Relationship between Climatic Variables and the Production of Maize, Rice, Sorghum and Cowpea in Kaduna State, Nigeria (2010-2025)

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ABSTRACT

This study examined the relationship between climatic variables and the production of maize, rice, sorghum and cowpea in Kaduna State, Nigeria, over sixteen years, 2010 to 2025. Sixteen years of crop yield data obtained from the National Agricultural Extension and Research Liaison Services and the National Bureau of Statistics were matched with corresponding climatic variables derived from Nigerian Meteorological Agency rainfall and temperature records, including total rainfall, dry spell frequency, rainfall onset and cessation dates, length of the growing season, and air temperature, and the relationships were quantified using multiple linear regression. Maize production ranged from 798.43 to 943.19 metric tons, with a coefficient of variation of 5.32 percent, and the fitted model explained 78 percent of yield variation, with rainfall and dry spell frequency as the strongest predictors. Sorghum production ranged from 812 to 927.75 metric tons, and the model explained 86 percent of yield variation, with rainfall, dry spells and air temperature all statistically significant. Rice production ranged from 300 to 470 metric tons, with a coefficient of variation of approximately 11.7 percent, and the model explained 89 percent of yield variation, with rainfall and minimum temperature as significant predictors. Cowpea production ranged from 100.07 to 195.45 kilograms per hectare, with a coefficient of variation of 31 percent, the highest among the four crops, and the model explained 87 percent of yield variation, with rainfall and dry spell frequency as highly significant predictors. Predictive validation using root mean square error confirmed strong model reliability, with deviations of 13 kilograms per hectare for maize, 11.29 for sorghum, 9.32 for rice and 9.99 for cowpea. Across all four crops, rainfall and dry spell frequency emerged as the most consistent determinants of yield, while the strength and direction of onset, cessation, temperature and growing season effects varied by crop. The study recommends crop-specific climate advisory services, expanded access to dry-spell-tolerant varieties, and the integration of climate-yield regression models into seasonal agricultural planning in Kaduna State.

Keywords: Climate-Yield Relationship, Maize, Rice, Sorghum, Cowpea, Multiple Linear Regression, Kaduna State.

1. INTRODUCTION

Agriculture remains central to Nigeria's economy and food security, contributing approximately 35 percent of gross domestic product in 2024 and employing the majority of the working population (National Bureau of Statistics, 2024). Approximately 78 percent of Nigeria's land area is devoted to agriculture, yet only about 1 percent of farmland is irrigated, leaving the sector predominantly rain fed and highly exposed to climatic shocks (Food and Agriculture Organization, 2018). Projections indicate that rising temperatures, increased frequency of extreme rainfall events, prolonged dry spells and increasing aridity will significantly disrupt agricultural systems across the country (Intergovernmental Panel on Climate Change, 2021).

Kaduna State, in the northern Guinea savanna zone of Nigeria, is a leading producer of maize, sorghum, rice and cowpea, staple crops whose productivity is closely tied to the timing and distribution of rainfall and temperature. Climate variability affects these crops differently, depending on their physiological sensitivity to

moisture stress, temperature extremes and growing season length, so that interventions designed around aggregate climatic trends may not adequately address crop-specific vulnerabilities (Shiferaw, Tesfaye, Kassie, Abate, Prasanna and Menkir, 2011). Understanding the statistical relationship between specific climatic variables and the yield of each crop is therefore essential for designing targeted, climate-informed agricultural advisory services.

While the general impact of climate change on agriculture in Nigeria has received considerable research attention, quantitative, crop-specific regression analyses linking climatic variables to the yields of maize, rice, sorghum and cowpea within Kaduna State remain limited. This study addresses this gap by developing multiple linear regression models relating rainfall, dry spell frequency, rainfall onset and cessation, length of the growing season and air temperature to the production of these four staple crops over 2010 to 2025, and by validating the resulting models against observed yield data.

