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PAPER

Evaluating the use of nitrogen and phosphorous fertilization as crop management options for maize adaptation to climate change in the Nigeria savannas

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Abstract

Poor soil fertility and climate variability are major constraints to maize production in the Nigeria savannas. The application of nitrogen (N) and phosphorus (P) as adaptation strategy may enhance maize yield under climate change. In this study, the already calibrated and validated CERES-maize model in DSSAT was used to simulate the response of maize varieties to N and P in three agroecological zones. Similarly, the model, coupled with data for representative concentration pathways (RCP4.5 and RCP8.5) scenarios, was applied to simulate maize yields for mid-century and end-of-century periods and to estimate the effect of use of N and P as a strategy for maize adaptation to climate change. Results of a 30-year sensitivity analysis showed that the optimum grain yields were obtained with application of 150 kg N + 30 kg P ha^{-1} to the two varieties in Kano and Zaria. In Abuja, the optimum grain yields were obtained with the application of 150 kg N ha^{-1} + 30 kg P ha^{-1} to SAMMAZ–15 and 120 kg N ha^{-1} + 30 kg P ha^{-1} to SAMMAZ–16. When P is not applied, the simulation results show that across all N rates, maize yield would decrease by 25%–52% and 32%–52% for the mid- and end-of-century, respectively, under RCP4.5 for both varieties. There would be a greater reduction under RCP8.5, with a decrease of 32%–59% and 52%–69% under mid- and end-of-century scenarios, respectively. When P is applied at 30 kg ha^{-1}, the reduction in yield due to climate change is lower. Under RCP4.5, the yield would decrease by 9%–15% and 11%–21% for the mid- and end-of-century, respectively. There would be a reduction of 12%–21% and 32%–41% for mid-century and end-of-century, respectively, under RCP8.5 scenario. This suggests that the application of optimum P could reduce the impact of yield loss due to climate change.

1. Introduction

Maize (*Zea mays* L.) is among the most important cereal crops in Nigeria, serving both as a source of food and income. Nigeria is the second largest producer of maize in Africa, producing about 12 million metric tonnes from 7.5 million hectares in 2021 (FAOSTAT 2022). The northern Nigerian savanna is the most suitable zone for maize production in Nigeria due to high incident solar radiation, adequate rainfall, and moderate incidences of biotic stresses (Shehu *et al* 2019). Despite the increase in production over the past decades, maize yields are still low in the Nigeria savannas, with yields mostly below 2 t ha^{-1} leading to low overall production and the need to import maize to address the 4 million metric ton demand gaps annually. Major constraints to maize production in the Nigeria savannas are low soil fertility (Adnan *et al* 2017), climate variability (Tofa *et al* 2021) leading to drought (Kamara *et al* 2012), and *Striga hermonthica* parasitism (Dugje *et al* 2006).

Nitrogen is the most limiting nutrient in maize production in the savannas of Nigeria (Oikeh *et al* 1997). Nitrogen deficiency is caused by several factors, including low organic carbon content (Kamara *et al* 2013), the leaching of soil N below the root zone due to torrential rainfall (Bennett *et al* 1989), and the application of sub-optimal levels of inorganic fertilizers due to high prices and non-availability (Smith *et al* 1997). Kamara *et al* (2009) reported a drastic yield decline in maize in the Nigerian savannas when nitrogen was not applied. Nitrogen stress limits maize production in the Nigeria savannas (Carsky and Iwuafor 1995, Sharifai *et al* 2008, Kamara *et al* 2009, Arunah *et al* 2014). Nitrogen stress before anthesis reduces leaf area development, photosynthesis rate, and the number of ears per cob, while N stress during anthesis results in kernel and ear abortion. However, stress during grain-filling hastens leaf senescence and reduces crop photosynthesis required for sink filling, which results in reduced kernel weight (Bänziger *et al* 2000).

In most agricultural soils in the Nigeria savannas, phosphorus (P) is the second major nutrient essential for plant growth (Mohammed *et al* 2020). It is also the second most limiting plant nutrient in crop production after nitrogen (Akande *et al* 2010). Shehu *et al* (2015) rated the soils in the savanna areas of northern Nigeria as mostly very low in P with values mostly below 3 mg kg^{-1} soil. Ekeleme *et al* (2014) reported that 80% of the fields were either very low or low in P in the Nigeria savannas. Similarly, Kamara *et al* (2008), reported that P levels were lower than critical values of 7 mg kg^{-1} in 93% of soils in the SS and 92% of the soils in the northern Guinea savanna (NGS) of Nigeria. Phosphorus deficiency has been reported to reduce the response of crops to mineral N application through its negative influence on the photosynthetic activity of crops, resulting in poor growth and yield (Smalberger *et al* 2006, MacCarthy *et al* 2009). Maize responds significantly to N fertiliser when P fertilizer is applied (FAO 2006, MacCarthy *et al* 2009, Onasanya *et al* 2009, Fosu-Mensah *et al* 2012). Studies have shown a significant response in maize grain yield to the combined application of N and P in the Nigerian savannas (Adediran and Banjoko 1995, Oikeh *et al* 1997, Jaliya *et al* 2008). Adediran and Banjoko (1995) reported maize response to the application of P at a rate of 20–30 kg ha^{-1} in the Nigerian savannas, and they recommended 50–100 kg N ha^{-1} and 20 kg P ha^{-1} for optimum maize yield. In addition, Jaliya *et al* (2008) reported a higher yield of maize with an application of 150 kg N ha^{-1} and 26 kg P ha^{-1} in the northern Guinea savanna agroecological zone of Nigeria. However, there has been an emphasis on nitrogen for maize fertilization in the Nigeria savannas with a drive towards the use of fertilizer blends that are lower in phosphorus and more in nitrogen. This is likely to generate imbalanced crop nourishment since maize is cultivated in highly heterogeneous fields (Kihara *et al* 2016, Shehu *et al* 2018). It could also result in poor economic returns for the farmers (Adnan *et al* 2017).

Maize production in Nigeria could further decline due to the changing climate, which is already impacting food production in the country. There are current and projected reports on the impact of climate change in Nigeria, either in the form of increasing temperatures or drought (Adefolalu 2007, Olapido 2010, Blanc 2012, Omotosho *et al* 2014, Amanchukwu *et al* 2015) which would negatively affect maize productivity. In the Nigerian savannas, Tofa *et al* (2021) predicted temperatures would increase by 2.2 °C–2.9 °C in the mid-century and up to 3.9 °C–5.0 °C by the end of the century under RCP8.5 scenario. The models also predicted increase in rainfall in the drier Sudan savanna and a reduction in the Guinea savannas (Tofa *et al* 2021). In the absence of adaptation strategies, climate change could result in crop yield losses of 30%–50% by 2020 and up to 90% by 2100, with a greater impact on maize crops in northern Nigeria (BNRCC 2011). Tofa *et al* (2021) reported maize yield reductions in the range of 13%–43% in the Nigeria savannas for the drought-tolerant variety by the end of the century. To mitigate the adverse impacts of climate change, many adaptation technologies have been proposed. This includes the use of improved crop management practices like nitrogen fertilizer application (Kassie *et al* 2015), planting date manipulation (White *et al* 2011), supplementary irrigation (Kassie *et al* 2015, Araya *et al* 2017), and the deployment of drought-tolerant varieties (Bänziger *et al* 2006, Tesfaye *et al* 2018, Tofa *et al* 2021). In the Central Rift Valley of Ethiopia, increasing nitrogen fertilization has been demonstrated to reduce the detrimental impact of climate change by increasing maize grain yield (Kassie *et al* 2015).

While individual plot level studies have been reported for the effects of the combined application of N and P on maize productivity, the evaluation of maize response to N and P on a large scale is time-consuming and involves expensive large-scale experiments across maize growing regions like the savannas in northern Nigeria. We therefore used the DSSAT-CERES-Maize model to assess the response of maize to the application of N and P in the Nigeria savannas. We also used the model to evaluate the use of N and P as adaptation strategy to climate change. The CERES-Maize model of DSSAT has been evaluated and used by many researchers who found good correlations between observed and simulated values for a wide range of experimental N and P fertilization practices against field data and environmental conditions. For example, Dzotsi *et al* (2010) tested the ability of a soil-plant P model in the model in Ghana to mimic wide differences in maize responses to P as preliminary attempts to test the model on highly weathered soils. They indicated that the P model achieved good predictability for final grain yield and biomass. Tetteh and Nurudeen (2015) used DSSAT-CERES Model to evaluate wide differences in maize responses to N and P and suggested more efficient and sustainable N and P options for maize production in the Sudan Savanna agroecological zone of Ghana. They concluded that the

DSSAT model can be used as a tool for developing site-specific fertilizer recommendations for improved maize and other crops in similar agroecological zones. The CERES-Maize model has also been used to quantify impacts of current and future climate changes on crop yields (Sangotegbe *et al* 2012, Asseng *et al* 2015, Tofa *et al* 2021) and evaluate different crop management strategies as adaptation measures to climate change (Sultan *et al* 2013, Abera *et al* 2018, Falconnier *et al* 2020, Tofa *et al* 2021, Araya *et al* 2022) .The specific objectives of this study were to (i) to simulate the response of maize grain yield to inorganic N and P fertilization across diverse agroecological zones in northern Nigeria (ii) assess the effect of the use of N and P as strategy for maize adaptation to climate change in the selected zones.

