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Assessing the Impact of Climate Change on Crop Suitability in Nigeria

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Dedication

This research project is dedicated to WASCAL (West African Science Service Centre on Climate Change and Adapted Land Use), which offered me the opportunity to further my knowledge of informatics and climate change and enabled me prepare for a prospective career in technology.

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Abstract

A global phenomenon, climate change has a particular influence on the food availability for the next generation. Nigeria, the most populous nation in Africa with a population that is increasing at a geometric rate annually, will need to look at ways to preserve its agriculture, which is the main source of food, jobs, and the nation's economy. The goal of this study is to determine how climate change would affect the future crop suitability of cowpea, maize, and cassava (which are the main food crops in Nigeria) in the various agro - ecological zones (Sahel, Sudan, Guinea Savannah, Tropical Rainforest and Coastal zone) of the country. To do this, the EcoCrop model was used to assess the historical performance of the selected crops, and the findings were then utilized to inspire estimates for the suitability of the crops in the future. The EcoCrop model demonstrated substantial effects on the spatial distribution of the three selected crops across the zones as well as the ideal future planting months. It evaluated both historical and future simulations for the three selected crops adequately. The effectiveness of the EcoCrop as a tool for assessing projections for Nigeria's food security is shown by this study.

Keywords: Climate Change; Crop Suitability; EcoCrop; Nigeria

Résumé

Phénomène mondial, le changement climatique a une influence particulière sur la disponibilité alimentaire pour la prochaine génération. Le Nigéria, le pays le plus peuplé d'Afrique avec une population qui augmente à un rythme considerable chaque année, devra chercher des moyens de préserver son agriculture, qui est la principale source de nourriture, d'emplois et de l'économie du pays. L'objectif de cette étude est de déterminer comment le changement climatique affecterait la future aptitude des cultures de niébé, de maïs et de manioc (qui sont les principales cultures vivrières au Nigeria) dans les différentes zones agro - écologiques (Sahel, Soudan, Savane guinéenne, Tropical forêt tropicale et zone côtière) du pays. Pour ce faire, le modèle EcoCrop a été utilisé pour évaluer les performances historiques des cultures sélectionnées, et les résultats ont ensuite été utilisés pour inspirer des estimations de l'adéquation des cultures à l'avenir. Le modèle EcoCrop a démontré des effets substantiels sur la répartition spatiale des trois cultures sélectionnées dans les zones ainsi que sur les futurs mois de plantation idéaux. Il a évalué à la fois les simulations historiques et futures pour les trois cultures sélectionnées de manière adéquate. L'efficacité de l'EcoCrop en tant qu'outil d'évaluation des projections de la sécurité alimentaire du Nigeria est démontrée par cette étude.

Mots-clés : Changement climatique ; Aptitude aux cultures ; EcoCrop ; Nigeria

Acronyms and Abbreviations

°C	Degree Celsius
%	Percent
IPCC	Intergovernmental Panel on Climate Change
GDP	Gross Domestic Product
AEZs	Agro-Ecological Zones
LDS	Little Dry Season
NPC	National Population Commission
UNICEF	United Nations Children's Fund
APP	Agriculture Promotion Policy
REDD+	Reducing Emissions from Deforestation and Forest Degradation
NEWMAP	Nigeria Erosion and Watershed Management Project
AAD	Action Against Desertification
ABP	Anchor Borrowers Program
GON	Government of Nigeria
NATIP	National Agricultural Technology and Innovation Plan
BH	Boko Haram
FAO	Food and Agriculture Organization
IOM	International Organization for Migration
IDPs	Internally Displaced Persons

IOM-DTM	Displacement Tracking Matrix
ACLED	Armed Conflict Location & Event Data Project
ITCZ	Inter-Tropical Convergence Zone
GFSI	Global Food Security Index
SDGI	Sustainable Development Goal Index
IFAD	International Fund for Agricultural Development
GCMs	General Circulation Models
CMIP5	Coupled Model Intercomparison Project
RCPs	Representative Concentration Pathways
GHG	Greenhouse Gas
CORDEX	Coordinated Regional Downscaling Experiment
SIV	Suitability Index Value
PM	Planting Months
CCD	Climate Change Departure

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Introduction

Climate change has become a serious concern for countries all over the world, resulting in noticeable changes in geography, ecology, economy, and, most critically, food supply. The change in precipitation patterns and the increases in temperature and carbon dioxide (CO2) concentrations influence crop yield in different ways (Asseng et al., 2015), which can decrease or improve depending on the area (Egbebiyi et al., 2019). Heat waves can cause plant stress, which in turn can result in decreased biomass accumulation (Barlow et al., 2015) with declined grain produce. Whereas, crop suitability is the process of assessing the appropriateness or ability of a given type of land on the basis of growing conditions of a particular crop (Singh et al., 2018).

Increasing temperatures will lead to changes in the phenological growth and development of crops and make them susceptible to adverse weather conditions (Asseng et al., 2015). This will shift the sensitive plant periods (i.e. flowering stage) making them prone to drought, frost, critical heat, or heavy precipitation (Trnka et al., 2015).

I. Climate Factors Affecting Crop Production

There are three factors affecting crop production: (a) variation in precipitation regimes, (b) global warming, and (c) increase in CO_2 concentration (World Bank Group, 2021). A brief examination of these factors will be presented in the following paragraphs.

a. Variation in precipitation regimes

In response to climate change, the dry zones in the tropics are projected to become drier and the temperate areas are projected to become wetter (FAO, 2008). The precipitation regimes are forecasted to become unpredictable and irregular (Abdallah, 2018). The soil moisture content, which is one of the significant factors for determining crop yields, will be affected by the changing precipitation. Hence, rainfall reduction in the Near East will lead to increased aridity, decreased soil water content, amplified groundwater depletion, and the resultant effect is the loss of arable land in this region (Sub-county et al., 2019).

Therefore, the influence of climate change in altering the precipitation pattern would reduce agricultural production.

b. Global warming

As a result of climate change, maximum, minimum, and average temperatures are projected to increase across the world (Ayinde et al., 2020). Regions located in low latitudes will experience increases in temperature, where crop yields will be affected due to response to 1-2 °C increase in temperature (Alcamo et al., 2007). This is due to accelerated evapotranspiration and decreased soil moisture content (Sub-county et al., 2019). Slight increase in temperature will bring some improvements in the growth of crops only when the temperature is below the optimum level, while it will negatively affect crops if the temperature approaches or exceeds its maximum limit (Cohen, 2007). If the temperature exceeds the tolerated maximum level of the crop, reductions will occur to crop yields due to insufficient vernalization where the seeds upon germination will not be cooled enough to accelerate the flowering stage (Trnka et al., 2015)

Other reasons proving yield reductions are increased transpiration and reduced photosynthesis (Trnka et al., 2015) and shortening of growing seasons (Cohen 2007). Consequently, some arable lands in the tropics will become unsuitable for agriculture and yields will consequently decline due to this phenomenon (Sub-county et al., 2019). The degree of yield reduction in the future is uncertain and some researchers predict that severe reductions may occur in agricultural production.

c. Increase in CO2 concentration

The elevated CO_2 concentration effects (CO_2 fertilization) on plants have been globally simulated and analyzed. It is estimated that the atmospheric CO_2 concentration will reach 550 ppm by 2100 under RCP 2.6 (lowest emission scenario) (Schmidhuber & Tubiello, 2007). This increase in CO_2 concentration has a beneficial effect on plants via promoting plant growth and development. It will enhance photosynthesis and increase the water-use efficiency, and the resultant effect is an increase in both the biomass and yield of crops (Long et al., 2014). Despite this beneficial effect of CO_2 fertilization, it will globally elevate the greenhouse effect and global warming (Abdallah, 2018).

II. Climate Change Impacts on Global Crop Production

Despite the increase in crop yields due to technological advances, the United States Global Change Research Program report states that extreme weather variations have adversely impacted crop production (Al-hamdani et al., 2015). This report indicates that warmer temperatures not only shorten the growth phases, but also reduce crop yields. Shortened periods of growth can be suitable in areas where the soils have low water content; conversely this, leads to rapid growth and development in some crops such as corn through shortening the seed germination period, crop maturity, and crop growth (Nielsen, 2000).

Eventually, for a given portion of land, the accelerated growth of the crops leads to a substantial decline in crop yields. Zinyengere et al. (2014), agrees with the concept that agricultural production is highly affected by climate change although the magnitude will vary from crop to crop and from place to place mainly due to different anthropogenic and natural factors that contribute to this change. Asseng et al. (2015) also discovered that crop yields will increase due to the high amounts of carbon dioxide, this can lead to temperature rise which will decrease the crop yield eventually.

The influence of climate change on crop productivity thoroughly depends on the plant species and climatic variability of the region. The sensitivity of crops to variations in temperature, solar radiation, atmospheric CO_2 concentration, and precipitation is proved by the results of experimental studies and crop simulation models (Adejuwon, 2006). These variations will affect trop productivity through changes in crop yield, planting date, harvesting date, and time to maturity (Cohen, 2007).

Clearly, Africa is not exempted from the impacts of climate change. Since 1901, much of Africa has warmed by more than 1 degree Celsius, with an increase in extreme climatic events. The Intergovernmental Panel on Climate Change (IPCC) projects a decrease in precipitation over North Africa and the southwestern sections of South Africa by the end of the century (Schmidhuber & Tubiello, 2007). According to recent research devoted to Africa, rising temperatures and sea levels, shifting precipitation patterns, and more extreme weather are affecting human health and safety, food and water security, and socioeconomic growth (State of the Climate in Africa 2019 Report).

Agriculture is extremely important to the African economy; it employs almost two-thirds of the workforce, generates 37 percent of Gross Domestic Product (GDP), and accounts for half of the exports (FAO, 2022). It remains a huge source of income and has a considerable impact on African countries' overall economic success. Agriculture is essential to the survival of people in West Africa. It is the primary source of employment for the region's 290 million residents, employing 60% of the population and accounting for 35% of the region's gross domestic output. In Nigeria, agriculture provided 22.35% of the overall Gross Domestic Product (GDP) between January and March 2021 (Ugo 2022). Over 70% of Nigerians work in agriculture, mostly for subsistence (Manyong et al., 2003). As a result, agriculture is the primary source of income for the majority of Nigerians.

Nigeria has 70.8 million hectares of agricultural land, according to the Food and Agricultural Organization (FAO), with maize, cassava, guinea corn, yam, beans, millet, and rice as the most important crops. Rainfall amount and distribution is a major climatic parameter affecting agriculture in Nigeria, which is primarily rain-fed. In recent times, rainfall amount and distribution has become unpredictable and erratic thereby leading to agricultural loses (Mar et al., 2018). Climate change, is projected to lead to the incidence of pest and poor agricultural output, which can in turn lead to diminished agricultural productivity and economic activity (FAO, 2015). Eventually, a bigger proportion of the population will be impoverished (Cassandra 2017).

Due to insufficient economic and institutional ability to adapt to climate threats, West Africa is one of the world's most susceptible areas to climate change impacts. Climate change and variability are a reality in West Africa today, hurting rural life and posing a major threat in the area, particularly in agriculture. The poor and disadvantaged communities, who rely on agriculture for their livelihoods with limited adaptation capacity would be the most negatively affected by the impacts of climate change, especially on agriculture (World Social Report, 2020).

Seasonal rainfall deficits or late rainfall onset would likely result in major declines in agricultural output owing to crop failure in Nigeria, due to its high sensitivity to climate change and reliance on rain-fed agriculture (Haider, 2019).

Problem Statement

Despite its economic importance, agriculture in Nigeria mainly relies on rainfall, exposing the country to the adverse effects of climate change. Egbebiyi *et al* (2020) investigated the potential impact of 1.5, 2, and 3 °C global warming levels on crop suitability and planting season over West Africa. They found that the projected suitability of various crops would vary at all warming levels with the impact of global warming beyond 1.5°C and 2.0°C, to be more drastic on cereals, roots and tubers over West Africa. They also reported the projected changes in the planting months for different crops across the different Agro-Ecological Zones (AEZs) of West Africa, where the increased warming resulted in early or late planting months for different crops. The study of Egbebiyi et al (2020) provides a broad overview of projected changes in crop suitability and planting season over the entire West Africa under global warming and did not account for country-level impact. There is the need to provide policymakers with more specific information at national and local levels for better decision-making. The aim of this research will, therefore, be to assess projected changes in the suitability of Cassava, Maize, and Cowpea in Nigeria's climatic zones using a crop suitability model.

Research Questions

1. How well does EcoCrop reproduce the suitability of selected crops over the historical period (1981–2000)?
2. How will climate change impact the suitability of selected crops (Cassava, Maize, Cowpea) in Nigeria in the future?
3. How will climate change influence the planting periods for Cassava, Maize, and Cowpea in Nigeria?

Research Hypotheses

1. EcoCrop model can be used to determine crop suitability in the historical period
2. The suitability of Cassava, Maize, and Cowpea may reduce in Nigeria because of climate change.
3. The planting periods of Cassava, Maize, and Cowpea may change due to changes in spatial distribution of precipitation and temperature caused by climate change.

Main Objective

To assess the impact of climate change on the suitability of Cassava, Maize and Cowpea in Nigeria and possible changes to their planting season.

Specific Objectives

1. To evaluate the ability of EcoCrop model in simulating crop suitability;
2. To quantify projected changes in the spatial distribution in the suitability of Cassava, Maize, and Cowpea using a crop suitability model;
3. To assess changes in the planting seasons of the crops in Nigeria for optimum and sustainable production in the future.

Chapter 1

Literature Review

1.1 Climate Change in Nigeria

Nigeria is characterized by three distinct climate zones, a tropical monsoon climate in the south, a tropical savanna climate for most of the central regions, and a Sahelian hot and semi-arid climate in the north of the country. This leads to a gradient of declining precipitation amounts from south to north. The southern regions experience strong rainfall events during the rainy season from March to October with annual rainfall amounts, usually above 2,000 mm, and can reach 4,000 mm and more in the Niger Delta (Adejuwon, 2018).

The central regions are governed by a well-defined single rainy season (April to September) and dry season (December to March). The dry season is influenced by the Harmattan wind from the Sahara. Coastal areas experience a short drier season with the most rain occurring from March to October. Annual rainfall can reach up to about 1200 mm. In the north, the rain only falls from June to September in the range of 500 mm to 750 mm. The rest of the year is hot and dry. Northern areas have a high degree of annual variation in their rainfall regime, which results in flooding and droughts.

The most significant temperature difference in Nigeria is between the coastal areas and its interior as well as between the plateau and the lowlands. On the plateau, the mean annual temperature varies between 21°C and 27°C whereas, in the interior lowlands, temperatures are generally over 27°C. The coastal fringes have lower means than the interior lowlands. Seasonal mean temperatures are consistently over 20°C throughout the country and diurnal variations are more pronounced than seasonal ones (Dike et al., 2019) The highest temperatures occur during the dry season, and vary little from the coast to inland areas. Similar to rainfall, the relative humidity in Nigeria decreases from the south to the north, with an annual mean of 88% around Lagos.

According to Adejuwon (2018), mean annual temperature for Nigeria is 26.9°C, with average monthly temperatures ranging between 24°C (December, January) and 30°C

(April). Mean annual precipitation is 1,165.0 mm. Rainfall is experienced throughout the year in Nigeria, with the most significant rainfall occurring from April to October and with minimal rainfall occurring from November to March.

