Chapter

Perspective Chapter: Microclimate, Plant Stress and Extension of Cacao Frontiers to Marginal Agroecologies of the Rainforest Tropics

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Abstract

Cacao (*Theobroma cacao* L.) is an important cash crop of the rainforest tropics where it is a major foreign exchange earner, industrial raw material, livelihood, and offer ecosystem services. The rainforest of the tropics is noted for high productivity potential for cacao, however, and its development prospects is beset with numerous challenges among which is the threat of climate change which is setting new ecological boundaries. The new regimes of climate are expected to affect the area suitable for agriculture, thus, crop species are bound to grow in areas where they were not previously grown and areas that were hitherto not suitable for their production. Nevertheless, the shifting environment conditions and associated marginal growing environment conditions (weather: (increasing warming and drought) and soil) may offer opportunities for extending crop frontiers beyond its current ecological boundaries. It is therefore necessary to develop strategies for alleviating constraints imposed by changing environmental conditions thus setting the agenda for climate smart adaptable and sustainable production systems. In addition, efforts to unlock the potentials of the new environmental boundaries for crops will benefit from knowledge, technologies and innovations and climate mitigation.

Keywords: Theobroma, cultivation, marginal, agroecology, mitigation resilience, climate stress

1. Introduction

The global environment change (GEC) including climate change has resulted in major shifts of crop growing environments (agroecologies, weather, soil) and thus changes in the suitability of agroecologies for crops especially fruit tree species (cocoa, citrus, oil palm). Climate change has been projected to cause shifts in the present day growing conditions and set new environment boundaries and habitat range for crops and livestock, and such would crop yields and crop growing area suitability. In particular, increases in temperatures and declining rainfall had led to large parts of sub-Saharan The shifting climate in Sub-Saharan Africa has produced changes in rainfall pattern, temperature, season length and abiotic stress and shifts in suitability of crop growing areas especially for fruit tree species (cacao, oil palm, citrus, coffee etc.) along ecological transect of wet to dry forests. There is however, increasing need to extend production and thus, frontier of fruit tree cultivation to meet rising global demand along other benefits (food security, livelihood, ecosystem services). The new climatic regimes within agroecologies of Saharan Africa (SSA) will affect water resources, agriculture, food and nutrition security, livelihoods and economic growth.

Cacao (*Theobroma cacao*) is an important cash crop in Africa, Central and South America and Asia with an estimated annual production of 4.92 million tons [1]. In these regions, cacao is a major foreign exchange earner, and important as industrial raw material, livelihood, and ecosystem services provision. Based on its global importance, is the need for increased yields and expansion of cultivation to meet rising global demand for cacao beans.

In West Africa, the rainforest belt constitutes the cocoa growing regions where annual rainfall is high (ranging between 1500 and 2000 mm in a bi-modal distribution pattern, and wet-dry season transitions. The dry season is a terminal drought situation for crops especially for plantation (permanent) crops which undergo moderate to severe hydrothermal stresses [2–4].

Rainfall is most important determinant of the success of farming operation within the rainfed farming system where crops are seldom irrigated despite the climate stress of the seasonal wet and dry transitions.

In the West African cocoa producing regions, climate variability and extreme weather events constitute the greatest production constraint to crop productivity [5–7]. Climatic variability has produced significant reductions in cocoa yields and deterioration in bean quality [5, 6]. Agrometeorological studies would contribute to improved understanding of the effects of climate factors on plant environment. The understanding will help to improve farming practices, but also to assess certain risks to the cocoa tree due to irregular rainfall, extreme temperatures and humidity, and low insolation.

In the West Africa, farmers often grow crops in mixed stands (intercropping and agroforestry practices) which subject them to varying intensities of shading. Reports form cacao-based agroforestry system of tropical rainforest belt have shown that over 100 species covering 30 families of shade trees are found in cacao agroforests. Timber and fruit tree species are widely used by farmers to provide shade for transplanted cacao seedlings on the field [8, 9]. The heterogenous shading regime sin cacao agroforests are constituted by shade tree species; timber and fruit trees forming structurally complex closed canopy multi-strata system (under-growths, middle and upper storey species) which retain attributes of natural rainforest ecosystem. The agroforestry system retain the positive attributes of natural forest climax. The co-occurring species crops/trees therefore grow under variable shade intensities (20 to 70% reduction in incoming radiation) and some pockets of unshaded area (full sunlight). Thus, the variable shading scenarios in natural cacao based agroforestry systems of the humid tropics can be constituted by: A: 30:70 timber trees and fruit tree species in mixture - PAR interception ranging from 70 to 20%, B: 50:50 timber trees and fruit tree species in mixture - PAR interception ranging from 70 to 20%, and C: open field (full sun) cacao where light regimes is greater than 70% PAR interception [10].

Shade is known to buffer the effects of stress factors (high irradiance, temperatures and atmospheric deficits (low humidity) of the dry season on tropical perennial fruit tree species in plantations and lower incidence of shoot/branch die-back and tree mortality [11].

However, despite shade provision for transplanted cacao seedlings, high mortality percentages are recorded between first and second dry season. Such seedling death is attributable to high hydrothermal stresses of the terminal drought condition of the dry season [9].

The high seedling mortality constitutes constraints to establishment of seedlings in cocoa rehabilitation efforts following dry season drought. Other factors including low soil fertility, pests (termites and capsids) and poor access to improved planting materials [12].

The naturally occurring shading regimes and variable light intensities are known to expose cacao to modified microclimate, and altered availability and balance of resource use to crops (enhanced competition). Cacao-based agroforestry system ameliorated weather conditions, improved ecological benefits and ecosystem health, the resultant enhance carbon sequestration will reduce global warming.

