005	1.011	1.036
Pearl millet	1.006	1.012	1.027
Plantain	1.000	1.008	1.042

Also, our finding showed the trends in projected change of PM for the six crops over West Africa are positive for the three global warming levels. However, there was no change in the magnitude of the trend value of PM for all crops across the three warming levels (Table 4.5). The trend magnitude is 1.0 for all the crops across the three warming levels. The trends are significant at 95% level.

Table 4.5: Trends in projected changes in planting month over West Africa at different warming levels

Crop	GWL1.5	GWL2.0	GWL3.0
Cassava	1.000	1.000	1.000
Cowpea	1.000	1.000	1.000
Groundnut	1.000	1.000	1.000
Maize	1.000	1.000	1.000
Pearl millet	1.000	1.000	1.000
Plantain	1.000	1.000	1.000

4.4. Discussion

4.4.1 Sensitivity of different Crop types to different Global Warming levels in West Africa

The crops examined in this study do not respond homogeneously to global warming. Of the three crops types, root and tubers are most negatively impacted in comparison to cereals and legumes. Root and tuber crops (cassava and plantain) are one of the six most important food crops in the world and cassava is an important staple crop in West Africa (Jarvis et al., 2012a; Sultan & Gaetani, 2016). From our findings, spatial contraction and decrease in SIV suitability are projected for both plantain and cassava, in the Guinea and Savanna AEZs under GWL1.5 and GWL2.0. However, under GWL3.0 cassava will no longer be suitable for cultivation in the southern Sahel and to the north of the Savanna zone (between 10 - 14°N). This may be detrimental for food security and trade as cassava is one of the most important cultivated crop in the region as it can be processed into different product being consumed by the inhabitants of the region (Thiele et al., 2017). In contrast to root and tubers, a spatial expansion into the Sahel AEZ and increased suitability is projected for the legumes (groundnut and cowpea) under the three global warming levels. This may result in increased cultivable area and improving yield for crops like groundnut which agree with previous findings (Sultan & Gaetani, 2016; Parkes et al., 2018). For the cereal crops (millet and maize), sensitivity to global warming level results in more northward expansion but with a corresponding spatial contraction for both crops under GWL1.5 and 2.0. an increased intensity in the spatial contraction and loss of suitable areas for the cultivation of the crop is expected under GWL3.0. The spatial expansion northward may be as a result of a projected wetter Sahel (Nicholson, 2013). The projected change in PR of maize corresponds to main rainy season in the Savanna-Sahel zone. This might be linked to projected increase in suitability of maize in this zone.

An additional 0.5ºC (GWL2.0 - GWL1.5) and 1.5ºC (GWL3.0 – GWL1.5) warming- leads to both spatial expansions and contractions of suitability in specific regions and influence the time of planting, early and delay planting over West Africa. The projected change due to the impact of additional 0.5ºC and 1.5ºC warming comes with both opportunities and constraints for different crops across the AEZs of the region. Over the Sahel, will likely become wetter with increasing greenhouse gas emission (Nicholson, 2013; Sylla et al., 2013) resulting in the northward expansion of crops into the Sahel. There is also a projected increase in the length of the rainy season (LRS) over the Guinea and Savanna zones (Kumi & Abiodun, 2018). This may be responsible for the sustained levels of suitability despite the projected spatial contraction (decrease in suitability) under GWL1.5 and 2.0 but not at GWL 3.0 especially for the cassava and cereals where some areas become unsuitable due to the increased warming and the delay in month of planting for the different crop types in the zone. This provides opportunities for more cultivated land which may have a significant role in improving crop yield and production over the region and might influence the socio-economy of the region which is dependent on rainfed agriculture (Kurukulasuriya & Mendelsohn, 2006).

On the other hand, an additional 0.5 and 1.5ºC warming will also lead to constraint in suitability and spatial extent of some crops, most notably cassava, millet and plantain. In the context of GWLs, delta 0.5 & 1.5ºC may have limited impact on actual cropping with changes in suitability from highly suitable to suitable (e.g. millet and plantain). However, although not the purpose of this study, it will be very useful to quantify this change and investigate how it may influence crop yield and production over the regions, which are projected to decrease over the region in literature especially at GWL3.0 (Roudier et al., 2011; Challinor et al., 2014). Furthermore, the projected increase in risks to crop production as global warming levels rise from GWL1.5 to GWL2.0 and finally GWL3.0 is very evident. While all the crops are still suitable and can be cultivated over the region under GWL1.5 and to a reasonable level under GWL2.0, the condition is much worse under GWL3.0 for all of the crops except cowpea and groundnut as some current suitable areas becomes unsuitable due to more warming, potentially compromising sustained crop production in West Africa. This further reiterate the importance and need for policymakers to ensure their commitment in meeting the Paris agreement or accords by member states of limiting global warming to 1.5^{o}C above pre-industrial level. This also calls for and put a responsibility on each member countries to implement their plan for addressing climate change challenge beyond 2020 aimed at limiting temperature below 2^{o}C (Rogelj et al., 2016), otherwise this may be devasting and further compound the woes of a highly vulnerable region like West Africa and with low adaptive capacity.

The impact of the projected global warming levels varies for the different crop types; however, the influence is more pronounced on root and tuber and cereal crops especially cassava and maize respectively. In general, projected delay in PM from one to over four months may be experienced at over the region across the three AEZs under different warming levels. The projected delays to the four crops, cowpea, groundnut, pearl millet and plantain across the three warming levels and share common spatial characteristic pattern and sometimes in magnitude in the month of delay except for some pockets of area notably along the coastal areas or the Sahel zones where an early projected planting may expect for these crops. The impact of the projected delay in the planting and cultivation of these crop will be of concern to farmers (crop production and source of livelihoods) and policy makers (economic growth and international trade) which may further aggravate the impact of climate change on the regions. On the other hand, the impact of the global warming level on the PM is more drastic and obvious for cassava and maize. The projected change for cassava and maize show delays in PM are expected in the south notably over the Guinea and central Savanna zone and early planting in the north in the Savanna-Sahel AEZs. The projected change in PM suggests an all-around planting season for these crops, which are very crucial and important to the inhabitants of the region in terms of livelihoods and economy in relation to crop production and food security as well as regional and international trade to boost the economy respectively especially cassava in which West African is one of the leading global producers of the crop.

4.4.2 Regional crop suitability, changes in Planting months, Adaptation and socio-economy in West Africa

Projected variability and shift in regional crop suitability and months of planting will be crucial to the socio-economic activity and regional trade in West Africa. Increased agricultural productivity can enhance economic growth resulting in industrial growth (Sultan & Gaetani, 2016). As seen from our findings above, projected crop suitability and notably the northern spatial expansion is one of the important factors that may enhance increased agricultural productivity. Increased suitability coupled with the planting during the best PMs, potentially linked to an increased Length of Rainy Season (LRS), may result in more cultivated land for crop growth and harvested areas. As earlier mentioned, the projected increased LRS with increased warming under RCPs 4.5 and 8.5 over the Guinea-Savanna and Sahel zones respectively (Kumi & Abiodun, 2018) and a wetter Sahel (Nicholson, 2013) can help improve agricultural productivity in the regions and have a positive impact on the economy and livelihoods of the inhabitants. Also, variation in suitability and planting months of the different crops can help increase the socio-economic livelihoods through regional trade amongst countries. Some countries with projected suitability expansion can improve their production through the availability of more cultivated lands to meet their needs and create a market for countries with no or projected contraction in suitability to help offsets their production deficits. Also, the variation in the period of planting for the different AEZs can create regional opportunity as crop production will be at different times of the years and this may help with regional and international trade amongst the different countries.