2. STUDY AREA

Kaduna State lies in northwestern Nigeria, between latitudes 8 degrees 49 minutes 30 seconds North and 11 degrees 15 minutes 20 seconds North, and longitudes 6 degrees 45 minutes 45 seconds East and 8 degrees 26 minutes 15 seconds East. Agriculture is the primary livelihood and largest employer of labour in the state, with Kaduna ranking first nationally in maize and ginger production, second in soybean, third in tomato, fourth in sorghum and tenth in cowpea production (NAERLS and Federal Ministry of Agriculture and Rural Development, 2019).

The state lies within the northern Guinea savanna zone, experiencing a tropical continental climate with a single wet season from April or May to October, peaking in July and August, and a dry season from November to March dominated by the Harmattan. Annual rainfall ranges from about 1,000 millimetres in the north to over 1,500 millimetres in the south, and the length of the growing season varies from approximately 150 days in the north to over 180 days in the south. Maize is cultivated widely across the state, cowpea is concentrated in the northern-central local government areas of Giwa, Igabi, Soba and Zaria, sorghum is concentrated in the northeastern areas of Makarfi and Ikara, and rice is cultivated predominantly in the southern local government areas of Kajuru, Kachia, Zangon Kataf, Kaura and Jema'a, where higher rainfall, lowland valleys and river floodplains support both rain fed and irrigated production.

3. METHODOLOGY

Data Sources

Annual yield data for maize, rice, sorghum and cowpea for the period 2010 to 2025 were obtained from the National Agricultural Extension and Research Liaison Services and the National Bureau of Statistics. Corresponding daily rainfall and temperature data for the same period were obtained from the archives of the Nigerian Meteorological Agency and aggregated into the annual climatic indices described below. All datasets were reviewed for completeness and consistency before analysis.

Derivation of Climatic Predictor Variables

Six climatic predictor variables were derived for use in the regression models: total annual rainfall, computed by summing daily rainfall within each year; dry spell frequency, defined as the number of consecutive days with rainfall not exceeding 0.85 millimetres, computed separately for the early and late season periods; rainfall onset and cessation dates, determined in Julian days using the method of Walter (1967) as modified by Olaniran (1983) for onset, and the soil water balance and rainfall threshold methods of Adefolalu (1985) for cessation; length of the growing season, computed as the interval between onset and cessation; and mean annual air temperature, computed from daily maximum and minimum temperature records.

Multiple Linear Regression Modelling

For each crop, a multiple linear regression model was specified to estimate yield as a linear function of the relevant climatic predictors, selected on the basis of established agronomic relevance and statistical significance

in preliminary testing. The general form of the model is yi equals b0 plus b1x1 plus b2x2 plus the sum of further terms bnxn, where yi is predicted crop yield, b0 is the intercept, and b1 through bn are the estimated regression coefficients for each climatic predictor x1 through xn. Model coefficients were estimated using ordinary least squares in Python, and the statistical significance of each coefficient was assessed using t-tests at the 1, 5 and 10 percent levels. The overall explanatory power of each model was assessed using the coefficient of determination, R squared.

Model Validation

The predictive performance of each model was validated by comparing predicted yields, generated from the fitted regression equation, with the corresponding observed yields for each year of the study period. Model accuracy was quantified using the root mean square error, computed as the square root of the mean of the squared differences between observed and predicted values across all sixteen years, together with the relative error expressed as a percentage of the observed yield range.

4. RESULTS AND DISCUSSION

4.1 Production Levels of Maize, Rice, Sorghum and Cowpea

Maize production exhibited a broadly consistent upward trajectory over the study period, rising from approximately 798.43 metric tons in 2010 to peaks near 900 metric tons by 2014, with the highest yield of 943.19 metric tons recorded in 2022 and a notable decline to 815.16 metric tons in 2024. The coefficient of variation of 5.32 percent indicates moderate year to year fluctuation and comparatively high production stability relative to the other three crops, and trend analysis yielded a highly significant positive slope (p less than 0.001), reinforcing the central role of climatic parameters, particularly rainfall, in sustaining Kaduna State's position as Nigeria's leading maize producing state.