2. Materials and methods

2.1. Soil and weather conditions of the study sites

The studies were carried out in three locations; Abuja in the southern Guinea savanna agroecological zone (SGS), Kano in the Sudan savanna (SS) agroecological zone and Zaria in the northern Guinea savanna (NGS) agroecological zone. In Kano in the SS, the soils were loamy sand textured with higher sand and very low clay content in all the 6-horizons (table S1). In this location the soils had a neutral reaction with very low OC (<1.0 g kg^{-1}), total nitrogen (0.1–0.2 g kg^{-1}), and available phosphorus (<7 mg kg^{-1}). The mean lower limit water content of the soil was 0.059 (range 0.054–0.072), while the mean drain upper limit was 0.116 (range 0.107–0.127). In Zaria in the NGS, five out of the six layers were silt loam textured with higher silt and lower sand content when compared to Kano. The soils were slightly acidic, with low OC (5.9 g kg^{-1}) at the surface layer and very low OC content in the other profile layers. In this location, the total nitrogen is low (range 0.107–0.127 g kg^{-1}) and the available phosphorus (<7 mg kg^{-1}) is also within the low fertility class. The mean lower limit water content of the soil was 0.076 (range 0.040–0.092) while the mean drain upper limit was 0.204 (range 0.101–0.270) in Zaria. In Abuja in the SGS, four out of the five layers were silt loam textured with high silt and low clay contents. The soils were slightly acidic with low OC (5.8 g kg^{-1}) at the top layer. Soil total nitrogen and available phosphorus fell within the low fertility class each, except that the 3rd and 4th layer each had very low total N and available P content, respectively. The mean lower limit water content of the soil was 0.239 (range 0.228–0.249) while the mean drain upper limit was 0.388 (range 0.356–0.406) in Abuja.

The long-term historical climate data for a 30-year (1985–2014) period used for model application show that rainfall was higher and more evenly distributed in Abuja in the SGS and Zaria in the NGS than in Kano in the SS. For the SS, NGS, and SGS, the average rainfall during a 30-year period was 795, 1042, and 1611 mm, respectively. The average minimum and maximum daily temperatures and solar radiation in Abuja over a 30-year period were 21.4 °C, 33.0 °C, and 19.6 MJ m^{-2} day^{-1}, respectively. The averages in Zaria were 19.3 °C, 31.9 °C, and 21.1 MJ m^{-2} day^{-1}, respectively. Kano had average temperatures of 20.2 °C (minimum) and 33.9 °C (maximum), with an average solar radiation of 21.3 MJ m^{-2} day^{-1}.

2.2. DSSAT model and input data, calibration and evaluation

The DSSAT-CSM is a collection of computer programmes and tools combined into a single software package to ease the use of crop simulation models in research and decision-making (de Abreu Resenes *et al* 2019). The CERES-maize model is one of the maize growth simulation models in DSSAT that operates on a daily time step and is cultivar and site-specific. It dynamically simulates the development of roots, shoots, and final grain yield as a function of soil/weather conditions, crop management practices, and cultivar genetic coefficients of characteristics (Ritchie *et al* 1998). The model combines mathematical equations to express the basic flow and transformation processes of soil carbon, water, and nutrient balances on a daily or hourly basis (Adnan *et al* 2019). It also predicts the temporal changes in crop growth, nutrient uptake, water use, and final yield as well as other plant, soil, and weather traits and outputs (Boote *et al* 2010). The basic input data required by the CERES-Maize model includes: (i) daily weather data (maximum and minimum temperature, precipitation, and solar radiation); (ii) soil data, which includes general site and soil surface information, soil profile characteristics (physical and chemical), and key levels of water availability at each soil layer for saturated water content (SAT), drained upper limit (DUL), lower limit (LL), and soil layer thickness; (iii) crop management data; and (iv) the genotype specific parameters (GSPs), or genetic inputs that describe physiological processes and developmental differences among crop varieties (Hoogenboom *et al* 2021).

2.3. Seasonal analysis of nitrogen and phosphorus on simulated grain yield

Using the already evaluated model in the study area, the seasonal analysis tool in DSSAT was used to test the effect of varying N and P application rates on the grain yield of intermediate-maturing maize in three locations in Kano (SS), Zaria (NGS) and Abuja (SGS). In the SS, the sowing date was June 15th, and in the NGS and SGS, the sowing dates were both June 30th. Generally, sowing was set at a soil depth of 5 cm with a planting density of 5.3

plants m^{-2}. Five rates of nitrogen fertilizer (30, 60, 90, 120, and 150 kg N ha^{-1}) using urea and three rates of phosphorus fertilizer (0, 30 and 60 kg P ha^{-1}) using single super phosphate (SSP) were simulated. In the Model, half of N and full rate of P was applied as per treatment at 10 days after sowing while a second N application (the remaining half of N) was carried out at 45 days after sowing. Because potassium (K) was considered to be non-limiting, K sub-models were turned off. The model was set to harvest when the crop reached harvest maturity. For the sensitivity analysis, soil data from Kano, Zaria, and Abuja (table S1) were used. Simulations are initiated at planting for 30 years; each year's simulation was independent of the previous year. This was done to evaluate the sensitivity of the treatments based on the annual rainfall variability, not the residual effects of the previous treatments. Thirty-year (1985–2014) records of daily precipitation, daily minimum and maximum temperatures, and daily solar radiation were used for the long-term simulation studies. These were obtained from the Nigerian Meteorological Agency (NIMET) for each location. The weather data were inputted into the weatherman utility software on the DSSAT v4.7.5 where it was checked for errors before use. The mean, minimum, and maximum yields with their standard deviations for 30 years for each treatment and location were calculated. Thirty (30) years of cumulative function plots of crop yields were calculated under different N and P management strategies. In addition, the effects of N and P treatments on crop yield were compared by using an analysis of variance (ANOVA) test in GenStat 17th Edition. Data were analyzed as a split-plot factorial experiment. Nitrogen and phosphorus were combined to form the main plot factor while variety was the sub plot factor. Differences between the treatment means were separated using Fisher's protected least significant difference (LSD) test at a 5% level of probability.

An economic analysis was also carried out in DSSAT to compare N treatments in economic terms under the application rate of 30 kg P ha^{-1} only. The cost of inputs and their application as well as the basal cost of production were collected from 2016 survey data (unpublished, IITA) conducted in the study areas. The model was set to use \$433, \$427, and \$483 t ha^{-1} as the price of maize grain, obtained from the Famine Early Warning Systems Network (FEWSNET) data repository. The base production cost, which includes the cost of ploughing, planting, weeding, and harvesting, was \$725, \$725, and \$820 ha^{-1} and the cost of N fertilizer was \$0.87, \$0.83, and \$0.90 kg^{-1} each in Kano, Zaria, and Abuja, respectively. The seed cost was set at \$1.33 kg^{-1} in all the locations. Since P and K factors are constant, the cost of P and K components was ignored in the economic editor of distribution in DSSAT to compare the N treatment. The maize value and costs of production were calculated by converting the Naira value (₦, Nigerian currency; 1 USD = ₦300) to US dollar values based on the market exchange rate in 2016. Using the same tool, strategic analysis was carried out to compare treatments in economic and strategic terms. The results of strategic analyses were also confirmed by economic evaluation through Mean-Gini Stochastic Dominance (MGSD) analysis as described in Tsuji *et al* 1998 and Kisekka *et al* 2017. The model assessed the effectiveness of each N application rate by measuring the degree of concentration of obtaining an average mean return per hectare (Gini coefficient) across 30 repeated simulations.

2.4. Climate scenarios for assessing the impacts of climate change on maize

For the three studied sites, baseline climate parameters, including daily rainfall, maximum and minimum temperatures, and solar radiation, were collected from the Nigerian Meteorological Agency (NIMET) for 30 years (1980–2009). Using the delta-based method, the protocols developed by the global Agricultural Model Intercomparison and Improvement Project (AgMIP) team (Rosenzweig *et al* 2016) were used to generate future climate scenarios using RCP4.5 and RCP8.5 for mid-century (2040–2069) and end-century (2070–2099). Projected climate scenarios under RCP4.5 and RCP8.5 imply increasing CO2 concentrations of 499 and 571 ppm, respectively, compared to the current 380 ppm. The future climate data for daily rainfall, temperatures were obtained by perturbing the daily baseline data with the delta factor method (Diaz-Nieto and Wilby 2005, AgMIP 2013). Four contrasting bias corrected GCMs (CESM1-CAM5, CSIRO-MK3.6.0 HadGEM2-ES, and MRI-CGCM3) from Fifth Coupled Model Inter-comparison Project (CMIP5) were used in for the analysis. Detailed about the four GCMs and changes in rainfall and temperatures based on GCM outputs have been reported in Tofa *et al* (2021). The climate change impact assessment was carried out by comparing the simulated yield of two maize varieties using the baseline climate data (1980–2009) against the simulated yield for the mid-century climate data (2040–2069) and end of century (2070–2099) periods under RCP4.5 and RCP8.5 scenarios. Before running the model, the N and P treatments for each variety was assigned in the model management files. There were six N application rates (0, 30, 60, 90, 120 and 150 kg N ha^{-1}) and three P application rates (0, 30, and 60 kg P ha^{-1}). However, only 30–150 kg N were reported since the 0 N treatment did not result in a substantial yield change even when the climate changed (see figures S1–3). Similar procedure described in section 2.3 was applied for the fertilizer application. Other variables such as soil, cultivar and crop management practices are held constant as in section 2.3. A simple mathematical averaging was performed using excel to access the climate model ensemble mean. The impact of climate scenarios on maize yield was compiled and relative yield deviation from the baseline against the corresponding future climate scenarios was computed according Tofa *et al* (2021) in equation (1):

$$\Delta\text{Yield} = \frac{\text{Yield}_{scenario} - \text{Yield}_{baseline}}{\text{Yield}_{baseline}} * 100\ \% \tag{1}$$

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

3. Results

3.1. Model calibration and validation

The DSSAT-CSM version 4.7.5 (Hoogenboom *et al* 2019) used in this study was calibrated and validated for the maize varieties (SAMMA 15 and SAMMAZ 16) by Tofa *et al* (2020). The model was evaluated using 4 independent data sets from field experiments conducted over 2 years (2015–2016) at Iburu and Zaria as described by Tofa *et al* (2020). From the results of both model calibration and evaluation, a good agreement in the model prediction of all the evaluated parameters was observed, as evidenced by low RMSE, a reasonably high d-index, and good model estimation efficiency (Tofa *et al* 2020). This indicates that the model has been adequately validated and that it may be used as a decision support tool for long-term scenario analysis in various agro-environments.