In regions where there are contractions in the spatial extent of suitability or reductions in the suitability index, improved adaptation strategies will be key to mitigate the impacts of these changes. With impact of GWL2.0 and GWL3.0 more drastic on crops such as cassava and maize, with their high socio-economic importance in West Africa, an improved understanding about the timing of for adaptation cannot be overemphasized owing to the high vulnerability and low adaptive capacity of West Africa (Niang et al., 2014). This is important with the variation in projected changes in the month of planting for the different crop types. New knowledge about developing adaptation strategies, such as transformational adaptation as proposed by Rippke et al. (2016), may assist in mitigating the impact of GWL1.5, GWL2.0, GWL3.0 on crop suitability coupled with the projected changes in the month of planting over

West Africa notably for cereal and root and tuber crops, with spatial contraction and decrease suitability (Roudier et al., 2011; Challinor et al., 2014). These types of adaptation strategies could improve food security in the region through not only maximizing the yield potential of suitable areas, but also enhance regional trades amongst countries through trade-offs based on crop suitability status of each country (Rippke et al., 2016).

4.5. Summary and Conclusion

In this study we assessed the impact of 1.5, 2 and 3^{o}C warming on crop suitability over West Africa. Climate characteristics result from 10 CMIP5 GCMs downscaled with RCA4 under RCP8.5 scenarios, and were used as input into crop suitability model, Ecocrop for the past and future climate over West Africa. The impact of 1.5, 2, and 3^{o}C warming were computed using 1971-2000 as the reference period for six crops, millet, cassava, groundnut, cowpea, maize and plantain. Our findings are as follows:

- a low or no suitability to the north and high suitability to the south separated marginal suitability line over West Africa in the historical climate for all the six crops, in general, marginal suitability lines are observed around 14^{o}N for all the crops across the region except for plantain. Plantain has its marginal suitability line south of 12^{o}N.
- at GWL1.5, there is a broadly similar spatial pattern of variation in suitability as the historical climate. However, a suitability shift (both spatial expansion and contraction simultaneously) is projected under 1.5^{o}C warming for cereals, legumes, groundnut along the central southern Sahel (around 13-14^{o}N) and in the Guinea-Savanna zones for root and tuber, plantain.
- projected changes in crop suitability and suitable areas under the GWL1.5 shows all the crops remain suitable across the three AEZs of West Africa although with reduction in the SIV of some crops like cassava and the cereals.

- with GWL2.0, the impact is more drastic on cereals and root and tubers with decrease in SIV of crops and a reduction in the suitability of some areas but are still suitable compared to legumes which have a relatively no change.

- the impact of GWL3.0 leads to a more devastating effect such as a high decrease in the crop SIV resulting in more suitable areas becoming less suitable and unsuitable for cultivation notably south of the region. In contrast, warming under GWL3.0 leads to a northern extension of suitable area in growing cereals and legumes in the central area of the southern Sahel. However, the suitable areas lost are far more than those gained with the increasing warming.

- the projected impact of GWL3.0 in comparison to GWL1.5 are most drastic on cereals and root and tuber crops with cassava the most impacted crop. The increase in warming, results in loss of suitable areas in the southern Savanna and northern Sahel zone of the region become unsuitable for cassava the south coast of Nigeria in the Guinea zone become marginally suitable for pearl millet and very high reduction, up to 0.3 in SIV for other crops. This further emphasize the need for commitment to the Paris Accord by member country and the benefit of limiting global warming to 1.5^{o}C that provides a suitable and favourable condition for cultivation and growth of the crops over West Africa.

- the projected changes in crop suitability under GWL2.0 are less than at GWL3.0. The change shows that an additional 1.0^{o}C beyond GWL2.0 results in decrease in SIV of the crop with drastic impact on the suitable area in the past climate leading to reduction in suitability of cultivated areas south of 14^{o}N over West Africa This benefit in keeping global warming well below 2^{o}C compared to GWL3.0 cannot be overemphasized with the fast-growing population and food demand over West Africa.

- the impacts of the three GWLs for planting month varies for the different crop types but is more pronounced on root and tuber and cereal crops especially cassava and maize respectively. In general, projected delay in PM from one to over 4 months may be experienced over the region across the three AEZs under the three GWLs for legumes, pearl millet and plantain.

- the projected change for cassava and maize show delays in PM are expected in the south notably over the Guinea and central Savanna zone and early planting in the north in the Savanna-Sahel AEZs.

- there is an increasing trend in the projected change in crop suitability with increasing warming over the region for all the crops except cowpea and for groundnut between GWL1.5 and GWL2.0. Although there were projected changes in PM for the crops, there was no change in the magnitude of trend value for the historical period and the three warming levels.

Although the present study has enhanced our understanding on the impact of GWL1.5, 2.0 and 3.0 warming on crop suitability and planting season over West Africa, future studies may investigate the impact of GWL1.5, 2.0 and 3.0 warming on crop suitability over the region using more RCMs other than the single RCM with the different forcing GCMs used in this study as inputs into Ecocrop for robust findings. Furthermore, the present study only considers six crops over the region, future work may use more crops and crops classes such as horticultural crops like pineapple, tomatoes, fruit crops like oranges, mango, more cereals like wheat, rice; cash crops like oil palm, root and tuber-like yam to mention a few. Such research is needed to help guide policymakers at both the national and the regional level in reducing the impact and risk associated with food insecurity/scarcity in changing climate in West Africa. Nevertheless, the present work has established that using RCM, RCA4 to downscale GCM simulations to drive a crop suitability model, can help improve our understanding on the impact of GWL1.5, 2.0 and 3.0 on crop suitability over West Africa. In addition, the study also shows the benefit of keeping global temperature below 2°C warming and most especially GWL3.0 on crop suitability growth and month of planting over West Africa

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This last chapter reflects on previous chapters and summarises the main findings. It then synthesises the research findings and constructs emerging conclusions about crop-climate departure, its timing and urgency of adaptation. Finally, it proposes future work to further consolidate and advance knowledge in this study area.

CHAPTER 5

5.1 Final Conclusions

This dissertation has presented a thorough description of the spatio-temporal effects of projected climate on crop suitability over West Africa. The successful conceptualization and development of the crop-climate departure concept provided a tool for an improved understanding of the crop-climate relationship, particularly crop suitability departures under a changing climate in West Africa. This concept enabled the assessment of future changes in crop suitability and planting season by the end of century, revealing the benefits and constraints in the spatio-temporal variability of crop suitability distribution for different crop types across the region. The influence of the projected global warming levels (1.5, 2.0 and 3.0^{o}C) on crop suitability was also investigated specifically up to the warming levels (GWL3.0^{o}C) of Nationally Determined Contribution (NDC) which was unavailable in previous methodologies and studies.

The key findings are as follows:

A cue was taken from the methodology of Mora et al. (2013) to develop an appropriate approach to define crop-climate departure and to understand the projected future climate driven crop departures based on the crop suitability characteristics. It was demonstrated that the concept helped to characterise the suitability changes of different crops over three climatic stations from the three AEZs of West Africa. It further reveals variability in crop suitability across the AEZs showing a projected constraint in the cultivation of cassava and pineapple in the Guinea zone by mid-century and a future opportunity via a northward expansion of the suitable area for maize into the southern Sahel zone by the end of the century. The Savanna zone seem to be the most sensitive zone to the impact of crop-climate departure compared to the Guinea and Sahel zone. The ability of the method to provide information on future characteristic of crop departure at the station across the three AEZs suggests it may have potential in addressing a detail gap in the spatio -temporal characteristic at regional level.

An analysis of future changes in crop suitability spatial distribution for different crop types revealed a spatial variability in projected suitable area with horticulture, cereals, root and tuber are the most negatively impacted with a decrease in suitable area from the near-future period

(2031-2050). A northward expansion leading to an increase in suitable area for cereals, legumes crops, and mango, is expected in the southern Sahel zone under RCP8.5. There is an increasing trend (either for expansion or reduction in suitable areas) in the projected suitability change for all the crops except yam. The study shows the applicability of the concept of crop-climate departure in characterising the sensitivity of crops through spatial variability in crop suitability changes at different time periods, from near future until the end of the century.

