# Potential impact of climate change on drought-tolerant maize varieties and nitrogen fertilization in Nigeria savannas: a decision support tool (DST) analysis

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## Abstract

**Purpose** – Nitrogen fertilization is a crucial factor in sustainable agriculture practices because it enhances the resilience of maize crops to climate change. This study aims to quantify location-specific adaptation measures to climate change using drought-tolerant maize varieties and N fertilization in the savannas of Nigeria using the Agricultural Production Systems Simulator (APSIM) model.

**Design/methodology/approach** – The calibrated APSIM-maize module was validated using an independent dataset from field experiments conducted under different N fertilization levels within savanna agroecological zones (AEZs). The impacts of climate change were assessed under low and high emissions representative concentration pathways (RCPs), 4.5 and 8.5 W $m^2$ scenarios, for the near-term (2010–2039) and mid-century (2040–2069).



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**Findings** – The study found that the yields of early and medium maturing maize varieties decreased under climate change scenarios. For the early variety (2009EVDT), yields decline by 1–4% under RCP 4.5 and 3–8% under RCP 8.5 in the near term, and 2–12% under RCP 4.5 and 1–12% under RCP 8.5 mid-century. For the medium variety (IWDC2SYNF2), grain yield decreases were 1–5% under RCP 4.5 and 2–11% under RCP 8.5 near-term, and 1–8% under RCP 4.5 and 3–14% under RCP 8.5 mid-century. Applying N-fertilizer at 90–120 kg ha$^{-1}$ can minimize these effects across the three AEZs.

**Practical implications** – This study supports strategic nitrogen fertilization and drought-resistant maize varieties to maximize yields and ensure food security under climate change. The government and relevant agencies should strengthen policies to help farmers adopt adaptive strategies to cope with projected high temperatures and droughts, to enhance sustainability.

**Originality/value** – The originality of this paper stems from the contributions of the various authors: Conceptualization, A.B., A.Y.K. and J.M.J.; methodology, A.B., A.Y.K. and J.M.J.; validation, A.B., A.Y.K. and A.I.T.; formal analysis, A.B. and F.M.A.; field experimentation, A.B. and A.I.T.; resources, A.Y.K. and J.M.J.; data curation, A.B., A.I.T. and F.M.A.; writing original draft preparation, A.B., A.Y.K. and F.M.A.; writing review and editing, A.B., A.Y.K., J.M.J, A.I.T. and F.M.A.; supervision, A.Y.K., J.M.J. and F.M.A.; funding acquisition, A.Y.K. and J.M.J. All authors have read and agreed to the published version of the manuscript.

**Keywords** Adaptation, APSIM model, Climate change, Maize, Nitrogen fertilization, Yield

**Paper type** Research paper

## 1. Introduction

Climate change poses a significant threat to agriculture in Nigerian Savannas, affecting crop production and food security (Abravi *et al.*, 2023). The region is increasingly challenged by longer dry spells, erratic rainfall, and extreme weather events (Akinseye *et al.*, 2020). Despite a substantial increase in maize cultivation from 0.9 million hectares in 1976 to over 5.8 million hectares in 2022, with a total production of 12 million tons of maize in 2022, representing 1% of global production (FAO, 2023), productivity remains constrained. The average maize yield in Nigeria ranges from 1.8–2 t ha$^{-1}$, which is significantly lower than the global average of 5.7 t ha$^{-1}$ (FAOSTAT, 2023). Climate change is expected to further reduce maize production, worsening food security in the country.

There are several current and projected reports on climate change in Nigeria in the form of increasing temperature, rainfall, or drought (Odjugo, 2010; WBG, 2020; Ogunrinde *et al.*, 2022). For example, Odjugo (2010) reported a 1.1°C rise in the historical average temperature between 1901 and 2005. Analysis from the German Climate Service Center, based on 32 Global Climate Models (GCMs), indicates that temperatures across Nigeria are projected to rise by 2.9°C to 5.7°C by the end of the century (CCKP, 2021). Temperature increases are anticipated to be less severe in southern Nigeria and to rise more rapidly in the central and northern regions (Nigeria, 2020). Rainfall trends in Nigeria have become increasingly unpredictable, with a significant decrease in the reliability of seasonal rains, however, by 2050, rainfall is expected to increase by 20–30 mm annually in some regions under the representative concentration pathway (RCP) 8.5 W m$^2$ scenario (WBG, 2020). Rain-fed crop production has become increasingly unpredictable owing to fluctuations in rainfall patterns, leading to greater risks for savanna farmers during the growing season (Kamara *et al.*, 2022).

Additionally, Tofa *et al.* (2021) projected higher yield losses for non-drought-tolerant maize varieties than for drought-tolerant varieties under climate change caused by increasing temperatures. The projected change indicates a negative yield impact of 13% to 43% by the end of the century in the savannah region of Nigeria. The optimum temperature for maize growth and development is generally 25°C (Liu *et al.*, 2008), which is applicable to varieties cultivated in warmer environments, including arid and semi-arid regions. Maize grows faster under warmer conditions, but yields decline significantly when temperatures exceed 35°C because of reduced photosynthesis and pollen viability (Waqas *et al.*, 2021; Crafts-Brander and Salvucci, 2002).

Much empirical evidence exists on the impact of climate change on maize production in Africa. For example, in the forest-savanna transition zone of Ghana, Tachie-Obeng *et al.* (2013) reported a projected average maize yield decline of 41% in the major season and 28.5% in the minor season. Abera *et al.* (2018) showed that maize yields could change by −24% to +51% due to the projected rainfall variability and rising temperatures in Ethiopia. Adaptation strategies are crucial for mitigating the negative impacts of climate change on agriculture (Markos *et al.*, 2023; Chisanga *et al.*, 2024), especially in regions such as the Nigerian Savannas, where maize is a staple crop. Suggested measures include improved crop management practices, such as nitrogen fertilizer application (Kassie *et al.*, 2015), the use of supplementary irrigation (Araya *et al.*, 2017), and the deployment of drought-tolerant varieties (Tesfaye *et al.*, 2018; Tofa *et al.*, 2021). For example, increasing nitrogen fertilization has been shown to reduce the negative impact of climate change on maize production in the Central Rift Valley of Ethiopia (Kassie *et al.*, 2015), whereas a study by Turner and Rao (2013) demonstrated that increasing the nitrogen fertilizer rate under a 3°C temperature rise improved sorghum yields by 1570% in Kenya. Markos *et al.* (2023) reported that optimizing nitrogen use, mulch, and their interaction with planting dates and tillage practices could mitigate the adverse effects of climate change and close yield gaps in Ethiopia.