The rainy season in Nigeria's coastal and southeastern regions normally begins in February or March, when moist Atlantic air, known as the southwest monsoon, invades the country. High winds and severe but dispersed squalls are frequently present towards the start of the rainy season. In most years, the rainy season has begun in most of the territory south of the Niger and Benue River valleys by April or early May. In the far north, the rainy season normally begins in June or July. In August, when air from the Atlantic blankets the whole country, the rainy season reaches its climax across most of northern Nigeria. The August precipitation decreases in southern locations during this time, the dryness in the south of 10°N at this time is referred to as the Little Dry Season (LDS). Although rarely completely dry, this drop in rainfall, which is particularly noticeable in the southwest part of the country, can be beneficial to agriculture by providing a brief dry time for grain harvesting (FAO, 2015)

1.1.2 Nigeria’s Monthly Precipitation and Temperature Distribution

Tables 1 to 3 show Nigeria’s monthly mean, minimum and maximum temperatures for both past and current climatology, with Table 4 showing Nigeria’s monthly precipitation from 1901 to 2020.

Table 1:Nigeria’s Observed Average Seasonal Mean Temperature (Source: Tomalka et al., 2021)

Observed Average Seasonal Mean Temperature

The identified sub-national units with the highest and lowest mean temperatures reflect the latest climatology, 1991-2020

	1991-2020				1961-1990				1931-1960				1901-1930			
Units: °C	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**
Country: Nigeria	25.91	29.88	26.53	26.65	25.38	29.28	26.13	26.15	25.91	29.49	26.04	26.49	25.38	29.36	26.12	26.33
Highest: Sokoto	25.48	32.61	28.69	28.37	24.88	31.84	28.29	27.70	25.48	32.04	28.12	28.05	24.74	31.87	28.31	27.89
Lowest: Kaduna	24.78	28.73	24.84	25.20	24.22	28.06	24.46	244.67	24.83	28.28	24.32	25.04	24.21	28.17	24.48	24.91

Table 2: Nigeria’s Observed Average Seasonal Minimum Temperature (Source: Tomalka et al., 2021)

Observed Average Seasonal Minimum Temperature

The identified sub-national units with the highest and lowest minimum temperatures reflect the latest climatology, 1991-2020

	1991-2020				**1961-1990**				**1931-1960**				**1901-1930**			
Units: ^{o}C	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**
Country: Nigeria	18.35	23.79	22.25	20.90	17.74	23.18	21.85	20.35	18.15	23.24	21.73	20.59	17.90	23.02	21.68	20.40
Highest: Lagos	23.47	24.34	22.69	23.08	22.88	23.85	22.29	22.65	23.04	24.03	22.39	22.98	22.83	23.87	22.32	22.79
Lowest: Kaduna	17.10	22.69	20.69	19.23	16.39	21.96	20.26	18.61	16.81	21.98	20.08	18.82	16.52	21.86	29.13	18.69

Table 3: Nigeria’s Observed Average Seasonal Maximum Temperature (Source: Tomalka et al., 2021)

Observed Average Seasonal Maximum Temperature

The identified sub-national units with the highest and lowest maximum temperatures reflect the latest climatology, 1991-2020

	1991-2020				**1961-1990**				**1931-1960**				**1901-1930**			
Units: ^{o}C	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**
Country: Nigeria	33.51	36.02	30.86	32.46	33.08	35.43	30.46	32.00	33.72	35.79	30.40	32.45	32.91	35.75	30.61	32.30
Highest: Borno	33.42	40.03	34.52	35.52	32.96	39.19	33.90	34.83	33.75	39.54	33.63	35.27	32.69	39.83	34.11	35.14
Lowest: Bayelsa	32.61	32.06	29.02	30.20	32.07	31.67	28.63	29.76	32.16	31.75	28.69	29.90	32.00	31.61	28.63	29.78

Table 3: Nigeria’s Observed Seasonal Precipitation (Source: Tomalka et al., 2021)

Observed Seasonal Precipitation

The identified sub-national units with the highest and lowest precipitation reflect the latest climatology, 1991-2020

	1991-2020				**1961-1990**				**1931-1960**				**1901-1930**			
Units: ^{o}C	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**
Country: Nigeria	15.64	213.92	604.75	328.54	17.12	216.16	601.21	304.96	22.00	238.93	601.36	342.30	19.95	238.23	598.39	327.90
Highest: Akwa Ibom	98.14	568.80	947.20	743.77	109.73	553.70	1012.13	754.76	153.19	617.44	948.60	832.13	139.86	604.49	987.51	814.46
Lowest: Yobe	0.27	35.10	434.37	126.44	0.16	34.90	390.79	94.90	0.15	43.25	448.00	124.29	0.16	40.33	402.98	100.93

1.1.1 Temperature

- Temperature increases of 0.03°C per decade were seen in the country between 1901 and 2016, with 0.19°C per decade increases in the last 30 years.

2.1.1.2 Precipitation

- Precipitation patterns in Nigeria are highly variable, and during the previous few decades, the predictability of seasonal rains has decreased across the country.
- Since the 1960s, rainfall has been steadily decreasing across the country. (World Bank Group, 2021)

2.1.2 Nigeria’s Climate: Past and Current

Nigeria's past and present climatic observations were described as follows by climate details in Nigeria: The Yola weather station recorded the highest temperature between 1952 and November 2022. A temperature of 46.4 °C was recorded here in April 2010. Based on all 10 weather stations in Nigeria below 1290 meters in height, the hottest summer from July to September was recorded in 1981, with an average temperature of 26.9 °C. The meteorological station Yola reported the coldest day in the last 70 years. In November 2015, the temperature plummeted to 11.1 °C. Yola is located at a height of 186 meters above sea level. With an average temperature of 26.6 °C, the coldest winter (January to March) was in 1957. In Nigeria, the average temperature during these three months is 27.6 degrees Celsius.

The month with the greatest precipitation was July 1955. The Port Harcourt weather station reported the highest monthly average in the last 70 years, at 25.8 mm per day. The area near Port Harcourt experiences the highest rainfall throughout the year. Near Maiduguri is the driest region. Individual values are averaged and augmented by their elements, and the data of the individual measuring stations is based on the German Weather Service archives (World Bank Group, 2021). To arrive at a representative national average, average values were calculated for each region of the country before being summed up at the national level. As a result, if a large number of weather stations are concentrated in a small location, the national average is unaffected. Nigeria has a total of 12 stations. In nine situations, data from bordering yet close weather stations were used to generate more precise results. Because Nigeria's agriculture is primarily rain-fed, acquiring and analyzing climate data is essential.

1.2 Agriculture in Nigeria

Despite Nigeria's abundant agricultural resources, the agriculture industry has been growing at a slower rate. Only around half of the country's arable land is being used for agriculture. Smallholder and traditional farmers cultivate the majority of this land, with low yields due to basic agricultural techniques.

Smallholder farmers have numerous challenges, including limited access to modern inputs and loans, poor infrastructure, insufficient market access, land, and environmental deterioration, and insufficient research and extension services, to name a few. Since the oil boom of the 1970s ended, the prevalence and severity of poverty in Nigeria have risen dramatically, owing in part to the diminishing performance of the agricultural sector, which employs the vast majority of the poor. Furthermore, poverty in Nigeria has taken on new dimensions, such as household income poverty, food poverty/insecurity, low access to public services and infrastructure, unhygienic conditions, illiteracy and ignorance, life and property insecurity, and so on (Manyong et al., 2003).

1.2.1 Agriculture and Nigeria’s economy

Agriculture provided 22.35 percent of the overall gross domestic product between January and March 2021. Over 70% of Nigerians work in agriculture, primarily for subsistence (Manyong et al., 2003).

Despite its economic contribution, Nigeria's agriculture industry is confronted by several obstacles that impact its productivity. Poor land tenure, low irrigated farming, climate change, and land degradation are among them. Low technology, high production costs, and inadequate input distribution are among the others, as are restricted finance, large post-harvest losses, and poor market access (Kiaya, 2014).

These issues have hindered agricultural output, impacting the sector's contribution to the country's GDP, as well as increased food imports as a result of population growth, resulting in diminishing food sufficiency levels. For example, between 2016 and 2019 Nigeria's total agricultural imports were N3.35 trillion, four times larger than the N803 billion in agricultural exports over the same period (Oyaniran, 2020)

To address the situation, the government had implemented several initiatives and programs, including the Agriculture Promotion Policy (APP), Nigeria–Africa Trade and Investment Promotion Programme, Presidential Economic Diversification Initiative, Economic and Export Promotion Incentives, and the Zero Reject Initiative, Reducing Emissions from Deforestation and Forest Degradation (REDD+); Nigeria Erosion and Watershed Management Project (NEWMAP); Action Against Desertification (AAD) Programme, among others (Oladunni, 2021).

All of these initiatives are aimed at increasing agricultural productivity to supply enough food to fulfill domestic demand as well as a surplus of commodity crops for worldwide export. They also seek to reverse forest loss and degradation, promote sustainable natural resource management, restore degraded areas, and reduce erosion and climate vulnerability.

Maize, cassava, guinea corn, yam, beans, millet, and rice are the main crops grown on Nigeria's 70.8 million hectares of agricultural land. Rice output in Nigeria increased from 3.7 million metric tons to 4.0 million metric tons in 2018. Despite this, just 57% of the 6.7 million metric tons of rice consumed in Nigeria each year is produced domestically, resulting in a 3 million metric tons shortfall that is either imported or illegally imported. In order to boost domestic production, the government prohibited rice imports in 2019.

Nigeria was the world's greatest producer of cassava in 2017, with 59 million tons produced (*Agricultural Value Chain*, 2017) (approximately 20 percent of global production). The economic potential is huge, with significant revenue returns from domestic value addition and derived income, as well as government revenues (*Harnessing the Economic Potential of Cassava Production in Nigeria*, 2020). Manufacturing is expected to rise as cultivars and production processes improve.

1.2.2 Nigeria's agricultural trade

Agriculture in Nigeria: Nigeria buys $10 billion to make up for food and agricultural output shortages (mostly wheat, rice, poultry, fish, food services, and consumer-oriented foods).

Agricultural imports come mostly from Europe, Asia, the United States, South America, and South Africa. To diversify its economy away from oil, the Nigerian government has launched agricultural projects such as the Anchor Borrowers Program (ABP). GON authorized the execution of a new agricultural strategy called the "National Agricultural Technology and Innovation Plan" during the Council on Agriculture and Rural Development's regular meeting (NATIP) (Boluwade, 2021). The four-year plan aimed at assisting COVID-19's economic rehabilitation. This policy was supposed to take the place of the Agriculture Promotion Policy (APP), which was implemented in 2016 but was expected to be phased down in December 2020.

Several shocks have harmed Nigeria's agricultural economy, including periodic floods, Boko Haram (BH) insurgencies, and confrontations between herders and local farmers. Food processing continues to be beset by funding and infrastructural issues. In 2021, food inflation reached 22.95%. There were price rises across the board, including grains, yam, meat, fish, and fruits. Food inflation is caused by rising farmer-herder conflict, banditry, kidnapping, and insurgency in Nigeria's agriculture belt, which the GON is battling to subdue. The devaluation of the local currency (Naira), which has been devalued many times in 2021, adds to the increasing pressure. Food costs have also risen as a result of increasing gasoline prices (CBN, 2021).

1.2.3 Factors constraining agricultural performance

The issues limiting Nigeria's agricultural performance have been extensively examined in the literature by several authors, including Manyong et al. (2003), Olayemi (1988), Olayemi, Issa et al. (2011) and Azu (2018). The following is a list of the key limitations identified:

- Technical Limitations: They include high pest and disease incidence, insufficient infrastructure, reliance on unimproved inputs, and unsophisticated technologies. Inadequate extension services, an inefficient input supply, and distribution system, and significant environmental dangers are among the other issues.
- Resource constraints: The rising migration of able-bodied youth from rural to urban regions is a key cause of agricultural labor shortages. Seasonal labor shortages are a result of the significant youth movement, particularly during peak labor demand

seasons (during land preparation, planting, weeding, and harvesting). There's also the issue of agricultural worker productivity being poor. Land is under rising population pressure, and land quality is deteriorating. The low pace of land development is due to the largely traditional farmers' low rate of capital investment.

- Scarcity and high cost of improved farm inputs, inefficient marketing arrangements characterized by high marketing margins, lack of grades and standards, and lack of legally enforceable ownership and control rights over land, which serves as a disincentive to investing in agriculture and arises from the lack of an appropriate land tenure system are among the socio-economic problems that constrain Nigeria's agriculture.

  Other socio-economic factors include a lack of extension services and credit facilities, a low rate of growth in international demand for primary export commodities due to competition with synthetic products; low-income elasticity of demand; and an increasing food deficit and high reliance on food imports due to disequilibria in the national agricultural resource base, a largely traditional agricultural production system, and some domestic population dynamics.

- Organizational Constraints: Agricultural output is mostly controlled by a large number of disorganized small-scale farmers distributed across the country. Farmers' engagement in agricultural and rural development is hindered by a lack of structure and the dispersed nature of farm communities. It obstructs the delivery of extension services, farm financing, and other critical inputs to farmers in particular.

1.3 Climate Change and Food Security in Nigeria

Climate change has an influence on the four essential characteristics of food security: availability, stability, accessibility, and usage of food. Climate change has a direct influence on agricultural product availability by affecting crop yields, pests and diseases, soil fertility, and water–holding characteristics. Climate change has an indirect impact on it because of its effects on economic growth, income distribution, and agricultural demand.

Furthermore, fluctuating weather conditions have a severe impact on crop yields and food supplies. Climate change will have a detrimental impact on physical, economic, and social access to food as agricultural productivity diminishes, food costs increase, and buying power declines. Last but not least, climate change threatens food use by affecting human health and spreading illnesses to previously unaffected areas. Climate change is anticipated to reduce agricultural output in underdeveloped nations by 20% by 2080, whereas it is expected to fall by 6% in developed ones. Climate change is also expected to reduce harvests in poorer nations by 15% on average by 2080 (Nations, 2008). Climate change will also impair people's capacity to use food sustainably by changing food safety conditions and modifying illness pressure from vector, water, and food–borne diseases (Schmidhuber & Tubiello, 2007).

1.3.1 Climate change drivers affecting food security in Nigeria

Climate change and food security are linked because the climatic conditions that allow for optimal food production are affected by climate change. However, research reveals that climate change would not affect all nations equally, with tropical regions such as Sub-Saharan Africa likely having the greatest influence owing to their geographical location (Barlow et al., 2015). This means that nations presently dealing with food security will most likely struggle even more in the future if immediate efforts and measures to mitigate climate change and adapt to climate-smart agriculture are not adopted. For example, (Zinyengere et al., 2014) reported that food production in Sub-Saharan African nations, including Nigeria, would decline owing to present and future climate change trends.

Small-scale farmers, on the other hand, would suffer more than large-scale farmers unless early planting and suggested fertilizer rates are used to attain food sufficiency in those locations. Floods, desertification, and growing season disruption are all projected to intensify as a result of climate change (Ruane & Rosenzweig, 2017). According to (Ayinde et al., (2020); Res & Adejuwon, (2006), a two to four degrees Celsius increase in average world temperatures above pre-industrial levels may cut crop yields by 15 to 35% in Africa. According to their different research Abdallah, (2018); Ruane & Rosenzweig,(2017); Zinyengere et al., (2014), climate change would cut grain output by 10% by 2050, which is the staple food in West Africa. Climate change has become a worldwide problem, posing a threat to Nigerian agriculture's long-term growth (Barlow et al., 2015).

Future climate change is expected to have a significant impact on small-scale farmers, particularly those who rely heavily on agriculture for their livelihood. This contradicts Sultan's (2014) assertion that climate change will have the least impact on small-scale farmers in the region. In contrast, (Carr et al., 2022) employed process-based modeling to examine the influence of climate change on crop yields and adaptation choices in the Niger River Basin, West Africa. They found that climate change will have both positive and negative impacts on food production in the studied region.