For the planting month, our analysis showed no change in planting date is expected for plantain, pineapple over the region and for cassava over the Guinea and western Savanna zone. However, about one-month delay for legumes and cereal crops over the region except maize with projected 1-2months early planting notably on Savanna zone and tomato except the Sahel zone. Perennial crop, orange and mango, and tomato projected to experience about two months delay over the southern Sahel for mango and orange but till mid-century while up to three-month delay is projected for yam in the Guinea- Savanna zone. In contrast, about two months early planting is projected for maize and mango in the Savanna-Sahel zone and up to three months for cassava from central to eastern Savanna zone. The result also applicability of the concept of crop-climate departure in characterising the sensitivity and temporal variability of crop departure and suitability changes over the region.

The final part of this dissertation presented an analysis of the impact of the different global warming levels (GWL1.5^{o}C, GWL2.0^{o}C and GWL3.0^{o}C) on crop suitability and planting months of different crops over West Africa. The result indicated that all crops except cowpea and groundnut showed increased suitability with increasing global warming levels, with the least impact under GWL1.5^{o}C and the worst occurring under GWL3.0^{o}C. Cassava is the most negatively affected crop with decreasing suitability area while cowpea and groundnut are simulated to increase in suitable area into the southern Sahel zone. The study further confirms the need to keep global temperature below 1.5^{o}C as crops largely remain suitable under this warming threshold, where food security may be compromised for warmer changes.

The question was asked whether the inability to meet the NDC plan and the potential of reaching a projected temperature increase up to 3^{o}C will affect crop suitability and agriculture over West Africa? An increase in suitable area in the central Sahel zone for cereals and further decrease in suitable area for cassava except in the southern Savanna and Guinea zone suggests a constraint in growing cassava only in the southern part of region and expansion of cereals crops into the southern Sahel. The result provides a new insight that inability to meet the NDC plan and reaching a global warming level up to 3°C comes with both limitation and opportunities in West Africa.

The analysis of the GWLs impact on crop suitability and suitability index value provides a new insight that can be employed in examining how specific global warming threshold is useful in monitoring spatial variability of crop suitability over West Africa. This provides information on the opportunity and constraints in suitable areas for a specific global warming level over a geographical area that can be useful to scientist and guide policy makers in their future planning and choice of adaptation strategies.

5.2 Implication of key findings

5.2.1 Defining crop-climate departure using crop suitability characteristics

For this study, I engage critically the issues of climate change, change in climate variability and departure of cropping systems under climate change, in highly sensitive, vulnerable and with low adaptive capacity condition as typical in the West African rainfed agricultural sector. Agriculture, especially crop growth and yield, is highly dependent on weather events in SSA, where 97% of agricultural land is rain-fed (Roudier et al., 2011; Rockström et al., 2014). The impact of climate change on crop yields is already a major concern in this region and further warming with an increase in the human-induced carbon emission will aggravate the existing climate change impact in SSA (Mora et al., 2013; Challinor et al.,2014). Crop growth and yield are directly proportional to its suitability threshold (Luo, 2011).

Having observed dependency and sensitivity of crop on the climate, i.e. a crop-climate relationship and future projection identifying West Africa as one of the hotspots for climate departure, in chapter 2, I proposed a definition on the concept of crop-climate departure to demonstrate the crop realisation of the departure in crop suitability over the region. The crop suitability characteristics was employed to describe the concept of crop-climate departure at the three stations which are representative of the three West African AEZs (chapter 2). This was useful in identifying the variation in suitability of different crops over the AEZs as simulated by crop suitability model, Ecocrop. In chapter 3, I further explore to assess the application of this concept for different crop types at different climate change windows, the near-future period until the end of the century over the region. This reveals the impact of the increasing warming on crop suitability distribution over West Africa at different climate change windows. I showed the decreasing spatial suitability distribution and suitability index values as simulated by Ecocrop as approach the end of the century. In chapter 4, the concept was employed to characterise the spatial suitability distribution of different crops at global warming levels, 1.5, 2 and 3^{o}C over West Africa. This reveals the impact and shows the variation in the suitability distribution over the region at different global warming levels. Over the two chapters, I argue that the ability and application of the concept of crop-climate departure to characterize crop suitability distribution spatially and over a time period makes it a highly suitable tool to improve agricultural production and improve security, particularly over region with low adaptive capacity and high vulnerability to climate change impacts and one of the hot spots for climate departure whose livelihoods is dependent on rainfed agriculture like West Africa.

5.2.2 Spatial variability of crop suitability and Regional socio-economic development

As with climate, crop suitability varies across space and time in response in part to the variability in climates' spatio-temporal characteristics. Crop suitability projection can help provide information on future geographical opportunities and constraints that arise from increasing and reducing suitable croplands respectively in certain countries and regions. In chapter 2, the characterisation of crop suitability helps reveal the variability in spatial suitability distribution across the three AEZs. I showed the potential future opportunities and constraint for the different crops due to increased warming across the AEZs and particularly highlighting the Savanna zone as the most sensitive and impacted zone with spatial variability of crop departure. The projected future opportunities and constraint arising from the spatial variability in croplands were shown to be sensitive to warming and showing amplified constraints with higher warming. The increase in future geographical constraint is expected by the mid of century for most crop types notably horticulture and cereals while legume crops and maize are expected in enjoy more suitable land by extending into the southern Sahel zone (chapter 3). In Chapter 4, spatial variability in suitable areas and croplands were further observed at different global warming levels. Comparatively best suitability opportunities are projected in scenarios remaining under 1.5^{o}C global warming.

The projected spatial variability in suitable areas provides opportunity for mutual trade revision regional trade and socio-economic growth amongst countries in West Africa. This is very important to improve the livelihood and economy of the individual and countries at large. The variability in a suitable area can assist with regional interaction in terms of regional vision of suitability for mutual trade to help balance expected opportunities and constraints amongst countries or AEZs within the region. The regional vision will allow countries with opportunities or expansion in suitable area for specific crops may seek to form a trade alliance in line with the mutual trade benefits with those with constraint or reduction in suitable area for similar crop but with other potential benefits. Although, while we do not ignore the inability of countries to make a deal with food security at heart readily compared to oil trade deals or other resources with simply competitive advantage or potential to generate revenue however such a process may help improve access to food, reduce the prevalence of chronic hunger and improve food security and economic growth in the region.

5.2.3 Benefits of understanding the timing of crop-climate departure and timely adaptation in anticipating Food security

Improved knowledge of the timing of crop-climate departure from past climate-crop threshold pattern may assist with climate-crop suitability projections and increase food security (Ramirez-Villegas and Thornton, 2015). This provides information on future constraints and opportunities that may arise from the reduction and increasing croplands in certain countries and regions. In chapter 2, at a station level, I provide evidence through the timing of the crop-climate departure of future constraint leading to a reduction in croplands over the Savanna zone of West Africa by mid-century for cassava and pineapple. The result shows a future constraint in growing these crops, notably cassava only the Guinea zone by mid-century. In contrast, an evidence of future opportunity resulting in increased croplands in the Sahel zone by the end of the century for maize is expected. In chapter 4, at a regional scale, I further provide evidence on the associated influence of the different global warming levels on crop departure resulting in future constraints and opportunities in crop suitable areas croplands and planting season across the region. Future opportunities with increase in suitable agricultural land is expected under a

GWL1.5^{o}C for cowpea and groundnut compared to the historical period. However, higher constraints with more reduction in suitable croplands are expected for cassava under GWL3^{o}C. A similar approach as in chapter 2 was employed over the region at a different climatic window to provide evidence future constraints and opportunities in cropland and planting months. The result showed an increase in croplands are associated with legumes and cereals but a reduction in crops suitable agricultural lands for horticulture and cassava (Chapter 4).