Variety adaptation has been recognized as one of the most effective agricultural adaptation measures (Challinor *et al.*, 2014). Using an ensemble of seven global crop models and five CMIP6 climate models, Zabel *et al.* (2021) reported that 39% of global croplands may require new crop varieties to prevent yield loss under high warming scenarios (SSP5-8.5) by the end of the century. Shiferaw *et al.* (2014) showed that climate-resilient varieties provide a yield advantage of 5–25% in many maize-growing areas of Eastern and Southern Africa. Martre *et al.* (2024) used an ensemble of wheat simulation models to demonstrate that improving sink and source traits in wheat genotypes can increase yields by 16% with current nitrogen fertilizer levels, under both present and mid-century climate scenarios. Ferreira *et al.* (2023) suggested that adjusting sowing times and using maize cultivars with enhanced drought tolerance and extended post-anthesis phases could help mitigate the adverse effects of climate change on maize production in Limpopo Province, South Africa.

Drought-tolerant maize varieties, which are more nitrogen-efficient than non-drought-tolerant varieties, have been developed and deployed in Nigerian savannas (Kamara *et al.*, 2012), but their performance under future climate change scenarios remains unevaluated. The impact of rising $CO_2$ levels on crops and advancements in crop breeding is also recognized as crucial, but remains understudied. Elevated atmospheric $CO_2$ is known to enhance net photosynthesis rates, growth, and crop yields (Reddy *et al.*, 2010), as well as contributes to higher temperatures, which can accelerate crop life cycles and shorten growth periods for crops such as maize (Vanaja *et al.*, 2024; Abebe *et al.*, 2016). Additionally, prolonged exposure to high temperatures has been shown to increases photorespiration in plants (Yamori *et al.*, 2014).

Knowledge and technological advancements in agriculture can be transferred to farmers, policymakers, and planners through system-based experimentation. This can be achieved using decision support tools (DSTs), such as APSIM, which has been proven effective in explaining yield variations resulting from management practices, environmental factors, and genotypes under different climate conditions (Boote *et al.*, 2021). Our study aimed to quantify site-specific adaptation measures to climate change using drought-tolerant maize varieties and varying nitrogen fertilization rates in Nigerian savannas. However, quantification of the magnitude of climate change impacts on drought-tolerant maize varieties in Nigerian savannas, remains limited. However, such efforts may significantly contribute to increased productivity and adoption of heterogeneous production systems currently practiced in the region (Akinseye *et al.*, 2020).

## 2. Materials and methods

### *2.1 Study area*

This study was conducted at three sites representing distinct agroecological zones in Nigeria: Abuja (9°9′N, 7°20′E; 447 m above sea level [a.s.l.]}, Zaria (11°1′N, 7°37′E; 681 m a.s.l.), and Kano (11°59′N, 8°25′E; 466 m a.s.l.), as shown in Figure 1. Abuja represents the Southern Guinea Savanna (SGS), Zaria the Northern Guinea Savanna (NGS), and Kano the Sudan Savanna (SS). In the SGS zone, temperatures during the growing season range from 26 to 28°C (maximum) to 18–22°C (minimum). Rainfall is unimodal, varying from 1000 to 1524 mm, and is distributed over 181–210 days (Ayanlade, 2016). Predominant soils in this zone include lithosols, ferric cambisols, and luvisols (FAO, 2015).

In the NGS zone, the growing season temperatures range from 27 to 30°C (maximum) to 20–22°C (minimum). The average annual rainfall is 1125 mm, with a growing season lasting 151–180 d. The dominant soil types are luvisols, acrisols, and lithosols (FAO, 2015). The SS zone features a shorter growing season of approximately 90 days, with annual rainfall ranging between 600 and 800 mm (Adnan *et al.*, 2017). During the growing season, temperatures range from 33 to 38°C (maximum) to 22–26°C (minimum) (Kamara *et al.*, 2009). The

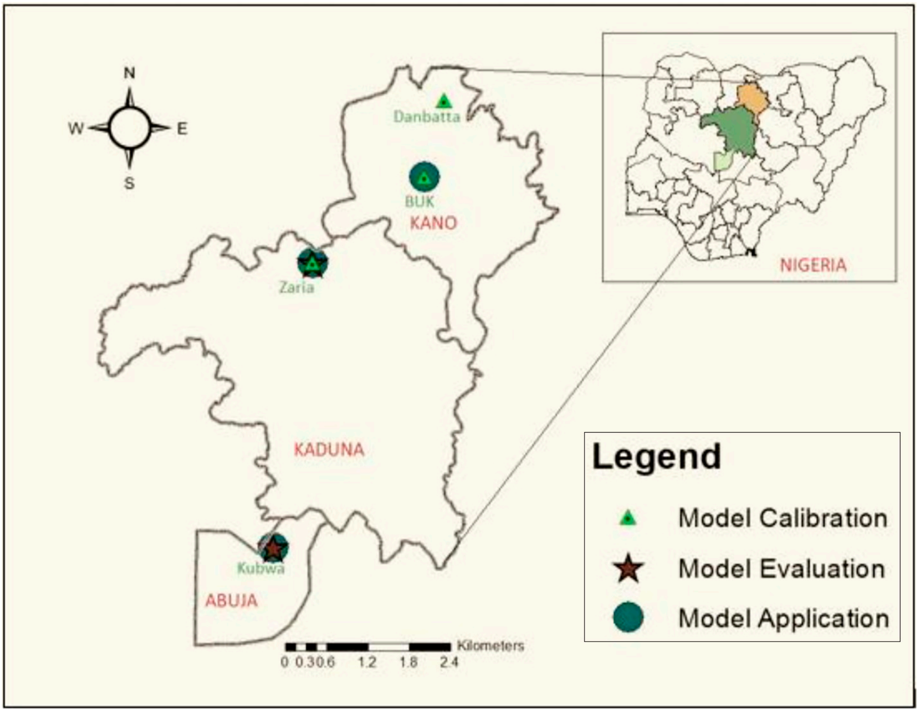


**Figure 1.** Map of the study area
**Source:** Authors' own creation

primary soils in this zone are alfisols, inceptisols, and vertisols (FAO, 2015). Soil profiles from the experimental sites in all three zones were collected and analyzed before planting, and detailed physical and chemical soil properties are presented in Table S1 of the Supplementary Material.