3.2. Seasonal analysis

The simulated mean grain yields (table 1) were obtained based on long-term historical daily weather data and the soil characteristics of the sites. Generally, SAMMAZ-15 produced a higher grain yield than SAMMAZ-16 across all the treatments and the study areas. The simulated results show that application of P increases maize response to N. In all locations, linear increases in grain yield were observed with an increase in P application from 0 to 30 kg ha^{-1} for both varieties. Increases in P fertilizer from 30 to 60 kg ha^{-1} produced similar responses in all agro-ecologies for the two varieties (table 1). Therefore, the results for maize response to N applications under 60 kg P ha^{-1} were not reported.

In Kano in the SS, when no P was applied, increasing N application from 30 to 60 and 90 kg ha^{-1} significantly increased long-term average grain yield from 1.67 t ha^{-1} to 2.62 and 3.36 t ha^{-1}, respectively, for SAMMAZ-15 and from 1.52 to 2.14 and 2.34 t ha^{-1}, respectively, for SAMMAZ-16. Increases in yield were not significant with N application beyond 90 kg ha^{-1} for SAMMAZ 15 and beyond 60 kg ha^{-1} for SAMMAZ-16. The magnitude of response of both varieties to N was significantly higher when P was applied at 30 kg P ha^{-1}. For both varieties, increasing the N rate from 30 to 150 kg ha^{-1} significantly increased the average grain yield. For SAMMAZ-15, grain yield increased from 1.36 t ha^{-1} at 30 kg N ha^{-1} to 2.53, 3.69, 4.74, and 5.51 t ha^{-1} with N applications of 60, 90, 120, and 150 kg N ha^{-1}, respectively. The grain yield increased from 1.31 t ha^{-1} for 30 kg ha^{-1} N application to 2.43, 3.52, 4.34, and 4.91 t ha^{-1} for 60, 90, 120, and 150 kg ha^{-1} N application, respectively, for SAMMAZ-16.

In Zaria in the NGS, when P fertilizer was not applied, increasing N application from 30 to 60 kg ha^{-1} resulted in an increase in the average grain yield of SAMMAZ-15 from 1.50 to 2.21 t ha^{-1} and from 1.36 to 1.72 t ha^{-1} for SAMMAZ-16. Further increases in N beyond 60 kg ha^{-1} did not result in a significant increase in yield for both varieties. The application of P at 30 kg ha^{-1} consistently increased maize response to applied N. The average yield increased from 1.34 t ha^{-1} at 30 kg N ha^{-1} to 2.73, 4.28, 5.85, and 6.68 t ha^{-1} with 60, 90, 120, and 150 kg N ha^{-1} application, respectively, for SAMMAZ-15 and from 1.27 t ha^{-1} at 30 kg N ha^{-1} to 2.58, 4.0, 5.16, and 5.73 t ha^{-1} for SAMMAZ-16.

In Abuja in the SGS, when P was not applied, N application only significantly increased grain yield at 60 kg N ha^{-1} for both varieties. A further increase in N from 60 to 90–150 kg ha^{-1} did not significantly increase grain yield. When P was applied at 30 kg ha^{-1}, and N was applied at 30 kg N ha^{-1}, the simulated grain yield for SAMMAZ-15 was 1.67 t ha^{-1} and 1.56 t ha^{-1} for SAMMAZ-16. When N was increased to 60 kg ha^{-1} the average yield was 3.08 t ha^{-1} for SAMMAZ-15 and 2.83 t ha^{-1} for SAMMAZ-16. When N was increased to 90, 120, and 150 kg ha^{-1}, the average grain yields for SAMMAZ-15 were 4.30, 4.94, and 5.18 t ha^{-1}, respectively, and 3.70, 4.16, and 4.26 t ha^{-1} for SAMMAZ-16.

Figures 1–3 show cumulative function (CF) plots for simulated grain yields of the two varieties in Kano, Zaria, and Abuja. In Kano, the CF plots show that for SAMMAZ 15, a grain yield of 1519 kg ha^{-1} was obtained in 22.5 (75% probability) out of 30 years at an N application rate of 30 kg ha^{-1} when no P was applied. Grain yields ranging from 2211–2314 kg ha^{-1} were obtained with N application of 60–150 kg ha^{-1} in the same number of years (figure 1(a)). When P was applied at 30 kg ha^{-1}, significant differences in yield were recorded for every increase in nitrogen application in all simulated years. At 75% probability, a grain yield of 1286 kg ha^{-1} was obtained with the application of 30 kg N ha^{-1}. Further increases of N to 60, 90, 120, and 150 kg ha^{-1} resulted in an increase in grain yield of 2363, 3501, 4493, and 5098 kg ha^{-1}, respectively (figure 1(b)). The variety

Table 1. Mean grain yield (t ha^{-1}) of 30-year (1985–2014) seasonal analysis for SAMMAZ-15 and SAMMAZ-16 using different N and P in the of Nigeria savannas.

Treatments		Kano in SS		Zaria in NGS		Abuja in SGS	
	N (kg ha^{-1})	SAMMAZ-15	SAMMAZ-16	SAMMAZ-15	SAMMAZ-16	SAMMAZ-15	SAMMAZ-16
0 kg P ha^{-1}							
	30	1.67^{d} (1.1–2.1)[¶]	1.52^{c} (1.1–1.8)	1.50^{c} (0.9–2.0)	1.36^{b} (0.8–1.8)	1.85^{b} (1.4–2.3)	1.67^{b} (1.3–2.0)
	60	2.62^{c} (1.4–3.9)	2.14^{b} (1.1–3.4)	2.21^{b} (0.9–3.8)	1.72^{a} (0.8–3.5)	2.54^{a} (1.6–3.5)	2.05^{a} (1.3–3.2)
	90	3.36^{b} (1.5–5.7)	2.34^{ab} (1.1–4.1)	2.57^{ab} (0.9–5.7)	1.87^{a} (0.8–4.9)	2.70^{a} (1.6–5.0)	2.09^{a} (1.3–3.9)
	120	3.75^{ab} (1.5–6.2)	2.49^{a} (1.1–5.3)	2.77^{a} (0.9–7.0)	1.90^{a} (0.8–5.2)	2.75^{a} (1.6–5.6)	2.07^{a} (1.3–3.9)
	150	3.95^{a} (1.5–6.6)	2.56^{a} (1.1–6.0)	2.83^{a} (0.9–7.3)	1.94^{a} (0.8–5.7)	2.75^{a} (1.6–5.6)	2.07^{a} (1.3–3.9)
	LSD$_{5\%}$	0.424	0.292	0.404	0.260	0.252	0.136
30 kg P ha^{-1}							
	30	1.36^{e} (1.0–1.7)	1.31^{e} (1.0–1.6)	1.34^{e} (1.0–1.6)	1.27^{e} (0.8–1.5)	1.67^{e} (1.3–2.3)	1.56^{d} (1.3–2.0)
	60	2.53^{d} (1.6–3.2)	2.43^{d} (1.4–3.2)	2.73^{d} (2.2–3.3)	2.58^{d} (1.8–3.2)	3.08^{d} (2.5–4.1)	2.83^{c} (2.2–3.7)
	90	3.69^{c} (2.2–4.7)	3.52^{c} (2.1–4.5)	4.28^{c} (3.4–5.1)	4.00^{c} (2.8–4.7)	4.30^{c} (3.5–5.5)	3.70^{b} (2.8–4.7)
	120	4.74^{b} (2.7–6.0)	4.34^{b} (2.2–5.4)	5.85^{b} (4.3–6.6)	5.16^{b} (3.8–6.1)	4.94^{b} (3.9–6.4)	4.16^{a} (3.0–5.4)
	150	5.51^{a} (3.2–6.6)	4.91^{a} (2.6–6.0)	6.68^{a} (4.8–7.6)	5.73^{a} (4.2–6.7)	5.18^{a} (3.9–6.6)	4.26^{a} (3.0–5.5)
	LSD$_{5\%}$	0.180	0.181	0.150	0.141	0.104	0.148
60 kg P ha^{-1}							
	30	1.20^{e} (0.8–1.7)	1.20^{e} (0.9–1.6)	1.34^{e} (1.0–1.6)	1.27^{e} (0.9–1.5)	1.67^{e} (1.3–2.3)	1.56^{d} (1.3–2.0)
	60	2.55^{d} (2.0–3.4)	2.60^{d} (2.0–2.3)	2.73^{d} (2.2–3.2)	2.57^{d} (1.8–3.1)	3.08^{d} (2.5–4.1)	2.83^{c} (2.2–3.7)
	90	3.86^{c} (3.1–5.1)	3.79^{c} (3.2–5.1)	4.27^{c} (3.4–5.0)	3.99^{c} (2.8–4.7)	4.31^{c} (3.5–5.5)	3.70^{b} (2.8–4.7)
	120	5.03^{b} (4.1–6.3)	4.62^{b} (3.7–5.8)	5.83^{b} (4.3–6.6)	5.14^{b} (3.8–6.1)	4.95^{b} (4.0–6.4)	4.15^{a} (2.9–5.4)
	150	5.69^{a} (4.5–7.0)	5.04^{a} (4.0–6.2)	6.66^{a} (4.8–7.6)	5.73^{a} (4.2–6.7)	5.20^{a} (4.0–6.6)	4.26^{a} (3.0–5.5)
	LSD$_{5\%}$	0.164	0.159	0.148	0.138	0.174	0.150

Within each column and treatment group mean followed by same letter(s) are not significantly different at 5% probability level using Least significant different (LSD), [¶]values in brackets give the grain yield range.