5.3 Contribution to Knowledge

This research contributes to our understanding on the crop-climate relationship as learned from historical norm and projected in terms of temporal and spatial realisation of crop suitability departure and the urgency of response where it exists. The study has helped defined and developed a methodology on future climate driven crop departure assessment called the concept of crop-climate departure. The crop-climate departure concept acknowledging that climate and food systems are not linearly related shows a departure in climate regime is not necessarily related to a departure in cropping system, as well as a cropping system could radically change as a response to a marginal climate change. The concept of crop-climate departure provides a tool for characterizing crop suitability departure and improve our knowledge of food production and food security in a warming climate.

Also, although the GWL threshold (1.5, 2.0, 3.0^{o}C) do not have a direct agricultural meaning, the research provides a new insight at identifying varying responses such as expansion and contraction in suitable area at a specific global warming level/threshold for different crop and location. We showed agriculture suitability as in opportunity to sustainably produce food remains within the norm under the GWL1.5 and will become abnormally challenged beyond however acknowledging different space and time responses, depending on crops and locations.

In addition, the study suggests a new approach that can be employed by scientist and guide policy makers in future planning and prioritization of actions (e.g. adaptation strategies) that will be an important aspect for development in a changing climate as evident through the projected timing of crop departures. Moreover, projected opportunities (through expansion of suitable area) and constraints (reduction in suitable area) in crop suitability and planting season can provides a great opportunity for socio-economic development and trade at the national, regional and international level. This information is very important especially at region/global scale where powers (countries) cannot rely anymore on the current or foreseeable situation but must account for distant projection and leverage regional/global alliances as observed in the different spatial variability.

5.4 Concluding Remarks

This dissertation shows the importance of how information on future changes in the spatio-temporal characteristics of crop suitability can be used improve food production and especially food security in West Africa. The dissertation provides evidence on the suitability and applicability of the concept crop-climate departure in understanding future changes in crop suitability and planting season in a projected climate over West Africa. Taking a cue from the methodology of Mora et al (2013), I explored the climate change induced crop realizations of the climate departing from historical variability, developed and proposed the concept called the crop-climate departure (CCD) in the context of recent climate historical variability and future climate projections. The dissertation presents a suitable technique based on crop suitability characteristics to examine and show the departure in crop suitability from historical variability both over three stations representative of three AEZs of West Africa. The lack of information of the future spatio-temporal characteristics of crop suitability and planting period has led to many flaws in planning and agricultural development programs against future impact of climate change on agricultural production in a West Africa. Hence, the region like among others in Africa still lags in food security compared to other parts of the globe, despite its great potential to be independent in food production and a major producer in the continent and world at large. It demonstrates the applicability and usefulness of CCD over different time period from near future to end of century for different crop types. This dissertation highlights and provides information on the projected opportunity and constraints in spatial variability of crop suitability for the different crop types over different climate period and under different global warming levels. The evidence of projected increase in suitable areas for crops like cereals into the southern Sahel while constraints resulting reduction in suitable area is projected for some crops by mid-century. In addition, the dissertation also provided information varying response to the global warming levels (1.5, 2.0 and 3.0^{o}C) showed agriculture suitability as in opportunity to sustainably produce food remains within the norm under the GWL1.5^{o}C. Thus, the application of CCD aims to underpin future works to advance the study of future changes in crop suitability and planting season in any region of the world. This type of analysis is important for adaptation options and planning for future changes in the crop suitability and planting period to improve food security.

References

Abatan, A.A. 2011. “West African extreme daily precipitation in observations and stretched-grid simulations by CAM- EULAG” (2011). Graduate Theses and Dissertations. Iowa State University. Available: https://lib.dr.iastate.edu/etd/10401.

Abbate, P.E., Dardanelli, J.L., Cantarero, M.G., Maturano, M., Melchiori, R.J.M. & Suero, E.E. 2004. Climatic and water availability effects on water-use efficiency in wheat. *Crop Science*. 44(2):474–483. DOI: 10.2135/cropsci2004.0474.

Abiodun, B.J., Pal, J.S., Afiesimama, E.A., Gutowski, W.J. & Adedoyin, A. 2008. Simulation of West African monsoon using RegCM3 Part II: Impacts of deforestation and desertification. *Theoretical and Applied Climatology*. 93(3–4):245–261. DOI: 10.1007/s00704-007-0333-1.

Abiodun, B.J., Adeyewa, Z.D., Oguntunde, P.G., Salami, A.T. & Ajayi, V.O. 2012. Modeling the impacts of reforestation on future climate in West Africa. *Theoretical and Applied Climatology*. 110(1–2):77–96. DOI: 10.1007/s00704-012-0614-1.

Abiodun, B.J., Adegoke, J., Abatan, A.A., Ibe, C.A., Egbebiyi, T.S., Engelbrecht, F. & Pinto, I. 2017. Potential impacts of climate change on extreme precipitation over four African coastal cities. *Climatic Change*. 143(3–4):399–413. DOI: 10.1007/s10584-017-2001-5.

Abiodun, B. J., Makhanya, N., Petja, B., Abatan, A. A., & Oguntunde, P. G. (2019). Future projection of droughts over major river basins in Southern Africa at specific global warming levels. *Theoretical and Applied Climatology*, *137*(3-4), 1785-1799. https://link.springer.com/article/10.1007/s00704-018-2693-0

Adger, W.N. 2003. Social Capital, Collective Action, and Adaptation to Climate Change. *Economic Geography*. 79(4):387–404. DOI: 10.1111/j.1944-8287.2003.tb00220.x.

Ahmed, K.F., Wang, G., Yu, M., Koo, J. & You, L. 2015. Potential impact of climate change on cereal crop yield in West Africa. *Climatic Change*. 133(2):321–334. DOI: 10.1007/s10584-015-1462-7.

Alliance for Green Revolution in Africa (AGRA). 2014. *The Africa Agriculture Status Report 2014 : Climate Change and Smallholder Agriculture in Sub-Saharan Africa*. Nairobi, Kenya. Available: http://agra-alliance.org/our-results/agra-status-reports/.

Baidu, M., Amekudzi, L.K., Aryee, J.N.A. & Annor, T. 2017. Assessment of long-term spatio-temporal rainfall variability over Ghana using wavelet analysis. *Climate*. 5(2):1–24. DOI: 10.3390/cli5020030.

Barrett, H. & Browne, A. 1996. Export Horticultural Production in Sub-Saharan Africa: The Incorporation of The Gambia. 81(1):47–56. DOI: 10.1007/sl0869-007-9037-x.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E. & Thiombiano, L. 2006. Bationo, A., Hartemink, A. E., Lungo, O., Naimi, M., Okoth, P., Smaling, E. M. A., & Thiombiano, L. (2006). African soils: their productivity and profitability of fertilizer use: In *Background paper for the Africa Fertilizer Summit 9-13th June 2006, Abuja,*. Available: https://library.wur.nl/WebQuery/wurpubs/fulltext/26759.

Benhin, J.K.A. 2008. South African crop farming and climate change: An economic assessment of impacts. *Global Environmental Change*. 18(4):666–678. DOI: 10.1016/j.gloenvcha.2008.06.003.

Blein, R., Soulé, B.G., Faivre Dupaigre, B. & Yérima, B. 2008. *Agricultural Potential of West Africa. Farm Foundation, ECOWAS. February,* Available: *http://www.fondation-farm.org/IMG/pdf/potentialites_rapport_ang_mp.pdf.*

Bloom, D. 2011. 7 Billion and Counting Tamanho da População e Crescimento. *Science*. 333(July):562–569. DOI: 10.1126/science.1209290.

Brown, M.E. & de Beurs, K.M. 2008. Evaluation of multi-sensor semi-arid crop season parameters based on NDVI and rainfall. *Remote Sensing of Environment*. 112(5):2261–2271. DOI: 10.1016/j.rse.2007.10.008.

Butt, B., Turner, M.D., Singh, A. & Brottem, L. 2011. Use of MODIS NDVI to evaluate changing latitudinal gradients of rangeland phenology in Sudano-Sahelian West Africa. *Remote Sensing of Environment*. 115(12):3367–3376. DOI: 10.1016/j.rse.2011.08.001.