*2.2 Baseline and future climate datasets in the study areas*

A complete set of daily weather data from 1980 to 2009 was obtained from the globally bias-adjusted Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) data set (Rosenzweig *et al.*, 2013). This data set, developed under the Agricultural Model Inter-comparison and Improvement Project (AgMIP) protocols (AgMIP, 2013), was used to create baseline climate data (1980–2009) and project future climate scenarios for the Nigerian savannas. These projections included near-term (2010–2039) and mid-century (2040–2069) periods under two representative concentration pathways (RCPs): RCP4.5 and RCP8.5, using the delta-based method outlined by AgMIP (2013).

RCPs, officially recognized by the IPCC, represent scenarios for future greenhouse gas concentrations. The baseline climate assumed a $CO_2$ concentration of 360 ppm, while the near-term and mid-century projections under RCP4.5, and RCP8.5, assumed elevated $CO_2$ concentrations of 499 and 571 ppm, respectively. These scenarios provide insights into the potential impacts of medium (RCP4.5) and high (RCP8.5) greenhouse gas concentration pathways on the region's climate and agriculture.

Climate change projections were derived using four global climate models (GCMs): GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory Earth System Model, USA), HadGEM2-ES (UK Met Office Hadley Centre), MIROC5 (Model for Interdisciplinary Research on Climate, Japan), and MPI-ESM-MR (Max Planck Institute for Meteorology Earth System Model, Germany). These GCMs were selected for their established performance, high resolution, and extensive history of development and evaluation (Msongaleli *et al.*, 2014; Chawdhery *et al.*, 2022; Zhang *et al.*, 2024).

*2.3 Model validation with an independent dataset*

The present study used two maize varieties, 2009EVDT *and* IWDC2SYNF2, calibrated using the APSIM-maize module as reported by Beah *et al.* (2021). These calibrated varieties were further validated using an independent data set derived from field trials conducted under varying nitrogen (N) application rates under rain-fed conditions. The detailed crop management practices used for validation experiments are listed in Table 1. The observed agronomic parameters used in the model validation included total dry matter and grain yield. To evaluate the performance of the model in predicting these parameters, statistical measures such as the mean bias error (MBE), root mean square error (RMSE), normalized root mean square error (RMSEn), and coefficient of determination ($R^2$) were employed (Jones and Thornton, 2014). The model simulation performance was categorized based on RMSEn values: as excellent if RMSEn was less than 10%, good if it was between 10% and 20%, fair if it was between 20% and 30%, and poor if it was 30% or higher (Jamieson *et al.*, 1991). This framework ensured a rigorous assessment of the accuracy and reliability of the model for simulating the agronomic performance of maize varieties under rain-fed conditions.

*2.4 Crop simulation model*

The use of decision support tools, such as the APSIM and DSSAT models, has proven valuable in analyzing the impact of climate change on maize production (Gummadi *et al.*, 2020; Tofa *et al.*, 2021). APSIM operates on a daily time step, simulating biophysical processes based on weather conditions, soil properties, and management practices, to predict

**Table 1.** Crop management information for model validation experiment for maize

| Parameter | Details |
|---|---|
| Trial locations | Kubwa Station Abuja (9°9′N 7°20′E, 447 m a.s.l.) and Shika-Zaria (11°11′N 7°38′E, 686 m a.s.l.) |
| Growing seasons | 2016 and 2017 |
| Experimental design | Split-plot factorial arrangement |
| Main plot | Five levels of nitrogen (0–120 kg $ha^{-1}$ at 30 kg intervals) |
| Subplots | Maize varieties (2009 EVDT and IWDC2SYNF2) |
| Replications | Three replications |
| Subplot size | 15 $m^2$ (4 rows, 0.75 m apart, 5 m length, 0.25 m intra row spacing) |
| Plant density | 53,333 plants $ha^{-1}$ |
| Planting dates | 19 June 2016 and 17 June 2017 at Abuja and 25 June 2016 and 20 June 2017 at Zaria |
| Fertilizer application | SSP (Single Super phosphate) and MOP (Muriate of Potash) applied at 60 kg $ha^{-1}$ at one week after planting (1 WAP) and N (Urea), applied twice (1 WAP and 5 WAP) |
| Weed control (chemical) | Gramaxone and Primextra, each at 1 L $ha^{-1}$ at planting |
| Weed control (manual) | At 2 WAP and 7 WAP |

**Source(s):** Authors' own creation

crop yields under various scenarios (Chisanga *et al.*, 2020; Akinseye *et al.*, 2020). This agricultural system model integrates several modules including biophysical management, data input and output, and a simulation engine (Keating *et al.*, 2003).

The APSIM model assesses the impact of climate change on crop production by evaluating temperature stress, average canopy temperature, and daily heat exposure, while accounting for variables such as soil moisture and heat accumulation (Wimalasiri *et al.*, 2023). It uses daily weather data, including the maximum and minimum temperatures, precipitation, and solar radiation. The model employs two soil water balance methods: SoilWat ("cascading bucket") and APSWIM (Richard's equation) to simulate soil water dynamics (Keating *et al.*, 2003).

In this study, APSIM version 7.10 was utilized to simulate near-term and mid-century maize yields under varying nitrogen rates using four bias-corrected GCMs and two representative concentration pathways (RCPs). This approach provides insights into how different climate scenarios coupled with nitrogen management, could impact maize production in the coming decades.