Cacao-based agroforestry ecosystem contributes to terrestrial carbon budget via carbon storage in soil and crops, as well as microclimate amelioration, improved ecological benefits and ecosystem health. These services exert feedback on terrestrial climate. Reports indicate that the high potentials of net gains in C sequestration from cacao-based agroforestry system is a promising CO_2 mitigation strategy [11].

2. The global economic and social impact of cocoa

The cocoa industry has made enormous contribution to global socio-economies. Global cocoa production and expansion of the chocolate industry had retail value of USD 100 billion in 2021, this is expected to grow further until 2027 [13]. Other reports projected expansion growth of about USD 69.1 billion by 2030 [14, 15]. However, over 79% total annual cocoa bean production is processed into cocoa butter, chocolate, or other products outside the main producing centres especially in the Sub-Saharan Africa for example, Europe followed by Asia and Oceania [13]. Cocoa is vital for Nigeria's economy. More than 70% of cocoa farmers are smallholders with average farm size less than 1.5 ha, yield increases are mostly due to expansion of cocoa land area Cocoa yields are principally affected by soil and climatic variables [10, 16, 17]. There has been declining cocoa export from the mid-1980s to till date.

3. Agricultural ecology of the rainforest of Nigeria

The rainforest zone of Nigeria is characterized by annual rainfall of over 1500 mm distributed in a bimodal pattern of seven to 8 months duration (the growing season), and 3 to 4 months of dry season (typically from late November to march) characterized by low humidity, temperatures over 32°C and clear skies. Rainfall is characterized by unpredictable onset and cessation dates, variable lengths of growing seasons, increasing intensities and duration of terminal drought situations and elevated soil and air temperatures.

Seasonality of sowing implies that crop production is rainfed and linked to seasonally available soil water (rainfed agriculture). The four to 6 months of dry weather results in soil water deficits and high soil and air temperatures [8, 10]. In fruit trees, unfavorable e soil and weather conditions of the short and long dry seasons are known to affect flowering and pod production with negative consequences on bean size. In fruiting trees, water deficits result in lower yields and an increase in the level of mirid (capsid) damage and tree mortality. Since cacao is seldom irrigated, trees undergo severe water stress during the dry season, leading to branch die-back, and for pod-bearing trees, hydrothermal stresses affect pod filling and bean size. Additionally, the wet-dry seasonal transitions cause seasonal leaf shedding at the onset of dry season and leaflessness until beginning of rain. Under the episodes of drought of the dry season, tree crops including cacao, may be subjected to water stress-induced hydraulic failure and cavitation events in the soil-canopy continuum. Thus, fruit trees would have to adjust water relations and water use and other physiological functions for optimum productivity.

4. Climate change and extreme weather events and the changing cocoa production landscapes in West Africa

The scenarios of climate change especially, temperature and rainfall patterns for West Africa including Nigeria have been variously modeled using process-based methods of the General Circulation Models (GCM) and Simple Climate Models (SCM) [18, 19]. The studies have indicated projected decline in mean annual rainfall by −3.1, −12.1 and −20.2% in year 2020, 2050, and 2080, respectively.

Cocoa is sensitive to changes in climate conditions for example, sunshine hour, temperature, rainfall, soil conditions and their effects on evapotranspiration. Drought affect growth and yield of cocoa, and the pattern of cropping of cocoa is related to rainfall distribution. Under the projected climate change from 2020 to 2080, cocoa yields may decrease significant below its current yield levels.

It is reported that climate change had produced shifts in the geographical distribution of host and pathogen/pests, altered crop yields and crop loses, stages and rates of development of cocoa pests and pathogens while modifications in host resistance and physiology of host-pathogen/pests interaction may change. Extreme climate induces drought and tree mortality events worldwide, and further increases in tree mortality events are predicted under future climate. Tree mortality enhanced by drought is also noticeable even in moist and wet tropical forests [20, 21]. Climate change is expected to exacerbate mortality events in tropical forest species especially the fruit tree species. Within ecosystems, plant species respond to drought and high temperature stresses of the wet-dry season transitions, environmental (climate) changes will affect ecosystem and plant distribution.

Climate projections using Global Climate Models and change scenarios (SSP-RCP2.5, 4.5 and 8.5), have identified important shifts and shrinkage of suitable areas for tropical crops [19, 22]. The change projections have indicated significant areas of West Africa are likely to experience unfavorable climatic conditions by 2050 [19]. Other reports have affirmed the shifting agroecological landscapes for cocoa in Ghana, Cote D'Ivoire [22]. These reports indicate the need for adaptation planning to ensure sustainability of crop production under current and future climate scenarios [23].

The projections of climate scenarios are relevant for assessing vulnerabilities and impacts of climate change on agriculture, also useful for identifying adaptation strategies capable of sustaining crop production under future climates. Such projections have been made using CORDEX RCP 4.5 and 8.5 in some cocoa producing regions of West Africa [24]. Results showed that critical temperatures thresholds (33°C) would be exceeded which will result in decline in cocoa performance.

There has been declines in quantity and quality of land and accelerated nutrient depletion within the cacao growing agroecology of West Africa particularly Nigeria.

The ecological transect of wet/moist to dry forests of the humid tropics is characterized by increasing frequencies and intensities of droughts and dry spells, water resource scarcity, high temperatures, soil and atmospheric aridity, land degradation (soil erosion and fertility depletion), insect pests and disease pressures. The changing climate and agroecological conditions (vegetation and soil) constitute constraints to sustainable cocoa production in the West African rainforest belt.

5. Climate and soil requirements for cocoa

Cocoa is essentially a plant of the tropical rainforest, it grows well within about 20° north and south of the equator. The equatorial environment with high temperatures and heavy rainfall (between 1500 and 3500 mm) and nitrogen-rich soil is best agroecology for cocoa.