Cantelaube, P. & Terres, J.M. 2005. Seasonal weather forecasts for crop yield modelling in Europe. *Tellus, Series A: Dynamic Meteorology and Oceanography*. 57(3):476–487. DOI: 10.1111/j.1600-0870.2005.00125.x.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P. & Kassam, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*. 83(3):381–399. DOI: 10.1007/s10584-007-9249-0.

Challinor, A.J., Wheeler, T.R., Slingo, J.M. & Hemming, D. 2005. Quantification of physical and biological uncertainty in the simulation of the yield of a tropical crop using present-day and doubled CO2 climates. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 360(1463):2085–2094. DOI: 10.1098/rstb.2005.1740.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., Hawkins, E., Sutton, R., et al. 2013. Time of emergence of climate signals over China under the RCP4.5 scenario. *Nature Climate Change*. 39(1):1–5. DOI: 10.1177/0309133310397582.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R. & Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*. 4(4):287–291. DOI: 10.1038/nclimate2153.

Chen, J., Brissette, F.P. & Lucas-Picher, P. 2015. Assessing the limits of bias-correcting climate model outputs for climate change impact studies. *Journal of Geophysical Research: Atmosphere*. 120:1123–1136. DOI: doi:10.1002/2014JD022635.

Cong, R.G. & Brady, M. 2012. The interdependence between rainfall and temperature: Copula analyses. *The Scientific World Journal*. 12. DOI: 10.1100/2012/405675.

Déqué, M., Calmanti, S., Christensen, O.B., Dell Aquila, A., Maule, C.F., Haensler, A., Nikulin, G. & Teichmann, C. 2017. A multi-model climate response over tropical Africa at +2 °C. *Climate Services*. 7:87–95. DOI: 10.1016/j.cliser.2016.06.002.

Diasso, U. & Abiodun, B.J. 2017. Drought modes in West Africa and how well CORDEX RCMs simulate them. *Theoretical and Applied Climatology*. 128(1–2):223–240. DOI: 10.1007/s00704-015-1705-6.

Dixon, J., Gulliver, A. & Gibbon., D. 2001. *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World. FAO & World Bank, Rome, Italy & Washington, DC, USA.* DOI: 10.1017/S0014479702211059.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G. and Swingedouw, D. 2015. Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proceedings of the National Academy of Sciences*, *112*(43), pp. E5777-E5786.

Egbebiyi, T.S. 2016. Future changes in extreme rainfall events and African easterly waves over West Africa, Thesis/Dissertation, University of Cape Town, South Africa. Available: https://open.uct.ac.za/handle/11427/20581.

Egbebiyi, T.S., Crespo, O., & Lennard, C. 2019. Defining Crop–climate Departure in West Africa: Improved Understanding of the Timing of Future Changes in Crop Suitability. *Climate*. 7(9):1–19. DOI: 10.3390/cli7090101.

Egbebiyi, T.S., Lennard, C., Crespo, O., Mukwenha, P., Lawal, S., Quagraine K. 2019. Assessing Future Spatio-Temporal Changes in Crop Suitability and Planting Season over West Africa : Using the Concept of Crop-Climate Departure. *Climate*. 7(9):1–30. DOI: 10.3390/cli7090102.

Egbebiyi, T.S, Crespo, O., Lennard, C., Zaroug, M., Nikulin, G., Harris, I., Price, J., Forstenhäusler, N., Warren, R. 2020. Investigating the potential impact of 1.5, 2 & 3^{o}C global warming levels on crop suitability and planting season over West Africa. PeerJ-Life & Environment Journal. DOI: doi 10.7717/peerj.8851. In press

Famien, A.M., Janicot, S., Delfin Ochou, A., Vrac, M., Defrance, D., Sultan, B. & Noël, T. 2018. A bias-corrected CMIP5 dataset for Africa using the CDF-t method - A contribution to agricultural impact studies. *Earth System Dynamics*. 9(1):313–338. DOI: 10.5194/esd-9-313-2018.

FAO. 2018. *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition. Rome, FAO. Licence: CC BY-NC-SA 3.0 IGO*. DOI:

10.1093/cjres/rst006.

FAOSTAT. 2014. *FAO STATISTICAL YEARBOOK 2014, Africa, Food and Agriculture Organization of the United Nations, Regional Office for Africa, Accra, vol. 39, no. 5, pp. 561-563*.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., et al. 2014. *IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [F*. Cambridge, United Kingdom and New York, NY, USA. DOI: 10.1016/j.renene.2009.11.012.

Gbobaniyi, E., Sarr, A., Sylla, M.B., Diallo, I., Lennard, C., Dosio, A., Dhiédiou, A., Kamga, A., et al. 2014. Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. *International Journal of Climatology*. 34(7):2241–2257. DOI: 10.1002/joc.3834.

Gizaw, M.S. & Gan, T.Y. 2017. Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa. *Climate Dynamics*. 49(1–2):665–682. DOI: 10.1007/s00382-016-3366-2.

Grolle, J. 1997. Heavy rainfall, famine, and cultural response in the West African Sahel: the ‘Muda’ of 1953–54. *GeoJournal*. 43(3):205–214.

Hansen, J., Sato, M. & Ruedy, R. 2012. Perception of climate change. *Proceedings of the National Academy of Sciences*. 109(37):E2415–E2423. DOI: 10.1073/pnas.1205276109.

Harris, I., Jones, P.D., Osborn, T.J. & Lister, D.H. 2014. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*. 34(3):623–642. DOI: 10.1002/joc.3711.

Hawkins, E. & Sutton, R. 2012. Time of emergence of climate signals. *Geophysical Research Letters*. 39(1):1–6. DOI: 10.1029/2011GL050087.

Hertel, T.W., 2011. The global supply and demand for agricultural land in 2050: A perfect storm in the making? *American Journal of Agricultural Economics*, *93*(2), pp.259-275.

Hertel, T.W. 2015. The challenges of sustainably feeding a growing planet. *Food Security*. 7(2):185–198.

Hewitson, B.C. & Crane, R.G. 2005. Gridded area-averaged daily precipitation via conditional interpolation. *Journal of Climate*. 18(1):41–57. DOI: 10.1175/JCLI3246.1.

Hijmans, A.R.J., Phillips, S., Leathwick, J., Elith, J. & Hijmans, M.R.J. 2017. *Hijmans, Robert J*.

Hijmans, R.J., Guarino, L., Cruz, M. & Rojas, E. 2001. Computer tools for spatial analysis of plant genetic resources data: 1. DIVA-GIS. *Plant Genetic Resources Newsletter,*. 127:15–19.

Hof, A.F., den Elzen, M.G.J., Admiraal, A., Roelfsema, M., Gernaat, D.E.H.J. & van Vuuren, D.P. 2017. Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. *Environmental Science and Policy*. 71(January):30–40. DOI: 10.1016/j.envsci.2017.02.008.

Hountondji, Y. & Ozer, P. 2011. Submitted to the 1 st International Conference on Energy , Environment And Climate Changes Trends in extreme rainfall events in Benin (West Africa), 1960-2000. (May 2015).

Hunter, R. & Crespo, O. 2018. *Large Scale Crop Suitability Assessment Under Future Climate Using the Ecocrop Model: The Case of Six Provinces in Angola's Planalto Region*. Springer, Cham. DOI: 10.1007/978-3-319-92798-5_4.

IFAD, UNEP. 2013. Smallholders, food security and the environment Rome Int. Fund. Agric. Dev. p. 54

IPCC. 2014. *Climate change 2014. Synthesis report. Versión inglés*. DOI: 10.1017/CBO9781107415324.

IPCC, 2013: 2013. *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, . DOI: 10.1017/CBO9781107415324.

IPCC, 2018. 2018. *IPCC, 2018: Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global*. Geneva, Switzerland.