### *2.5 The impact of nitrogen management in response to climate change*

The future yields of the two drought-tolerant maize varieties were simulated based on the established planting windows for each agroecological zone at representative sites (Beah *et al.*, 2021; Tofa *et al.*, 2021). Sowing was automatically initiated in each season when the top 15 cm of the soil reached more than 50% of its field capacity within the designated planting windows: May 31 to July 31 for Abuja, June 1 to July 31 for Zaria, and June 15 to July 31 for Kano. Future fertilizer applications included four nitrogen (N) levels (30, 60, 90, and 120 kg $ha^{-1}$), ranging from low to fully recommended fertilizer application. The varieties were sown at a planting distance of 75 x 25 cm for each of the four global climate models (GCMs) under both historical and future climate scenarios. Fertilizer application followed the current recommendations, with two splits applied at 7 and 35 days after emergence. The

APSIM model was used to simulate maize yields under future climate conditions using automatic sowing rules within specified planting windows and fertilizer rates.

The impact of climate change on maize yields was assessed by calculating the percentage of yield change from the baseline to future simulated yields, as described by Faye *et al.* (2018) in equation (1). The results were organized to present simulations from two RCPs, four GCMs, and two future periods (near-term and mid-century), all compared to a single baseline. This approach allowed for a comprehensive analysis of how different climate scenarios, planting dates, and fertilizer management strategies might impact maize production in the future:

$$\Delta Yield = \frac{Yield_{scenario} - Yield_{baseline}}{Yield_{baseline}} * 100 \ [\%] \quad (1)$$

where:

$\Delta$ Yield is the yield change due to climate change; $\text{Yield}_{Scenario}$ and $\text{Yield}_{baseline}$ are the yields obtained under scenario and baseline weather conditions, respectively.

## 3. Results

### *3.1 Model performance with an independent dataset*

Comparisons between the simulated and measured values for grain yield and total dry matter (TDM) for both maize varieties in response to different nitrogen rates are shown in Figures 2 and 3. The model evaluation for both maize varieties demonstrated good agreement between the simulated and observed grain yield values at the two representative sites. Statistically, the performance of grain yield and TDM indicated that the mean bias error (MBE) and root mean square error (RMSE) values were low, whereas the model accuracy (RMSEn) varied from high to low across both locations. For the 2009EVDT variety (Figures 2a and b, ), the model slightly underestimated the observed values for grain yield, with MBE ranging from −155 to −109 kg ha$^{-1}$, low RMSE values of 225 and 212 kg ha$^{-1}$, RMSEn of 7.3% and 6.7%, and $R^2$ values of 0.98 and 0.97 in Abuja and Zaria, respectively. The accuracy of the model in predicting TDM for 2009EVDT was generally good, as indicated by the low RMSE values of 733 and 711 kg ha$^{-1}$, RMSEn of 11% and 10%, and $R^2$ of 0.94, for both Abuja and Zaria, respectively (Figures 2c and d, ).

Similarly, the grain yield of IWDC2SYNF2 (Figures 3a and b, ) was well simulated with high model accuracy, indicated by MBE values of −66 and −119 kg ha$^{-1}$, RMSE values of 237 and 262 kg ha$^{-1}$, RMSEn values of 6% and 7%, and $R^2$ values of 0.98 and 0.97 for Abuja and Zaria, respectively. Better results were obtained for TDM, with low MBE values of −864 and −454 kg ha$^{-1}$, RMSE values of 981 and 992 kg ha$^{-1}$, RMSEn values of 11% and 12%, and $R^2$ values of 0.96 and 0.90 for Abuja and Zaria, respectively (Figures 3c and d, ). The grain yield and TDM predicted for both varieties under optimal conditions and at different N levels, with low RMSE values, suggest that the APSIM model effectively captured a significant portion of the variation in grain yield and TDM for each cultivar at both sites. This implies that the model can be used to optimize production under both high and low nitrogen input levels.

### *3.2 Future climate characteristics relative to baseline in the study areas*

Climate change projections for monthly rainfall and temperature (minimum and maximum) at the three selected sites are shown in Figure S1. There is considerable variability in the projections of annual mean temperatures and rainfall by individual GCMs for the future scenarios under both RCP4.5 and RCP8.5 (Tables S2 and S3 in the supplementary materials).

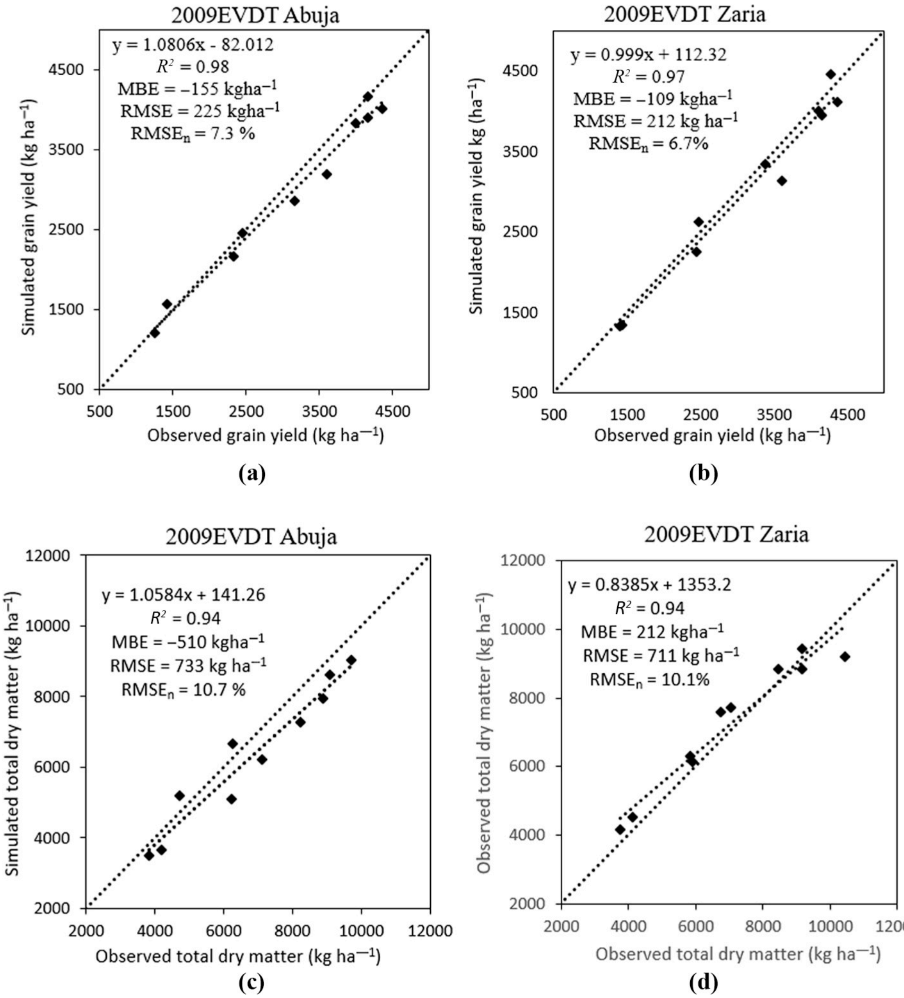


**Figure 2.** (a–d): Comparison of observed and simulated for grain yield and total dry matter (TDM) across N–fertilizer applications in two growing seasons (2016 and 2017) at Abuja and Zaria for 2009EVDT maize variety