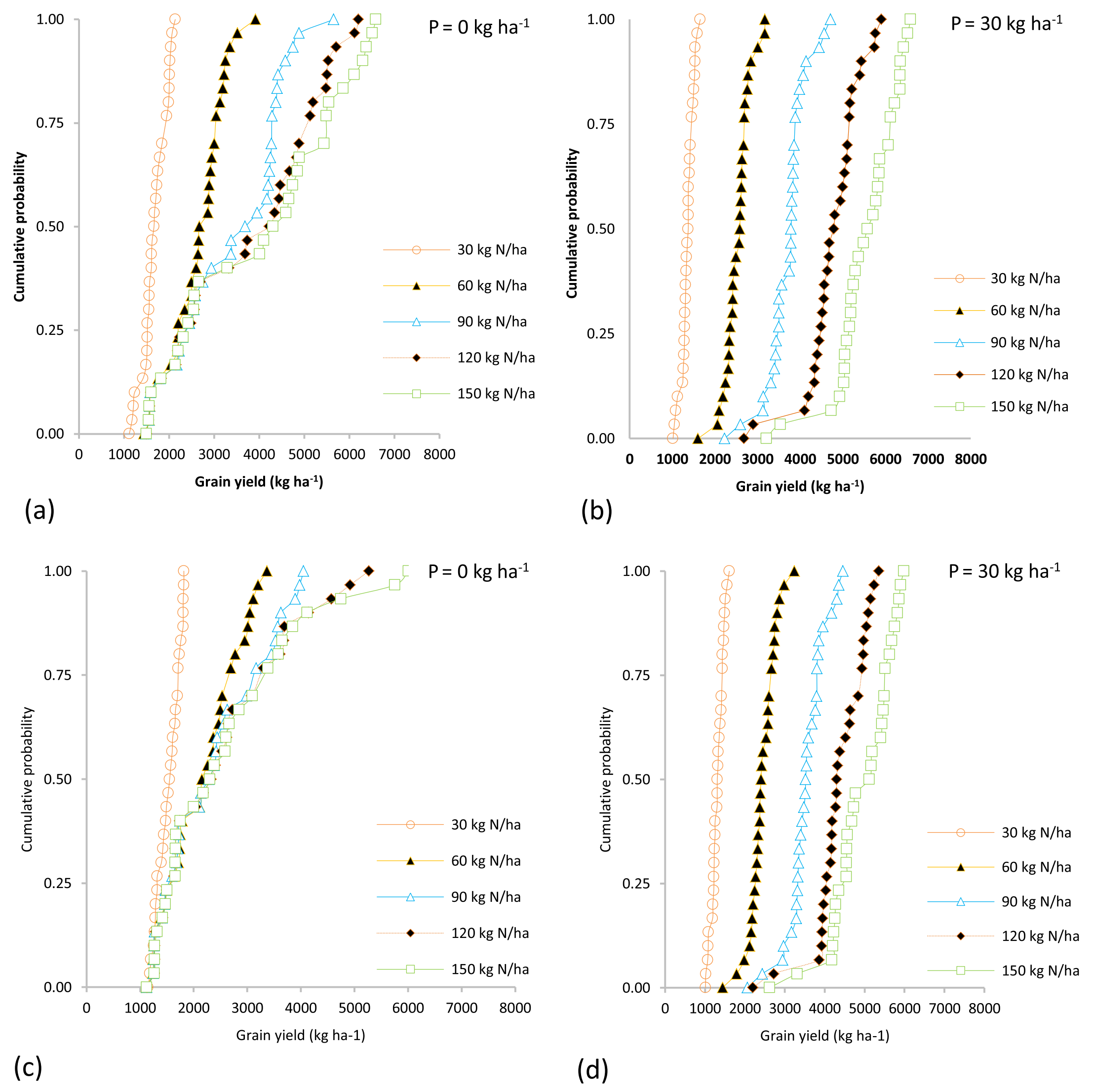

Figure 1. Cumulative probability of maize grain yield in response to N and P fertilization in Kano in the Sudan savanna for SAMMAZ 15 (a) and (b), and SAMMAZ 16 (c) and (d).

SAMMAZ-16 produced 1319 kg ha^{-1} at N rate of 30 kg ha^{-1} and 1502 kg ha^{-1} for all other N rates when no P was applied at a 75% probability level (figure 1(c)). At the same probability level, grain yield ranged from 1221 kg ha^{-1} at N rate of 30 N ha^{-1} to 4356 kg ha^{-1} at N rate of 150 kg ha^{-1} (figure 1(d)).

In Zaria, the CF plots show that for SAMMAZ-15, a marginal grain yield of 1331 kg ha^{-1} was simulated at all N rates when no P was applied in 75% of the years (figure 2(a)). When P was applied at 30 kg ha^{-1}, a grain yield of 1275 kg ha^{-1} was obtained with the application of 30 kg N ha^{-1}. Increases in N to 60, 90, 120, and 150 kg ha^{-1} resulted in grain yields of 2544, 4033, 5433, and 6159 kg ha^{-1} in 22.5 out of 30 years (figure 2(b)). A grain yield of 1158 kg ha^{-1} was simulated for SAMMAZ-16 for all N rates when no P was applied (figure 2(c)). When P was applied at 30 kg ha^{-1}, simulated grain yield ranged from 1181 kg ha^{-1} at N rate of 30 N ha^{-1} to 5368 kg ha^{-1} at N rate of 150 kg ha^{-1} with a probability of 75% (figure 2(d)).

In Abuja, when no P was applied, a grain yield of 1670 kg ha^{-1} was simulated in 22.5 years out of 30 years at N application rate of 30 kg ha^{-1} for SAMMAZ-15. A grain yield of 1968 kg ha^{-1} was obtained with N application of 60–150 kg ha^{-1} in the same number of years (figure 3(a)). With the application of 30 kg P ha^{-1} and 30 kg N ha^{-1}, the grain yield was 1564 kg ha^{-1}. Further increases of N to 60, 90, 120, and 150 resulted in an increase in grain to 2805, 3895, 4435, and 4688 kg ha^{-1} respectively in 75% of the years. However, no pronounced increase in yield was observed when N was increased from 120 to 150 kg ha^{-1} (figure 3(b)). A grain yield of 1640 kg ha^{-1} was simulated for SAMMAZ-16 for all N rates when no P was applied (figure 3(c)). Grain yield ranged from 1439 kg ha^{-1} at a N rate of 30 kg ha^{-1} to 3836 kg ha^{-1} at a N rate of 120 kg ha^{-1} when P was applied at 30 kg ha^{-1}; further application to 150 kg N resulted in no further yield improvement (figure 3(d)).

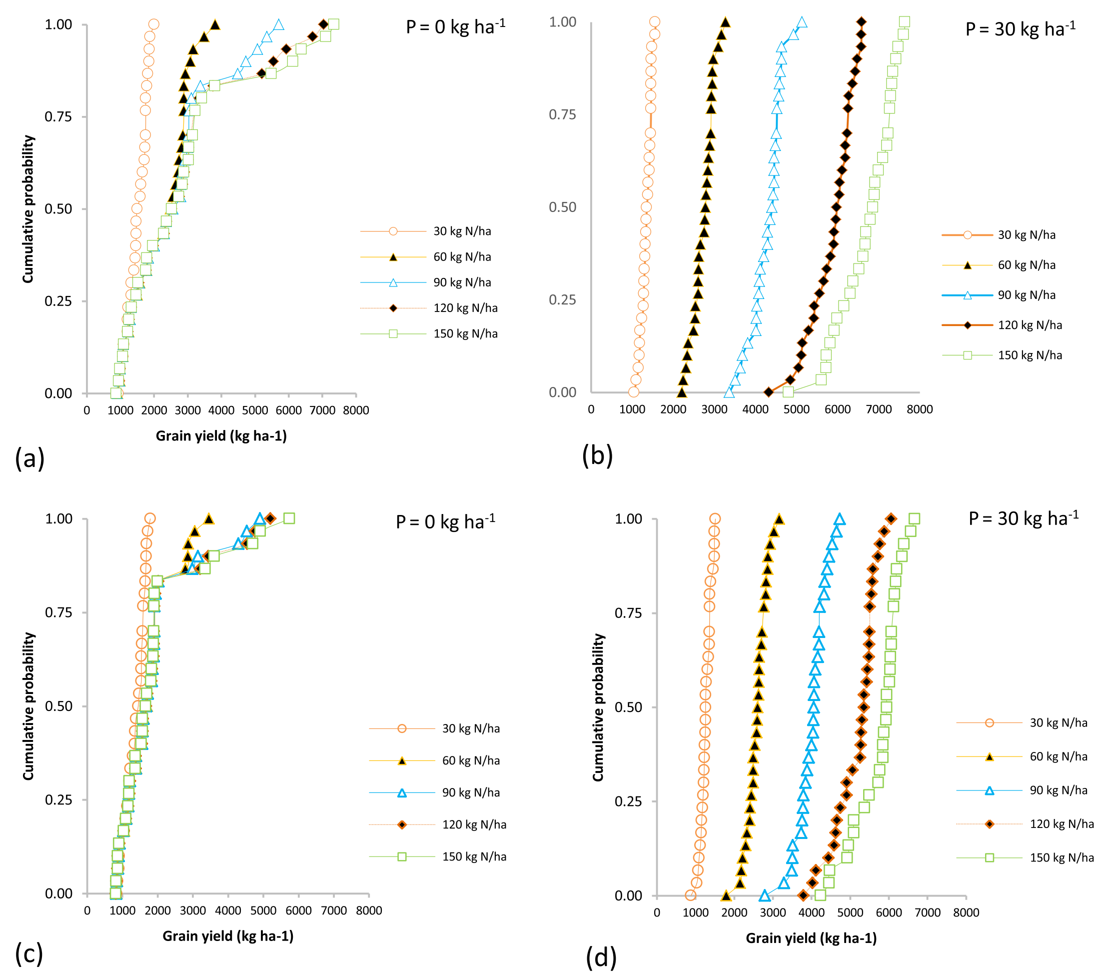

Figure 2. Cumulative probability of maize grain yield in response to N and P fertilization in Zaria in the northern Guinea savanna for SAMMAZ-15 (a) and (b), and SAMMAZ-16 (c) and (d).