According to an estimate by the International Organization for Migration (IOM) in October 2018, over 1.8 million people were relocated throughout Borno, Yobe, and Adamawa states, with Borno state housing over 1.4 million internally displaced individuals (IDPs). According to a Global Rights study, 3,188 people were slain in 2019, including 2,707 civilians and 481 security personnel. Between August and October 2019, the IOM-DTM estimated that nearly 2 million people were displaced in the northeastern states of Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe, while ACLED claimed 507 fatalities nationwide in January 2020 (NET, 2020).

Intense insurgency strikes in northeast Nigeria, according to (NET, 2020), have resulted in an increase in the number of people displaced, with food requirements. In the central and northern states of Zamfara, Katsina, Kaduna, Taraba, Plateau, Benue, Nasarawa, and Adamawa, the conflict between farmers and herders has a severe impact on many households. The violence prevented households from engaging in routine livelihood activities like farming because they lacked access to markets and earning possibilities.

According to the predicted results, climate change would have a favorable impact on maize and sorghum output in the Southern Guinea savanna zone, increasing it by roughly 2% to 6%. Climate change, on the other hand, is expected to reduce productivity by 2% to 20% in the Northern Guinea savanna (Carr et al., 2022). These findings and studies indicate that further research is needed to fully understand the effects of climate change on food security in diverse parts of Africa, particularly on individual crops.

1.3.2 Flood and drought induced by climate change

Flooding and drought are caused by a variety of events, including natural disasters and climate change. Floods are also caused by incorrect trash disposal and overall bad waste management, particularly with solid wastes. As a result, it is necessary to discern between these reasons rather than incorrectly attributing all severe events to climate change. Drought is defined as a situation of extensive but short-term climatic volatility that results in insufficient rainfall to fulfill the socio-economic demands of an area in terms of water supply for home and industrial purposes, agriculture, and the environment, (Dakaiye & Ojo, 2018).

Charney (1977) published one of the earliest and most significant explanations of the cause of drought in the Sahel, suggesting that rainfall reductions were caused by human activities. Drought in the Sahel area is sometimes linked to the Inter-Tropical Discontinuity (ITD) moving southward, however, this theory has been rejected since it fails to explain several crucial properties of rainfall, such as late commencement or early halt (Egbebiyi et al., 2019). Similar studies by Adejuwon (2018) and *Guide to Meteorological Instruments and Methods of Observation,* (2008) used long-term data from a number of synoptic stations in Nigeria to generate some very helpful information on the occurrence, persistence, and frequency of severe droughts in Nigeria also yielded some extremely important information. Therefore, there is an urgent need to evaluate droughts caused as a result of climate change.

According to Odufuwa et al., (2012) floods are the world's most common disaster and pervasive natural hazard. Floods have caused 84 percent of catastrophe deaths worldwide, with an average of 20,000 deaths each year, according to another research (UN-Water and WHO, 2012), making just a few nations immune to floods. As a consequence of the devastating floods across Nigeria, many people have died, hundreds of thousands have been made homeless, and properties worth billions of Naira have been damaged, according to Nigerian flood damage data (Adejuwon, 2006).

Extreme occurrences such as floods, drought, or other environmental changes can truncate any of the food security components, resulting in a condition of food insecurity; hence, there is a link between flooding and food (in) security. and other countries bordering desert zones (Dakaiye & Ojo, 2018). As a result, if proper measures are not done, severe occurrences such as floods and droughts will continue to damage agricultural and food production, particularly in African nations, according to FAO (2015).

1.4 Nigeria's GFSI and SDGI

Nigeria has a population of 205,323,520 people, according to World Data Lab (6 May 2020), with 102,407,327 people living in extreme poverty (50% of the total population) (World Data Lab 2020). Nigeria is Africa's most populated country, ranking seventh internationally with a projected annual growth rate of 2.43% and an 88% dependence ratio. Nigeria's population is comparable to 2.64% of the global population, according to Ayinde et al., (2020), and is expected to reach 401 million by 2050

Nigeria, the world's tenth-largest crude oil producer, was designated as a middle-income country in 2014. Despite Nigeria's oil wealth, half of the country's population lives in abject poverty, earning less than $1.90 per day (World Data Lab, 6 May 2020). Food insecurity in Nigeria is presently at an alarming level, necessitating prompt action. Nigeria's ranking in the Global Food Security Index (GFSI) has risen steadily since 2013 (when it was ranked 86 out of 107 countries with a 33/100 score) and is now ranked 94 out of 113 countries (with a 48.4/100 score), behind Ethiopia, Niger, and Cameroon in the 2019 GFSI overall ranking table (the closer to 100 the better) (Ayinde et al., 2020).

Nigeria also has a poor Africa's Sustainable Development Goals Index (SDGI) rank and score (43rd out of 52 African nations with a 47.03/100 score), trailing Sudan (42nd with 47.38/100 score) and Comoros (41st with 47.5/100 score) (SDG Centre for Africa and Sustainable Development Solutions Network, 2019; (Ayinde et al., 2020).. Even though the International Fund for Agricultural Development (IFAD) ranked Nigeria as the world's top producer of cassava, yam, and cowpea in 2012, and is still the world's top producer of cassava and yam today, the country remains food insecure and severely import-dependent.

Nigeria has plenty of lands suitable for agriculture (75%), but only 40% of it is exploited for that purpose. The great majority of rural households continue to practice subsistence farming, barely feeding their immediate family. Lack of infrastructure, such as decent roads, has exacerbated rural poverty by cutting farmers off from required inputs and markets for their goods (Kiaya, 2014)

In every section of Nigeria, chronic and seasonal food insecurity persists, exacerbated by high food costs, the effect of insurgency-related warfare (particularly in the Northeast), armed banditry, community, pastoralist/farmer crises, abduction, cattle rustling, and climate change (NET, 2020). The Northeast, North-Central, and South-South are the three geopolitical zones in Nigeria most affected by conflict events (reoccurring conflict events are terrorism in the Northeast (73%), land or resource access in the North Central (55%), and cultism/criminality in the South-South (36%), according to NBS/World Bank (2018) and Ayinde et al. (2020).

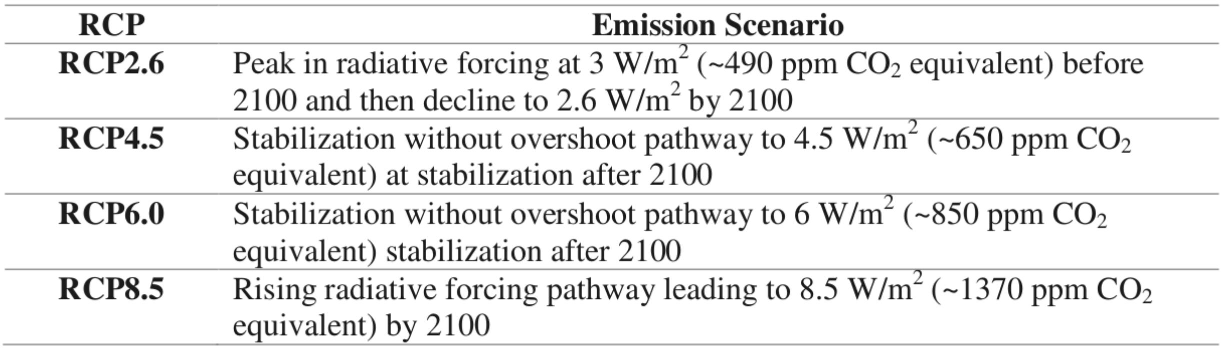
1.5 Climate Change Emission Scenarios

In the modern era, future projections of meteorological data are estimated using General Circulation Models (GCMs) (Ayinde et al., 2020). GCMs are numerically coupled models that characterize several aspects of the earth system including land surfaces, atmosphere, sea-ice land, and oceans(Abdallah, 2018). They are based on physical laws of energy, mass and, momentum and are employed to downscale meteorological data and simulate climate change using the forecasted atmospheric greenhouse gas concentrations and aerosols (Abdallah, 2018). GCMs simulate & predict current and future climate conditions, respectively, under different climate scenarios. According to IPCC, a climate scenario can practically describe the future climate based on a range of climatological relationships and assumptions of radioactive forcing. The new generation of GCMs, called Phase 5 of the Coupled Model Intercomparison Project (CMIP5), has been involved in the preparations of the IPCC 5 the fifth assessment Report (AR5).

The new emission scenarios, called representative concentration pathways (RCPs), were used in several experiments included in the CMIP5 (Prather et al., 2012). Recently, researchers are using the AR5 to simulate future climate change under RCP scenarios (Abdallah, 2018). Based on the radiative forcing level by 2100, the RCPs are named (Afshar et al., 2018). “The radiative forcing due to a perturbation in the concentration of a gas is defined by the net radiative flux change induced at the tropopause. The forcing is usually interpreted as a gain (positive) or a loss (negative) for the surface-troposphere system as a whole”(Abdallah, 2018). Four RCPs represent the emission scenarios in AR5: RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Vuuren et al., 2011).

The lowest emission scenario is RCP2.6 and its radiative forcing will peak at 3 W/m 2 (~490 ppm CO 2 equivalent) by 2050 and decline afterward. The radiative forcing of RCP4.5, which is known as a stabilization scenario, will increase till 2070, after which its greenhouse gas (GHG) concentration will remain stable after 2070. Moreover, the radiative forcing of RCP8.5, which is the highest emission scenario, will reach its stability at 8.5 W/m 2 by the end of 21st century (Abdallah, 2018). To sum up, an overview by (Vuuren et al. (2011) for the RCPs is presented in Table 5.

Table 4: Overview of representative concentration pathways (RCPs) (Source: Van Vuuren et al. 2011)



RCP	Emission Scenario
RCP2.6	Peak in radiative forcing at 3 W/m^2 (~490 ppm CO_2 equivalent) before 2100 and then decline to 2.6 W/m^2 by 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 equivalent) at stabilization after 2100
RCP6.0	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 equivalent) stabilization after 2100
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 equivalent) by 2100

Coupled GCMs provide an appropriate opportunity to simulate future climate conditions under various radiative forcing scenarios(Fyfe et al., 2021). GCMs, however, face errors and lack the spatial and temporal accuracy that is crucial for a detailed regional analysis (Abdallah, 2018). Therefore, as mentioned by Cuculeanu et al. (2002), more than one model will be better for dealing with the accurate projection problem.

1.6 Crop Suitability

The term crop suitability has no straightforward definition in the scientific literature (Egbebiyi et al., 2019), and it is hard to distinguish this term from the following: yield potential, productivity, and attainable yield. In this research for the Near East, crop suitability means how a specific location has the mean meteorological conditions to meet the crop requirements. The suitability score ranges from 0 to 1, where a suitability of 1 indicates a high crop suitability for a specific site (Egbebiyi et al., 2019). A suitability score of 0 means that the crop can’t tolerate the mean climate conditions for a certain region. In fact, a suitability score of 1 has nothing to do with the yield level for a specific region and it is just an indication that the site has the suitable biophysical conditions to grow a certain crop.

Therefore, a crop simulated to have a high suitability will successfully perform better than that of a low suitability score. On the contrary, there is a possibility of crop failure in an extreme year even if the model predicted a high suitability score, and vice versa (Gao et al., 2021).

1.6.2. Crop suitability model

Simulating the suitability of crops under current and future climate change scenarios are performed to assess if a crop can undergo agricultural production given the meteorological components (Gao et al., 2021). It also helps in identifying adaptation strategies and alternative locations for crop production based on climate and land factors that will suit the growth and development of the crops (Egbebiyi et al., 2019). Examples of existing tools serving that purpose are remote sensing software (such as GIS) and complex crop simulation models and tools (such as Maxent and EcoCrop). But for this research, we will be using the EcoCrop model.

The EcoCrop model is a simple model used to simulate the climate change effects on crops based on environmental ranges for precipitation and temperature as inputs (Abdallah, 2018). The output of this model is a suitability index for any specific region. A suitability index measures the fraction of each grid cell that is suitable for production for any specific crop.

The EcoCrop model has been formerly used to assess the climate change impact on various crops, including sorghum (Ramirez-Villegas et al., 2013, Egbebiyi et al., 2019, 2020), cassava (Ceballos, Ramirez, Bellotti, Jarvis, & Alvarez, 2011; Jarvis et al., 2012, Egbebiyi et al., 2019, 2020), groundnut (Vermeulen et al., 2013, Egbebiyi et al., 2019, 2020), and banana (Van den Bergh et al., 2010, Ramirez et al., 2011; Egbebiyi et al., 2019, 2020).

Consistency analysis for EcoCrop results was performed and reported reliable and uniform data compared with other approaches (Ramirez-Villegas et al., 2013; Vermeulen et al., 2013). Moreover, the EcoCrop model was widely used by researchers to assess the climate suitability of crops for production in an area.

Chapter 2

Materials and Methods

2.1 Study Area

In terms of location, Nigeria is situated between 4°N and 14°N and 3°E to 14°E (Figure 1). The area, which is bounded by the Atlantic Ocean, Benin, Cameroon, and the Niger in the north, is approximately 923,770 km2 (south) (AQUASTAT Survey, 2005). According to Kamoru et al., (2016), (Omotosho & Abiodun, 2007) and modified by Gbode et al. (2019) three eco-climatic zones are recognized in Nigeria: The Guinea coast (4–8°N), the Savannah (8–11°N), and the Sahel (13–14°N). Similarities in land use or cover, climate, and ecosystems are used to classify these zones (Iloeje, 1981; Omotosho & Abiodun, 2007.

The Guinea coast zone, which is in the southernmost portion of the nation, has a sub-humid climate with an average annual rainfall between 1,575 mm and 2,533 mm. The Savannah zone, which is a semi-arid region, has an average annual rainfall between 897 and 1,535 mm (Oguntunde et al., 2011). The Sahel zone has a unimodal rainy season with an average yearly rainfall between 434 mm and 969 mm (Oguntunde et al., 2011).

Geographical Features: Nigeria is made up of a variety of diverse landscapes, including deserts, plains, marshes, mountains, and steamy rainforests. It has one of the world's biggest river systems, including the Niger Delta, the world's third-largest delta. The plains and savannas cover much of Nigeria. The Niger and Benue Rivers are the country's most prominent geographical features. The two rivers join in the south-central section of the country to create the upper arms of a flattened letter Y, and then flow south as the Niger River, fanning out into a massive and convoluted delta as the waters approach the Gulf of Guinea.

Population: Nigeria's population has been predicted to be about 216.7 million in 2022. Nigeria's population expanded by more than 2% on average between 1965 and 2022. The population increased by 2.6 percent in 2021 over the previous year. Nigeria is Africa's most populated country. As a result, the African continent has the world's greatest growth rate. (United Nations, 2017)

Occupation: Nigeria's agriculture industry is the country's major employer of workers and source of money (Oladunni, 2021).

Soil type: Fluvisols, regosols, gleysols, acrisols, ferrasols, alisols, lixisols, cambisols, luvisols, nitosols, arenosols, and vertisols are the principal soil types in Nigeria, according to FAO (2014) soil taxonomy mythology. The agricultural potential of these soil types varies.

Nigeria, features various natural landmarks and animal sanctuaries. Waterfalls, deep rainforests, savanna, and uncommon primate habitats may be found in protected locations like Cross River National Park and Yankari National Park. Nigeria has a tropical climate, with rainy and dry seasons that vary depending on where you are. The southeast is hot and humid for most of the year, whereas the southwest and deeper interior are dry. The rainy season in the south lasts from March to November, but it only lasts from mid-May to September in the extreme north.