**Source:** Figure courtesy of Beah *et al*. (2021)

Relative to the baseline temperature, the projected ensemble GCMs mean minimum temperatures for the near term are 0.9°C and 1.1°C in the SGS; 1.3°C and 1.6°C in the NGS; and 0.9°C and 1.2°C in the SS, each under RCP4.5 and RCP8.5, respectively. The corresponding changes in maximum temperatures are 0.9°C and 1.0°C in the SGS; 0.9°C and 1.1°C in the NGS; and 0.9°C and 1.0°C in the SS. In the mid-century, the ensemble mean changes in minimum temperatures are 1.7°C and 2.5°C in the SGS; 2.2°C and 3.0°C in the NGS; and 1.8°C and 2.6°C in the SS, under RCP4.5 and RCP8.5, respectively, relative to baseline condition. For maximum temperatures, the projected changes are 1.7°C and 2.3°C

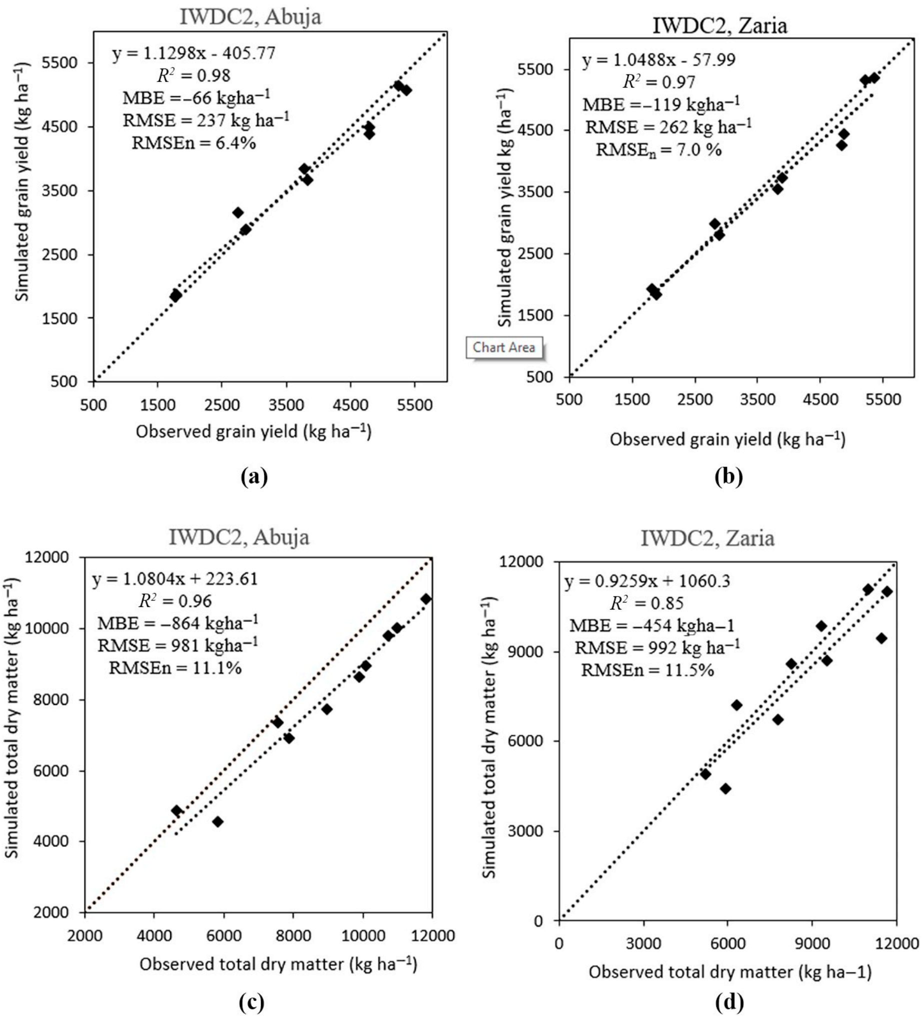


**Figure 3.** (a–d): Comparison of observed and simulated for grain yield and total dry matter (TDM) across N–fertilizer applications in two growing seasons (2016 and 2017) at Abuja and Zaria for IWDC2SYNF2 maize variety

**Source:** Figure courtesy of Beah *et al.* (2021)

in the SGS; 1.8°C and 2.3°C in the NGS; and 1.8°C and 2.4°C in the SS, under RCP4.5 and RCP8.5, respectively (Figure 4). As shown in Figure 4, the projected changes in both temperatures under RCP8.5 are higher than those under RCP4.5 for the respective periods.

