Chapter

Potential of Impact of Stratospheric Aerosol Geoengineering on Cocoa Suitability in Nigeria

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Abstract

Cocoa is an important cash crop that contributes to the economy of Nigeria *via* job creation and foreign exchange earnings. However, escalating global warming trends threatens Cocoa cultivation and have resulted in a decline and heightened variability in Cocoa production in Nigeria, with potential for further exacerbation in the future. A potential way to reduce the warming is through climate intervention (CI) techniques, including Stratospheric Aerosol Injection (SAI), which involves the injection of sulphur into the stratosphere to reflect a small percentage of incoming solar radiation and lower earth's temperature. To gauge GHG and SAI impact on Cocoa suitability in Nigeria, we used Geoengineering Large Ensemble Simulations (GLENS) dataset as input into Ecocrop model for historical (2011–2030) and future periods (2070–2089). Our results show GHG impact will increase mean and minimum temperatures (up to 3°C) and total monthly rainfall (up to 15 mm) by the end of century in the southwest and north-east area of Nigeria while rainfall decrease of similar magnitude in the other parts of the country. With SAI intervention, rainfall may decrease by about 10–20 mm over the country and reduce mean and minimum temperature by 2°C. Suitable land for Cocoa cultivation in Nigeria may decrease by 24 and 18% under GHG and SAI, respectively, while unsuitable may increase by 14 and 24% by the end of century. Our study has implications for the economies based on Cocoa production in Nigeria.

Keywords: cacao, Nigeria, Ecocrop, crop suitability, stratospheric aerosol injection

1. Introduction

Cocoa (*Theobroma cacao*) holds immense economic significance in Nigeria, contributing significantly to the social and economic well-being of the country. With a history spanning centuries, Cocoa has played a pivotal role in shaping Nigeria's economy and fostering rural livelihoods before the discovery of crude oil [1, 2]. Nigeria has achieved significant milestones in Cocoa production, ranked as one of the top four Cocoa-producing nations globally [2, 3], with Cocoa production largely concentrated in the southern regions of the country [1]. The crop has become a cornerstone of Nigeria's agricultural sector, providing a livelihood for millions of smallholder farmers and supporting numerous downstream industries, such as Cocoa processing and chocolate production [4–6]. The foreign exchange earnings from Cocoa exports have also significantly contributed to Nigeria's overall revenue and balanced trade [1]. The Cocoa industry's growth and achievements have made it an essential component of Nigeria's socio-economic fabric. Moreover, its Pan-Africa significance as a tropical African plant cultivated for its oil and bold foliage places indispensable economic and livelihood significance on Cocoa amongst the people engaged in its cultivation [7–10]. However, climate change poses a severe threat to Cocoa cultivation, impacting its suitability and potentially hampering Cocoa-dependent economies.

The potential impact of climate change or global warming on Cocoa production and suitability in Nigeria is a pressing concern that has garnered extensive research attention. A number of studies (e.g., [11]) have underscored the alarming implications of rising temperatures and changing weather patterns on Cocoa yields. Global warming's adverse effects on Nigeria's Cocoa industry are evident, as projected decreases in Cocoa yield pose substantial economic risks for Cocoa farmers [12, 13]. Furthermore, Nwachukwu et al. [14] emphasise the vulnerability of Cocoa productivity to climate change-induced shifts in temperature and rainfall. These changes, combined with limited adaptation measures, could potentially exacerbate the negative effects on Cocoa suitability. Agbongiarhuoyi et al. [7] delve into the perceived effects of climate change, highlighting the concerns of Cocoa farmers about the impact on various aspects of Cocoa cultivation. In light of these findings, adaptation strategies become paramount. Jamal et al. [15] stress the importance of climate adaptation efforts, particularly for small-scale farmers who are disproportionately affected. These studies collectively underscore the significant potential impact of climate change on Cocoa production and suitability in Nigeria, urging the implementation of effective strategies to mitigate its adverse effects.

Solar Radiation Management (SRM) has been identified as a potential technique for climate mitigation efforts [16–18] aimed at reducing CO_2 emissions to limit the increasing global temperature. One of the SRM prominent approaches is the Stratospheric Aerosol Injection (SAI) which involves the release of gaseous aerosol precursors such as sulphur dioxide (SO_2) into the stratosphere to form aerosols that reflect into space a small amount of incoming solar radiation with the aim to reduce temperature at the earth's surface [18, 19]. Although this strategy may decrease global temperature, studies have revealed that it could have a negative impact on rainfall notably in most parts of Africa [20–24]. For example, findings have shown that the impact of SRM will help increase crop yield via the reduction in temperature and heat stress, whilst its resultant effects in rainfall deficit may lead to a reduction in suitable areas for crop cultivation and yield in other regions [16, 20]. Xia et al. [20] also revealed that SRM poses a threat to food security notably in areas like Nigeria, where agricultural productivity is dependent on monsoon rainfall [20, 25]. However, despite this research, there is still a dearth of information on how the SAG will affect Cocoa suitability and yield in Nigeria and the present study is in that direction.

This chapter explores the potential impact of SAI to counteract the adverse effects of climate change on Cocoa cultivation suitability in Nigeria. Section 2 describes the data and methodology on the paper, the results are presented and discussed in Sections 3 and 4, respectively, whilst the summary and conclusions are in Section 5.