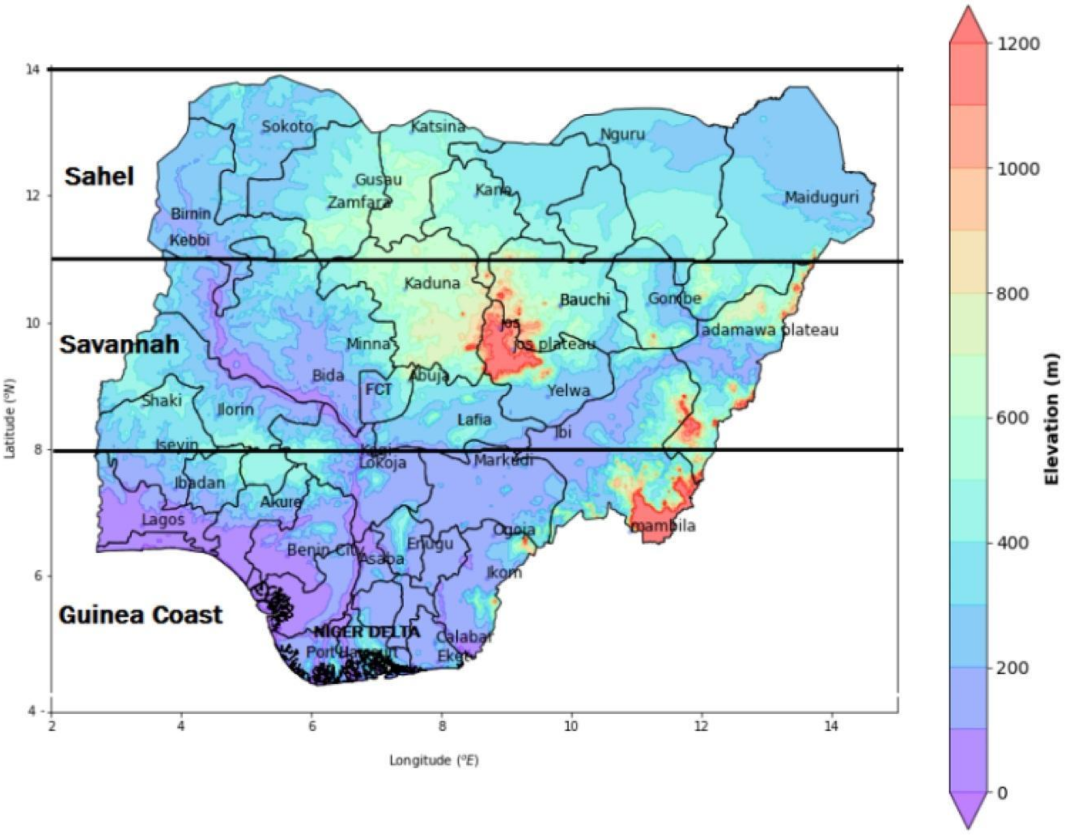


Figure 1: Map of Nigeria (Source : Kamoru et al. 2016)

2.1.1 Study Domain

For this study, the Nigerian map was classified using five eco-climatic zones: Sahel, Sudan, Guinea Savannah, Tropical Rainforest, and Coastal zones (Figure 2).

The Sahel climate is characterized by extreme temperatures with fluctuating periods of rainfall and intense drought. The area is particularly vulnerable to climate change, according to the United Nations, with temperatures increasing at 1.5 times the rate of the global average (Tomalka et al., 2021). Depending on soil and bio-climatic conditions, the main food crops produced by smallholder farmers in the Sahel are maize, sorghum, cowpeas (black eye peas), and millet. Sorghum and millet are more drought tolerant than maize which are most common in the drier, northern areas of the Sahel.

The Sudan zone has a tropical climate. Summer temperatures often exceed 43.3 degrees Celsius (110 degrees Fahrenheit) in the desert zones, and rainfall is negligible. Dust storms frequently occur in the desert zone. High temperatures also occur in the south throughout the central plains' region, but the humidity is generally low. Main crops include cotton, peanuts (groundnuts), sesame, gum arabic, sorghum and sugarcane. The main subsistence crops are maize and millet, with smaller amounts of wheat, corn and barley. 38-47% of the food energy consumed in the Sudan zone comes from crops that are not native to the region.

Guinea Savannah zone has a unimodal rainfall distribution with the average annual temperature and rainfall of about 27.3 degree Celsius and 1051.7 mm, respectively. The climates and soil types of all Guinea Savannah of Nigeria give opportunities for mass agricultural production. Food crops such as maize, millet, sorghum, cowpea and yam are the main crops cultivated in this region.

Nigerian coastal zone experiences a tropical climate consisting of the rainy season (April to November) and dry season (December to March). Maize, sorghum, millet, cowpea, and groundnut are the major food crops grown in the region.

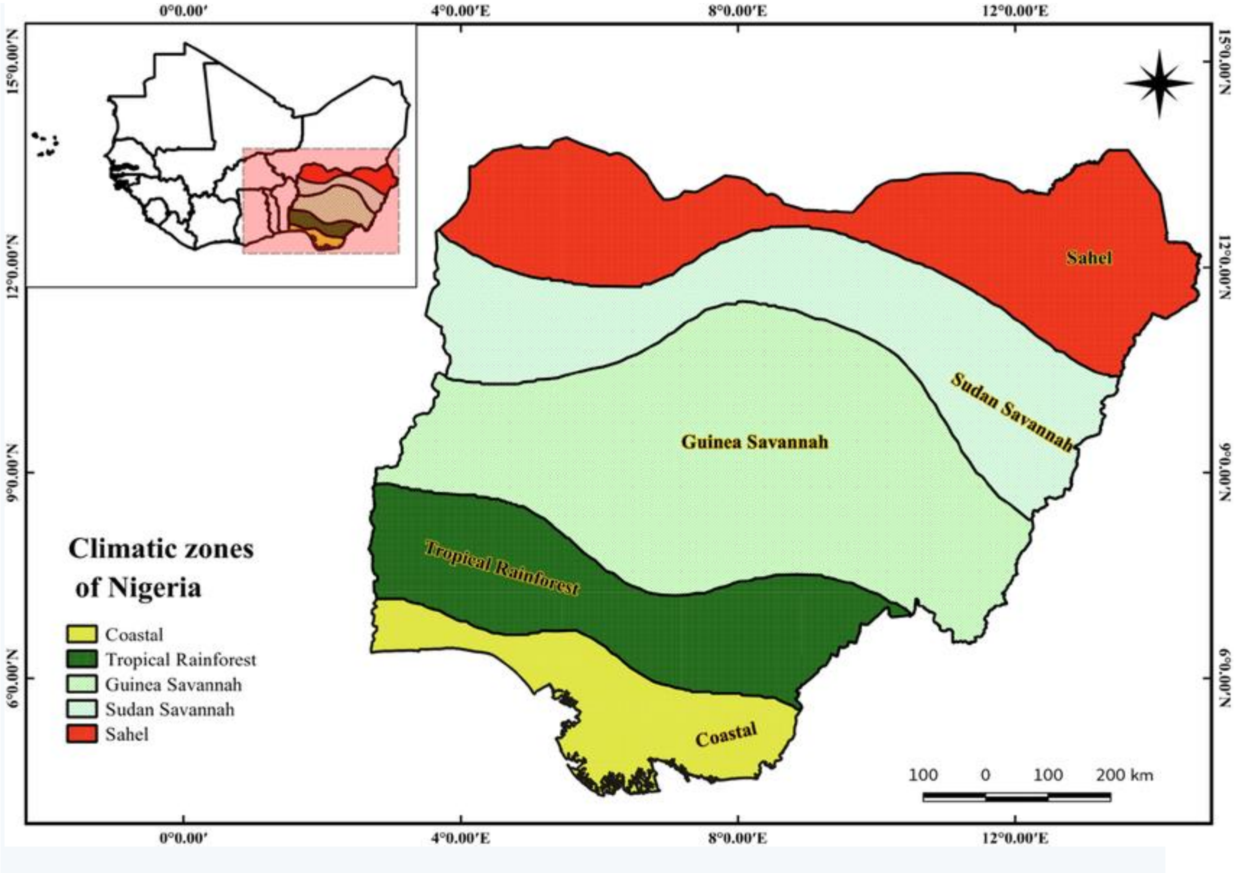


Figure 2: Map of Nigeria showing eco-climatic zones (Source: Akinsanola and Ogunjobi, 2014)

2.2 Data

2.2.1 Climate Data (Observation and Climate Model datasets)

Three datasets (i) observed, (ii) simulated historical and (iii) projected climate data were used in this study. The climate data was used as input into the crop suitability model, Ecocrop, for simulation of historical and projected crop suitability index. The observational dataset was from the Climate Research Unit (CRU TS4.01) University of East Anglia, gridded dataset (Harris et al., 2014). The CRU data is at 0.5◦×0.5◦ resolution for total monthly precipitation, monthly minimum and mean temperature from 1901 to 2020; however, we used the period of 1980-2009 for this study.

In order to assess the impacts of climate change on crop suitability and possible changes to planting periods, bias-corrected climate projection data from the Coordinated Regional Downscaling Experiment (*CORDEX*) (Giorgi et al., 2022) was employed. The CORDEX data is from the Swedish Meteorological and Hydrological Institute, RCA4 (SMHI-RCA4) model which was driven by ten Global Climate Models (GCM) of the *CMIP5* project (Samuelson, 2011). Ten CMIP 5 GCMs datasets downscaled by SMHI-RCA4, were analyzed to assess the impacts of climate change on crop suitability and planting season over Nigeria from three different crop types. The three crops which are Cassava (root and tuber), Maize (cereals) and Cowpea (legumes) used in this study were selected based on the rate of consumption by the population. The list of downscaled GCMs data is presented in Table 6

Temperatures and rainfall are significant climatic variables that are used to assess climate change consequences at various scales (Cong & Brady, 2012; IPCC 2015). Crop yield is significantly affected by these two climatic factors. While rainfall has an impact on crop output in terms of photosynthesis and leaf area, temperature has an impact on growing season length (Olesen & Bindi, 2004; Cantelaube & Terres, 2005). The bias-corrected data of monthly precipitation, minimum and mean temperature were used in this research. The crop suitability model EcoCrop is driven with downscaled model Table 6.

Table 5: List of dynamically downscaled Global Climate Models (GCMs) used in the study (Source: Egbebiyi et. al 2019)

Modelling Institution	Institute ID	Model Name	Resolution
Canadian centre for climate modelling and analysis	CCCMA	CanESM2	2.8° × 2.8°
Centre National de Recherches Météorologiques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifique	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	MPICanESM2	MPI-ESM-LR	1.9° × 1.9°
Norwegian Climate Centre	NCC	NorESM1-R	2.5° × 1.9°

2.3 EcoCrop Suitability Model

For this study, crop suitability is calculated using the Ecocrop model. It is built on a monthly basis and may analyze crop adaptability in connection to climatic conditions over a geographic region (Hijmans et al., 2001). To identify the probable acceptable climatic condition for a crop, Ecocrop uses the environmental ranges of a crop combined with a numerical assessment of the environmental condition. The agricultural yield, which is partly reliant on the intensity of the climatic signal in the agricultural output, may be connected to the suitability rating (Ramirez-Villegas et al., 2013). The use of these datasets to compute optimum, suboptimal, and non-optimal circumstances enables the modeling of crop suitability in response to the 12-month climate using minimum temperature, mean temperature, and precipitation (Hijmans et al., 2001).

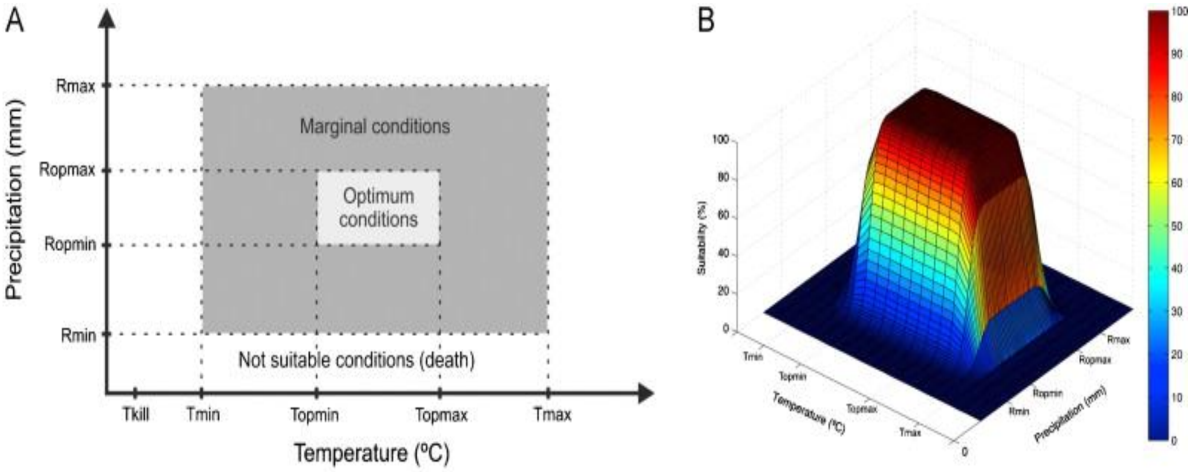


Figure 3: How EcoCrop works (Source : Ramirez-Villegas et al., 2013)

The total suitability ($Total_{suit}$) is calculated by the product of both rainfall *(Rsuit)* and temperature (T*suit*) suitability as shown in the equations below as described by Ramírez-Villegas et al. (2013).

$$\text{Total}_{\text{suit}} = Rsuit * Tsuit \qquad \ldots\ldots (1)$$

$$Rsuit = \begin{cases} 0 & Rtotal < Rabs\_min \\ 0 & Rtotal > Rabs\_max \\ 1 & Ropt\_min \leq Rtotal \leq Ropt\_max \\ 1 - \frac{Ropt\_min + Rtotal}{Ropt\_min - Rabs\_min} & Rabs\_min \leq Rtotal < Ropt\_min \\ 1 - \frac{Ropt\_max + Rtotal}{Ropt\_max - Rabs\_max} & Ropt\_max < Rtotal \leq Rabs\_max \end{cases}$$

$$\ldots\ldots\ldots(2)$$

$$Tsuit = \begin{cases} 0 & Ttotal < Tabs\_min \\ 0 & Ttotal > Tabs\_max \\ 1 & Topt\_min \leq Ttotal \leq Topt\_max \\ 1 - \frac{Topt\_min + Ttotal}{Topt\_min - Tabs\_min} & Tabs\_min \leq Rtotal < Topt\_min \\ 1 - \frac{Topt\_max + Ttotal}{Topt\_max - Tabs\_max} & Topt\_max < Ttotal \leq Tabs\_max \end{cases}$$

$$\ldots\ldots\ldots\ldots (3)$$

The Ecocrop model assesses the relative adaptability of crops for optimal crop development in a variety of climates, including rainfall, temperature, and growing season. Table 7 below shows the suitability indices (Egbebiyi et. al 2019)

Table 6: Ecocrop Suitability Index Ranges (Source: Egbebiyi et. al 2019)

Ecocrop Suitability Index Ranges	
0 < 0.20	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

2.3 Method

To assess the impacts of climate change on the suitability of the three selected crops in Nigeria: Cowpea, Maize, and Cassava, ten CMIP5 GCM datasets downscaled using a CORDEX RCM SMHI-RCA4 were examined. The Suitability Index Value (SIV) for each crop was then calculated for the ten downscaled CMIP5 simulations over Nigeria. To do so, the Ecocrop suitability output was used to analyze the influence of climate change on crop adaptability over Nigeria from 1951 to 2100, based on historical variability in crop suitability and planting season.