Jalloh, A., Nelson, G.C., Thomas, T.S. & Roy-macauley, H. 2013. *West African Agriculture and Climate Change: A Comprehensive Analysis. International Food Policy Research Institute Washington, DC*. Washington, D.C. DOI: http://dx.doi.org/10.2499/9780896297951.

Janicot, S., Caniaux, G., Chauvin, F., De Coëtlogon, G., Fontaine, B., Hall, N., Kiladis, G., Lafore, J.P., et al. 2011. Intraseasonal variability of the West African monsoon. *Atmospheric Science Letters*. 12(1):58–66. DOI: 10.1002/asl.280.

Jarvis, A., Ramirez-Villegas, J., Campo, B.V.H. & Navarro-Racines, C. 2012a. Is Cassava the Answer to African Climate Change Adaptation? *Tropical Plant Biology*. 5(1):9–29. DOI: 10.1007/s12042-012-9096-7.

Jarvis, A., Ramirez-Villegas, J., Campo, B.V.H. & Navarro-Racines, C. 2012b. Is Cassava the Answer to African Climate Change Adaptation? *Tropical Plant Biology*. 5(1):9–29. DOI: 10.1007/s12042-012-9096-7.

Jayne, T.S., Chamberlin, J. & Headey, D.D. 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy*. 48:1–17.

Kirtman et al., 2013, Predictability, N.C.C.P. and, Coordinating Lead Authors: Ben Kirtman (USA), S.B.P. (Australia), Lead Authors: Akintayo John Adedoyin (Botswana), George J. Boer (Canada), Roxana Bojariu (Romania), Ines Camilloni (Argentina), Francisco Doblas-Reyes (Spain), Arlene M. Fiore (USA), Masahide Kimoto (Japan), Gerald Meehl (USA), Michael Prather (USA), Abdo, H.-J.W. (China), Contributing Authors: Nathaniel L. Bindoff (Australia), Philip Cameron-Smith (USA/New Zealand), Yoshimitsu Chikamoto (USA/Japan), Olivia Clifton (USA), Susanna Corti (Italy), Paul J. Durack (USA/ Australia), Thierry Fichefet (Belgium), Javier García-Serra, P.Y. (UK), Review Editors: Pascale Delecluse (France), Tim

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Klutse, N.A.B., Sylla, M.B., Diallo, I., Sarr, A., Dosio, A., Diedhiou, A., Kamga, A., Lamptey, B., et al. 2016. Daily characteristics of West African summer monsoon precipitation in CORDEX simulations. *Theoretical and Applied Climatology*. 123(1–2):369–386. DOI: 10.1007/s00704-014-1352-3.

Klutse, N.A.B., Ajayi, V.O., Gbobaniyi, E.O., Egbebiyi, T.S., Kouadio, K., Nkrumah, F., Quagraine, K.A., Olusegun, C., et al. 2018. Potential impact of 1.5 °c and 2 °c global warming on consecutive dry and wet days over West Africa. *Environmental Research Letters*. 13(5). DOI: 10.1088/1748-9326/aab37b.

Knox, J., Hess, T., Daccache, A. & Wheeler, T. 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*. 7(3). DOI: 10.1088/1748-9326/7/3/034032.

Kumi, N. & Abiodun, B.J. 2018. Potential impacts of 1.5 °c and 2 °c global warming on rainfall onset, cessation and length of rainy season in West Africa. *Environmental Research Letters*. DOI: 10.1088/1748-9326/aab89e.

Kurukulasuriya, P. & Mendelsohn, R. 2006. A RICARDIAN ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON AFRICAN\nCROPLAND. *AfJARE*. DOI: ISBN:1-920160-08-6.

Lobell, D.B. & Gourdji, S.M. 2012. The Influence of Climate Change on Global Crop Productivity. *Plant Physiology*. 160(4):1686–1697. DOI: 10.1104/pp.112.208298.

Lobell, D.B., Schlenker, W. & Costa-Roberts, J. 2011. Climate trends and global crop production since 1980 - Supporting Online Material. *Science*. 333(6042):616–620. DOI:

10.1126/science.1204531.

Lobell et al. 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030 Region. *Science*. 319(February):607–610. DOI: 10.1126/science.1152339.

Luderer, G., Pietzcker, R.C., Bertram, C., Kriegler, E., Meinshausen, M. & Edenhofer, O. 2013. Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environmental Research Letters*. 8(3). DOI: 10.1088/1748-9326/8/3/034033.

Luo, Q. 2011. Temperature thresholds and crop production: A review. *Climatic Change*. 109(3–4):583–598. DOI: 10.1007/s10584-011-0028-6.

Mahlstein, I., Daniel, J.S. & Solomon, S. 2013. Pace of shifts in climate regions increases with global temperature. *Nature Climate Change*. 3(8):739–743. DOI: 10.1038/nclimate1876.

Malhotra, S.K. 2017. Horticultural crops and climate change: A review. *Indian Journal of Agricultural Sciences*. 87(1):12–22.

Mason, S.C., Maman, N. & Palé, S. 2015. PEARL MILLET PRODUCTION PRACTICES in SEMI-ARID WEST Africa: A REVIEW. *Experimental Agriculture*. 51(4):501–521. DOI: 10.1017/S0014479714000441.

Mastrandrea, M.D., Mach, K.J., Barros, V.R., Bilir, T.E., Dokken, D.J., Edenhofer, O., Field, C.B., Hiraishi, T., et al. 2015. *IPCC, 2015: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Climate Change, Food, and Agriculture. World Meteorological Organization, Geneva, Switzerland, 68 pp.* Geneva, Switzerland. Available: https://www.ipcc.ch/pdf/supporting-material/Food-EM_MeetingReport_FINAL.pdf.

Mastrandrea, M.D., Mach, K.J., Barros, V.R., Bilir, T.E., Dokken, D.J., Edenhofer, O., Field, C.B., Hiraishi, T., et al. 2015. *IPCC, 2015: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Climate Change, Food, and Agriculture [Mastrandrea, M.D., K.J. Mach, V.R. Barros, T.E. Bilir, D.J. Dokken, O. Edenhofer, C.B. Field, T. Hiraishi, S. Kadner, T. K.* Dublin, Ireland. Available: https://www.ipcc.ch/pdf/supporting-material/Food-EM_MeetingReport_FINAL.pdf.

Maúre, G., Ndebele-Murisa, M., Nikulin, G., Lennard, C., Meque, A., Muthige, M., Pinto, I. & Dosio, A. 2018. The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models. *Environmental Research Letters*. 13(6):065002. DOI: 10.1088/1748-9326/aab190.

McCarthy, J, Canziani, O., Leary, N., Dokken, D. & White, C. 2001. *Climate Change 2001: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. & White, K.S. 2002. *IPCC, 2001: Climate change 2001: impacts, adaptation and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. DOI: 10.1002/joc.775.

Medori, M., Michelini, L., Nogues, I., Loreto, F. & Calfapietra, C. 2012. The impact of root temperature on photosynthesis and isoprene emission in three different plant species. *The Scientific World Journal*. 2012. DOI: 10.1100/2012/525827.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J. & Allen, M.R. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*. 458(7242):1158–1162. DOI: 10.1038/nature08017.

Mitchell, D., James, R., Forster, P.M., Betts, R.A., Shiogama, H. & Allen, M. 2016. Realizing the impacts of a 1.5 °C warmer world. *Nature Climate Change*. 6(8):735–737. DOI: 10.1038/nclimate3055.

Mora, C., Frazier, A.G., Longman, R.J., Dacks, R.S., Walton, M.M., Tong, E.J., Sanchez, J.J., Kaiser, L.R., et al. 2013. The projected timing of climate departure from recent variability. *Nature*. 502(7470):183–187. DOI: 10.1038/nature12540.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., et al. 2009. *Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., ... & Magalhaes, M. (2009). Climate change: Impact on agriculture and costs of adaptation (Vol. 21). Intl Food Policy Res Inst.* Washington, D.C. DOI: DOI: 10.2499/0896295354.