Sorghum production fluctuated between a minimum of 812 metric tons in 2016 and a maximum of 927.75 metric tons in 2010, with the fitted linear trend showing a gradual downward trajectory over the study period despite occasional recovery years. Production remained relatively high and stable during 2010 to 2015, generally exceeding 900 metric tons, in years that coincided with favourable rainfall onset conditions and lower dry spell intensity, before a sharp decline to the series minimum of 812 metric tons in 2016, coinciding with pronounced early season dry spells and erratic rainfall distribution.

Rice production ranged from a low of approximately 300 metric tons, recorded in 2016, 2017 and 2019, to a peak of 470 metric tons in 2022, reflecting a combination of early rainfall onset, minimal mid-season dry spell activity and favourable thermal conditions in that year, followed by a decline to between 310 and 320 metric tons in 2023 to 2025. The coefficient of variation of approximately 11.7 percent indicates comparatively low to moderate interannual variability, a pattern associated with the increased adoption of improved rice varieties and localised water management practices in the southern rice growing local government areas.

Cowpea production exhibited the greatest variability of the four crops, ranging from 100.07 to 195.45 kilograms per hectare, with a coefficient of variation of 31 percent. Low and unstable production characterised the early years of the study period, 2010 to 2012, followed by a sharp increase in 2013 and 2014 that produced the highest output of the series, a gradual decline between 2015 and 2017, and renewed fluctuation thereafter, including a rise to 161.95 kilograms per hectare in 2022 followed by declines to 142.42 kilograms per hectare in 2023 and approximately 140 kilograms per hectare in 2024, reflecting the combined influence of rainfall timing, input availability and pest and disease pressure.

4.2 Climate-Yield Relationship: Maize

The relationship between climatic parameters and maize yield was modelled as yi equals negative 617.1 plus 0.15x1 minus 6.09x2 minus 0.13x3 plus 45.52x4, where x1 is rainfall in millimetres, x2 is dry spell frequency in days, x3 is rainfall onset in Julian days and x4 is air temperature in degrees Celsius. Rainfall exhibited a statistically significant positive relationship with maize yield at the 1, 5 and 10 percent levels (p equals

0.0000577), with each additional millimetre of rainfall associated with a 0.15 metric ton increase in yield. Dry spell frequency had a significant negative effect at the 5 and 10 percent levels (p equals 0.0447), with each additional dry day reducing yield by approximately 6.09 metric tons, consistent with Kabore, Sivakumar and Traore (2021), who found that dry spells during tasselling and grain filling were the most damaging to cereal performance. Rainfall onset was negatively associated with yield but not statistically significant (p equals 0.4475). Air temperature showed a positive relationship significant at the 10 percent level (p equals 0.0795). The model explained 78 percent of the variation in maize yield (R squared equals 0.773).

Parameter	p-value	Significant at 5%
Rainfall (x1)	5.8E-05	Yes
Dry Spell Frequency (x2)	0.0447	Yes
Rainfall Onset (x3)	0.4475	No
Air Temperature (x4)	0.0795	No

Table 1: Significance of Climatic Predictors in the Maize Yield Model (R2 = 0.773)

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

4.3 Climate-Yield Relationship: Sorghum

The sorghum model was specified as yi equals 2398.91 plus 0.12x1 minus 5.83x2 plus 1.24x3 minus 61.95x4 minus 0.12x5, where x1 is rainfall, x2 is dry spell frequency, x3 is air temperature, x4 is rainfall onset and x5 is length of the growing season. Rainfall (p equals 0.0000639), dry spell frequency (p equals 0.00745) and air temperature (p equals 0.00299) were all statistically significant at the 1 and 5 percent levels. Each additional millimetre of rainfall increased yield by 0.12 metric tons, while each additional dry spell day reduced yield by 5.83 metric tons. Rainfall onset showed a strong negative influence, significant only at the 10 percent level (p equals 0.0714), with a one day delay in onset associated with a 61.95 metric ton reduction in yield, underscoring the importance of timely planting for sorghum establishment (Adiku, Dawoe and Codjoe, 2015). Length of the growing season was not statistically significant (p equals 0.8134). The model explained 86 percent of the variation in sorghum yield.