The models' capacity to simulate crop suitability spatial distribution and planting date/season during the reference month (1981–2000) was evaluated before using it to project changes in future crop suitability and planting season. The reference period was selected based on findings from recent research, journals and articles having selected 1981-2000 as reference period. Also, Earth's temperature has risen by 0.14° Fahrenheit (0.08° Celsius) per decade since 1880, but the rate of warming since 1981 is more than twice that: 0.32° F (0.18° C) per decade, thus its usage in this research work so as to keep up to date.

The projection is done under RCP 8.5, which is considered as “business as usual” scenario. It refers to the concentration of carbon that delivers global warming at an average of 8.5 watts per square meter across the planet. The RCP 8.5 pathway delivers a temperature increase of about 4.3˚C by 2100, relative to pre-industrial temperatures.

Variables used in this research work are temperature and rainfall. Temperature influences most plant processes, including photosynthesis, transpiration, respiration, germination and flowering. As temperature increases (up to a point), photosynthesis, transpiration and respiration increase and leaf area. For rainfall: If it is too wet or too dry, nutrients in the soil can run off and not make it to the plants' roots, leading to poor growth and overall health. Additionally, too much rain can also lead to bacteria, fungus, and mold growth in the soil.

The EcoCrop model was accessed through the R - Dismopackage which functions for species distribution modeling, that is, predicting entire geographic distributions form occurrences at a number of sites and the environment at these sites.

I. Usage

```
ecocrop(crop, tmin, tavg, prec, ...)

getCrop(name)

data(ECOcrops)
```

II. Arguments

`crop` An object of class 'ECOCROP', or the name of a crop as in getCrop

tmin	Vector of monthly minimum temperature (degrees C)
tavg	Vector of monthly average temperature (degrees C)
prec	Vector of monthly precipitation (mm)
…	Additional arguments

nameName of a crop (character). If missing a data.frame with all crop names is returned

III. Value

Object of class ECOCROP

IV. Author(s)

Robert J. Hijmans

Chapter 3

Results and Discussion

3.1 Result

3.1.1 Model Evaluation

The suitability index derived from downscaled CMIP5 models and their ensemble mean (ensmean) were compared to indices from the CRU observational gridded data for the historical period between 1980 and 2009. The ensemble mean (ensmean) is the average of the ten model versions run with each version of the model being slightly different from one another.

For model evaluation, it was observed that the results generated on assessing the crop suitability in the historical climate over Nigeria is similar to results of Egbebiyi et al. in 2019 where 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 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 (northern Sahel) for the simulation across the region except for the one observed around lat. 12◦N, the boundary between the Sahel and Savanna.

The RCA4 simulations for Cowpea and Cassava shows that the crops are suitable to the south of Nigeria but with no suitability to the north (Figures 4 & 6). While Maize shows unsuitability both at the south and north of Nigeria with only suitability at the Guinea Savannah region (Figure 4). Although Egbebiyi et al. (2019) shows that all the crops that is; Cowpea, Maize and Cassava are very suitable to the south of the MSL but with no or low suitability to the north.

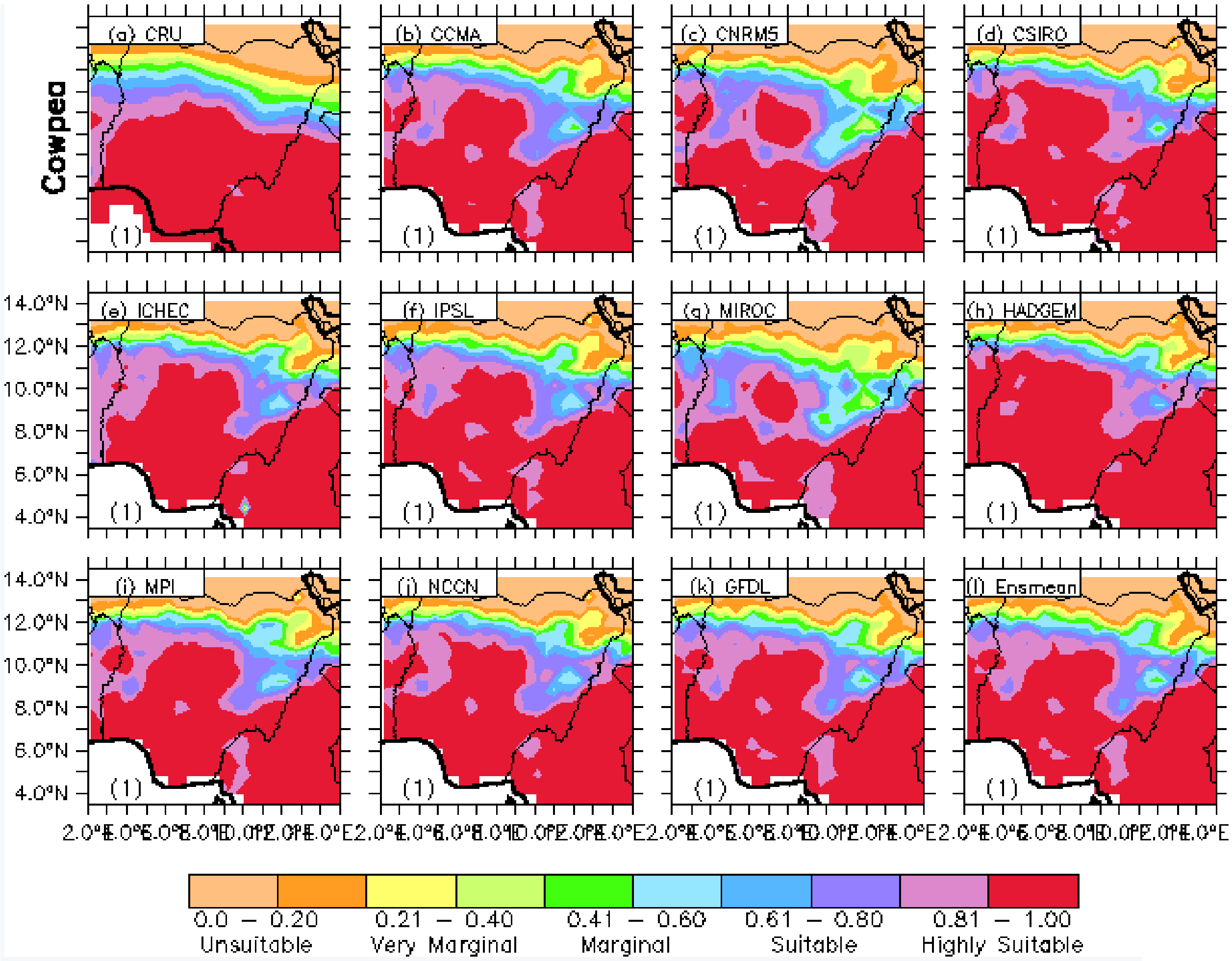


Figure 4: Cowpea suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

From the CRU observational dataset (Figure 4a), the result shows that cowpea production is most suitable in the southern part of Nigeria with suitability index of between 0.8 and 1.0. Crop suitability in Nigeria's Sudan savannah region ranged from 0.21 to 0.6, indicating a swing between very marginally suitable and marginal suitability. The Sahel is the most unsuitable region (0.0 - 0.2), also seen in Egbebiyi et al. (2019) which can be ascribed to the region's severe high temperatures combined with little or no rainfall. When compared to the highly suitable regions (Guinea Savannah, Tropical Rainforest, and Coastal Regions, it was found that these regions receive sufficient rainfall and have the lowest temperatures.

All the model derived index agrees with the index from the CRU observation (figure 4b-4i). This signal is replicated by all the model-derived index except minor variation is observed in CNRM5, CSIRO and MIROC. Generally, all the models simulated the observed crop suitability well, and they could, therefore, be used to assess future changes in cowpea crop suitability.

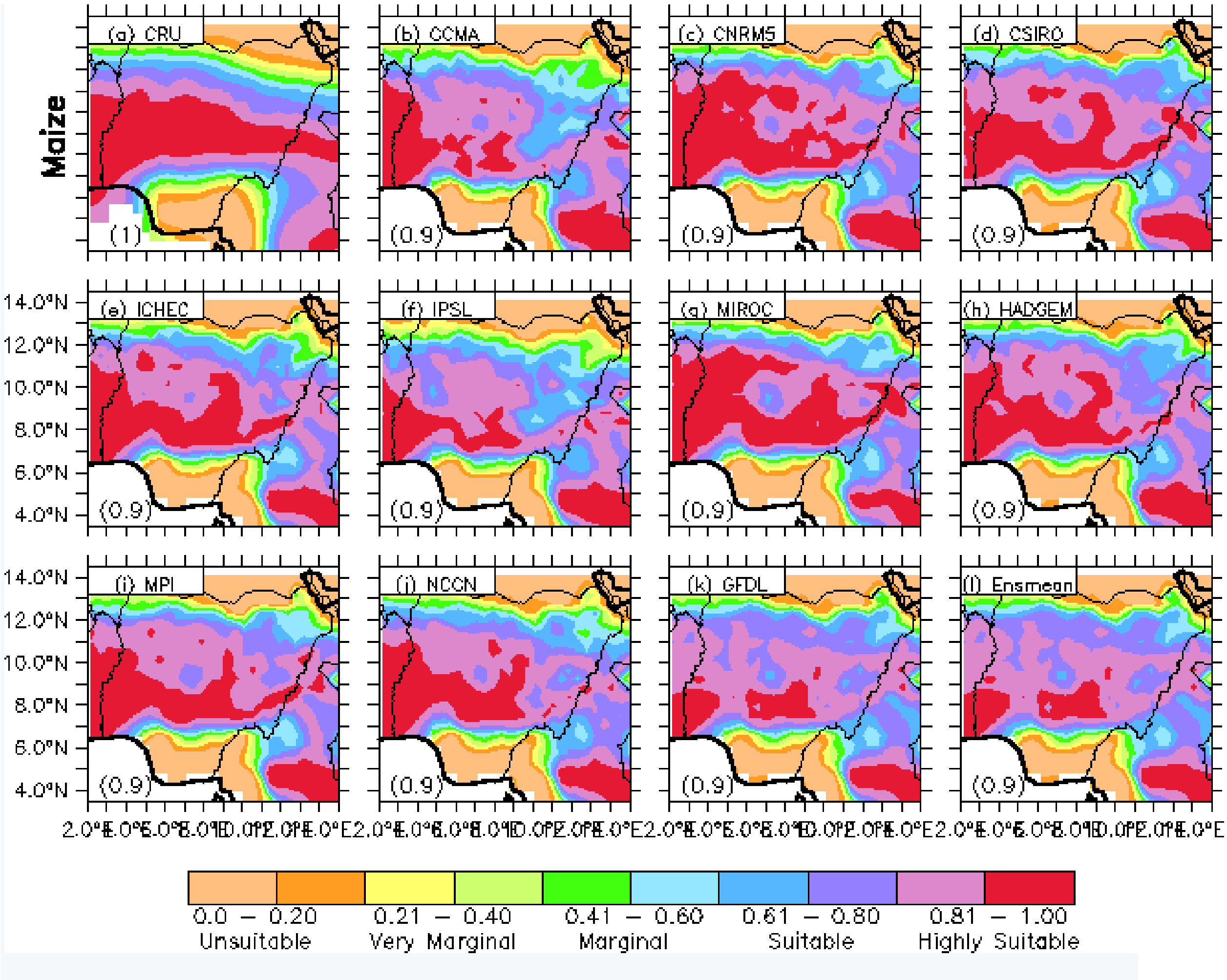


Figure 5: Maize suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

All simulations agree with the CRU observation data for Maize in Figure 5. All simulations indicate that maize is unsuitable (0.0-0.20) for the Nigerian Coastal region and the extreme northern Sahel region. These results differing from that of Egbebiyi et al in 2019. Within the Sudan, Guinea Savannah, and Tropical Rainforest sections of the country, all simulations demonstrated various degrees of suitability (0.21-1.00). From this analysis, we may deduce that states like Kwara, Jos, and Enugu are suitable for maize production, whereas cities like Lagos and Rivers are not.

For Maize, the RCM simulations forced with MPI, ICHEC, and NCCN (Figure 5i, 5e, 5j) all demonstrated similar spatial distribution signals, with MIROC, CNRM5, CSIRO and HADGEM (Figure 5g, 5c, 5d, 5h) exhibiting similar spatial distribution signals.

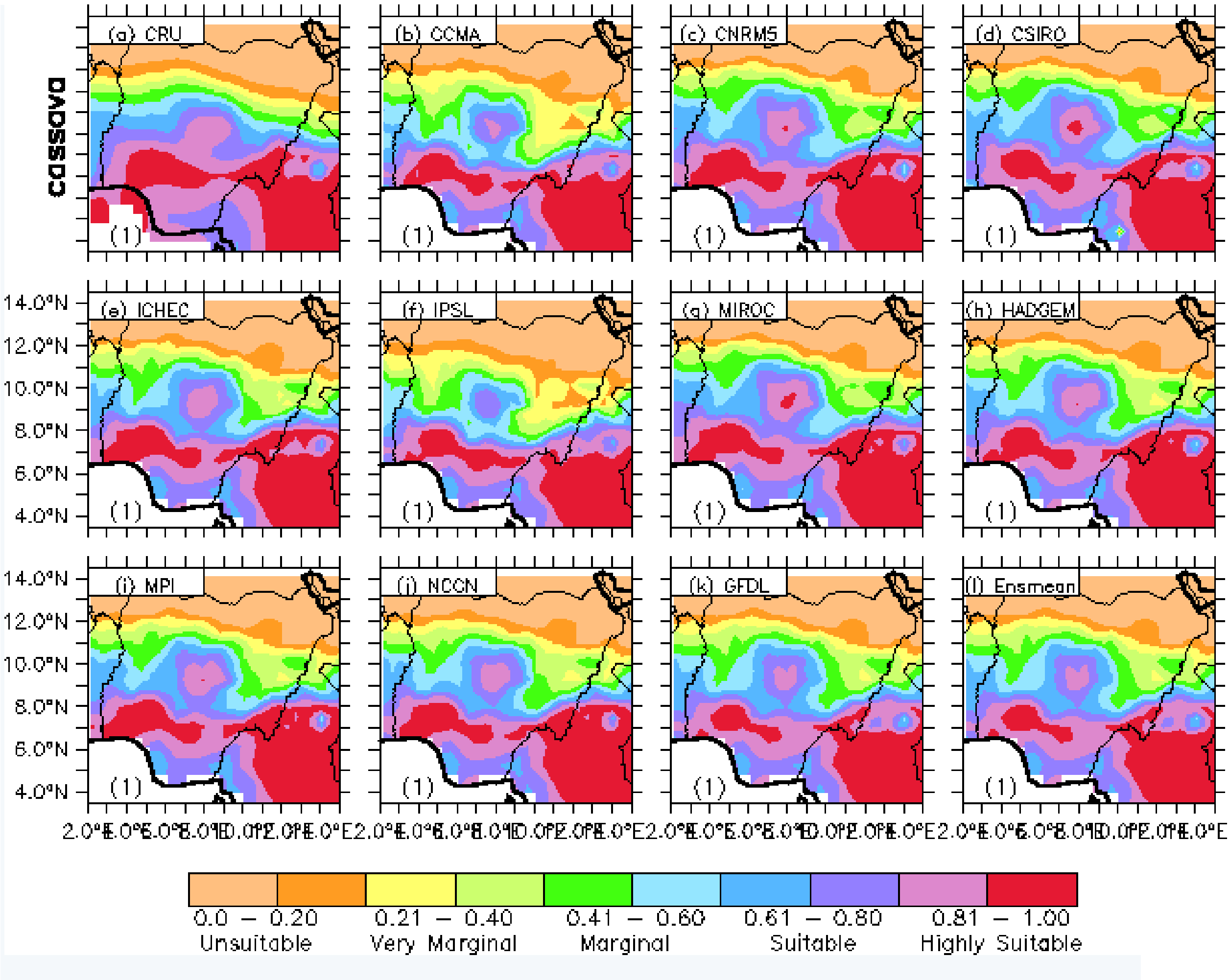


Figure 6: Cassava suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

In the case of cassava, all ten simulations and the ensemble mean also agreed with the CRU. Cassava requires a precise temperature range in order to produce appropriate yields, and it is clear that the temperature in the Sahel region was too high to allow the crop to grow since all simulations indicated the location is unsuitable for cassava, which is in agreement with observation CRU. The level of suitability in the remaining regions ranged from very marginally suited (0.20-0.40) for the Sudan region to highly suitable (0.61-0.81) for the coastal region. A part of the Tropical Rainforest in the south western part of Nigeria, demonstrated that cassava was well adapted to the region in historical period.