2. Data and methods

2.1 Study domain

Our study domain for this research is Nigeria, the most populous African nation and one of the four largest producers of Cocoa in the world (**Figure 1**). It has rainfed agriculture as its mainstay economy and means of livelihood. We define Nigeria domain from latitude 4–14°N and longitude 2.4–15°E with agroecological zones of Nigeria designated as Guinea, savanna and Sahel zones (**Figure 1**). The region is characterized by a strong north-to-south temperature and precipitation gradient [26] and the West African Monsoon Systems (WAMs) are the main rainfall-producing system in Nigeria [27]. The Nigeria climate is in the humid southern area, with rainfall amount up to 3000 mm/year and semi-arid in the north with rainfall amounting to about 450 mm/year [26]. The south experiences a bimodal rainfall regime between March–July and September–November whilst the Northern region experiences unimodal rainfall regime from May–October and agricultural production is highly dependent on rainfall [26]. Different crops are cultivated in different parts of Nigeria and contribute significantly to the economy of the country [26, 28]. Major crops grown in Nigeria include Maize, Yam, Cowpea, Cassava, Rice, Groundnut, Cocoa, Oil palm [29]. Cocoa is reported to be the most important cash crop in West Africa, particularly due to its substantial contribution to the country's GDP via export and foreign earnings [1, 30]. Hence, the need for this present study is to provide information on how climate geoengineering will affect Cocoa cultivation and suitability in Nigeria.

2.2 Data

2.2.1 GLENS datasets

For the study, we analysed the National Centre for Atmospheric Research Community Earth System Model (CESM1) simulation for the Stratospheric Aerosol Geoengineering Large Ensemble Project (GLENS) dataset [31]. The GLENS experiment uses the Whole Atmosphere Community Climate Model (WACCM) as its atmospheric component (WACCM; [32]) with a horizontal resolution of 0.9° latitude × 1.25° longitude and 70 vertical levels from the surface up to 140 km [31]. The experiment includes a multi-member ensemble simulation of future climate and we used two GLENS experiments, the control and the feedback, both experiments were forced with

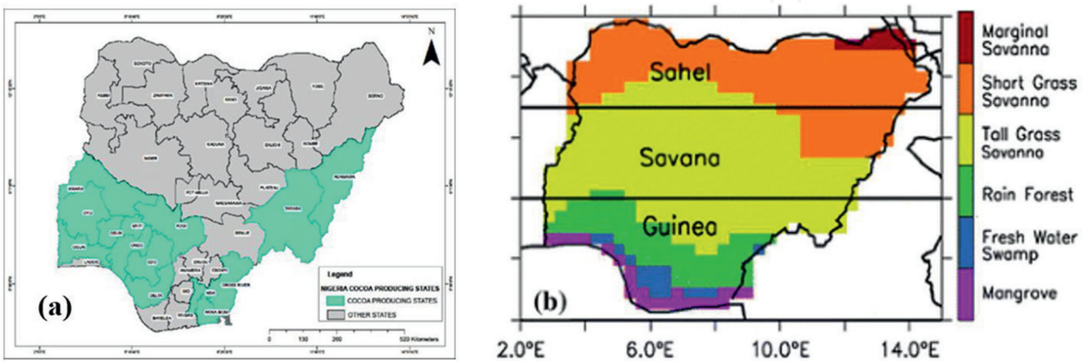

Figure 1.
Map of Nigeria showing (a)agroecological zones designated as Guinea, savanna and Sahel zones and Cocoa producing states in Nigeria (source: [1]).

high-end future greenhouse gas scenario (RCP8.5). However, for the feedback experiment, sulphur dioxide (SO_2) was injected into the stratosphere simultaneously at four different locations, along longitude 180°E and latitudes 15°S, 15°N at 25 km and 30°S and 30°N at 22.8 km over a grid point and between 5 and 7 km above the tropopause to keep near-surface global temperature at the 2020 value under the RCP8.5 emissions scenario [19, 31]. The control experiment has two datasets: the baseline (2010–2030) and the RCP8.5 simulation dataset (2010–2097), whilst the feedback experiment period is from 2010 to 2097. The control experiment baseline datasets and feedback datasets have 20 ensemble members with simulation over the period 2010–2030 and three members extended to the end of century, 2010–2097. Hence, for consistency, we used simulations from the three ensemble members that extend to the end of century.

We analysed 20-year periods in each simulation dataset. Firstly, for the control baseline simulation dataset (hereafter Hist), we used 2011–2030 period to understand the spatial distribution and characteristics of Cocoa suitability distribution during the present-day climate. This period was chosen based on the previous findings by Tilmes et al. [31] and Simpson et al. [24] which defined this timeframe as a target for SAI to keep the surface temperature at 2020 levels under RCP8.5 scenario until the end of century. The control RCP8.5 simulation (hereafter, GHG) dataset was used to evaluate the spatial characteristics of Cocoa suitability under RCP8.5 scenario for the period 2070–2089, whilst the feedback simulation dataset (hereafter, SAI) was used to understand the spatial characteristics of Cocoa suitability over West Africa under RCP8.5 scenario with SAI interventions for the period 2070–2089. We also evaluate the global model capability to represent the current period by comparing the control baseline simulation to CRU-WFDEI suitability output. We quantify the impact of climate change on Cocoa suitability under RCP8.5 scenario by GHG minus HIST. Meanwhile the SAI minus HIST shows the impact of RCP8.5 and SAI on future crop suitability over West Africa and SAI minus GHG shows the SAI intervention of future suitability of Cocoa in the regions. As with previous studies e.g., [22, 23, 33], we used monthly datasets of mean and minimum monthly temperatures and total monthly rainfall.

2.3 Methods

2.3.1 Bias correction

All the GLENS datasets were bias corrected using the Climate Research Unit (CRU) observation-based reference dataset at a horizontal resolution of 0.5^{o} for the period 1980–2009 [34]. A standard quantile-quantile bias-correction approach was employed to correct the two climate variables, temperature (minimum and mean) and rainfall required for our study period 2011–2030 for the historical/baseline period and 2070–2089 for RCP8.5 and SAI simulations [35]. The resultant bias corrected variables were used as input into Ecocrop model for our crop suitability experiments over Nigeria. This step is highly important because climate model simulation often deviates from the observed climatological data. Hence, the need for bias correction before the data is used for climate change impact assessments, such as hydrological modelling and agricultural impact studies [36].