The analysis of seasonal rainfall changes across three sites in Nigeria (Abuja, Zaria, and Kano) reveals that most Global Climate Models (GCMs) predict increasing rainfall relative to the baseline period under both RCP 4.5 and RCP 8.5 W m$^2$ scenarios (Tables S1 and S2). However, according to the ensemble GCM (mean outputs), seasonal rainfall was expected to

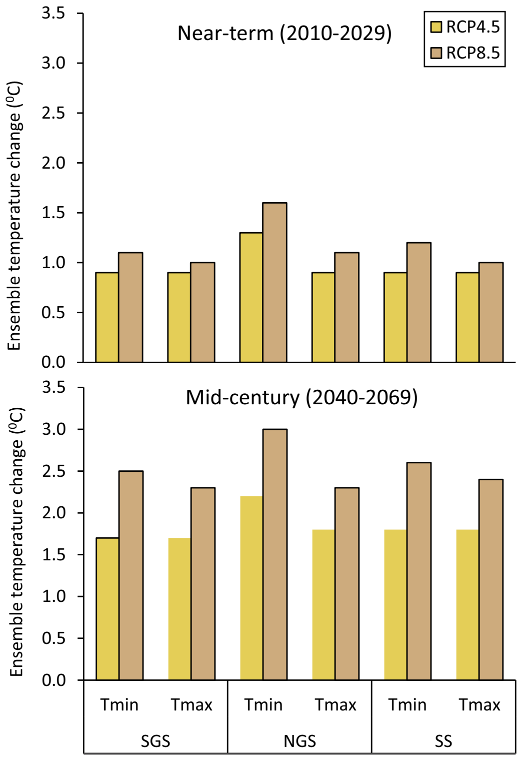


**Figure 4.** Change in minimum (tmin) and maximum (tmax) air temperature (°C) from the baseline period (1988–2018) for ensemble GCMs (GFDL-ESM2M, HadGEM2-ES, MICROC5, MPL-ESM-MR) under RCP4.5 and RCP8.5 for near term (2010–2029) and mid-century (2040–2069) periods at southern Guinea savanna (SGS), northern Guinea savanna (NGS) and Sudan Savanna (SS) of Nigeria
**Source:** Authors' own creation

increase in all study areas under all climate scenarios (Figure 5). In the near-term, the ensemble mean rainfall is expected to increase by 2.9% to 3.4% under RCP 4.5 and 1.4% to 3.1% under RCP 8.5, with the highest percentage increase projected for the NGS, followed by the SS and SGS. By the mid-century, increases in seasonal rainfall are projected to range from 1.8% to 5.1% under RCP 4.5, and 0.2% to 2.0% under RCP 8.5, with the greatest increases expected in the SGS for RCP 4.5, and the SS for RCP 8.5 (Figure 5).

### *3.3 Impact of climate change on maize yield under different N management*

The simulated mean grain yields for the baseline period and the average simulated yields under different climate scenarios and nitrogen rates are presented in Tables S4-S6. The projected changes in maize productivity under different climate change scenarios for RCP4.5 and RCP8.5, indicate a moderate decline in maize yield relative to baseline levels (Figure 6).

In Abuja, representing the Southern Guinea Savanna (SGS), the early maturing maize variety 2009EVDT is projected to experience grain yield reductions under RCP4.5. Specifically, in the near term, yield decreases are estimated at 3%, 2%, 2%, and 1% for

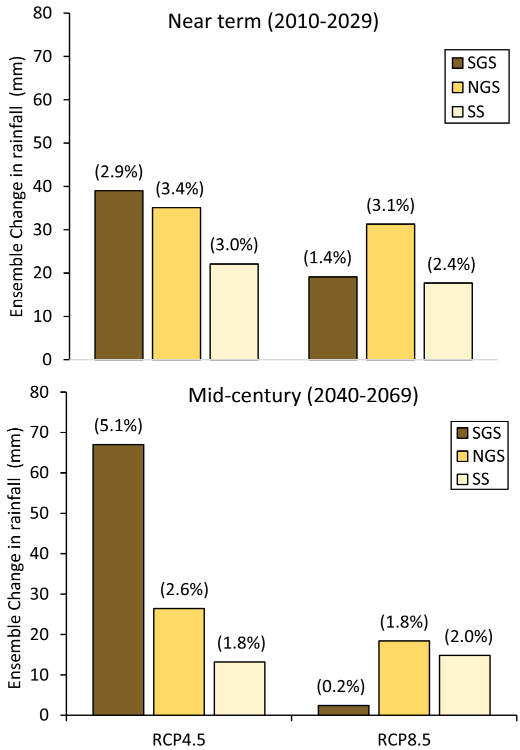


**Figure 5.** Changes in seasonal rainfall (mm) from the baseline period for ensemble GCMs (GFDL-ESM2M, HadGEM2-ES, MICROC5, MPI-ESM-MR), under RCP4.5 and RCP8.5 for near-term and mid-century periods in the Southern Guinea Savanna (SGS), Northern Guinea Savanna (NGS) and Sudan Savanna (SS) of Nigeria. Values in brackets indicate the percentage increase in average seasonal rainfall

**Source:** Authors' own creation

nitrogen fertilizer application rates of 30, 60, 90, and 120 kg N $ha^{-1}$, respectively. By the mid-century, these reductions increased to 5%, 4%, 3%, and 3%, respectively. For the intermediate-maturing variety IWDC2SYNF2, the simulated mean grain yield declined by 2%, 1%, 1%, and 1% in the near term, and by 3%, 2%, 1%, and 1% in the mid-century for the same fertilizer application rates [Figure 6(a)]. Under RCP8.5, yield reductions were more pronounced for both varieties. For 2009EVDT, applying nitrogen at 30, 60, 90, and 120 kg N $ha^{-1}$ results in simulated yield decreases of 7%, 5%, 4%, and 4% in the near term, and 8%, 7%, 6%, and 5% by mid-century, respectively. Similarly, for IWDC2SYNF2, the mean simulated grain yield decreased by 4%, 4%, 2%, and 2% in the near term and by 6%, 5%, 3%, and 3% in the mid-century for the corresponding nitrogen application rates [Figure 6(b)].