Models displaying similar signals for spatial demonstration for Cassava are CNRM5, CSIRO, MIROC, HADGEM and MPI (Figure 6c, 6d, 6h, 6g). While CCMA, ICHEC, IPSL, NCCN and GFDL depicting similar signals for spatial demonstration for the Cassava’s suitability in Nigeria over historical periods.

3.1.2 Evaluation of Stimulated Planting Season

RCA4 was used in simulating the best planting months over Nigeria for the historical period. 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 planting month and varies with crop types across the five agro-ecological zones of Nigeria. In general, best planting months in historical period for Cowpea was in Jan (January–March) and Feb (February–April) observed at the Sahel, Sudan and Guinea Savannah regions of Nigeria while July is simulated to be best planting months at the Coastal region. For Maize, best planting months in the Sahel shows Jan (January – March), while from the Sudan region down to the Coastal region shows Apr (April – June) and Jul (July - September) shows best planting months for Maize during historical period. Sahel and Sudan regions shows best planting months for Cassava to be Apr (April – June) with Jul (July - September) being the best planting month at the Guinea Savannah region for Cassava in Nigeria in historical period (Figures 7 – 9).

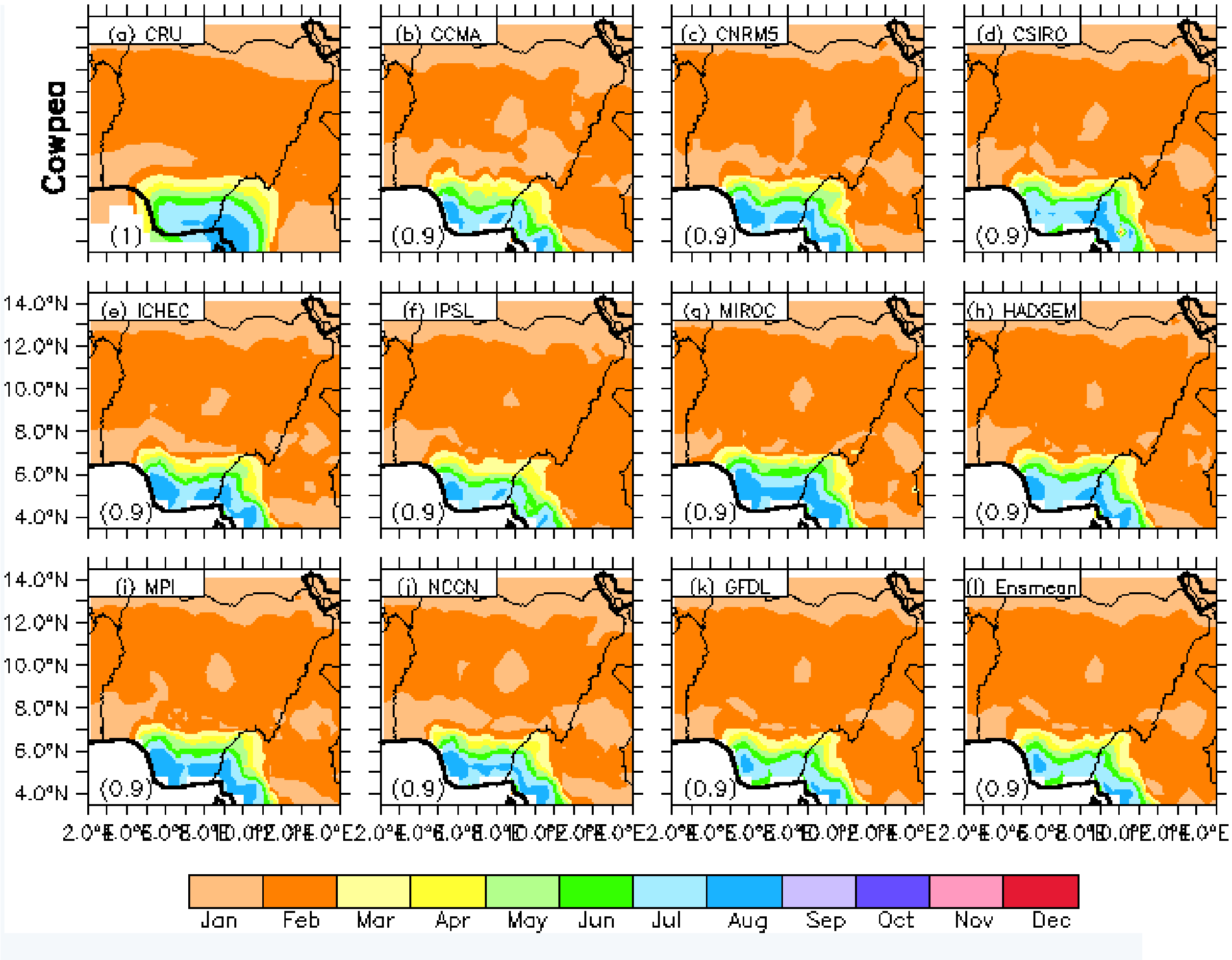


Figure 7: Cowpea's monthly planting suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

The CRU agrees well with all simulations (Figure 7b – 7i), implying that they could very well be used to evaluate best planting months for Cowpea in historical period. The simulations forced by ICHEC and NCCN shows very similar signals of spatial demonstration for Cowpea. The simulations showed that the best planting month for Cowpea in the Sahel region is January. In the Sudan region, the best planting month for cowpea is February, although simulations forced with CCMA, IPSL and NCCN showed that some parts (in the far east) of Sudan region support two planting months (January & February) with Egbebiyi et al. (2019) stating the same result, but this is not supported by CRU derived optima planting date.

In the Guinea Savanah region, all the ten models indicates that February is the best planting month for Cowpea, with the exception of the Jos Plateau, which has two best planting months (January and February), although this is in contrast with the observation, CRU (Figure 7a) which shows Cowpea's best planting month only to be in February. The optimum planting months for Cowpea in the Tropical rainforest zone were Jan (January, February, March) and Apr (April, May, June) according to all ten simulations. And at the Coastal region, best planting months for Cowpea during the historical period was Jul (July, August, September) as depicted by both CRU and the ten downscaled CMIP5 models.

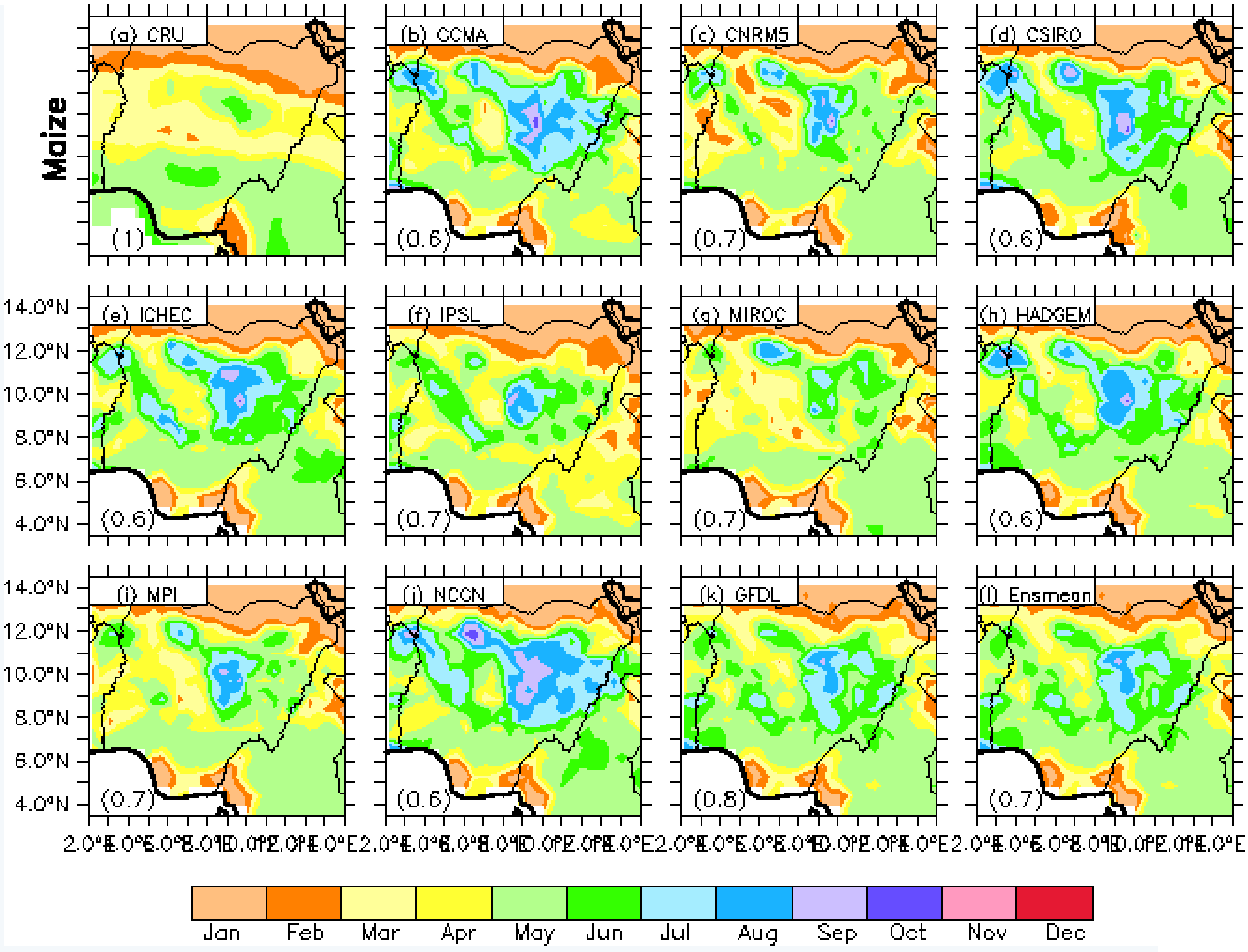


Figure 8: Maize's monthly planting suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

The Ecocrop used inputs for both observation and climate model simulations for determining the ideal planting month for Maize in Figure 8. All simulations agree with the observation, with some simulations having a higher level of conformity than others. When compared to the CRU, the RCM simulation forced with the GFDL model showed a level of spatial correlation of 0.8, which was the closest agreement. Others had reached level of spatial correlation of 0.6 and 0.7. Simulations forced CCMA, CSIRO, ICHEC, HADGEM, and NCCN into the spatial correlation 0.6 categories, while CNRM5, IPSL, MIROC, and MPI were seen to be in 0.7 category.

Best planting months for Maize in the Sahel area of Nigeria, according to Figure 8, are January and February for all simulations. While best planting months in Sudan region of Nigeria are Jan (January to March), Apr (April, May, June) and July (July, August, September), notably in the west and central Sudan, these contradicting signals given by the CRU in spatial demonstration.

At the Guinea Savanah region, best planting months for Maize were Apr (April, May, June) and Jul (July, August, September). Although with best planting months of Maize in July, August, and September being depicted at the central and eastern parts of the Guinea Savannah as observed by the CRU. The best planting months for Maize from CRU in the Tropical rainforest region was Apr (April, May, June). Also, all ten simulations demonstrated that Maize's best planting months was Jan (January, February, March), although not supported by CRU.

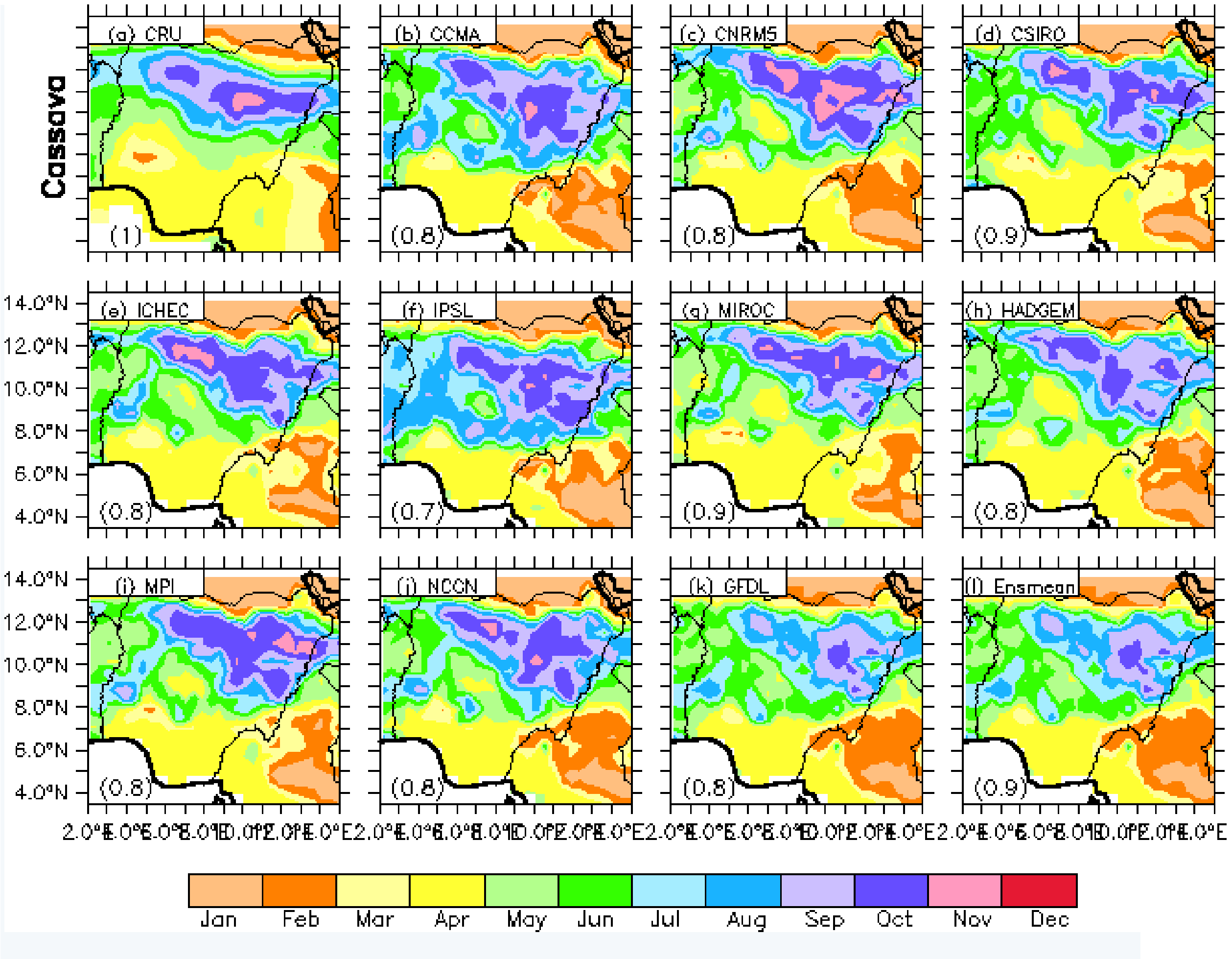


Figure 9: Cassava's monthly planting suitability in Nigeria between 1980-2009 as derived from (a) CRU (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL (l) Ensmean.