Recommended weather conditions for cocoa especially temperatures: maximum temperatures of 30–32°C and 18–21°C and absolute minimum of 10°C. Light use efficiency relates to temperature because temperatures below 24°C is reported to decreasing radiation use efficiencies especially for photosynthesis rate at light saturation [25]. Cocoa plant has low light saturation point (LSP) of 400 μ E m^{-2} s^{-1} and low maximum photosynthetic rate (7 mg dm^{-1} h^{-1}) at light saturation. It is reported that crop photosynthesis rate decreases if the photosynthetic apparatus is exposed to light intensities exceeding 60% of full sunlight (1800 μ mol m^{-2} s^{-1}), and prolonged exposure to high light intensities damages the photosynthetic apparatus of leaves [25]. Low light intensities however suppress flower and pod production in cocoa. Opeke [8] and Wood and Lass [26] reported that cocoa optimum growth occur under rainfall of 1250–3000 mm per annum (preferably between 1500 and 2000 mm), dry season not longer than 3 months, maximum temperature between 30 and 32°C, minimum of 18–21°C, and no strong winds. Reports from studies under controlled-environment facility (growth chamber) have showed that cocoa performed well under high humidity (80–95% RH) and about 27°C [25].

Cocoa does well on deep soil of loamy sand texture, friable clays, red or reddish-brown in color and soil pH greater than 6.0 [26, 27]. Cocoa can be successfully grown on heavy clay soil, yellow to red overlying a deposit of hydrated iron oxides. Reports from other studies from analyses of soils from the different countries tended to fall into *Alfisols* and *Ultisols* classification [26, 27]. Commonly used terminologies such as "ideal cocoa soils," "ideal cocoa climate" and "marginal cocoa climate" to describe the suitability of agroecologies for its production.

In Nigeria, cocoa cultivation is restricted to south western and eastern parts of the country where the annual rainfall is above 1200 mm. Thus, cocoa production activities are concentrated along rainforest zone of southern Nigeria across in Ondo, Cross River, Ekiti, Osun, Oyo, and Ogun States where the environmental conditions are most suitable. The major cocoa producing areas lie between Latitude 5° 32′ to 7° 47′N and between Longitude 3° 55′ to 8° 42′E (**Figure 1**). The most important varieties of cocoa are *Theobroma cacao* (officially named in 1753 by the Swedish scientist Carl von Linné) and Criollo, Forastero and Trinitario (with numerous hybrids for each strain).

Soils of the south western Nigeria have developed form metamorphic rocks of the basement complex, majority of these soils are of Pre-Cambrian age [27]. The soils are mainly classified as Typic Kanhaplustalf and Typic Haplustalf. The soils of the south eastern Nigeria are derived from basalt under humid tropical forest vegetation and are predominantly classified as Typic Tropohumult (**Figure 2**) [28].

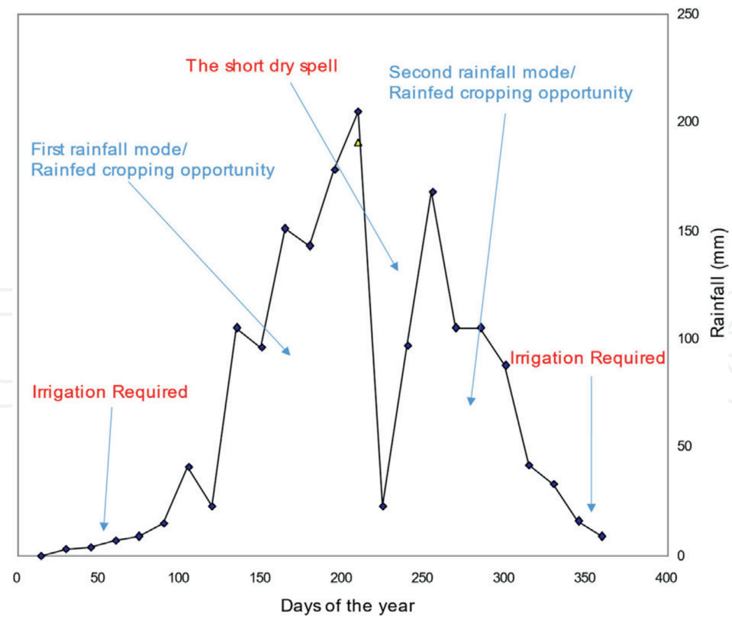

Figure 1.
Bimodal rainfall peaks of the rainforest zone of Nigeria: Rainfed and irrigation based cropping opportunities.