In Zaria, representing the Northern Guinea Savanna (NGS), the early maturing maize variety 2009EVDT is projected to experience grain yield reductions under RCP4.5. In the near term, the yield decline was estimated at 3%, 3%, 1%, and 1% for nitrogen fertilizer

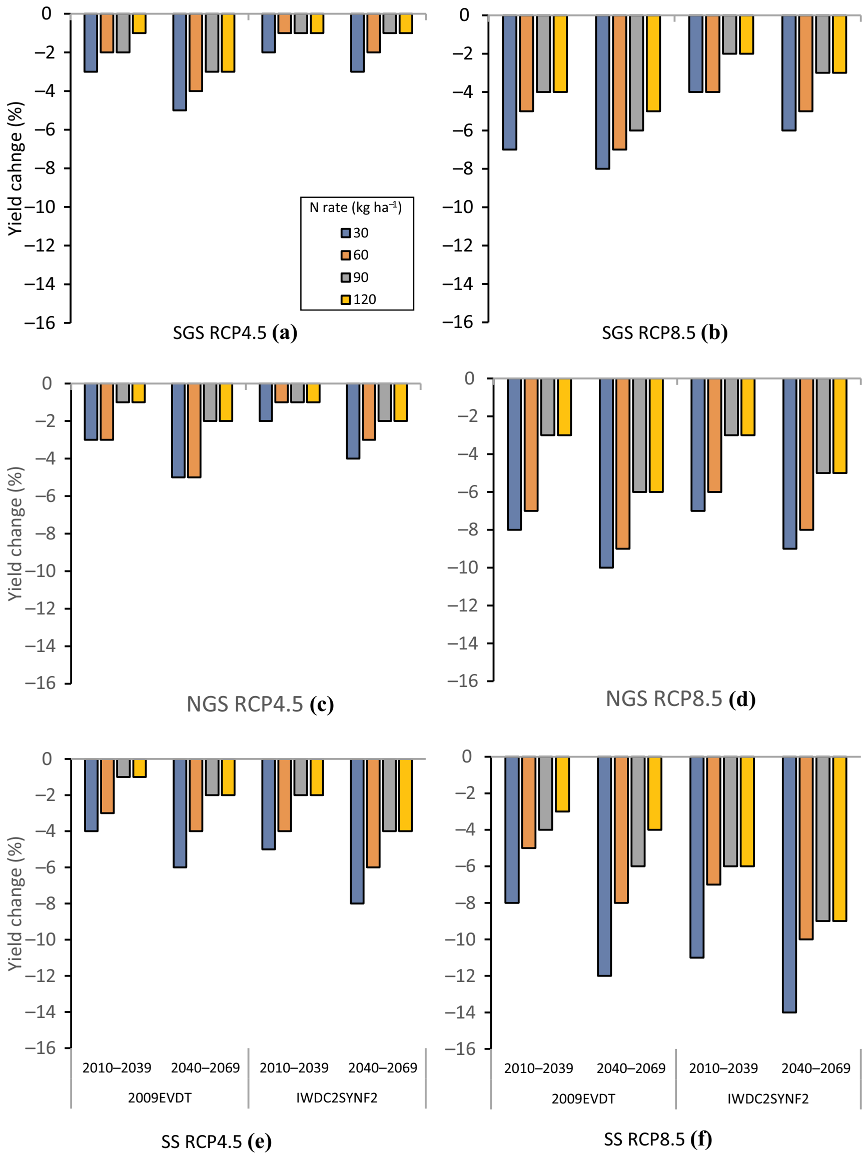


**Figure 6.** Changes in future maize yields under RCPs 4.5 and 8.5 in the near-term (2010–2039) and mid-century (2040–2069) relative to the baseline (1980–2009) in southern Guinea savanna (SGS), northern Guinea savanna (NGS) and Sudan savanna (SS) of Nigeria

**Source:** Authors' own creation

application rates of 30, 60, 90, and 120 kg N ha$^{-1}$, respectively. By the mid-century, these reductions had increased to 5%, 5%, 2%, and 2%, respectively. For the intermediate maturing variety IWDC2SYNF2, the yield was expected to decrease by 2%, 1%, 1%, and 1% in the near term, and by 4%, 3%, 2%, and 2% in the mid-century for the same nitrogen application rates [Figure 6(c)]. Under RCP8.5, the projected yield losses were more severe. For 2009EVDT, applying nitrogen fertilizer at rates of 30, 60, 90, and 120 kg N ha$^{-1}$ results in yield declines of 8%, 7%, 3%, and 3% in the near term, increasing to 10%, 9%, 6%, and 6% by mid-century. Similarly, for IWDC2SYNF2, grain yield reductions were estimated to be 7%, 6%, 3%, and 3% in the near term and 9%, 8%, 5%, and 5% in the mid-century for the same fertilizer application rates [Figure 6(d)].

In Kano, representing the Sudan Savanna (SS), the early maturing maize variety 2009EVDT is projected to experience mean grain yield reductions relative to the 1980–2009 baseline under the RCP4.5. Yield declines were estimated at 4%, 3%, 1%, and 1% in the near term, and 6%, 4%, 2%, and 2% by the mid-century for nitrogen application rates of 30, 60, 90, and 120 kg N ha$^{-1}$, respectively [Figure 6(e)]. For the intermediate-maturing variety IWDC2SYNF2, the simulated mean yield reductions were 5%, 4%, 2%, and 2% in the near term and 8%, 6%, 4%, and 4% in the mid-century for the same nitrogen application rates. Under RCP8.5, the projected yield losses for the 2009EVDT were more pronounced. The yield decreases were estimated to be 8%, 5%, 4%, and 3% in the near term and 12%, 8%, 6%, and 4% by the mid-century at nitrogen application rates of 30, 60, 90, and 120 kg N ha$^{-1}$, respectively. For IWDC2SYNF2, the mean simulated yield reductions were 11%, 7%, 6%, and 6% in the near term, increasing to 14%, 10%, 9%, and 9% by the mid-century, respectively, at the same nitrogen application rates [Figure 6(f)].

## 4. Discussion

Our model satisfactorily predicted crop yield changes influenced by nitrogen fertilization rates and maize varieties across the validation sites. The results of this study also confirmed previous findings using the APSIM model, which showed good agreement between the observed and simulated parameters for various management practices and climate scenarios (Kisaka *et al.*, 2015; Chisanga *et al.*, 2020). However, the discrepancies with Tofa *et al.* (2021) may stem from their focus on cultivar performance and the use of the DSSAT CERES-Maize model, which is more sensitive to high temperatures due to different parameter settings (Boote *et al.*, 2021). Variations in model parameterization also contribute to these differences, highlighting the need for careful consideration in crop modeling for accurate predictions