For Cassava, all ten simulations agree well with the observational CRU in Figure 9(a) as indicated. All simulations show the Sahel region's best planting months for Cassava to be Jan (January, February, March), and also showed Cassava's best planting months for the Sudan and southern part of the Sahel regions to be July, August, and September, while the Guinea Savannah region indicates best planting months in April and July. This implies that the Guinea region had both early (April, May June) and late planting months (July, August, September) for Cassava in historical period.

For the Tropical rainforest region, cassava's best planting months were April, May, and June, CRU indicates that the western part of the Tropical rainforest region would still give best planting month for Cassava in February, with simulations forced with MIROC, MPI and CSIRO (Figure 9g, 9j, 9d) depicting signals which slightly supports this. With April, May and June also being the best planting month for Cassava in the Coastal region as simulated.

3.1.3 Determining Crop Suitability Indexes

3.1.3.1 Crop suitability in future climate over Nigeria

The projected changes in the future crop suitability for the three selected crop (Cowpea, Maize and Cassava) from 2071 to 2100 predicts decrease in Maize and Cassava's (Figures 11 & 12) suitability within latitude 12 – 6◦N of Nigeria whilst no changes occurring in Cowpea's suitability within the same latitudes (Figures 10). The RCA4 simulated crop suitability from the observed climatology inputs (RCA4-Ecocrop) shows decreasing mean suitability from south to north over Nigeria. 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 0.05 - 0.35 to the coastal region at lat. 4◦N.

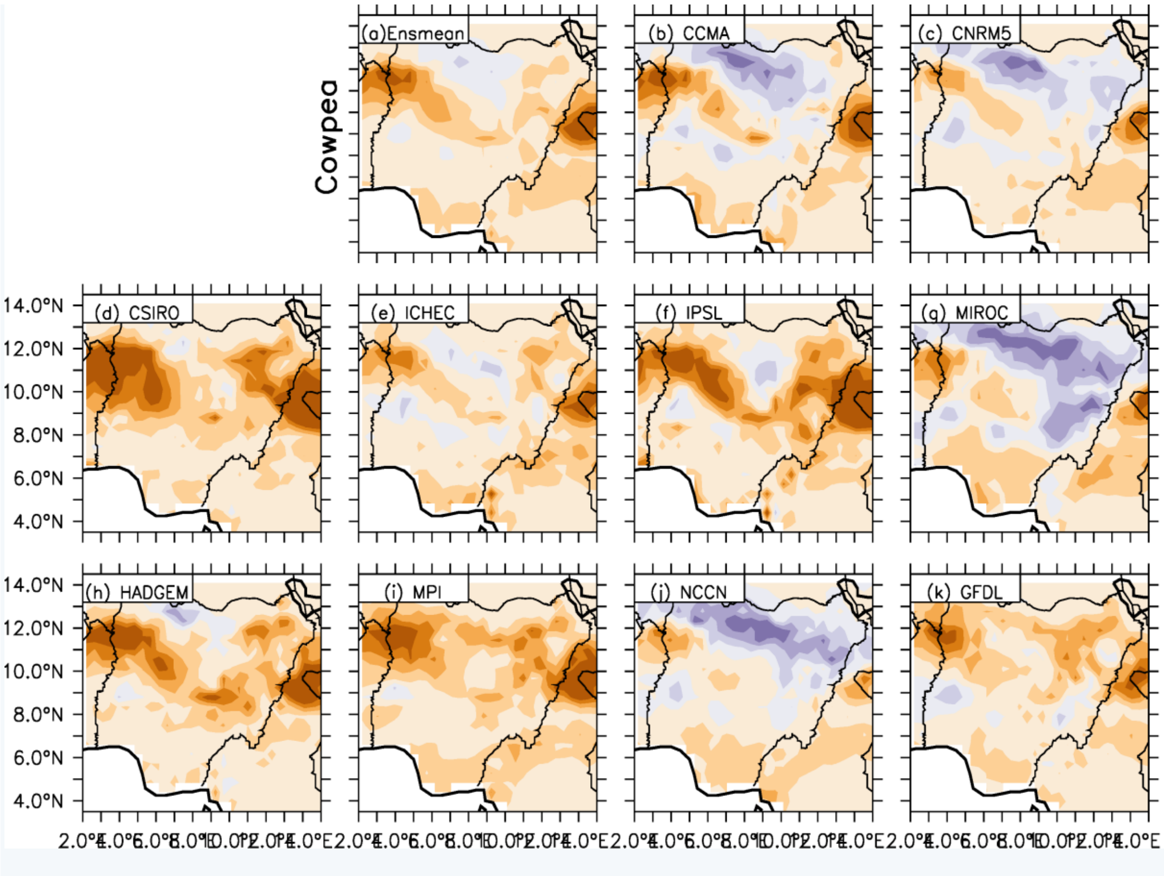


Figure 10: Projected changes in Cowpea's suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

Simulated spatial distribution for future Cowpea's suitability over Nigeria using the Ensmean (Figure 10a, indicates no changes expected although with a decrease in SIV of 0.1 at the western part of the Sudan region but will still be suitable for Cowpea's cultivation in the future (Egbebiyi et al., 2019). Simulations showing similar signals in spatial distribution are CCMA, CNRM5, MIROC and NCCN with increasing SIV (about 0.3) depicting Cowpea's suitability in the Sahel, Sudan and the eastern parts of the Guinea Savannah region. While CSIRO, HADGEM, MPI and GDFL depicts decreasing SIV (about 0.2) from the Coastal region to the Sudan region of Nigeria.

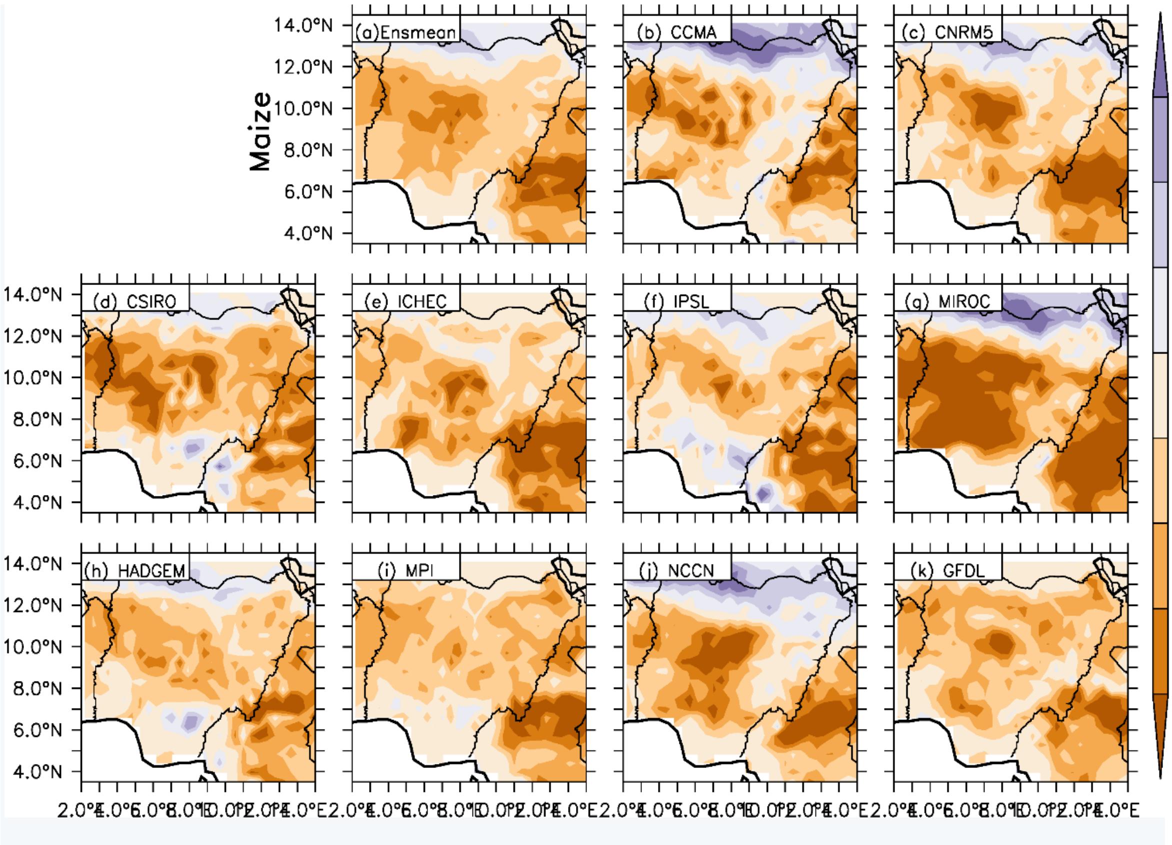


Figure 11: Projected changes in Maize's suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

Simulated spatial distribution for future Maize's suitability over Nigeria indicates that Maize will be unsuitable from the southern part of the Sahel region to the Tropical Rainforest because of the decreasing SIV to about 0.4, this is also confirmed with Egbebiyi et al., (2019). Although simulations such as CCMA, CNRM5, IPSL, HADGEM, MIROC and NCCN indicates otherwise, denoting that Maize will be suitable for planting in the Sahel and western part of the Coastal regions in the future. While simulations with similar spatial distribution projecting similar signals indicating unsuitability for Maize in the Sudan and Guinea savannah region in the future are CSIRO, IHEC, MPI and GFDL (Figure 11d, 11e, 11i, 11k)

In view of this result, Egbebiyi et al. (2019; 2020) predicted also the projected increase in unsuitability in the Sahel agrees with the previous finding for Maize in the Sahel zone with Climate Change Departure, CCD which 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.

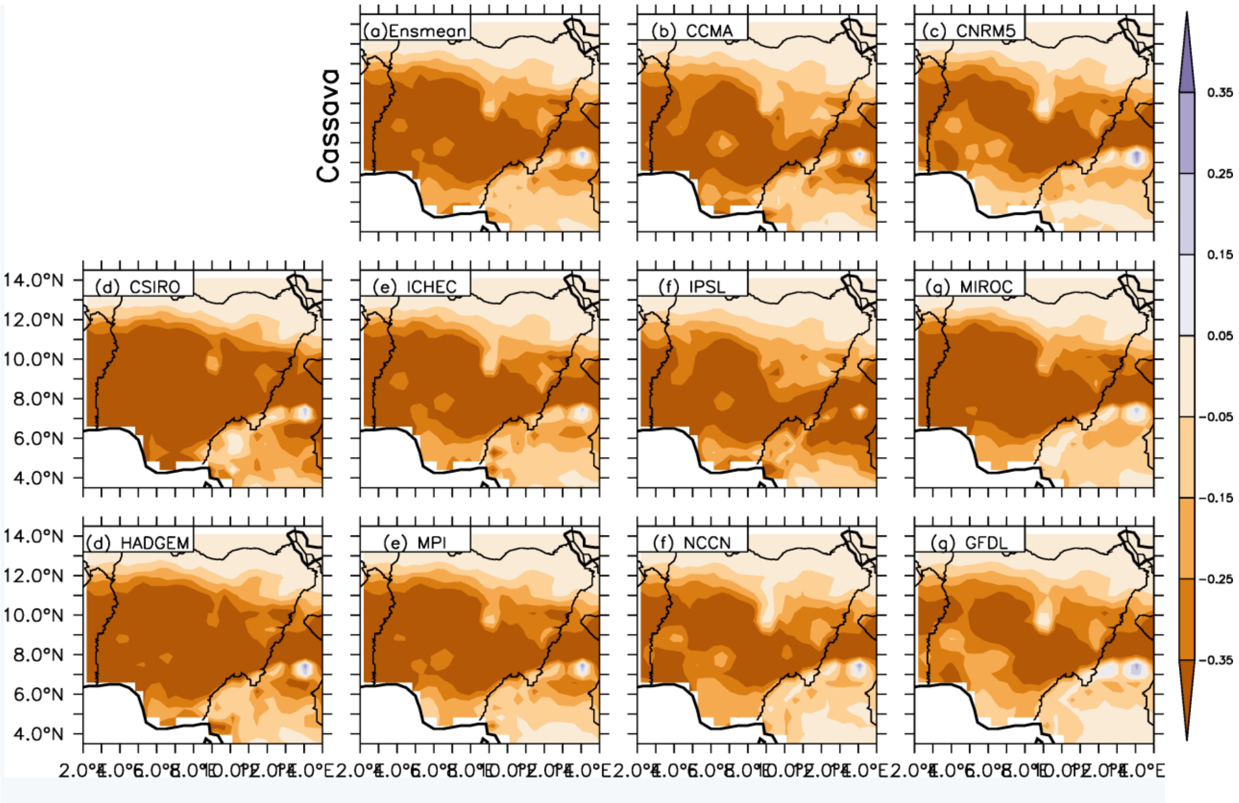


Figure 12: Projected changes in Cassava's suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

Simulated spatial distribution for future Cassava's suitability over Nigeria indicates decreased Cassava's future suitability with decrease in SIV to about 0.4 from the Guinea Savannah to the Tropical rainforest regions, this is clearly indicated by the ensmean. Also, with no changes expected to occur in projected changes for Cassava at the Sahel and Coastal regions, with all ten simulations projecting similar signals in spatial distribution.

This projected decrease in SIV and the reduction in the spatial distribution of suitable areas for cultivation of major crops such as Cassava 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 arising from the projected decrease in the crop suitable area may compound the climatic stress over the region due to the increase in food production to meet the present food demand but with the projected and limited available land for cultivation are not realistic and may become a mirage with the projected increase in the population over the region in the future (Egbebiyi et al., 2019).

3.1.3.2 Crop Suitability for best future planting months (Early and Late Planting ranges)

RCA4 was also used to simulate the future of all crop's (Cowpea, Maize, and Cassava) best planting months (PM) in terms of early and late planting ranges (Figures 13,14 &15). The simulated planting month represents the first of the best three months of the planting window. In general, RCA4 simulated delayed planting month of about two months between latitudes 10◦N and 5◦N, with most changes occurring in the Coastal region for Cowpea. For Maize, the simulations encouraged early planting of about two to four months with most changes occurring from the Sudan region to the Coastal region at lat. 12◦N and lat. 5◦N. While for Cassava, simulation also encouraging early planting months western part of the Guinea Savannah (between two to four months) and no changes occurring at the eastern part of the Guinea Savannah region for future period.

Keys: Brown color indicators encouraging early planting and blue color indicators for delayed planting.