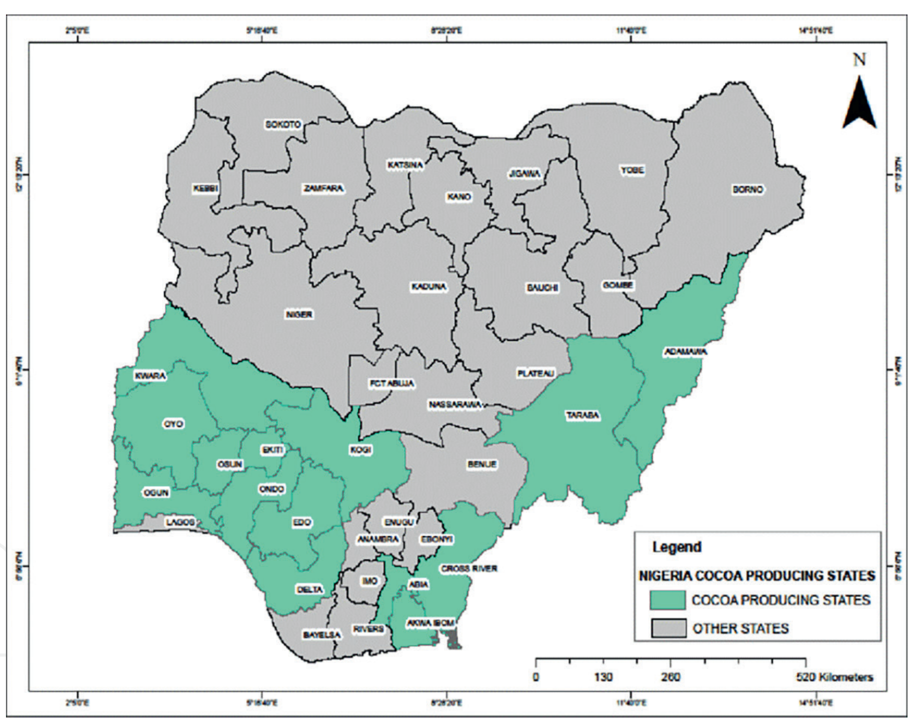

Figure 2.
Cocoa producing states in Nigeria.

6. Climate and agro-ecological conditions

Climate factors play a primary role in determining the ecology of a region [29, 30]. Ecological conditions have profound impacts on the types and scales of agricultural activities [30, 31]. The vegetation zones of Nigeria, are determined by the prevailing climatic conditions, the zones differ in amount and distribution of rainfall, humidity, temperature, atmospheric pressure. The zones are different in annual rainfall and temperature, and predominant species composition (**Figure 3**). These zones have

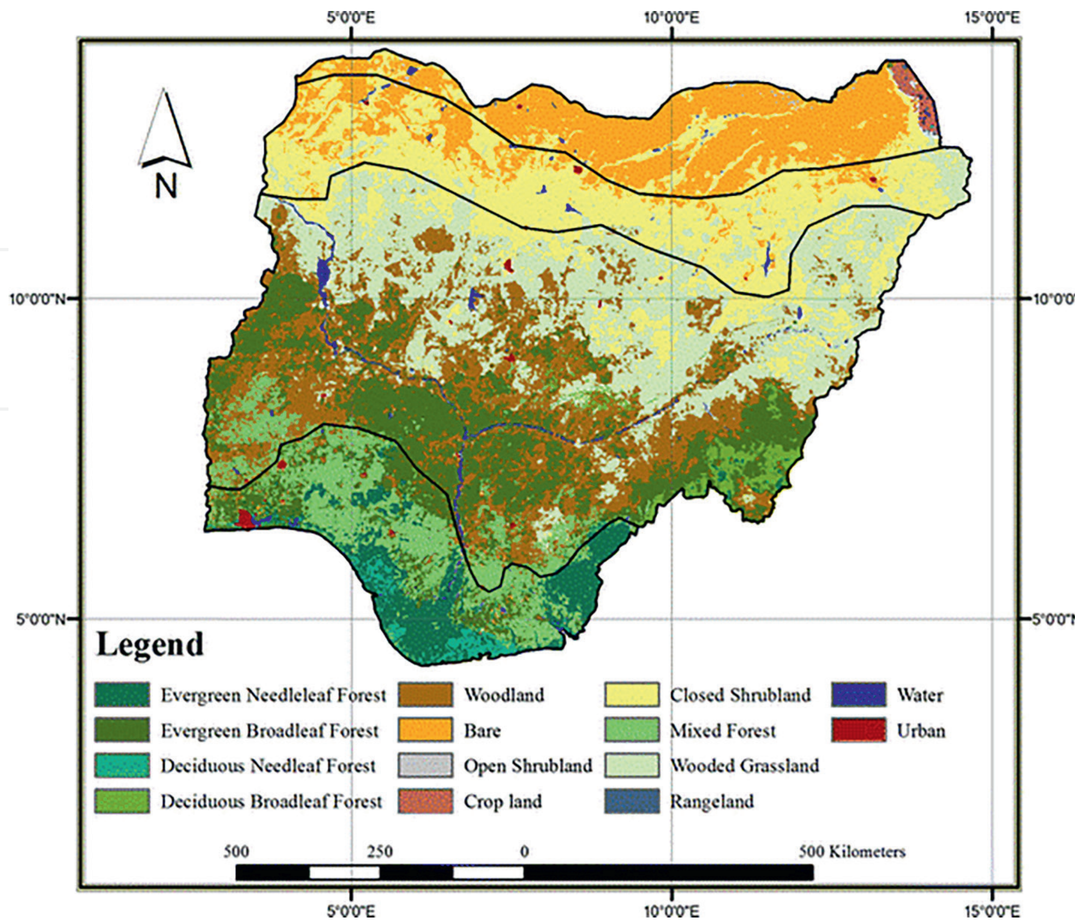

Figure 3.
Vegetation zones of Nigeria.

varying annual rainfall, temperature, atmospheric pressure, and predominant vegetation (dominant species).

Agro-Ecological Zonation (FAO-AEZ) identifies the land's suitability for crop farming and helps understanding of impacts of climate change on agriculture. Agroecological zonation has been used as a tool for identifying agricultural activities under current climate conditions and for predicting future area suitability for crops (FAO (1978, FAO/IIASA (2012) classified Africa into Agro-Ecological Zones (AEZs) based on temperature, precipitation, and soil moisture conditions. Agroceological zonation provides clear picture of land potentials of land resources for use through matching of production system requirements with the land characteristics within the agroecology. The most vulnerable crop producing zones to climate change can be delineated using the concept of AEZs [29, 32]. Modeling results have affirmed shifts in the AEZs under different climate change scenarios [33] and analysis of AEZ had established that climate change affects African landscapes and agroecologies. Results of such analyses for West Africa establish that that the moist (humid) and dry savanna are more vulnerable to climate change while the humid forest or sub-humid AEZs will become more productive in the future [33].