2.3.2 Crop suitability modelling using Ecocrop

The impact of SAI on Cocoa suitability in Nigeria was investigated using the Ecocrop suitability model. Crop suitability was calculated as described in

Ramirez-Villegas et al. [37] based on the crop growth suitability threshold from Food and Agriculture Organisation, FAO-Ecocrop database (**Table 1**) [37, 38]. The model evaluates the relative suitability of crops in response to a range of climates including rainfall, temperature, and the growing season for optimal crop growth and operates at a monthly scale with the capacity to analyse crop suitability across different geographical location [37, 39, 40]. Ecocrop works based on the environmental ranges of a crop coupled with numerical assessment of the environmental condition to determine the potential suitable climatic condition for a crop. The suitability rating can be linked to the agricultural yield which is partly dependent on the strength of the climate signal [37, 41]. We used Ecocrop to produce a monthly suitability index for Cocoa and demonstrate the impact of SAI on its suitability in Nigeria. Crop suitability thresholds are based on a FAO-hosted dataset which acts as a baseline from which to quantify departures in each scenario, under future climate simulation with natural forcing (GHG) and SAI at RCP8.5 using the GLENS ensemble simulation datasets.

2.3.3 Sensitivity to climatic variables, rainfall and temperature

We also independently test the influence of fluctuations and trends in rainfall and temperature on Cocoa suitability. For example, to test the influence of rainfall, we use total monthly rainfall values over the study period for both the historical (2011–2030) and future periods (2070–2089) but keep temperature constant. The constant temperature is from the long-term mean monthly temperature so that the monthly temperature (both minimum and mean temperatures) for January to December each year over the study period with or without SAI is the same. This experiment is called “rain-vary”. To test the influence of temperature, a similar approach was used, with the exception that total monthly precipitation values were held constant over the study period, whilst monthly temperatures, both minimum and average, varied from year to year. This experiment is called “temp-vary”. When all the three variables (rainfall, mean and minimum temperature) vary simultaneously, the experiment is called “all-vary”.

2.3.4 Statistical analysis

The robustness of the projected impact of GHG and SAI on Cocoa suitability and planting season crops over Nigeria was assessed based on the condition that all three simulations agree on the sign of change. Previous studies [23, 39, 40, 42–45] have all used the methods to test and indicate the robustness of climate change signals. We also examined the fractional percentage of suitability for the three experiments over Nigeria by aggregating the different suitability index value at each grid point for the study period.

Crop name	**Growing period (Days)**	**Climate variables**							
		Temperature				**Rainfall**			
Cacao	180–365	Tmin	Topmin	Topmax	Tmax	Rmin	Ropmin	Ropmax	Rmax
		10	21	32	38	900	1200	3000	7600

Table 1.
Cacao growth threshold as generated by the FAO-Ecocrop model.

3. Results and discussion

3.1 Impact of global warming and SAI on mean climate variables in Nigeria

Figure 2 shows the spatial distribution of the total monthly rainfall and temperature variables, minimum and mean temperatures over Nigeria. For example, CESM1 model shows rainfall gradient from south to north in rainfall distribution, as rainfall amount decreases as you move northward over Nigeria. Our simulation shows that the south coast in the Guinea zone of Nigeria receives the highest total monthly rainfall amount, 240 mm/year, whilst the lowest total monthly rainfall amount, 80 mm/year, is to the north. For temperature, our result shows the spatial distribution of both mean and minimum temperatures over Nigeria with about 20°C and 25°C, respectively. The impact of climate change, GHG (RCP8.5) relative to baseline period (2011–2030) varies for both rainfall and temperature in Nigeria (**Figure 2**, column 2). Whilst GHG shows a similar pattern of projected increase in mean and minimum temperature over Nigeria, there is a variation in the projected change in rainfall over the region. For example, an increase of 1°C minimum temperature is expected over the country except in Abuja, the north-central part, where a decrease of temperature of 1°C is projected. In contrast, a projected increase up to 2–3°C warming in mean temperature is expected over the country due to GHG. The projected increase in mean temperature is expected to be about 3°C around the south-east and northern Sahel, whilst a 2°C is expected in other parts of the country. For rainfall, with reference to the historical period, a projected increase in total monthly rainfall up to 25 mm (about 1.25 mm/month) by the end of century relative to the historical over the south-western part of Nigeria and up to 10 mm (0.5 mm/month) and 5 mm (0.25 mm/month) in the north-east and north-west Sahel zone of the country, were observed, respectively. On the other hand, GHG may lead to decrease in 10–15 mm in the south-east and central part of the country. These findings are in line with Pinto et al. [22] and Abiodun et al. [23].

The deployment of SAI shows a reverse pattern in total monthly rainfall and temperature variables in comparison to the baseline period and impact of RCP8.5 GHG over Nigeria (**Figure 2**, column 4). For example, the impact of SAI technique relative to historical period may lead to a decrease of about 1–2°C over Nigeria as it induces a cooling due to reduction in mean and minimum temperature. This implies that the deployment of SAI showed a reduction in climate warming over Nigeria and in total monthly rainfall up to about 5–25 mm relative to baseline period (2011–2030) across the country except the south-west zone of the country with higher magnitude up to 35 mm. Furthermore, we examined the impact of SAI deployment on rainfall and temperature relative to GHG. Our findings show that SAI deployment will lead to a decrease in mean and minimum temperature variables up to 3°C from the impact of GHG thus inducing further cooling over the country [46]. In addition, the projected impact of SAI deployment in comparison to GHG-induced impact shows a reduction in the magnitude of decrease in total monthly rainfall in the south-east zone of the country whilst it induces further drying in the south-west and north-east region of Nigeria.