Nelson, G.C., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlik, P., Heyhoe, E., et al. 2014. Agriculture and climate change in global scenarios: Why don't the models agree. *Agricultural Economics (United Kingdom)*. 45(1):85–101. DOI: 10.1111/agec.12091.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & P. Urquhart. 2014. *Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, 2014: Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Repo*.

Nicholson, S.E. 2008. The intensity, location and structure of the tropical rainbelt over west Africa as factors in interannual variability. *International Journal of Climatology*. 28:1775–1785. DOI: 10.1002/joc.

Nicholson, S.E. 2009. A revised picture of the structure of the "monsoon" and land ITCZ over West Africa. *Climate Dynamics*. 32(7–8):1155–1171. DOI: 10.1007/s00382-008-0514-3.

Nicholson, S.E. 2013. The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability. *ISRN Meteorology*. 2013:1–32. DOI: 10.1155/2013/453521.

Nikulin, G., Lennard, C., Dosio, A., Kjellstrom, E., Chen, Y., Hansler, A., Kupiainen, M., Laprise, R., et al. 2018. The effects of 1 . 5 and 2 degrees of global warming on Africa in the CORDEX The effects of 1 . 5 and 2 degrees of global warming on Africa in the CORDEX ensemble Manuscript version : Accepted Manuscript. *Environmental Research Letters*. (February). DOI: 10.1088/1748-9326/aab1b1.

OECD/FAO. 2016. *OECD/FAO (2016), OECD-FAO Agricultural Outlook 2016-2025, OECD Publishing, Paris. http://dx.doi.org/10.1787/agr_outlook-2016-en*. OECD Publishing, Paris. DOI: . http://doi.org/10.1787/agr_outlook-2016-en.

Ohlson, J.A. & Kim, S. 2015. *Linear valuation without OLS: the Theil-Sen estimation approach*. V. 20. DOI: 10.1007/s11142-014-9300-0.

Olesen, J.E. & Bindi, M. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*. 16(4):239–262. DOI: 10.1016/S1161-0301(02)00004-7.

Omotosho, J.B. & Abiodun, B.J. 2007. A numerical study of moisture build-up and rainfall over West Africa. *Meteorological Applications*. 14(July):209–225. DOI: 10.1002/met.

Paeth, H., Capo-Chichi, A. & Endlicher, W. 2008. Climate Change and Food Security in Tropical West Africa — A Dynamic-Statistical Modelling Approach. 2:101–115. Available: http://www.jstor.org/stable/25648102 .

Paeth, H., Hall, N.M.J., Gaertner, M.A., Alonso, M.D., Moumouni, S., Polcher, J., Ruti, P.M., Fink, A.H., et al. 2011. Progress in regional downscaling of west African precipitation. *Atmospheric Science Letters*. 12(1):75–82. DOI: 10.1002/asl.306.

Parkes, B., Defrance, D., Sultan, B., Ciais, P., Wang, X. & Parkes, C. Ben. 2018. Projected changes in crop yield mean and variability over West Africa in a world 1 . 5 K warmer than the pre-industrial era. *Earth Syst. Dynam.,*. 9:119–134.

Peng, H., Wang, S. & Wang, X. 2008. Consistency and asymptotic distribution of the Theil-Sen estimator. *Journal of Statistical Planning and Inference*. DOI: 10.1016/j.jspi.2007.06.036.

Population Reference Bureau. 2018. *2018 World Population Data Sheet*. Washington D.C.

Porter, J.R. & Semenov, M.A. 2005. Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 360(1463):2021–2035. DOI: 10.1098/rstb.2005.1752.

Portmann F. T., Siebert, S., & Döll, P. 2010. MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*. 24(1):1–24. DOI: 10.1029/2008gb003435.

Pretty, J.N., Morison, J.I.L. & Hine, R.E. 2003. Reducing food poverty by increasing agricultural sustainability in developing countries. *Agriculture, Ecosystems and Environment*. 95:217–234. DOI: 10.1016/S0167-8809(02)00087-7.

Ramirez-Villegas, J. & Thornton, P.K. 2015. J Ramirez-Villegas, Thornton PK 2015. Climate change impacts on African crop production. CCAFS Working Paper no. 119. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgia. *Working Paper No. 119*. (119):1–27.

Ramirez-Villegas, J., Jarvis, A. & Läderach, P. 2013. Empirical approaches for assessing impacts of climate change on agriculture: The EcoCrop model and a case study with grain sorghum. *Agricultural and Forest Meteorology*. DOI: 10.1016/j.agrformet.2011.09.005.

Ramírez-Villegas, J., Lau, C., Köhler, A.-K., Signer, J., Jarvis, A., Arnell, N., Osborne, T. & Hooker, J. 2011. Climate Analogues: Finding tomorrow's agriculture today CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available: www.ccafs.cgiar.org.

Ray, D.K. & Foley, J.A. 2013. Increasing global crop harvest frequency: Recent trends and future directions. *Environmental Research Letters*. 8(4). DOI: 10.1088/1748-9326/8/4/044041.

République du Bénin, W.B. 2011. *Inondation au Bénin. Rapport d'Evaluration des Besoins Post Catastrophiques*. Available: https://www.gfdrr.org/sites/default/files/publication/pda-2011-benin-fr.pdf.

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L. & Chookolingo, B. 2018. How much of the world's food do smallholders produce? *Global Food Security*. 17(January):64–72.

Riede, J.O., Posada, R., Fink, A.H. & Kaspar, F. 2013. *What's on the 5th IPCC Report for West Africa?* V. 19. J.A. Yaro & J. Hessellberg, Eds. Springer International Publishing Switzerland 2016. DOI: 10.1007/978-3-319-31499-0.

Rippke, U., Ramirez-Villegas, J., Jarvis, A., Vermeulen, S.J., Parker, L., Mer, F., Diekkrüger, B., Challinor, A.J., et al. 2016. Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Climate Change*. 6(6):605–609. DOI: 10.1038/nclimate2947.

Rogelj, J., McCollum, D.L., Reisinger, A., Meinshausen, M. & Riahi, K. 2013. Probabilistic cost estimates for climate change mitigation. *Nature*. 493(7430):79–83. DOI: 10.1038/nature11787.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., et al. 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature*. 534(7609):631–639. DOI: 10.1038/nature18307.

Rosenzweig, C. et al., in Climate Change (2007). Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the IPCC, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, C. E. Hanson, Eds. (Cambridge Univ. Press, Cambridge, 2007), pp. 79–131.

Roudier, P., Sultan, B., Quirion, P. & Berg, A. 2011. The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change*. 21(3):1073–1083. DOI: 10.1016/j.gloenvcha.2011.04.007.

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R. & Giller, K.E. 2014. Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: A participatory analysis. *Climate Risk Management*. 3:65–78. DOI: 10.1016/j.crm.2014.05.004.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellström, E., et al. 2011. The Rossby Centre Regional Climate model RCA3: Model description and performance. *Tellus, Series A: Dynamic Meteorology and Oceanography*. 63(1):4–23. DOI: 10.1111/j.1600-0870.2010.00478.x.

Sarr, B. 2012. Present and future climate change in the semi-arid region of West Africa: A crucial input for practical adaptation in agriculture. *Atmospheric Science Letters*. 13(2):108–112. DOI: 10.1002/asl.368.

Schlenker, W. & Lobell, D.B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*. 5(1). DOI: 10.1088/1748-9326/5/1/014010.

Schleussner, C.F., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., et al. 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. *Earth System Dynamics*. 7(2):327–351. DOI: 10.5194/esd-7-327-2016.

Screen, J. A., & Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, *464*(7293), 1334-1337.