Image analysis using spot-vegetation sensors have showed changes in the composition and extent of different vegetation zones across Nigeria. Reports have confirmed the encroachment of the savanna into the forest belt of southern part of the country. The expansion of non-forest areas, fragmentation and shrinkage of forested ecosystems have ecological and socio-economic consequences [22]. Unsustainable anthropogenic activities such as lumbering, open cast mining, and agriculture have accelerated the degradation of vegetation, soil quality, biodiversity loss, ecosystem services and climate change. The changes in the suitability of agroecologies and crop growing under the present and the future climate using model projections have affirmed differences in suitability ranges from moderate to marginal suitability and the very unsuitable.

7. Climate and agroecological suitability for cocoa

Land suitability classification relates to comparison of requirements of land-use types with properties of land units. Land suitability assessment is a valuable tool for rational soil use planning and sustainable land management.

Agroecological suitability is a measure of the ability of an agroecology to support intended uses (agricultural activities involving production of arable (annual) and permanent (plantation) crops.

Suitability is indicated separately for each land-use type, showing whether the land is suitable or not suitable. Classification of current crop suitability refers to land suitability for a defined use in its present condition, without major improvements. Crop suitability describes appropriateness of an area of land based on the growing threshold of a crop in relation to climatic conditions (minimum and mean monthly temperature and total monthly rainfall) [19, 34]. Crop suitability is also relate to the spatial appropriateness and distribution of land area based on the growing climatic suitability threshold of a crop over time period [35].

Multiple global circulation models (IPSL-CM5A-LR, BCC-CSM 1.1 and MIROC-ESM-CHEM) have been used to simulate changes in crop growing area suitability across the agroecological zones of West Africa future climate change scenarios (RCP 2.6, 4.5, and 8.5) [19, 36]. Areas with increasing and decreasing land suitability were predicted to increase with time, the changes were greater for RCP 4.5 while RCP 8.5 gave the worst prediction indicating higher risk of crop cultivation in the future [36].

Climate departure defines a shift in the climate pattern of a region outside the range of historical variability and such description may be based on local temperature exceeding historical high. Mora et al. [37] described climate departure as the year in which the average temperature of the coldest year after 2005 was warmer than the historic hottest year at a given location. Climate departure manifests as deviation from the historical mean and/or variance of the local climate of an area or region induced by global warming. The authors suggested that West Africa will experience a climate departure based on temperature rise will occur about two decades (2029) earlier than the global mean temperature (2047). The study established the likelihood of changes in large-scale crop and growing area suitability across West African agroecologies.

The concept of crop-climate departure (CCD) is useful for evaluating future changes in crop suitability over historical and future time periods. Crop-climate departure has been used to evaluate future changes in the crop suitability and planting month for crop species in some west African agroecologies [19]. The authors used using Global climate model simulations downscaled by the CORDEX regional climate model (RCA4) to drive the crop suitability model [36]. Results showed a reduction (negative linear correlation) and expansion (positive linear correlation) in area and crop suitability for the guinea and southern sahel zones of West Africa. The study recommended options for short and long-term adaptation and planning for future changes in the crop suitability and planting windows for improving food security and livelihood in West Africa savanna agroecologies.

Crop distribution over agroecologies is predicted using species distribution models (SDMs). Species distribution models are built on genetic algorithm for setting rule for production (GARP) and CLIMEX, and maximum -entropy (MaxEnt) [38–40]. Among the species distribution models, MaxEnt is the most widely used model in recent years [41, 42]. Predictions of impacts of climate (current and future scenarios) on area (agroecology) suitability for crops using Global Circulation Models and adapted MAXENT model. MaxEnt has shown outstanding predictive performance compare with other modeling methods [43, 44]. The simulation of present and potential area suitability or crops in agroecologies and under future climate (2030s, 2050s and 2080s) using MaxEnt model has indicated variabilities in current regional and global agricultural crop area suitability from medium to high suitability in addition to potential undeveloped suitable areas [36]. The predictions also affirmed shifts in the current distribution of crop growing area especially under future climates (2050 and beyond). Especially for West Africa, the studies showed that some current agroecologies of West Africa will be suitable for crops while some others will become unsuitable.

In the rainforest of West Africa, (the cocoa growing belt of the region), predictions have affirmed that yearly and monthly rainfall will decrease slightly by 2050 (aside the coastal areas) and yearly in addition to increases in monthly minimum and maximum temperatures by 2030 with continue increases up till 2050 [19, 36]. In general, West African climate will become less seasonal due to within the year variations, increases in temperature in specific districts by about 1.2°C by 2030 and 2.1°C by 2050 and less seasonal precipitation with decreases in number of dry months (from 4 to 3 months). This trend may imply changes in the suitability and distribution of growing areas within the current cocoa-growing areas in some parts of West Africa (Ghana, Côte d'Ivoire and Nigeria) by 2050 due to temperature increases.

The changing landscapes (agroecologies) and may require changes in agricultural practices as adaptation to new environmental conditions that will prevail while the climatic suitability for growing crops in some parts of West Africa rainforest belt. The development of site-specific adaptation strategies will reduce the vulnerability of smallholder farmers to climate change challenges. The imports of progressive changes in climate and the suitability of crop growing area in particular, with the current areas becoming unsuitable for certain crops may require farmers to shift to alternative crops.

The suitability or otherwise of cocoa growing areas in the rainforest of Nigeria under present and the two future climate models (HadGEM2 and CNRM-CM5 under RCP 4.5 and 8.5) is presented in **Figure 4**. The results showed that compare with present day climate and growing area for cocoa, the unsuitable areas will increase under both scenario predictions and higher magnitude of change for CNRM-CM5 RCP 4.5 and 8.5. greater decline in area suitability is projected for RCP 4.5 for both HadGEM2 and CNRM-CM5.