3.2 Evaluation Cocoa suitability in the historical period

Cocoa suitability varies over Nigeria for the historical period (**Figure 3**, column 1). In general, there is a decreasing suitability gradient from south to north of Cocoa over Nigeria. As a result, Cocoa suitability decreases northward and notably unsuitable in the northern part of Nigeria although with variation in spatial extent.

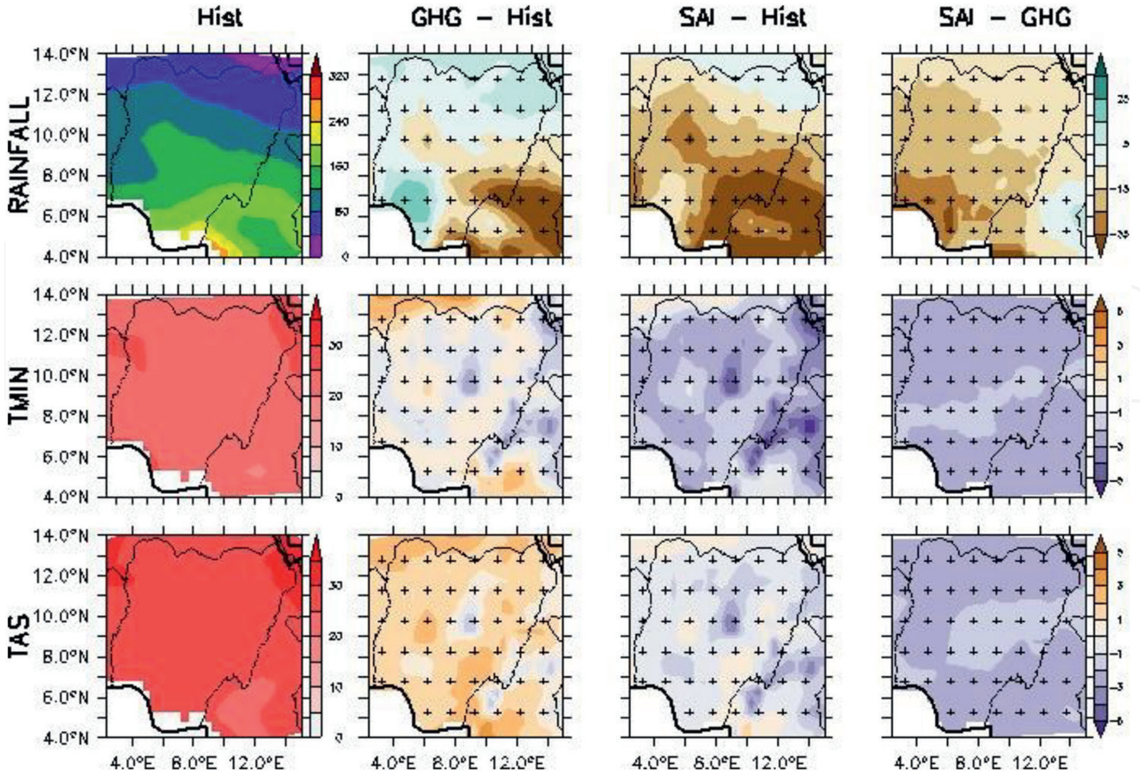

Figure 2.
The spatial distribution of climate variables (total monthly precipitation, mean and minimum monthly temperature) in the present-day climate over southern Africa (first column; 1980–2009) and their projected future changes in the period (2065–2090) under the RCP8.5 scenario without and with SAI (i.e., second and third columns, respectively). The extent to which the SAI influences the impacts of global warming on the variables is presented in the fourth column. The cross sign (+) indicates where at least 75% of the simulations agree on the sign of the changes.

Ecocrop spatial suitability characteristics simulation depicts that a large area to the north of 10°N is unsuitable with Suitability Index Value (SIV) below 0.20 (0–0.20) for Cocoa in Nigeria, notably in Sahel zone in the northern part of Nigeria. However, our result shows that higher suitability (SIV ≥ 0.5) of Cocoa is observed to the south of 10 N, notably in the Guinea agroecological zone. In general, the observed data, CRU-WFDEI shows a good agreement with CESM1-WACCM dataset in the spatial suitability distribution of Cocoa over Nigeria (**Figure 3**). The model captures well main Cocoa producing areas in Nigeria, notably the south-west zone (with SIV above

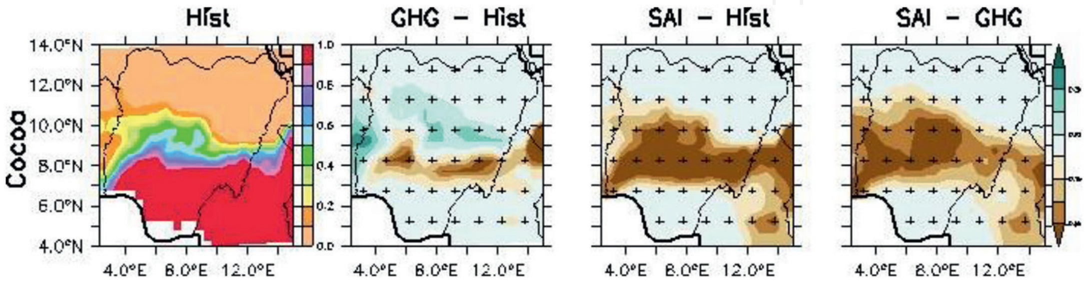

Figure 3.
The spatial distribution of Cocoa suitability for the historical period over Nigeria (first column; 2011–2030) and their projected future changes in the period (2070–2089) under the RCP8.5 scenario without and with SAI (i.e., second and third columns, respectively). The impact of SAI-induced effect on global warming on Cocoa suitability is presented in the fourth column. The cross sign (+) indicates where all ensemble members agree on the sign of projected changes.