3.3. Economic and strategy analyses

The results of the economic and strategy analysis are shown in table 2. Both economic and strategic analysis were done under the application of 30 kg P ha^{-1} only. According to the economic analysis of the long-term simulated yield, application of 30 kg N ha^{-1} would lead to negative returns in Kano and Zaria for both varieties. In Abuja, application of 30 kg N ha^{-1} was found to be economically feasible, but the returns were very negligible, with a mean profit of 72 USD for SAMMAZ-15 and 18 USD for SAMMAZ-16. Based on the 2016 price for maize grain and costs of production, applying 150 kg N ha^{-1} was found to be the most profitable (higher mean returns) for the 30-year simulation in Kano and Zaria for both varieties. The same rate was also the most strategically efficient for both varieties in the two agro-ecologies. In Abuja, application of 150 Kg N ha^{-1} was found to be more profitable (higher mean returns) and more strategic for SAMMAZ-15. For SAMMAZ-16, however, application of 120 kg N ha^{-1} was found to be more strategic and had higher returns.

3.4. Projected changes in temperature and seasonal rainfall

The future climate change projections for temperatures and rainfall for all the scenarios across the study locations were earlier reported by Tofa *et al* (2021). They projected that minimum and maximum temperatures, as well as seasonal rainfall, would increase across the study locations. Temperatures were anticipated to rise by 1.7 °C–2.4 °C for RCP4.5 and 2.2 °C–2.9 °C for RCP8.5 by the mid-century. Temperature rises of 2.2 to 3.0 °C under RCP4.5 and 3.9 to 5.0 °C under RCP8.5 by the end of the century. In the mid-century, the expected seasonal rainfall increases from 1.2%–7% for RCP4.5 to 0.03%–10.6% for RCP8.5. Rainfall is anticipated to increase by 2%–6.7% for RCP4.5 and 3.3%–20.1% for RCP8.5 by the end of the century.

3.5. Impact of future climate change scenario on yield of maize under application of N and P

The percentage changes in maize yield relative to baseline were computed for each location, and the corresponding results are presented in figures 4–6. Irrespective of the N and P applications, the

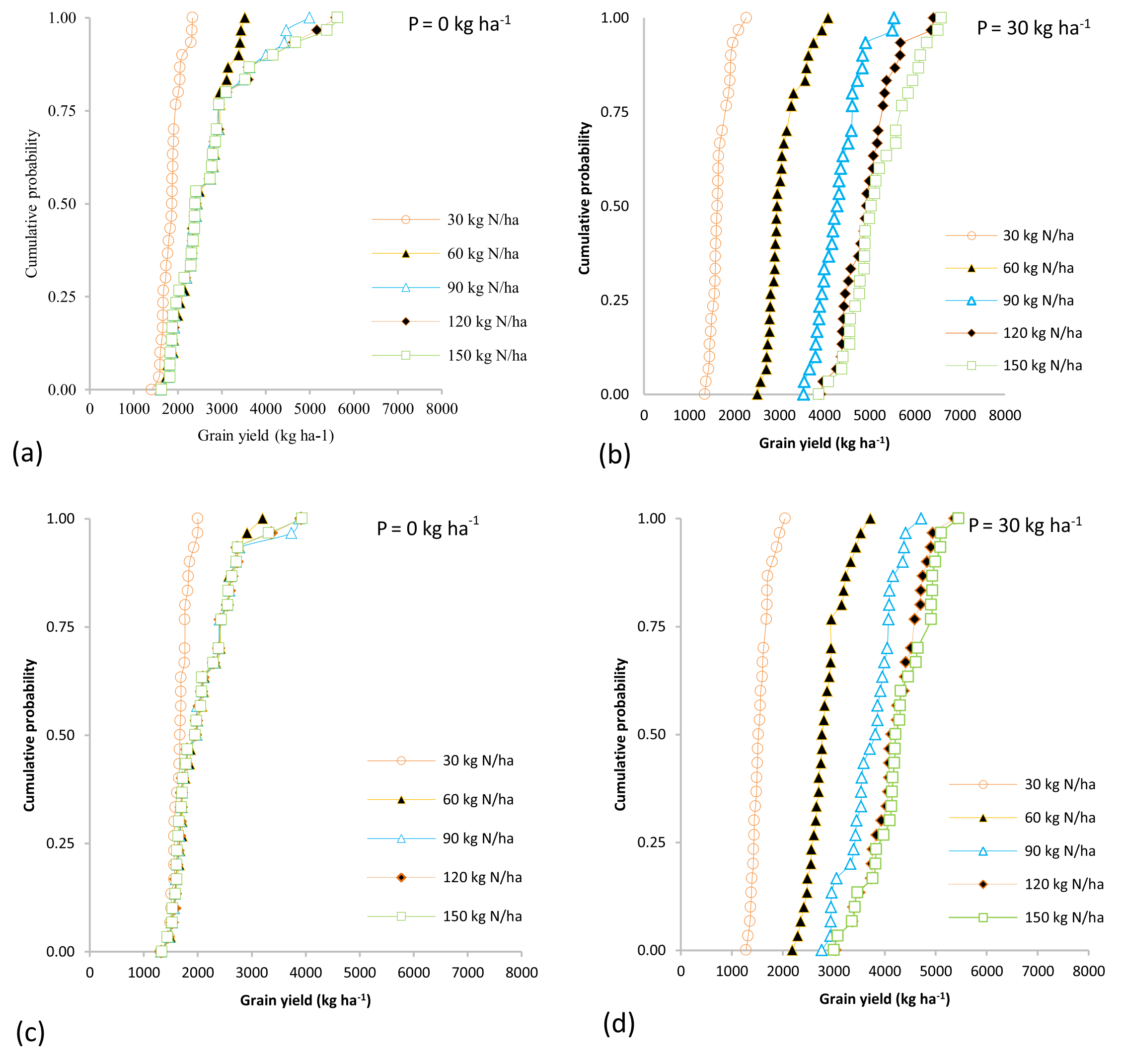

Figure 3. Cumulative probability of maize grain yield in response to N and P fertilization in Abuja in the southern Guinea savanna for SAMMAZ 15 (a) and (b), and SAMMAZ 16 (c) and (d).

simulated mean grain yield showed a consistent decline in maize yield for both future climates relative to the baseline period in all study areas, with higher decrease when P is not applied. Similarly, higher yield reduction was observed in Kano in the Sudan savanna agroecological zone under both RCPs in the two centuries. Generally, a moderate decline in maize yield was observed when P fertilizer was applied at the rate of 30 kg ha^{-1} relative to zero P maize yields. Further increases in the application of P from 30 to 60 kg ha^{-1} under changing climate conditions did not result in a significant change in yield across the three locations. For example, the average yield change between P application at 30 and 60 kg is 0% for both varieties in Abuja. In the two centuries the yield difference is −1% under RCP4.5 and −2% under RCP8.5 for SAMMAZ-16 only in Kano. In Abuja, however, the yield difference between the application of P at 30 and 60 kg for SAMMAZ-16 in the mid-century is −1% under both RCPs.

In Kano (figure 4), when P fertilizer is not applied, simulated maize yield reduced with increasing N rates. Maize yield would reduce from 21%–55% for SAMMAZ-15 and 25%–51% for SAMMAZ-16 with N application of 30–150 kg N ha^{-1}under RCP4.5 in the mid-century. The yield reductions would be 30%–61% for SAMMAZ-15 and 44%–66% for SAMMAZ-16 under RCP8.5. By the end of the century, the maize yield is projected to decrease by 29%–68% under RCP4.5 and by 51%–77% with N application range of 30–150 kg ha^{-1} under RCP8.5 for SAMMAZ-15. For SAMMAZ-16, the reduction would range from 26%–53% under RCP4.5 and from 44%–67% under RCP8.5. In this location, when P is applied at 30 kg ha^{-1}, lowest yield reductions were observed under 60 kg N application in all the climate scenarios for the two varieties. The projected yield reduction in maize yield would range from 10%–19% for SAMMAZ-15 and 10%–21% for SAMMAZ-16 under RCP4.5 with N application range of 30–150 kg ha^{-1} in the mid-century. The reductions would be 16%–27% for SAMMAZ-15 and 16%–29% for SAMMAZ-16 under RCP8.5. By the end of the century, the maize yield would

Table 2. Long-term (30 year) economic and strategy analyses for varying nitrogen fertilizer rates of the two maize varieties under the application of 30 kg P ha^{-1} only in Kano, Zaria and Abuja.