8. Climate change and distribution range for species

Climate change acts as a major cause of species extinction by impacting the distribution and abundance of species. Species may either keep their current range or respond to changing environmental conditions with range expansions, contractions or shifts [45, 46], which may ultimately contribute towards shrinkage in the forest cover and crucial biodiversity loss [47]. The non-significant changes in habitat suitability for species under climate change scenarios may indicate higher climate resilience. Climate warming can provoke species attrition (changes in species richness) in various ecologies, this may cause increases in colonization of new suitable

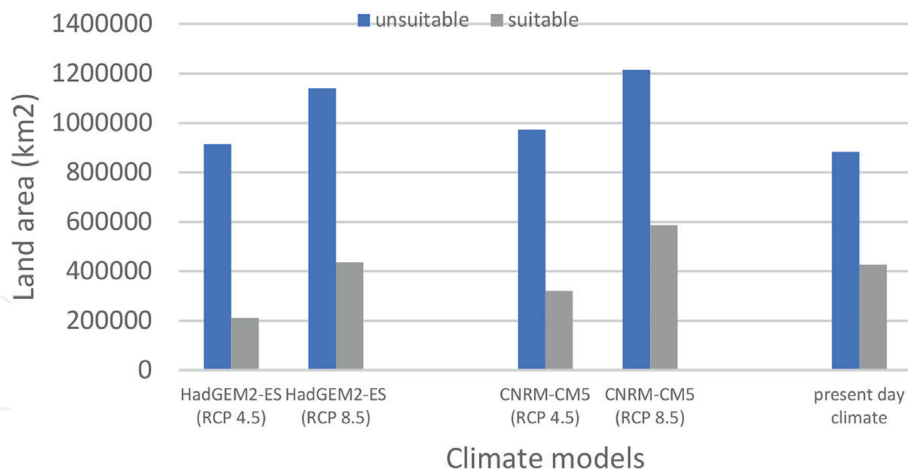

Figure 4.
Fruit tree species (including cacao) land areas of the rainforest zone of Nigeria under the present and future climate models.

areas (expansion range for species) or retractions from unsuitable sites with harsher environmental conditions. Such phenomenon may lead to local and even global species extinction events [46, 48].

9. Environmental factors driving crop growing area suitability

Environmental factors (weather and soil) drive changes in area suitability for crops in agroecologies (AZEs). Climate suitability relates to levels of climate variables which determine growing areas having the potential for successful cultivation and growth of certain crop (s) [45, 46]. Such bioclimatic variables include monthly temperature and rainfall, seasonality (annual range in temperature and precipitation) and extreme or limiting weather factors such as temperature of the warmest month, and rainfall of the wettest and driest months useful for generate biologically meaningful indicators for ecological niche modeling.

Temperature increases had been reported as a major driver of shifts in area suitability for crops under current and future climate. Reports identified temperature of the warmest month as the main driving factor. Temperature explains about 30% of the negative change in area suitability (under 2.4°C increases in temperature of the warmest month by 2050). Temperature seasonality has been identified as the main driving factor for negative change in suitability. The contribution of different bioclimatic variables to changes in crop growing area suitability between current and future climate scenarios, had shown decreasing and increasing trends for crop suitability in agroecologies.

10. Changes in global climate

Global warming denotes the unusually rapid increase *in* Earth's average surface temperature over the *past* century primarily due to the greenhouse [49]. Over both the last 140 years and 100 years, estimates have shown that global average surface temperature has increased by 0.6 ± 0.2°C that is by approximately 0.5–1.0°F (0.3–0.6°C) over the last century [50]. Trends in global average surface temperature between 1993 and 2022 in degrees Fahrenheit per decade confirmed that most of the planet is warming (**Figure 4**). Only a few locations, mostly in

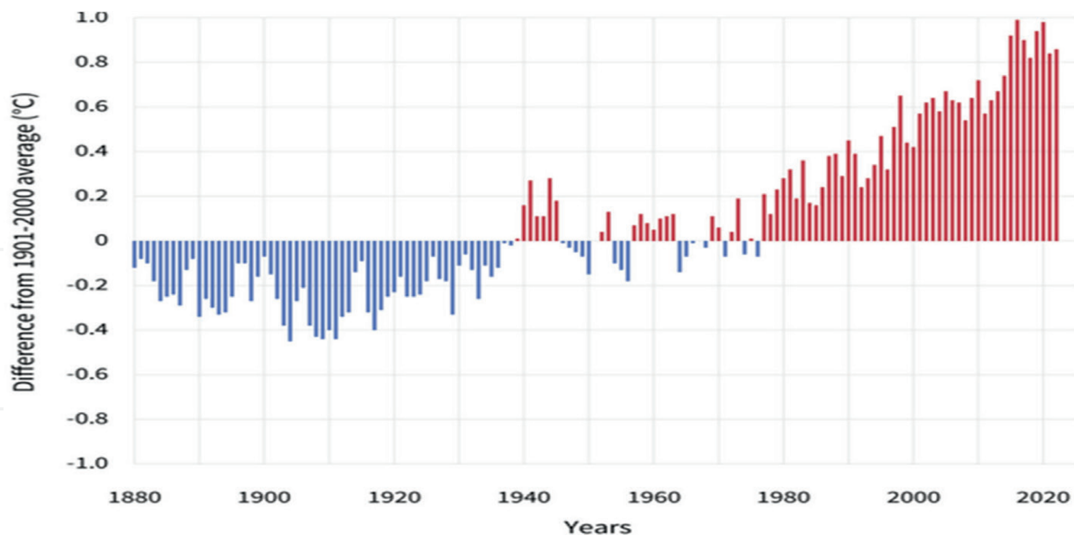

Figure 5.
Global average surface temperature: https://www.climate.gov/media/15022.The average yearly surface temperatures from 1880 to 2022. The cooler-than-average years are depicted in blue bars and warmer-than-average years are shown in red bars. (Source: NOAA Climate.gov graph, based on data from the National Centers for environmental information).