0.6) which contributes about 80% of its production. The output shows that there is a strong spatial correlation (r = 1) between CRU-WFDEI and CESM1-WACCM data for Cocoa. Our findings are consistent with the results of Afolayan [1] on the spatial suitability distribution of Cocoa over Nigeria.

3.3 Projected changes in Cocoa suitability in Nigeria

The impact of climate change (GHG) and SAI on Cocoa suitability shows a similar spatial pattern but with varied magnitude across the agroecological zones of Nigeria (**Figure 3**, column 2). GHG as projected may lead to an increase (up to 0.20) in suitability index of Cocoa along the south-west boundary of Oyo and Ogun state and about 0.1 along eastern savanna in Nigeria. On other hand, the projected impact of GHG over Nigeria may lead to a decrease (about 0.2) in Cocoa suitability in the Guinea-savanna zone (lat. 7–9°N). However, no change in Cocoa suitability is expected in the south coast of Nigeria in the Guinea zone, which means the area remains suitable for Cocoa as observed in the historical period. Similar characteristic is also observed in the northern Sahel zone north of 12°N, as the area remains unsuitable as observed in the historical period. These findings are consistent with previous studies e.g., [12, 14, 47] that reduction in rainfall and increases in temperature will affect the suitability and cultivation of Cocoa in Nigeria. Our result also agrees with Schroth et al. [30] that Guinea-savanna zone will be the most affected Cocoa cultivated area in Nigeria under GHG. Thus, reduction in suitable areas may lead to reduction in Cocoa yield and production over Nigeria [14, 48].

The impact of SAI on Cocoa suitability relative to the baseline period (2011–2030) shows a similar spatial suitability pattern as that of GHG but with a variation in the Guinea-savanna zone (**Figure 4**, column 4). With SAI, no change in Cocoa suitability is detected in the Guinea and Sahel zone of Nigeria, suggesting SAI preserves the spatial distribution of current Cocoa cultivation suitability in the future here. On the other hand, a decrease (up to 0.3) in Cocoa suitability is expected over Guinea-savanna zone of Nigeria with SAI, and the magnitude of the projected decrease in Cocoa suitability is expected to be higher with SAI deployment in comparison to GHG-induced impact. In addition, SAI intervention is projected to result in decrease in suitability index value (about 0.35) of Cocoa in most parts of Nigeria. No projected change is expected in southern and north-eastern part of the country, this signifies that the southern zone remains a key region for the cultivation of Cocoa with SAI deployment over the country. However, the north-east in the Sahel zone remains unsuitable for growing Cocoa as observed in the historical period. The general projected decrease in the suitability under SAI may be linked to the projected reduction in rainfall over Nigeria.

3.4 Impact of global warming and SAI on planting season in Nigeria

Our study also examines the best planting months (PM) within the Growing Season (GS) over Nigeria (**Figure 4**). The simulated planting month represents the best month of the planting window and varies across the three Agroecological zones of Nigeria. For the historical climate, Ecocrop simulation shows a variation in the planting windows for Cocoa over Nigeria (**Figure 4**, column 1). Ecocrop shows January as the best PM for Cocoa in Guinea zone south of 7°N and north of 12°N in the Sahel zone, both areas are notable for their suitability in the south and unsuitability in the north, respectively, for the cultivation of Cocoa in Nigeria. Also, March–May

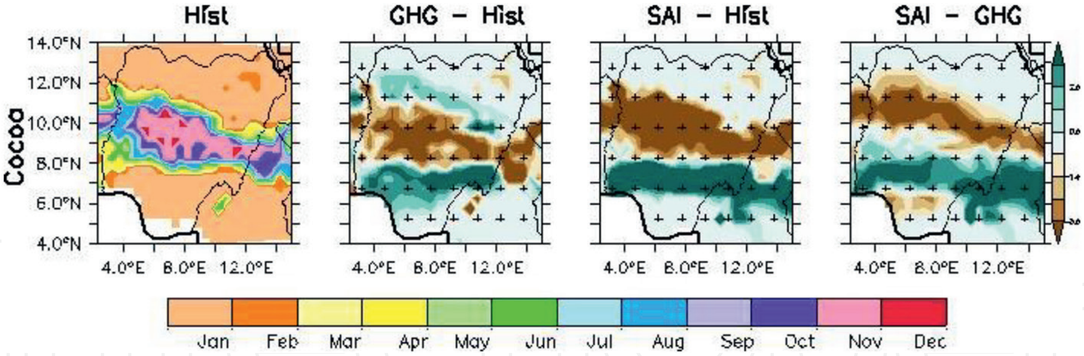

Figure 4.
The spatial distribution of planting season of Cocoa for the historical period over Nigeria (first column; 2011–2030) and their projected future changes in the period (2070–2089) under the RCP8.5 scenario without and with SAI (i.e., second and third columns, respectively). The impact of SAI-induced effect on global warming on Cocoa's planting season is presented in the fourth column. The cross sign (+) indicates where all ensemble members agree on the sign of projected changes.

is the best planting month over the south-west Guinea-savanna zones (lat. 7–10°N), notably in the major producing areas in the southern part of Nigeria. In addition, the months of October–November were observed as the most suitable period in the central extending to south-east savanna zones of the area. The simulated planting months are consistent with the past findings of Afolayan [1] that the months of March–May are the best planting months for Cocoa in Nigeria, notably in the southern part of Nigeria.