Sen, P.K. 1968. Estimates of the Regression Coefficient Based on Kendall’s Tau. *Journal of the American Statistical Association*. 63(324):1379–1389. DOI: 10.1080/01621459.1968.10480934.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., et al. 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*. 17(6):1585–1600. DOI: 10.1007/s10113-015-0910-2.

Sighomnou, D., Luc Descroix, Genthon, P., Mahe, G., Moussa, I.B., Gautier, E., Mamadou, I., Vandervaere, J.-P., et al. 2013. La crue de 2012 à Niamey: un paroxysme du paradoxe du Sahel?. 24:3–13.

Singh, P., Boote, K.J., Kadiyala, M.D.M., Nedumaran, S., Gupta, S.K., Srinivas, K. & Bantilan, M.C.S. 2017. Science of the Total Environment An assessment of yield gains under climate change due to genetic modi fi cation of pearl millet. *Science of the Total Environment*. 601–602:1226–1237. DOI: 10.1016/j.scitotenv.2017.06.002.

Slingo, J.M., Challinor, A.J., Hoskins, B.J. & Wheeler, T.R. 2005. Introduction: Food crops in a changing climate. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 360(1463):1983–1989. DOI: 10.1098/rstb.2005.1755.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., M.Tignor & Miller, H.L. 2007. *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of th*. Cambridge, UK., New York, USA. DOI: 10.1017/CBO9781139177245.

Srivastava et al. 2016. Climate change impact and potential adaptation strategies under alternate climate scenarios for yam production in the sub-humid savannah zone of West Africa. *Mitigation and Adaptation Strategies for Global Change*. 21(6):955–968. DOI: 10.1007/s11027-015-9639-y.

Sultan, B. & Gaetani, M. 2016. Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Frontiers in Plant Science*. 7(August):1–20. DOI: 10.3389/fpls.2016.01262.

Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G.L., McLean, G. & Lobell, D.B. 2014. Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters*. 9(10). DOI: 10.1088/1748-9326/9/10/104006.

Swennen, R. (1990). Plantain cultivation under West Africa conditions: a reference manual. Ibadan, Nigeria: IITA, (24 p.). https://hdl.handle.net/10568/101806

Sylla, M.B., Giorgi, F., Coppola, E. & Mariotti, L. 2013. Uncertainties in daily rainfall over Africa: Assessment of gridded observation products and evaluation of a regional climate model simulation. *International Journal of Climatology*. 33(7):1805–1817. DOI: 10.1002/joc.3551.

TAKANE, T. 2004. Smallholders and nontraditional exports under economic liberalization: the case of pineapples in Ghana. *African Study Monographs*. 25(1); March):29–43. DOI: 10.14989/68228.

Tarhule, A. & Woo, M.K. 1997. Towards an interpretation of historical droughts in northern Nigeria. *Climatic Change*. 37(4):601–616. DOI: 10.1023/A:1005319723995.

Taylor et al. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*. 93(4):485–498. DOI: 10.1175/BAMS-D-11-00094.1.

Theil, H., 1950: A rank-invariant method of linear and polynomial regression analysis. Indigationes Mathematicae 12, 85-91.

Thiele, G., Khan, A., Heider, B., Kroschel, J., Harahagazwe, D., Andrade, M., Bonierbale, M., Friedmann, M., et al. 2017. Roots, Tubers and Bananas: Planning and research for climate resilience. *Open Agriculture*. 2(1):350–361. DOI: 10.1515/opag-2017-0039.

Thornton, P.K., Jones, P.G., Ericksen, P.J. & Challinor, A.J. 2011. Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. 369(1934):117–136. DOI: 10.1098/rsta.2010.0246.

Travis, W. R. 2016. Agricultural impacts: Mapping future crop geographies. Nature Climate Change, (6), 544-545.

UNDP. 2015. The 2030 Agenda for Sustainable Development, A/RES/70/1. *UNDP*. 16301(October):13–14.

UNFCCC, 2015. 2015. *United Nations Framework Convention on Climate Change (UNFCCC): Adoption of the Paris Agreement, Conference of the Parties, Paris, France, 30 November–11 December, 2015*. Paris, France.

United Nations. 2013. *The Millennium Development Goals Report 2013*. New York, USA.

Vermeulen, S.J., Campbell, B.M. & Ingram, J.S.I. 2012. Climate change and food systems. *Annual Review of Environment and Resources*. 37(1):195–222.

Vermeulen, S.J., Challinor, A.J., Thornton, P.K., Campbell, B.M., Eriyagama, N., Vervoort, J.M., Kinyangi, J., Jarvis, A., et al. 2013. Addressing uncertainty in adaptation planning for agriculture. *Proceedings of the National Academy of Sciences*. 110(21):8357–8362. DOI: 10.1073/pnas.1219441110.

Vrac, M., Noël, T. & Vautard, R. 2016. Bias correction of precipitation through Singularity Stochastic Removal. (1):5237–5258. DOI: 10.1002/2015JD024511.Received.

Vrieling, A., De Leeuw, J. & Said, M.Y. 2013. Length of growing period over africa: Variability and trends from 30 years of NDVI time series. *Remote Sensing*. 5(2):982–1000. DOI: 10.3390/rs5020982.

Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J. & Viterbo, P. 2014. The WFDEI meteorological forcing data set: WATCH Forcing data methodology applied to ERA-

Interim reanalysis data. *Water Resources Research*. 50(9):7505–7514. DOI: 10.1002/2014WR015638.

Wheeler, T. & von Braun, J. 2013. Climate change impacts on global food security. *Science*. 341:55–60.

White, J.W., Hoogenboom, G., Kimball, B.A. & Wall, G.W. 2011. Methodologies for simulating impacts of climate change on crop production. *Field Crops Research*. 124(3):357–368. DOI: 10.1016/j.fcr.2011.07.001.

Wilcox, R.R. 1998. A note on the Theil-Sen regression estimator when the regresser is random and the error term is heteroscedastic. *Biometrical Journal*. 40(3):261–268. DOI: 10.1002/(SICI)1521-4036(199807)40:3<261::AID-BIMJ261>3.0.CO;2-V.

Wilcox, R.R. 2003. Simulations on the Theil-Sen regression estimator with right-censored data. *Statistics & Probability Letters*. DOI: 10.1016/s0167-7152(98)00022-4.

Williams et al. 2018. Williams, Portia Adade, Olivier Crespo, and Mumuni Abu. "Assessing vulnerability of horticultural smallholders' to climate variability in Ghana: applying the livelihood vulnerability approach." Environment, Development and Sustainability (2018): 1-22. *Environment, Development and Sustainability*. (0123456789):1–22. DOI: 10.1007/s10668-018-0292-y.

Willy, D.K., Muyanga, M., Mbuvi, J. and Jayne, T., 2019. The effect of land use change on soil fertility parameters in densely populated areas of Kenya. *Geoderma*, *343*, pp.254-262.

World Bank Report. 2009. *Making Development Climate Resilient. A World Bank Strategy for Sub-Saharan Africa. vol.1. DOI:10.1007/s12010-014-1375-3, Report No. 46947-AFR*. DOI: 10.1007/s12010-014-1375-3.

World Bank Report. 2010. World Development Report 2010: Development and Climate Change. Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/4387 License: CC BY 3.0 IGO." (Accessed 30 November 2018).

World Bank Report. 2013. *World Development Report 2013: Jobs. Washington, DC: World Bank. DOI: 10.1596/978-0-8213-9575-2. License: Creative Commons Attribution CC BY 3.0.*

World Meteorological Organization Report, W. 2015. *The Climate in Africa : WMO Report, 2015*.

Zhang, X. & Cai, X. 2013. Climate change impacts on global agricultural water deficit. *Geophysical Research Letters*. 40(6):1111–1117. DOI: 10.1002/grl.50279.

Zinyengere, N., Crespo, O. & Hachigonta, S. 2013. Crop response to climate change in southern Africa: A comprehensive review. *Global and Planetary Change*. 111:118–126. DOI: 10.1016/j.gloplacha.2013.08.010.