Southern Hemisphere and oceans have cooled over this time period [51]. Trends of increased warming since 1981, has been twice as fast at 0.32°F (0.18°C) per decade [52]. The earth's temperature has risen by an average of 0.14° Fahrenheit (0.08°C) per decade since 1880, or about 2°F in total. The 10 warmest years in the historical record have all occurred since 2010. Over the twentieth-century average of 13.9 and 1.06°C warmer than the pre-industrial period (1880–1900), the year 2022 had warmer surface temperature (0.86°C/1.55°F) (**Figure 4**). Each month of 2022 ranked among the ten warmest for that month (Global Climate Report from NOAA National Centres for Environmental Information, [51]). The "coolest" month was November, which was 1.35°F (0.75°C) warmer than global average (**Figure 5**).

11. The changing climate: the case of Africa

Based on the reports of [50] and Zougmoré et al. [53], over the coming decades, warming from climate change is expected across almost all the Earth's surface while global mean rainfall will increase. In particular, climate change constitutes increasingly serious threat for Africa, a region that has been described as among the most vulnerable continents to the challenges of climate change. Africa is warming faster than the rest of the world on average, records showed that surface temperatures have generally increased over Africa since the late nineteenth century to the early twenty first century by about 1°C, (**Figures 6** and 7). Based on climate projections, many African countries and regions, this will severely compromise agricultural production and food security [50, 54]. Omotosho et al. [55] reported that in West Africa, seasonal cycle of rainfall is driven by the south-north movement of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is characterized by the confluence between moist south-westerly monsoon winds and the dry north-easterly.

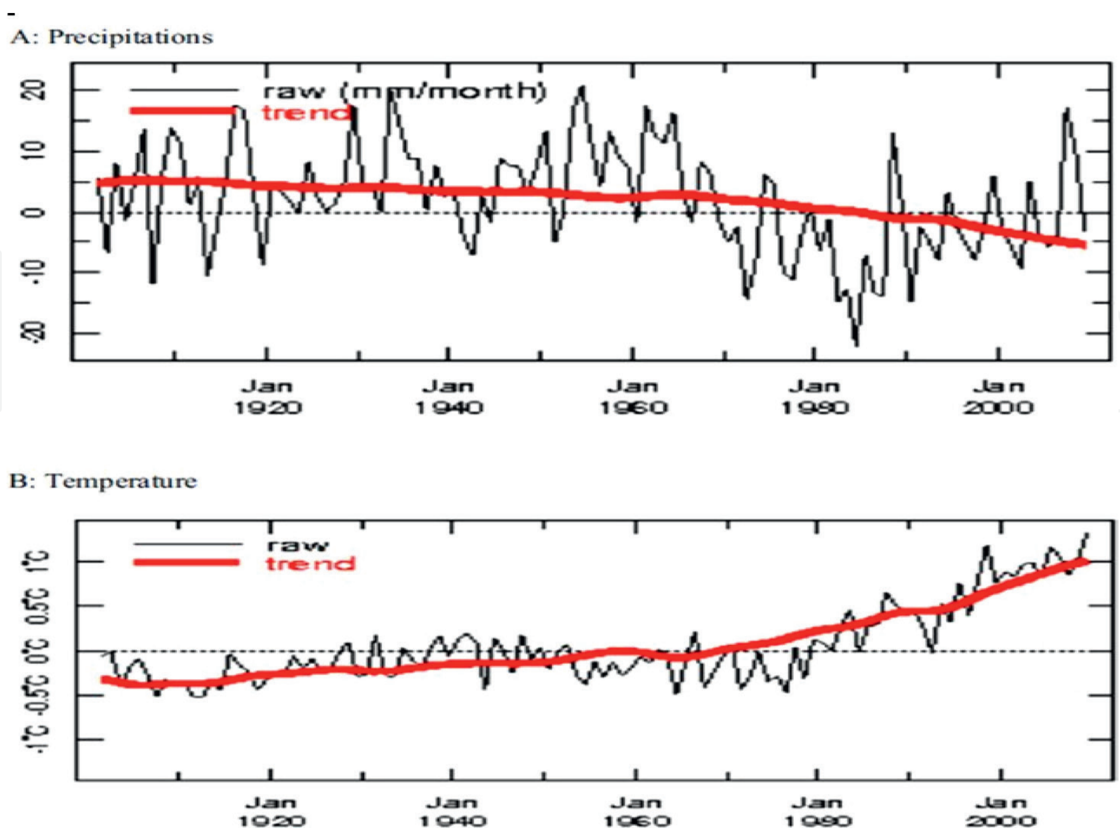

Figure 6.
Variations of the Earth's surface temperature over the last 140 years and the last millennium. Based on records of changes in precipitations (A) and temperature (B) in Africa from 1920 to 2000. (The international research Institute for Climate and Society, Columbia University, Ne. (after [53]).