Location/ N rate (kg ha^{-1})	SAMMAZ-15				SAMMAZ-16			
	Monetary return ($ ha^{-1})				Monetary return ($ ha^{-1})			
	E(x)	St. Dev.	E(x) - T(x)	Efficient	E(x)	St. Dev.	E(x) - T(x)	Efficient
Kano in the SS								
30	−53	66	−90	No	−73	69	−113	No
60	410	140	332	No	366	155	281	No
90	864	220	746	No	792	221	671	No
120	1274	305	1111	No	1103	296	946	No
150	1540	343	1354	Yes	1282	345	1089	Yes
Zaria in the NGS								
30	−65	56	−97	No	−97	63	−133	No
60	483	115	416	No	418	122	349	No
90	1099	172	1002	No	979	177	881	No
120	1725	242	1589	No	1429	241	1295	No
150	2014	300	1843	Yes	1608	269	1461	Yes
Abuja in the SGS								
30	72	105	14	No	18	89	−32	No
60	706	193	601	No	584	179	482	No
90	1249	245	1111	No	955	246	813	No
120	1531	295	1365	Yes	1154	274	997	Yes
150	1560	343	1364	Yes	1115	302	942	No

Mean-Gini Dominance: E(x) = mean return, T(x) = Gini coefficient, St. Dev. = Standard deviation.

decrease by 15%–26% for SAMMAZ-15 and by 15%–28% for SAMMAZ-16 under RCP4.5. The yield would reduce by 31%–49% for SAMMAZ-15 and by 31%–51% for SAMMAZ-16 under RCP4.8, with an N application range of 60–150 kg ha^{-1}.

In Zaria (figure 5), when P fertilizer is not applied, simulated maize yield reduced with increasing N application rates. Yield would decline by 45%–54% for SAMMAZ-15 and by 42%–45% for SAMMAZ-16 under both RCP scenarios at N rates of 30–150 kg ha^{-1} in the mid-century. By the end of the century, the maize yield would decrease by 45%–54% under RCP4.5 and by 55%–62% under RCP8.5 for SAMMAZ-15. For SAMMAZ-16, the reduction would range from 42%–44% and 52%–54% under RCP4.5 and RCP8.5, respectively with N application of 30–150 kg ha^{-1}. In this location, when P is applied at 30 kg ha^{-1}, the yield change in maize yield would range from 0%–23% for SAMMAZ-15. The yield will increase by 3% with N application of 30 kg ha^{-1} and reduce by 1%–25% with N application of 60%–150% for SAMMAZ-16 under RCP4.5. Under RCP 8.5, the yield would decrease by 3%–26% for SAMMAZ-15 with N application of 30–150 kg N ha^{-1}in the mid-century. Yield would increase by 1.4% with N application of 30 kg ha^{-1} and decrease by 2%–30% at N rates of 60–150 kg N ha^{-1} for SAMMAZ-16 under RCP8.5. Under RCP4.5. maize yield would decrease by 1%–25% for SAMMAZ-15 by the end of the century. Yield would increase by 2% with N application of 30 kg N ha^{-1} and decrease by 1%–28% with N application of 60–150 kg N ha^{-1} for SAMMAZ-16. The yield would reduce by 13%–49% for SAMMAZ-15 and by 12%–52% for SAMMAZ-16 under RCP4.8, with an N application range of 30–150 kg ha^{-1}.

In Abuja (figure 6), maize yield reduction increased with increase N application, with lower yield reductions under 30 kg N application. When P fertilizer is not applied, a reduction in maize yield would range from 2%–35% for SAMMAZ-15 and 10%–31% for SAMMAZ-16 under RCP4.5. The yield reductions would be 8%–42% for SAMMAZ-15 and 16%–39% for SAMMAZ-16 under RCP8.5 at N rates of 30–150 kg ha^{-1} in the mid-century. By the end of the century, the maize yield will decrease by 9%–42% under RCP4.5 and by 17%–62% under RCP8.5 for SAMMAZ-15. For SAMMAZ-16, the reduction would range from 17%–38% under RCP4.5 and from 38%–58% under RCP8.5, with an N application range of 30–150 kg ha^{-1}. In this location, when P is applied at 30 kg ha^{-1}, a reduction in maize yield would range from 1%–18% for SAMMAZ-15 and 1%–17% for SAMMAZ-16 under RCP4.5. The yield reductions would be 6%–24% for both varieties under RCP8.5 at N rates of 30–150 kg ha^{-1} in the mid-century. By the end of the century, the maize yield would decrease by 5%–23% for both varieties under RCP4.5 and by 17%–43% for SAMMAZ-15 and 19%–43% for SAMMAZ-16 under RCP 8.5, with an N application range of 30–150 kg ha^{-1}.

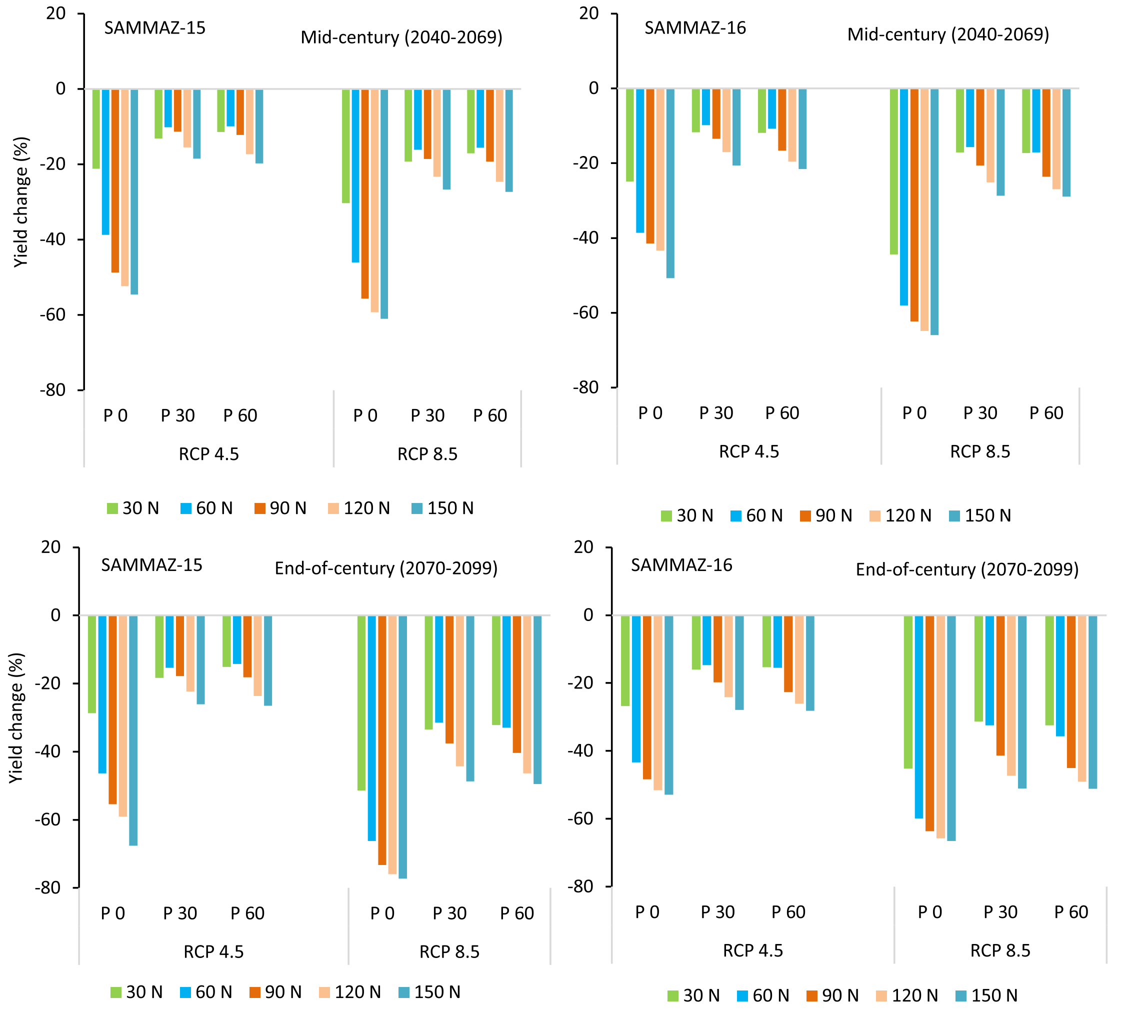

Figure 4. Changes in future maize yields under RCPs 4.5 and 8.5 at mid-century (2040–2069) and end-of-century (2070–2099) relative to the baseline (1980–2010) in Kano.

4. Discussion

The results of the current investigation of seasonal and sensitivity analyses using the CERES Maize model of DSSAT indicated wide variability in maize grain yields under the same N and P rates. This variation can be attributed to differences in rainfall, temperature, and solar radiation among the years within each agroecological zone. The simulations showed that application of N and P increased grain yields of the two test varieties across the three agroecological zones. This result is consistent with the findings of Onasanya *et al* (2009) whose report using field experiments confirms the role of nitrogen and phosphorus fertilizers in increasing the growth and yield of maize production in Nigeria. Similar results were reported by MacCarthy *et al* (2018) in a long-term simulation of maize response to inorganic fertilizers using the APSIM model in the sub-humid region of Ghana. There was a significant effect of nitrogen on grain yield with the application of P at 30 kg P ha^{-1} for both varieties in all the study areas. This is evidenced by the yield increase with an increase in nitrogen rate of above 30 kg N. This suggests that N is an important limiting factor for maize production in the Nigerian savannas. The importance of N to maize production in the savannas using field experiments has been reported by other authors (Sharifai *et al* 2008, Arunah *et al* 2014). Similar results were reported by Adnan *et al* (2017) in their long-term study of nitrogen management for maize in the Sudan savanna using the CERES-Maize model. However, our results also showed that there is a slight increase in yields of maize under zero P when the N application is low (30 kg N) for both varieties compared with applied P rates under the same N application rate, which could be as a result of nutrient imbalance. Unbalanced nutrient availability reduces crop productivity because it effects how plants absorb and utilise nutrients (Bado and Bationo 2018).