The impact of GHG and SAI on Cocoa planting season relative to the historical period shows similar spatial patterns across the different agroecological zones of Nigeria but with variation in magnitude (**Figure 5**, column 2). The impact of GHG may lead to a delayed planting season in the Guinea zone and an area in the Sahel zone of Nigeria although at different magnitude. For example, Cocoa planting season may be delayed by 2 months in south coast of Nigeria in the Guinea zone (south of 7°N) and south-east savanna around lat. 10°N whilst a month delay may be expected from the north-west Sahel zone extending to the central (about 11°N) savanna zone. Hence, GHG warming indicates a shift in Cocoa planting months to March over the Guinea zone and south-east savanna zone and February in the north-west Sahel zone and south-east savanna zone in comparison to the historical period. In contrast, a projected early planting may be expected over the Guinea-savanna zones (7–11°N) for Cocoa in Nigeria except along the south-west boundary between Ogun and Oyo state with one mouth delay. The projected early planting imply that June-July may be the best planting season in the Guinea-savanna zones and March along south-west boundary between Ogun and Oyo state of Nigeria. However, no change in planting season is expected in the north-east Sahel zone of Nigeria, hence, January remains the best planting month over the area. The impact of SAI on the plantings shows similar spatial pattern or characteristics as that of GHG effect relative to the historical period but at a higher magnitude. The projected delay and early planting in the Guinea-savanna and savanna-Sahel zones, respectively, may be up to 3 months under SAI relative to the historical period.

The impacts of SAI intervention (i.e., SAI-GHG) on planting season show a similar spatial characteristic as its impact relative to the historical period but with variation in magnitude (**Figure 5**, column 4). An early planting up to 3 months may be expected in the north savanna zone extending into the Sahel zone except in the north-east of Nigeria whilst a month early planting is expected in the south-coast of the country. On the other hand, the intervention may lead to a one-month delay in the planting of Cocoa and up to 3 months in the Guinea zone.

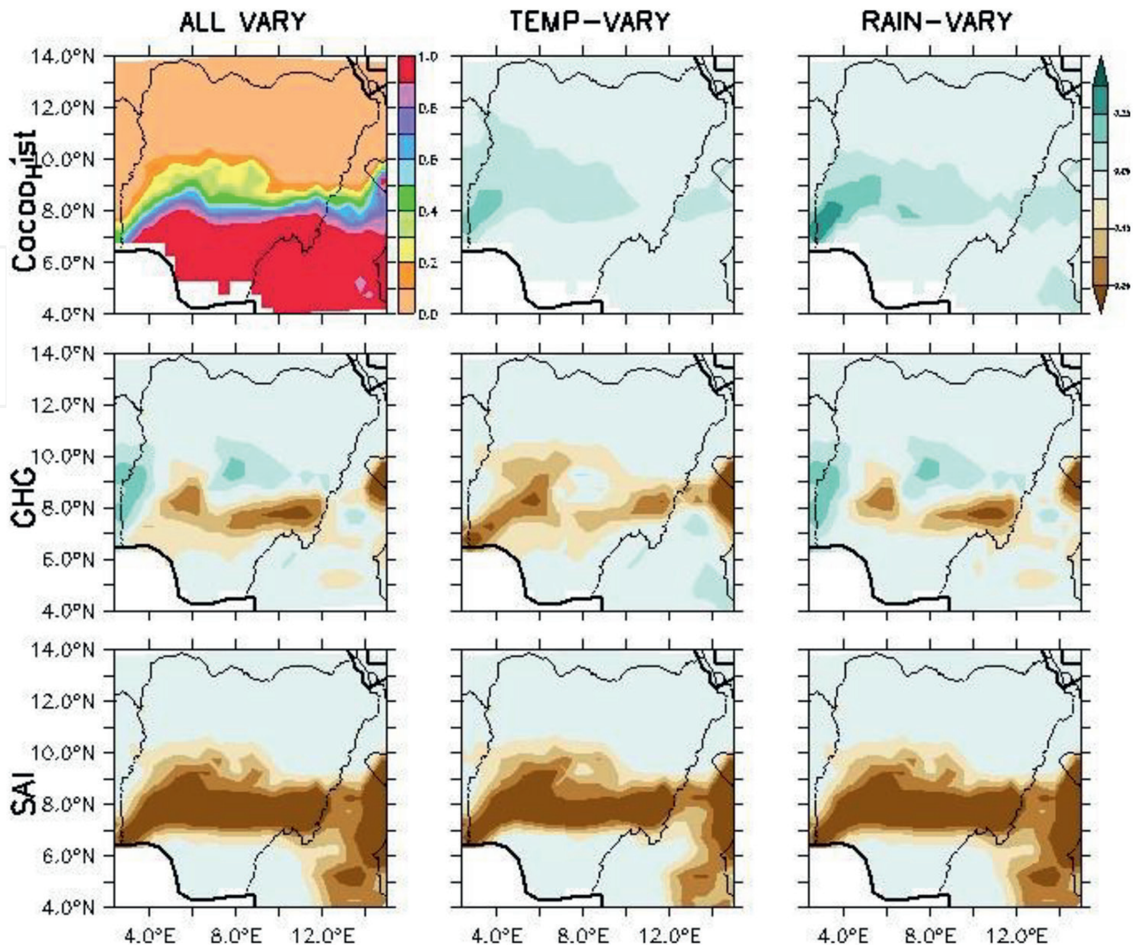

Figure 5.
The spatial distribution of Cocoas maize sensitivity to rainfall and temperature for the historical period over southern Africa (first panel, first row; 2011–2030) and relative changes over the historical period (first row, panel 2 & 3) and their projected future changes in the period (2070–2089) under the RCP8.5 scenario without (GHG) and with SAI (i.e., second and third rows, respectively). All-vary means both total monthly rainfall and monthly minimum and mean temperature varies, RAIN, monthly variation of minimum and mean temperature with annual mean total monthly rainfall (i.e., the same 12 monthly rainfall values are constant for the 30-year period) and TEMP; varying total monthly rainfall with constant annual minimum and mean temperature (i.e., the same 12 monthly minimum and mean temperature values are used for the 30-year period).