12. Rainfall and temperature anomalies of the rainforest zone of Nigeria (1980–2020)

The time series (year: 1980–2020) of a normalized annual departure of rainfall and temperatures standardized mean rainfall anomaly, δ) for the rainforest agro-ecological zone of Nigeria. moderate fluctuation in temperature and rainfall are represented by anomaly values of +5 while -5δ denote drought years, and above +0.5 as likelihood of flood events (**Figure 7a**). The normalized annual departure of

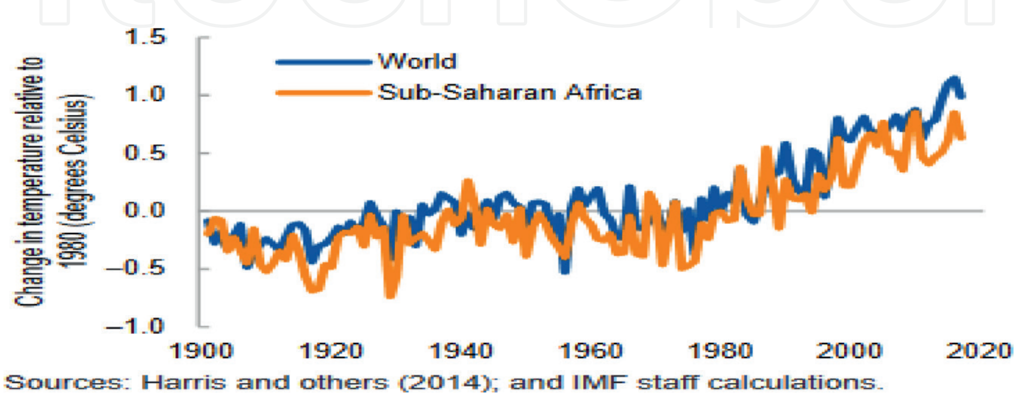

Figure 7.
Changes in global and sub-Saharan Africa (1900 to 2020). a. Rainfall anomaly trends (1980–2020) for rainforest zone of Nigeria. b. Maximum temperature anomaly trends (1980–2020). c. Minimum temperature anomaly trends (1980–2020).

temperatures (maximum and minimum temperatures) is illustrated in **Figures** 7 and **7b**. The results confirmed elevated temperatures characterized by high maxima and minima values which mean high probability of exceeding crop-specific high temperature thresholds. Temperature warming may elicit adjustment of plant physiological functions and water use. Such plasticity is important to acclimation to environmental stresses especially in plant species useful in the revegetation of degraded urban lands. The observed trends confirm changes in climate over Nigeria (for rainfall, maximum and minimum temperatures) for years 1980–2020).

13. Environmental factors driving growing area suitability

Bioclimatic variables are derivable from WorldClim database, from monthly temperature and rainfall values. These Bioclimatic variables are biologically relevant and are often used in ecological niche modeling. Environmental factors (weather and soil) driving change in area suitability for cocoa in the West Africa rainforest belt are exemplified by changes in mean annual temperature and rainfall), seasonality (annual range in temperature and precipitation) and extreme or limiting weather such as temperature of the warmest month, and rainfall of the wettest and driest months. The contribution of bioclimatic variables to the predicted shift in growing area suitability for cocoa between current and 2050 climate scenarios had showed decreasing suitability of weather, soil and vegetation (agroecologies) for cocoa in the tropical rainforest belts of West Africa. Temperature increases had been reported as a major driver of shifts in area suitability for crops especially the changes in suitability between current and future climate especially, the temperature of the warmest month as the main driving factor (it explains about 30% for negative change in area suitability [24]. Climate change will also increase the pressure on forest areas and on other important habitats for fauna and flora [24].

Projections for future climate change suggest a warmer and drier climate in the West African rainforest belt. Information and knowledge improvements with respect to effects of these changes on cocoa production and area suitability in the West African rainforest biome. Simulations using models for the suitability of cocoa's geographical distribution using ensemble of correlative models and projections of two future climate scenarios (RCPs 4.5 and 8.5) by 2050 had been conducted. The models generated information on climate and soil suitability for cocoa. The current and future suitability model had indicated how cocoa production may respond to climate change, and had suggested that reduction in precipitation and increases in temperature may result in reduction in the suitability of the West African rainforest belt cocoa production. The areas suitable for cocoa plantation will decrease by about 37.05 and 73.15% (area suitability for intensification and expansion) under RCP 4.5 and 8.5, respectively, compared with the current climate. Model results also suggest that reduction in precipitation and increase in temperature which may produce a reduction in agroecological suitability for cocoa production in the West African rainforest.

14. Conclusions

Global environment change including climate change has produced marginal environments (agroecologies, weather, soil) and thus major shifts in the suitability of agroecologies for crop production. Thus, climate change has created new environmental boundaries occasioned by changes in rainfall patterns and temperature regimes, seasonal shifts and habitat range for crops. Such changes are expected to affect the area suitable for agriculture, crop species are bound to grow in areas where they were not previously grown and areas that were hitherto not suitable for their production. Climate change may bring about decreases in area suitability for agriculture, and decreases in length of growing seasons and crop yield potentials.

The changing environment conditions are projected to limit cocoa production while the expansion of its production has placed increasing pressure on forest resources in particular along the ecological transect of wet to dry forests. Increase in mean annual temperature up to 2°C will cause considerable decrease in suitability of the rainforest belt of West Africa for cocoa production.

Results of agroecological zoning quantification, show a promise for the extension of suitable areas for the intensification and expansion of cocoa cultivation under future climate. However there will remain, some tracts of land with high levels of soil and climate suitability in the rainforest for cocoa production. Although, tropical crop species are naturally adapted to warmer climates and are developing increasing resilience to climate-related stresses.

Increases in temperatures and declines in rainfall will lead to large parts of sub-Saharan Africa becoming unsuitable for crops. This situation may necessitate a transition to more heat and drought resistant crops to ensure food and nutrition security in the sub-region. The new climatic regimes set by global climate change will affect water resources, agriculture, food and nutrition security, livelihoods and economic growth. In future climates, 2050 and beyond, high percentage loss in the suitability of the West African rainforest for crop production is envisaged. There is however, increasing need to extend production and thus, frontier of fruit tree cultivation to meet rising global demand along other benefits (food security, livelihood, ecosystem services). Sustainable management practices would be required for enhanced productivity and climate mitigation in the era of shifting cacao agroecology and landscapes.

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