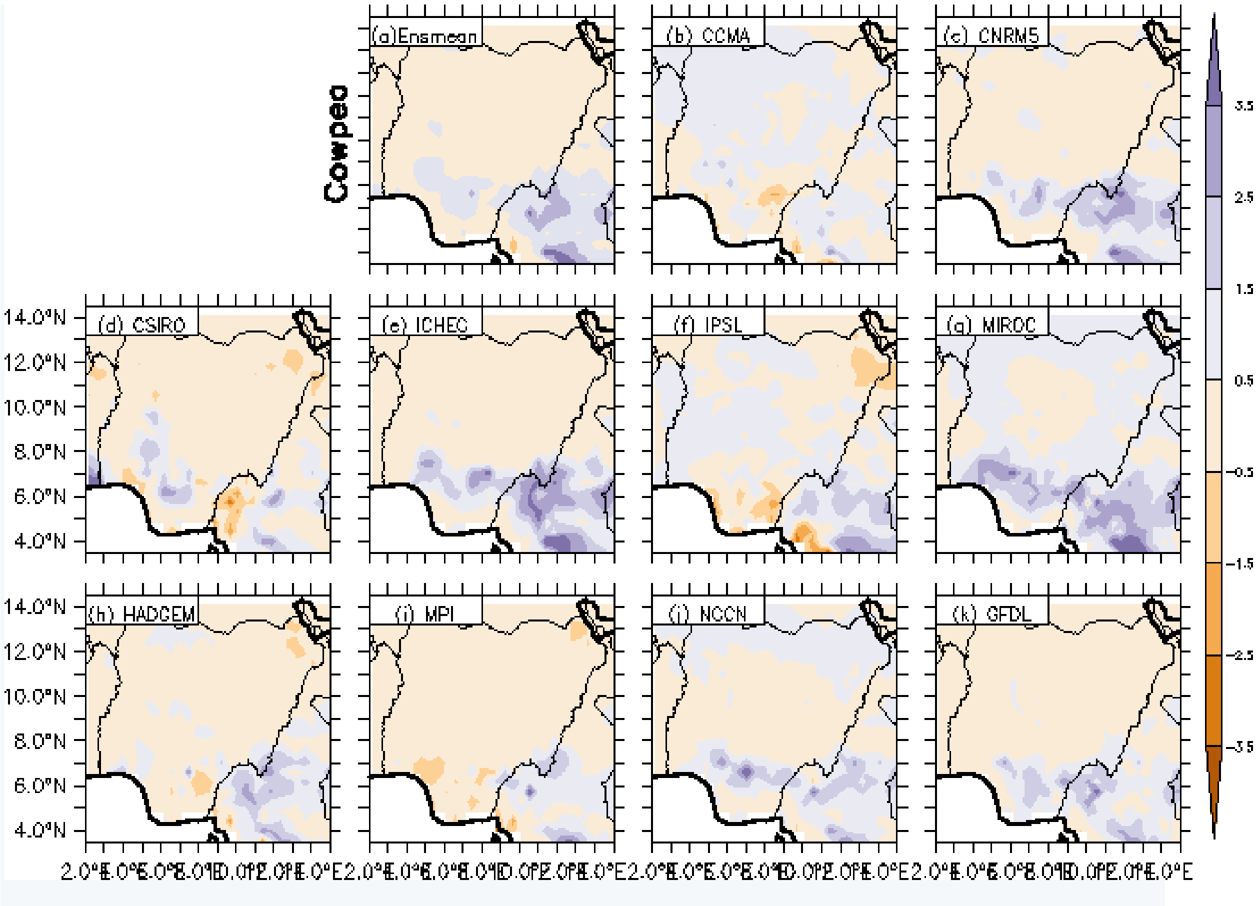


Figure 13: Projected changes in Cowpea's monthly suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

The EcoCrop projected early planting months occurring at the Tropical Rainforest and Coastal regions, but with no changes in planting months from the Sahel region to Guinea Svannah region, as indicated by the ensmean in the spatial distribution (Figure 13a – 13k). Other simulations showing similar spatial distribution with the ensmean are CNRM5, ICHEC, MIROC, NCCN and GFDL. Simulations such as HADGEM, MPI, IPSL and CCMA demonstrated similar signals in spatial distribution indicating no changes in Cowpea's projected monthly SIV over Nigeria in all agro-ecological zones but with possibilities of expected delayed planting months at the eastern part of the Coastal region of Nigeria.

This result is similar with comparisons from Egbebiyi et al. (2019) on legume crops, Cowpea and groundnut showing similar characteristics of no projected change in the planting month 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 the end of century.

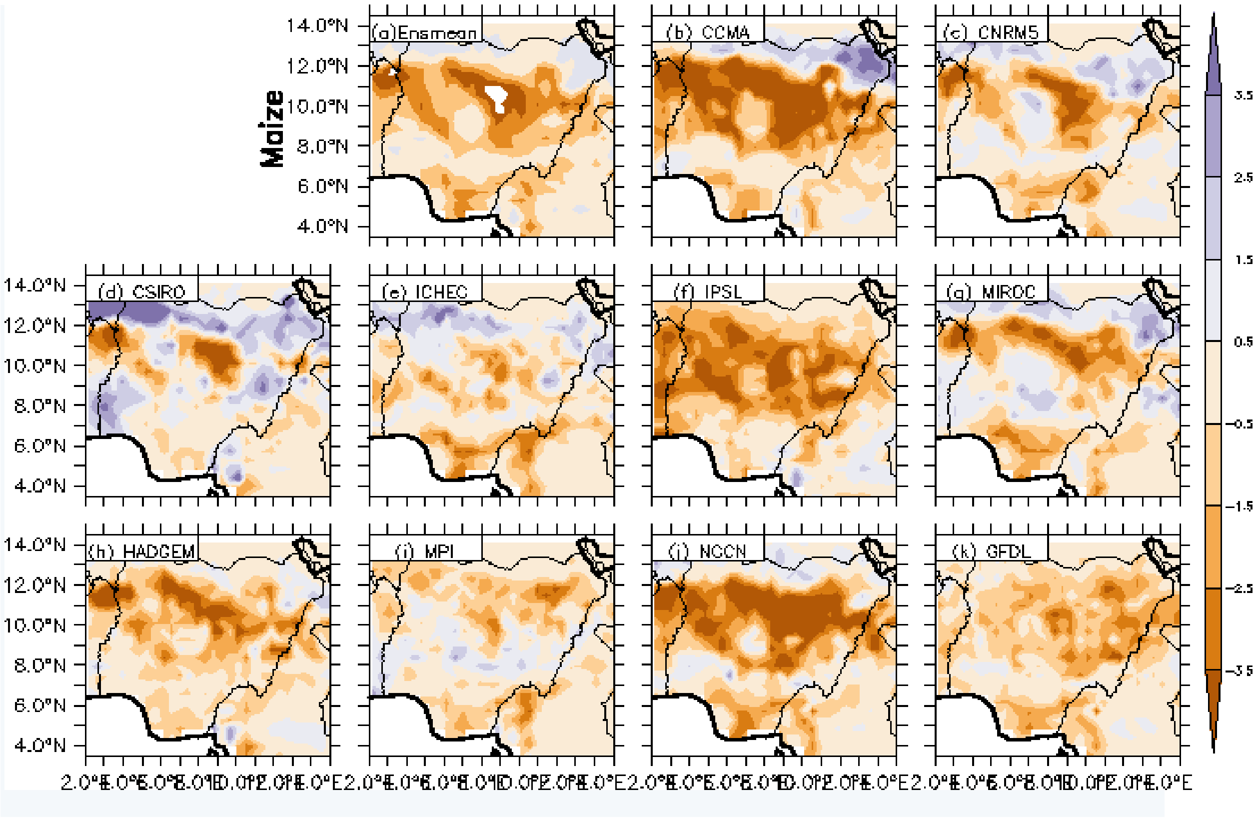


Figure 14: Projected changes in Maize's monthly suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

For projected changes in Maize's monthly SIV over Nigeria in Figure 14, the ensmean demonstrated early planting months for maize occurring at the Sahel and northern part of the Sudan region of Nigeria but with possibilities of delayed planting months in the southern Sudan, Guinea Savannah and the Coastal region, with no changes in planting months occurring at the Tropical Rainforest region. While Egbegbiyi et al. (2019) projects that cereal crops like Maize are expected to experience to have two to three months delay in planting especially at the south Coastal region of Nigeria.

Similar simulations having the same spatial distribution with the ensmean are: CCMA, CNRM5, and NCCN. Simulations demonstrating likelihood of delayed planting months throughout the zones in their spatial distribution are IPSL and GFCL. CSIRO, ICHEC and MIROC indicated similar spatial distribution in Maize's planting months indicating early planting at the Sahel and the tropical rainforest regions and delayed planting months at the Sudan and Coastal regions with no changes in planting months occurring at the Guinea Savannah region.

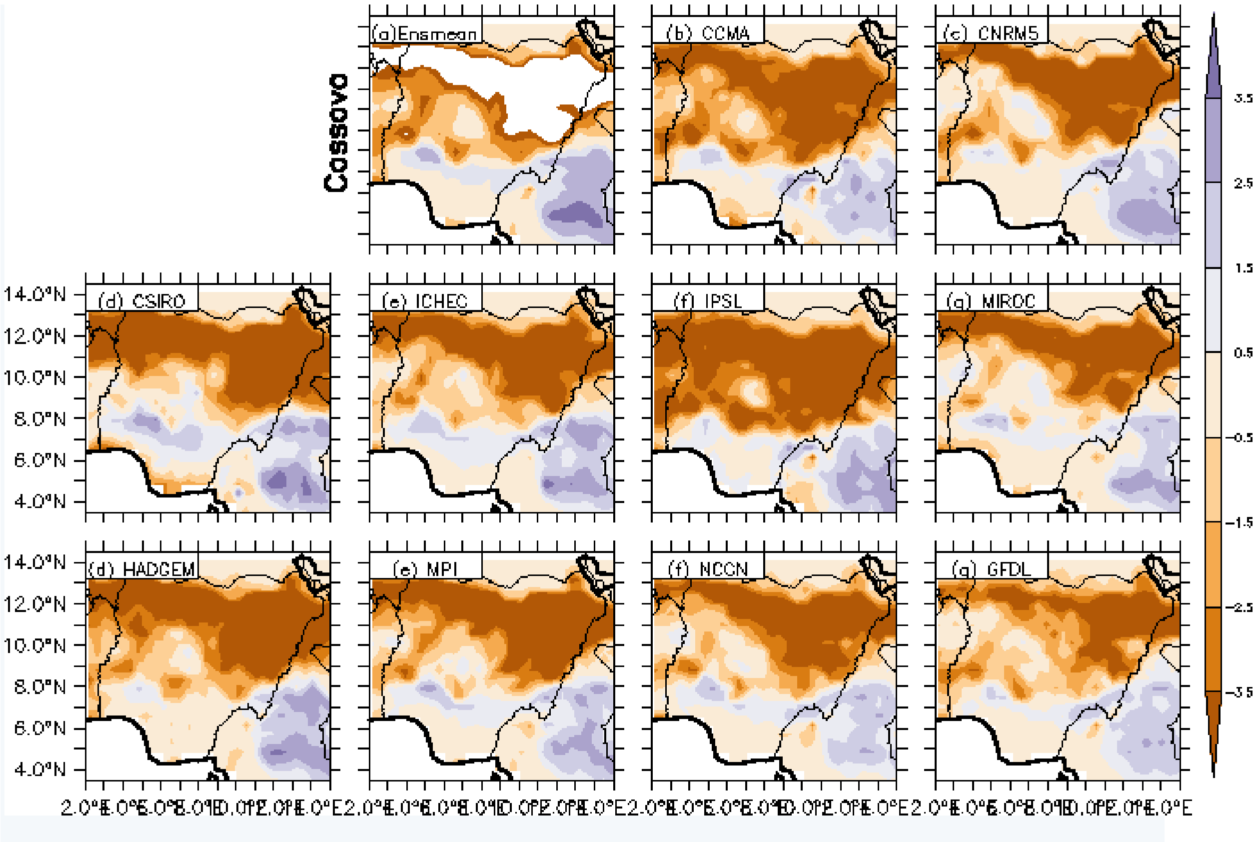


Figure 15: Projected changes in Cassava's monthly suitability index over Nigeria as derived from (a) ensmean (b) CCMA (c) CNRM5 (d) CSIRO (e) ICHEC (f) IPSL (g) MIROC (h) HADGEM (i) MPI (j) NCCN (k) GFDL for 2071 – 2100.

EcoCrop projection for Cassava's monthly SIV indicated chances of delayed planting months occurring at the northern Sahel region with no changes in planting months occurring from the southern Sahel to the eastern parts of the Guinea Savannah region, with delayed planting months also occurring at the western and central parts of the Guinea Savannah. Although from Egbebiyi et al. (2019) Cassava is expected to have up to two-months of delay in planting by the end of the century projected in the western Guinea-

Savanna region while an early planting is expected in other parts of the Savanna zone and north of the Guinea zones over the future period.

Possibilities of early planting occurring at the Tropical Rainforest region and towards the Coastal region, as indicated by the ensmean. However, the ten simulations indicated possibilities for delayed planting months to occur from the Sahel region to the Guinea Savannah region with early planting months occurring in the Tropical Rainforest and Coastal regions.

Conclusion and Perspectives

Considering our primary goal, EcoCrop was able to assess and accurately depict in spatial distribution the suitability of the chosen crops (Cowpea, Maize, and Cassava) for the historical periods. It also enabled the prediction of the performance of crops' suitability in future periods. It can be conclusively noted that questions from the hypotheses has been answered as stated below:

- First hypothesis: verified; EcoCrop is capable of determining crop suitability in the historical period (1981–2000) in Nigeria.

- Second hypothesis: partially verified; The suitability of the selected crops (Cowpea, Maize, Cassava) varied according to the different agro-ecological zones with no expected changes occurring in the future for some of the crops and with others being unsuitable in some regions in Nigeria.

- Third hypothesis: partially verified; model indicated possibility of “mostly” no changes occurring, although with likelihood of late and early planting months depending on the geographical region.

With the above answers derived, it can be concluded that the future performance of the three selected crop depends on the geographical location of that crop with expectations of a delayed or early planting months. This is indicated as Maize and Cassava’s projected suitability changed over the years by about 40%, between historical period to future period, while that of Cowpea had changed at about 15%. Furthermore, Maize and Cassava are expected to have a two to three early planting months in the future period with Cowpea expected to have two months delayed planting months especially at the Tropical rainforest region of Nigeria.

This study is therefore very important to policy makers in Nigeria to help take further decisions on adaptative or mitigative actions as to enabling food security for a sustainable future towards achieving SDG 1 and 2. Nigeria’s major source of employment and income, being agriculture will be drastically affected by climate change which will lead to poverty and hunger in the future. A major percentage of those involved in agriculture are the rural farmers which have their ideal cultural practices on agriculture. The government must look into ways to reaching the farmers at the grassroots and promote the synchronization of scientific predictions with cultural practices to effectively achieve SDG 1(End poverty in all its forms everywhere) and SDG 2 (Zero Hunger).

For recommendation, by utilizing GCM downscaled with RCMs, the current work illustrates the effects of climate change on crop suitability and planting season. This lays the groundwork for further research into how Nigeria's crop adaptability and planting season are affected by climate change. Future changes in how the crop adaptability and planting season might be studied have been shown by the use of the notion of climate change in this study.

Additionally, it lists the three ideal planting months for each growing season as well as any variations in planting time. To increase food security in Nigeria, this kind of study is important in identifying adaptation strategies and making plans for potential changes to the appropriateness of crops and planting seasons.

Further work on this research study will be in the creation of a web application as to increase the visibility of work done and its accessibility to decision makers. This research work should be replicated in the whole of Africa, especially in individual countries so that the government and policy makers can take actions towards combating issues arising for food security in the respective countries.

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