3.5 Sensitivity of Cocoa suitability to climate variables (rainfall and temperature)

We also examine the sensitivity of Cocoa suitability to temperature and rainfall to test independently the influence of their variation and trend for the three time periods, historical, GHG and SAI. In general, Cocoa suitability shows a decreasing suitability gradient from south to north over reference period for the all-vary experiment (see further description in Section 3.1) (**Figure 5**). The effect of rainfall variability at constant mean and minimum temperature (rain-vary) relative to the reference period (5a) shows no change in Cocoa suitability along the south coast, whilst southern savanna extending into the Sahel zone (5b-5i) will remain unsuitable. Similar suitability characteristics are also expected with variability in minimum and mean temperature at constant rainfall (temp-vary) over these zones. However, over the Guinea-savanna zones (7–10°N), about 0.15 suitability increase is expected and up to 0.25 along south-west boundary of Oyo and Ogun state.

The sensitivity of Cocoa suitability to rainfall and temperature variability shows a similar response under the GHG and SAI across the three experiments (all-vary, rain-vary and temp-vary) but with varied impact in the Guinea-savanna zones. Our results show the impact of GHG and deployment of SAI on all three experiments will lead to no change Cocoa suitability over south coast and northern Sahel zone of Nigeria. However, in the Guinea-savanna zone, the impact of the scenario across the three experiments varies for both GHG and SAI. The impact of GHG on all-vary and rain-vary experiments may lead to a SIV increase (0.15) in south-west boundary from Oyo to Ogun state and central savanna zone relative to the historical period. However, projected SIV decrease (up to 0.35) may be expected over the country except along south-west boundary from Oyo to Ogun state and central savanna zones. Also, SIV decrease (up to 0.35) is expected in the Guinea-savanna zones under temp-vary experiments. In contrast, the impact of SAI deployment on all three climate sensitivity over Nigeria is expected to lead to a decrease up to 0.35 in Cocoa suitability in the Guinea-savanna zones (6–10°N), whilst no change in suitability is expected in south coast (4–6°N) and northern Sahel zones (10–12°N) over Nigeria. This means that the deployment of SAI may lead to reduced area in the cultivation of Cocoa in Nigeria, as the south coast may be the only suitable for growing the crop.

In summary, we find that Cocoa suitability is sensitive to variability in both temperature and rainfall under SAI but more sensitive to rainfall variability with constant temperature under GHG. This agrees with past findings, by Challinor et al. [49] and Ramirez-Villegas et al. [37], that variability in rainfall affects the suitability of crops in Sub-Saharan Africa.

3.6 Percentage distribution of Cocoa suitability

We further examine the percentage distribution of different suitability condition to evaluate the impact of GHG and SAI on Cocoa at each grid point over Nigeria (**Figure 6**). The bar plot shows the percentage distribution of Cocoa suitability at each grid point over Nigeria for the historical period and the resultant impacts of GHG and SAI. Our result showed that about 42% of the land area in Nigeria is unsuitable for Cocoa cultivation and about 50% area is suitable (both suitable and highly suitable) over the historical period, whilst about 8% of the area is marginally suitable.

The impact of GHG and SAI on the percentage suitability distribution of Cocoa in Nigeria shows a similar pattern as the historical period albeit with varied magnitude. For example, global warming is projected to result in a decrease in suitable area for Cocoa cultivation in Nigeria relative to the historical period of about 18% and an increase (about 13%) in unsuitable area. This suggests that more areas will become unsuitable for growing Cocoa in Nigeria, as marginally suitable areas for Cocoa cultivation are projected to increase by about 2% across the country.

In addition, the impact of SAI shows a similar pattern in the percentage distribution of Cocoa suitability across grid points relative to the historical and GHG over Nigeria. SAI intervention may lead to a projected decrease of about 24% in suitable areas for Cocoa cultivation relative to the historical period and 18% decrease in comparison to the impact of GHG. In addition, the intervention may also lead to a further increase of about 14% and 24% in unsuitable areas for Cocoa relative to GHG and historical period, respectively, whilst no significant change was observed in areas with very marginal and marginal suitability for Cocoa in Nigeria.

The above result shows that GHG warming is projected to reduce the percentage of land suitable for Cocoa cultivation across Nigeria and SAI intervention would worsen this. Under both GHG and SAI scenarios, within in the GLENS modelling framework, there would be a resultant decrease in Cocoa production and yield in Nigeria [20].