Simulated grain yields under RCP8.5 were consistently lower than those under RCP4.5, regardless of the nitrogen application rate or time period at all sites. The decreased yields may be attributed to rising temperatures, particularly minimum temperatures, along the high-carbon pathway, despite the models predicting increased precipitation at all locations. Studies by Cairns *et al.* (2013) and Srivastava *et al.* (2017) reported accelerated plant growth due to high temperatures, leading to reduced yields in cereal crops. Similarly, Araya *et al.* (2017) found that rising temperatures in Ethiopia shortened the maize maturity time by 9–13%. Our study revealed that yield reductions due to climate change were more pronounced with low nitrogen application rates of 30 kg ha$^{-1}$ or 60 kg ha$^{-1}$ for both maize varieties across all sites. This suggests that suboptimal nitrogen application will lead to significant yield losses in maize production both in the near term and mid-century. These findings align with those of Thornton *et al.* (2011), who noted that increased fertilization of maize under future climate conditions in East Africa reduced yield loss by 16% to 25%. Our estimated yield decline, ranging from 2% to 16%, falls within the broad range reported for sub-Saharan Africa (Parry *et al.*, 2014) and is similar to projections over the Asian region (Nguyen Hang Thi *et al.*, 2025). Although increased fertilization can lead to higher yields, yield reductions due to higher nitrogen fertilization will be modest under projected climate change compared to baseline yields. This aligns with global results and under similar agroecological zones (Kassie *et al.*, 2015; Chisanga *et al.*, 2020; Tchonkouang *et al.*, 2024). Kassie *et al.* (2015) demonstrated that increasing nitrogen application from 20 kg $ha^{-1}$ to 70 kg $ha^{-1}$ in Ethiopia under climate change conditions is an effective adaptation strategy for enhancing maize yields. Additionally, the magnitudes of yield changes for both maize varieties under the two climate scenarios (RCP4.5 and RCP8.5) were relatively low, despite projected temperature increases of up to 3°C. This modest yield change may be linked to the fact that the varieties used in this study were bred to perform well under drought conditions.

Our results align with those of Cairns *et al.* (2013), who found that drought-tolerant varieties in sub-Saharan Africa are resilient to the effects of high temperatures. A study by Tesfaye *et al.* (2018) in South Africa under warmer and drier climate scenarios showed significant yield reductions of local maize varieties by 21%, 33%, and 50% with temperature increases of 1°C, 2°C, and 4°C, respectively. The observed differences in yield changes could also be attributed to variations in the GCMs used and projected time slices. Consistent with Tesfaye *et al.* (2018), we observed larger yield reductions in the drier Sudan savannas than in the wetter Guinea savannas owing to climate change. Although the varieties in this study were bred primarily for drought tolerance, the lack of a dramatic yield reduction under increased temperatures is likely because they were selected in regions where high temperatures are common.

Therefore promoting drought and heat tolerant maize varieties could therefore be an effective adaptation strategy to mitigate yield losses and sustain maize productivity under climate change conditions in areas similar to our study sites. The modest decrease in yields in the SGS and NGS regions may be attributed to higher rainfall and better soil conditions in these areas, which could have mitigated the effects of rising temperatures. This is consistent with the findings of Tofa *et al.* (2021), who reported that Guinea savannas are suitable for maize cultivation owing to their favorable soils and temperatures.

Conversely, the larger yield reductions in the SS region may be due to the lower average rainfall combined with the high temperatures projected in this study, which are expected to significantly increase water stress and reduce nitrogen uptake in future maize production. This finding aligns with that of Ezeaku *et al.* (2014), who reported significant yield variations between SS and SGS zones. They projected that, at a $CO_2$ concentration of 330 ppm, a 4°C increase in temperature would reduce maize yields by 11.7%, 19.7%, and 21.6% in the SGS, NGS, and SS zones, respectively. In relatively humid areas, such as Abuja (SGS) and Zaria, the effects of climate change were more pronounced for the early maturing variety 2009EVDT than for the intermediate-maturing variety IWDC2SYNF2. This may be due to the relatively high humidity and temperatures throughout the growing season, which affects early-maturing varieties more than mid-maturing varieties (Adnan *et al.*, 2017). In Kano (SS), the degree of yield change for the intermediate-maturing variety IWDC2SYNF2 was higher than that for the early-maturing variety, likely because of the shorter rainy season that accompanies the temperature regime. While climate change has a detrimental impact on both maize varieties, adverse effects can be mitigated through the application of higher nitrogen rates than the normal application rates used by farmers.

While higher nitrogen fertilizer levels mitigated yield losses in this study, this recommendation may not be feasible for all farmers because of economic or environmental constraints, potentially limiting the practical applicability of the findings. We recommend the development of more drought-tolerant maize varieties using advanced breeding technologies that require minimal nitrogen input for high yields. This approach would enable farmers to reduce fertilizer costs and mitigate the risks from higher temperatures and irregular rainfall during the growing season. Another limitation this study is its focus on the Nigerian Savanna region, which may not fully represent the challenges faced in other regions with different climatic conditions or agricultural practices. Future research should include broader regional and spatial analyses using different crop simulation models to better understand the wider impact of climate change on maize productivity across the entire country.



## 5. Conclusions

This study assessed the impact of climate change on drought-tolerant maize varieties in Nigerian Savanna, particularly in the Southern Guinea Savanna (SGS), Northern Guinea Savanna (NGS), and Sudan Savanna (SS) regions. The results showed that maize yields decline by 1–12% depending on location and climate scenario, underscoring the need for effective adaptation strategies. Although higher nitrogen fertilizer levels can mitigate yield losses, they are costly for smallholder farmers. The suitability of early and medium maturing maize varieties varies across regions, highlighting the importance of developing crop varieties tailored to specific agroecological conditions. To address these challenges, policymakers should prioritize the development of advanced drought-tolerant maize varieties that require less nitrogen. This would reduce excessive reliance on fertilizer and even fertilizer costs, enhance resilience to climate stressors, and promote sustainable agriculture. In addition, innovative financing mechanisms should be established to encourage the adoption of climate-smart technologies tailored to local contexts. By aligning adaptation strategies at the local scale, smallholder farmers can better cope with climate risks and improve maize productivity and food security in the Nigerian Savanna while supporting environmentally friendly farming practices. This approach will not only enhance climate resilience but also contribute to sustainable agricultural development and food security in Nigeria and across similar agroecological zones globally.

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## Further reading

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## Supplementary material

The supplementary material for this article can be found online.

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