When no P fertilizer was applied, grain yields were generally lower in response to added N rates, and maize response to N application beyond 60 kg ha^{-1} was marginal. This could be as a result of low photosynthesis, restrictions on leaf area expansion, and poor grain filling due to P stress effects (Probert 2004). The clear

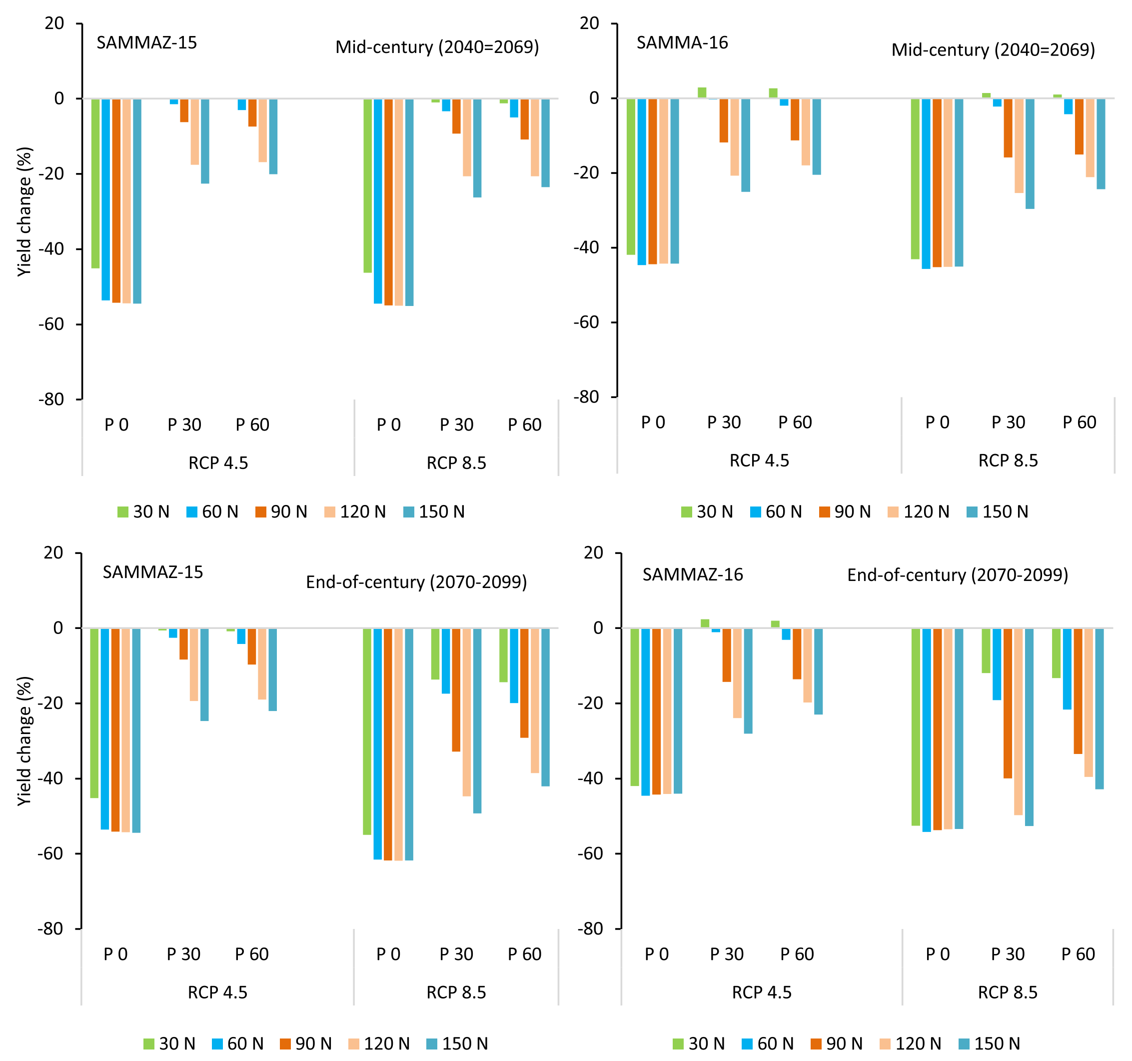

Figure 5. Changes in future maize yields under RCPs 4.5 and 8.5 at mid-century (2040–2069) and end-of-century (2070–2099) relative to the baseline (1980–2010) in Zaria.

response of maize to nitrogen with the application of P fertilizer from 0 to 30 kg ha^{-1}, shows that N response depends on P application at an optimum rate. These results showed that soils are deficient in P and that low soil phosphorus reduces the efficiency of N use by the crops, as suggested by Delve *et al* (2009). Similar results were reported for sorghum (MacCarthy *et al* 2009) in semi-arid region of Ghana and for maize (Kombiok and Elemo 2009) in northern savanna zone of Nigeria. They reported that application of P significantly increased the response of sorghum and maize to N. In all study areas, increasing P from 30 kg P ha^{-1} to 60 kg P ha^{-1} did not result in a significant yield response of maize to N (table 1). Therefore, application of 60 kg P ha^{-1} will not be beneficial as the average mean yield increase across all N rates was $\leqslant 3\%$ for each variety in the SS and approximately 0% for the two varieties in both NGS and SGS when compared with application of 30 kg P ha^{-1}. This is contrary to the blanket recommendations of 60 kg P ha^{-1} for maize in the Nigeria savannas (FFD 2012).

When no P was applied, SAMMAZ-15 only responded to additional N up to 60 kg ha^{-1} in Kano and Abuja and up to 30 kg ha^{-1} in Zaria in 22.5 of 30 years. The variety SAMMAZ-16 only responded to added N up to 30 kg ha^{-1} in all the sites in 22.5 out of 30 years. Therefore, the current study showed that where there is no access to P fertilizer, farmers should not apply N beyond 60 kg ha^{-1} for SAMMAZ-15 and 30 kg ha^{-1} for SAMMAZ-16 in the Sudan and southern Guinea savannas, respectively. When P fertilizer was applied, the varieties responded similarly to the added N. However, as compared to the other two agro-ecologies, the lower minimum guaranteed yield found in Sudan savanna, even at 150 kg N ha^{-1}, could be due to the low average rainfall (795 mm) observed in the region and higher variability in rainfall, with more than 56% of the years falling below the 30-year average rainfall. Our results showed optimum grain yields and higher economic returns with the application of 150 kg N and 30 kg P ha^{-1} to both varieties in Kano in the SS and Zaria in the NGS. In Abuja in the SGS, the optimum grain yields were obtained with the application of 150 kg N ha^{-1} + 30 kg P ha^{-1} to SAMMAZ-15 and 120 kg N ha^{-1} + 30 kg P ha^{-1} to SAMMAZ-16. However, applying 120 kg N ha^{-1} + 30 kg P ha^{-1} to both