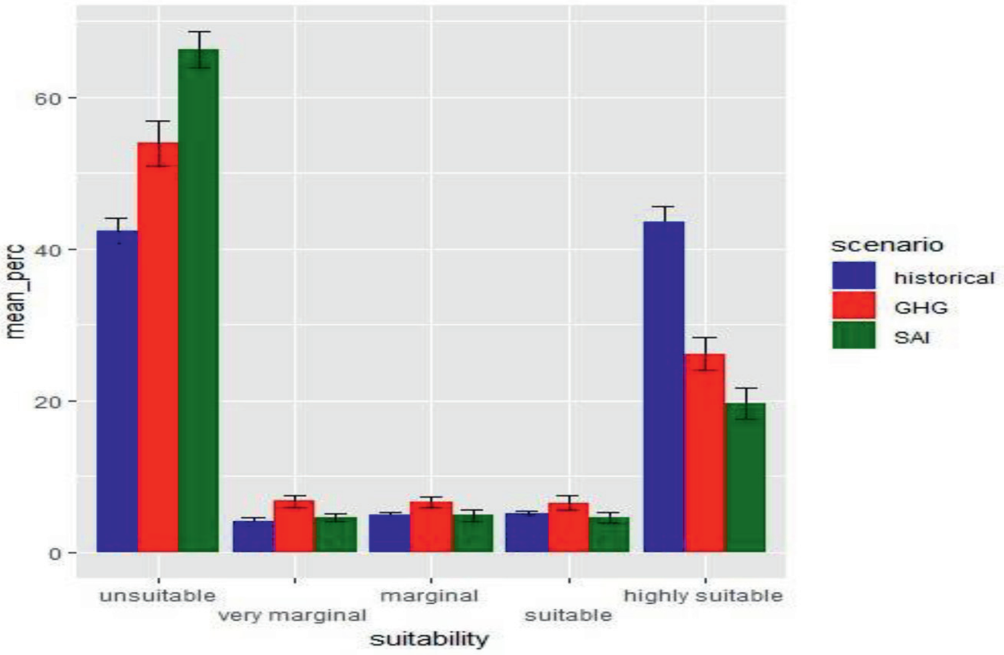

Figure 6.
A bar chart of percentage grid point distribution of Cocoa suitability over Nigeria for the historical period (2011–2030) and under the impact of GHG and SAI for the period (2070–2089).

3.7 Implication of SAI on Cocoa production and Nigerian economy

The availability of suitable land for cultivation is vital for crop growth and yield. The impact of SAI on Cocoa suitability and planting season is expected to have significant implication on socio-economy and GDP in Nigeria. The projected increase in unsuitable area in cultivating Cocoa and the corresponding decrease in suitable areas despite SAI intervention relative to the GHG impact over the country raises a concern considering the importance for Cocoa production to the economy of Nigeria. Cocoa is the major cash crops in Nigeria and most important agricultural export which can be processed into various products (e.g., Cocoa powder, Chocolates) for human consumption with a significant contribution to the socio-economy and GDP of the country via foreign exchange earnings [30]. SAI intervention on Cocoa suitability compared to the impact of climate change may further worsen the challenge of food and agricultural production in the region. This is because although SAI intervention reduces warming over Nigeria, its impact on Cocoa suitability relative to GHG will lead to a decrease in suitable areas for the Cocoa cultivation and may further lead to an increase in unsuitable areas relative to GHG as seen from our findings (**Figure 5**). The reduction of suitable land for Cocoa production and resultant decrease in production would lead to a decrease in Cocoa exports and its contribution to the GDP of the country [20, 30].

4. Conclusions

The present study examined the impact of SAI on Coca suitability and planting season over in Nigeria using the GLENS CESM1(WACCM) experiment. We used GLENS experiment, which is aimed at reducing the mean global surface temperature by injecting sulphur at four latitudes as a climate intervention measure to reduce the impact of greenhouse gases on Cocoa production in Nigeria. To examine the impact of

SAI intervention, we compared the GLENS output to historical and high-end emission scenario, RCP8.5 (GHG). We also examined the sensitivity of the crops to rainfall and temperature under GHG and SAI. The summary of our findings is listed below:

- Total monthly rainfall distribution decreases northward, with the least rainfall amount (80 mm) and the highest (240 mm) in the south coast in the Guinea zone over the historical period.

- The impact of GHG may lead to a 15 mm increase in total monthly rainfall by the end of century in south-west and north-east area of Nigeria with a decrease of the same magnitude in the other areas, whilst SAI intervention shows a reverse, leading to a decrease about 10 mm in total monthly rainfall and up to 20 mm in south-west Nigeria.

- GHG impact may lead to increase in both minimum and mean temperatures up to 3°C, whilst the SAI intervention will offset the warming resulting in a cooling over Nigeria.

- The impact of GHG may lead to an increase up to 0.2 in Cocoa suitability index value along the south west boundary of Ogun and Oyo with a decrease in the Guinea-savanna zones of Nigeria, whilst no change is expected in south coast (south of 6°N) and Sahel zone (north of 10°N).

- SAI intervention may lead to general decrease in suitable areas, whilst it results in a significant increase in unsuitable lands for Cocoa production in Nigeria.

- Percentage suitability distribution under GHG and SAI may result in a general decrease of 24% and 18%, respectively, in suitable available land with a corresponding increase about 14% and 24%, respectively, in unsuitable areas of Cocoa relative to the historical period over Nigeria.

- Cocoa is more sensitive to rainfall variability with a higher magnitude in the suitability index values and decrease in spatial extent over the region.

To our knowledge, this is the first study that examines the effect of SAI on Cocoa suitability in Sub-Saharan Africa. Hence, there are caveats to the interpretation of the result presented in this study. First, Ecocrop is a simple statistical model that evaluates crop suitability using total monthly rainfall and minimum and mean temperature climate variables. The model does not consider the effect of other factors, such as evapotranspiration and soil moisture, or non-climatic factors like pest and diseases and soil type which may further affect crop suitability. Also, the result is particular to solar geoengineering dataset, the GLENS experiment which used high-end representative scenario (RCP8.5) of climate geoengineering.

Nevertheless, the result from the study has helped improve our understanding of the potential impact of GHG and SAI on Cocoa suitability in Nigeria, the fourth largest producer of Cocoa in the world. Despite the caveats, one of advantage of using Ecocrop is that it is a simple and straight forward crop model to use with limited data requirement. Moreover, the observation and model representation of climate variables such as rainfall and temperature provide a basis for confidence in their outputs and the results are consistent with previous study on climate change and geoengineering impacts with complex models [20, 37]. Further studies on the impact of SAI on other crop types, such as legumes, root and tuber, other horticultural crops including vegetables are recommended in the quest to understand food security risk under both GHG emissions and SAI. These studies should use more than just the GLENS datasets and models should be used to provide robust information on the impact of SAI on Cocoa.

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