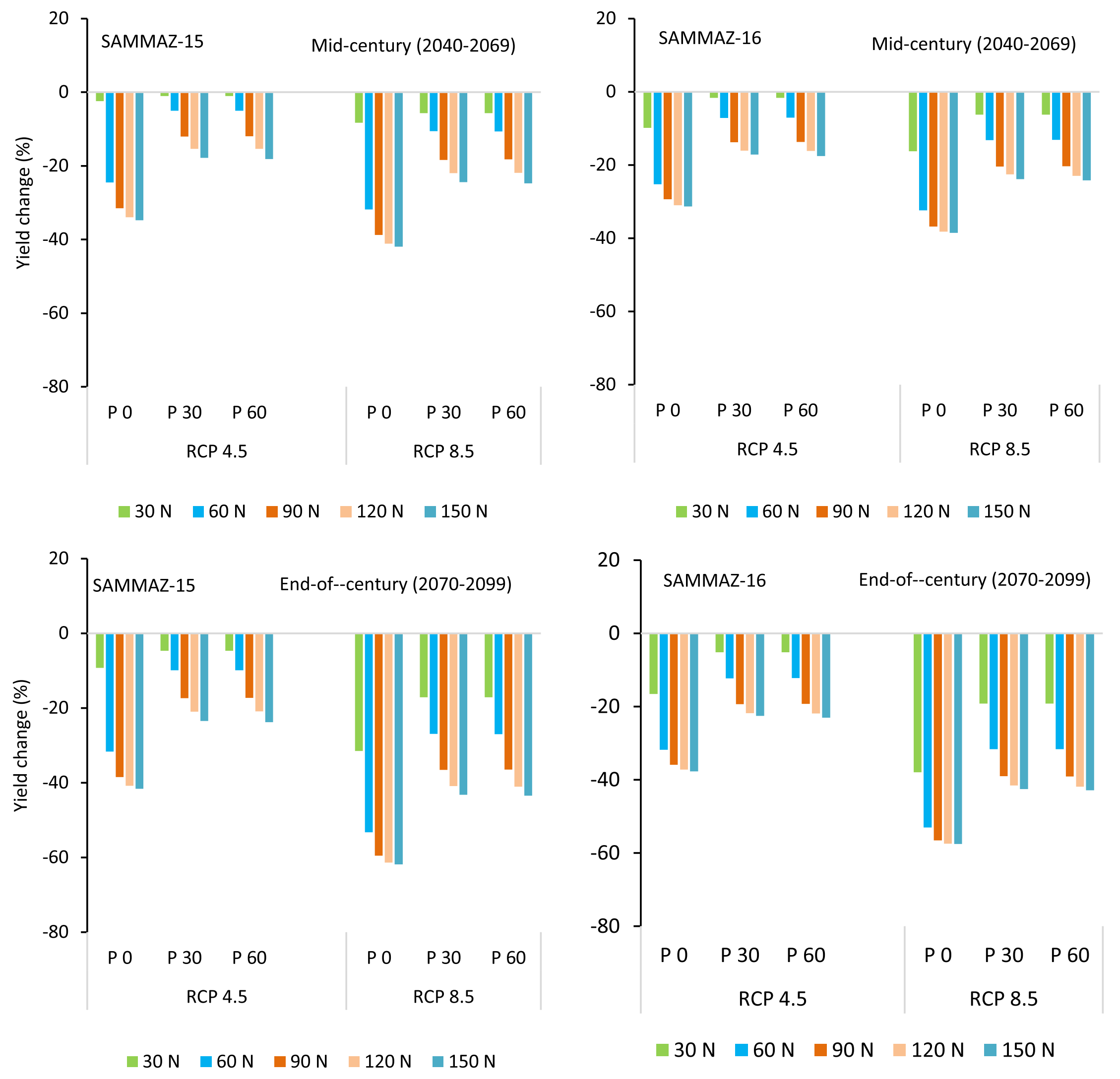

Figure 6. Changes in future maize yields under RCPs 4.5 and 8.5 at mid-century (2040–2069) and end-of-century (2070–2099) relative to the baseline (1980–2010) in Abuja.

varieties gives a higher mean return on investment and is also the most strategically efficient application rate in Abuja. This is contrary to the blanket national recommended rate of 120 kg N + 60 kg P ha^{-1} in these agro-ecologies, suggesting that maize yield response to added N depends on P application at an optimum rate, the variety, and location. With or without P fertilizer application, SAMMAZ-15 was consistently outstanding in all application scenarios across the three agro-ecologies. SAMMAZ-15 is a drought tolerant variety, allowing the variety to be more efficient in N uptake and utilization, as reported by Kamara *et al* (2012).

Our results for climate change analyses revealed that the simulated grain yield would decrease irrespective of P rate applied, variety and time slices (mid- and end-of-century) in all the three locations. Although increasing N resulted in increased yield when P was applied, the yield response of maize to N application was less under future climate conditions compared to baseline yield (figures S1–3). The general yield reductions may be attributed to the increases in temperatures since the models projected increase or no change in rainfall depending on the location of the study (Tofa *et al* 2021). Previous study also revealed that an increase in air temperature might affect maize growth and development (Abraha and Savage 2006, Meza *et al* 2008, Tachie-Obeng *et al* 2013). A reduction in total growth duration shortens the time available for anthesis. This causes a loss of kernels per plant, decreasing the expected yield in comparison to the baseline (Abraha and Savage 2006). Climate change, according to Meza *et al* (2008), will cause crops to mature in a shorter period of time, resulting to about 30% reduction in grain yield in the future. According to Tachie-Obeng *et al* (2013), future increases in air temperature may shorten crop life cycles and accelerate crop growth rates, resulting in higher respiration losses, reduced biomass accumulation, and lower crop yields. Similarly, the yield reductions due to climate change were more pronounced when N was applied at high rates (90–150 kg ha^{-1}) in all locations for both varieties, this could be as a result of high yields produced with high N application compared with lower N rates. This opposes the reports of Mulungu and Ng'ombe (2020), which showed that high nitrogen application reduced the impact of climate change more than low nitrogen application.

Clear trends of decreasing grain yield in the scenarios with no P fertilisation were projected under both centuries. When P is not applied, the simulation results show that across all N rates, maize yield would decrease by 25%–52% and 32%–52% for the mid- and end-of-century, respectively, under RCP4.5 for both varieties. Moreover, there would be a greater reduction under RCP8.5, with a decrease of 32%–59% and 52%–69% under mid- and end-of-century scenarios, respectively. This suggests that N application only will not reduce the impact of high yield loss due to climate change in the study areas. These findings contradict those of Turner and Rao (2013), who found that increasing the nitrogen fertilizer rate from 20 to 80 kg ha^{-1} at a temperature of 3 °C increased sorghum yields by 15%–70% in Kenya. Our findings also contrasted with those of Luo *et al* (2009), who found that increasing nitrogen levels from 25 to 75 kg ha^{-1} increased wheat production in Australia under climate change.

This study shows that yield reduction was lower when P is applied at 30 kg ha^{-1} than when no P is applied in all the locations. Under RCP4.5, yield could decrease by 9%–15% and 11%–21% for the mid- and end-of-century, respectively. There would be a reduction of 12%–21% and 32%–41% for mid-century and end-of-century, respectively, under the RCP8.5 scenario. There is no yield difference observed between application of P at 30 and 60 kg ha^{-1} under climate change scenarios. These suggests that application of optimum P could reduce the impact of yield loss due to climate change in both mid- and end- of century. According to MacCarthy and Vlek (2012), climatic change reduced grain yield by 20% when no fertilizer was applied, but increased yield by 4% when 40 kg N and 30 kg P ha^{-1} were added.

The highest reduction in maize yield would occur in Kano (in the Sudan savanna). The higher reduction in yield in in the Sudan savanna could be due to the increase in temperature predicted (Tofa *et al* 2021) coupled with short raining season in this location. This is consistent with the findings of Tesfaye *et al* (2018) and Tofa *et al* (2021), who both reported higher yield reductions in the drier Sudan savannas than the wetter Guinea savannas due to climate change. The moderate reduction in yield in Abuja and Zaria is probably due high rainfall predicted and better soil condition in these regions that could have reduced the effect of the increased in temperatures. While N and P were found to significantly influence maize yield in the study areas of northern Nigeria, other crop management practices that equally influence maize yield were not considered in the simulations. Other crop management practices that can be used to improve yield and crop resilience to the vagaries of climate change include irrigation (Kassie *et al* 2015, Araya *et al* 2017) and planting date (White *et al* 2011). In this study, the optimum planting date (Tofa *et al* 2020) was considered for both varieties in each location. One planting date may not be feasible for all the varieties under climate change, considering the climate variability between the seasons. Similarly, in the context of climate change, the intermediate-maturing varieties used in this research may not be a feasible option in the Sudan savanna agroecological zone. Therefore, early maturing maize cultivars should be evaluated to substitute for the current intermediate cultivars in the zone as a climate change adaptation strategy. Further research is therefore needed to look at the influence of other crop management practices like irrigation, planting date, and early maturing varieties for optimum maize production under climate change in northern Nigeria.

5. Conclusion

In this study, we examined the ability of the DSSAT CERES-Maize model to accurately simulate maize response to N and P fertilizer under changing climate in the Nigerian savannas. The 30-year, long-term simulation showed that the use of both N and P fertilizers significantly increased maize grain yield. This confirmed that soils in the Sudan and Guinea savannas of northern Nigeria are deficient in N and P, with N being the most limiting nutrient for maize production. The results also showed that maize response to nitrogen application was strongly dependent on the application of P in all the agroecological zones. When P was not applied, the response to N applications varied among varieties, years, and locations, suggesting the need to have fertilizer recommendations based on location and variety. Therefore, for optimum grain yields, an application of 150 kg N + 30 kg P ha^{-1} to the two varieties is recommended in Kano in the Sudan savanna and Zaria in the northern Guinea savanna. In Abuja, in the Southern Guinea savanna, the recommended N and P applications for optimum grain yields were 150 kg N ha^{-1} + 30 kg P ha^{-1} for SAMMAZ-15 and 120 kg N ha^{-1} + 30 kg P ha^{-1} for SAMMAZ-16. The climate change analyses showed that the simulated grain yield would decrease irrespective of P rate applied, variety, and time slices (mid- and end-of-century) but the reduction may vary with location. The general yield reductions may be attributed to the increases in temperatures projected in all the study areas. Yield reductions due to climate change were more pronounced when N was applied at high rates (90–150 kg ha^{-1}) compared with lower N rates for both varieties. When P is not applied, there would be a greater reduction in yield in both mid-century and end-of-century under the two RCP scenarios. This suggests that N application alone will not reduce the impact of high yield loss due to climate change in the study areas. Under future climate conditions, grain yield reduction was lower when P was applied at 30 kg ha^{-1} than when no P was applied. Under both climate change scenarios, there is no difference in yield between P applications at 30 and 60 kg ha^{-1}. These suggest that application of optimum P could reduce the impact of yield loss due to climate change in both the mid- and end of the century. Other crop management practices that can be used to improve yield and crop resilience to the vagaries of climate change include irrigation (Kassie *et al* 2015, Araya *et al* 2017) and planting date (White *et al* 2011). In this study, the optimum planting date (Tofa *et al* 2020) was considered for both varieties in each location. One planting date may not be feasible for all the varieties under climate change, considering the climate variability between the seasons. Similarly, in the context of climate change, the intermediate-maturing varieties used in this research may not be a feasible option in the Sudan savanna agroecological zone. Therefore, early maturing maize cultivars should be evaluated to substitute for the current intermediate cultivars in the zone as a climate change adaptation strategy. Further research is therefore needed to look at the influence of other crop management practices like irrigation, planting date, and early maturing varieties for optimum maize production under climate change in northern Nigeria.

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Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers.

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Author contributions

Kamara A Y designed the research and managed the project. Kamara A Y, Babaji B A, Tofa A I, Ademulegun T D, Bebeley J F facilitated the research and managed the data. Tofa A I prepared the manuscript with contributions from all co-authors.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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