Parameter	p-value	Significant at 5%
Rainfall (x1)	0.0000639	Yes
Dry Spells (x2)	0.00745	Yes
Rainfall Onset (x3)	0.0714	No
Air Temperature (x4)	0.00299	Yes
Length of Growing Season (x5)	0.8134	No

Table 2: Significance of Climatic Predictors in the Sorghum Yield Model (R2 = 0.86)

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

4.4 Climate-Yield Relationship: Rice

The rice model was specified as yi equals 385.86 plus 0.13x1 minus 33.45x2 plus 0.56x3 plus 8.95x4, where x1 is rainfall, x2 is minimum temperature, x3 is maximum temperature and x4 is length of the growing season. Rainfall was a highly significant positive predictor (p equals 0.0000011). Minimum temperature exerted a substantial negative effect, significant at the 5 and 10 percent levels (p equals 0.0252), with each unit increase in minimum temperature reducing yield by approximately 33.45 metric tons, consistent with evidence that elevated nighttime temperatures disrupt grain filling and reduce spikelet fertility in rice (Peng, Huang, Sheehy, Laza, Visperas, Zhong, Centeno, Khush and Cassman, 2004). Maximum temperature and length of the growing season were positively associated with yield but not statistically significant (p equals 0.3137 and p equals 0.0711

respectively). The model explained 89 percent of the variation in rice yield, the highest explanatory power among the four crops.

Parameter	p-value	Significant at 5%
Rainfall (x1)	1.1E-06	Yes
Minimum Temperature (x2)	0.0252	Yes
Maximum Temperature (x3)	0.3137	No
Length of Growing Season (x4)	0.0711	No

Table 3: Significance of Climatic Predictors in the Rice Yield Model (R2 = 0.892)

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

4.5 Climate-Yield Relationship: Cowpea

The cowpea model was specified as yi equals negative 0.06 plus 0.47x1 minus 0.16x2 minus 0.38x3 minus 0.88x4 plus 0.25x5 plus 0.50x6, where x1 is rainfall, x2 is dry spell frequency, x3 is length of the growing season, x4 is cessation, x5 is onset and x6 is temperature. Rainfall (p equals 0.000526) and dry spell frequency (p equals 0.000153) were both highly significant at the 1, 5 and 10 percent levels, confirming cowpea's strong sensitivity to water availability (Hall, 2004; Singh and Ajeigbe, 2002). Length of the growing season, cessation and onset were not statistically significant (p equals 0.3379, 0.3566 and 0.7530 respectively). The model explained 87 percent of the variation in cowpea yield.

Parameter	p-value	Significant at 5%
Rainfall (x1)	0.000526	Yes
Dry Spells (x2)	0.000153	Yes
Length of Growing Season (x3)	0.3379	No
Cessation (x4)	0.3566	No
Onset (x5)	0.753	No

Table 4: Significance of Climatic Predictors in the Cowpea Yield Model (R2 = 0.87)

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

4.6 Summary of Model Explanatory Power

Crop	R-squared (R2)	Percentage of Yield Variation Explained
Maize	0.773	77.30%
Rice	0.892	89.20%
Sorghum	0.86	86.00%
Cowpea	0.87	87.00%

Table 5: Coefficient of Determination for Each Climate-Yield Regression Model, Kaduna State, 2010-2025

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

4.7 Model Validation and Predictive Accuracy

The predictive performance of each model was validated against observed yields across the sixteen year study period. The maize model achieved a root mean square error of 13 kilograms per hectare, with predicted and actual yields closely aligned in most years, for example, 2010 actual yield of 798.43 against a predicted value

of 801.64, and the 2022 peak actual yield of 943.19 against a predicted value of 942.50. The sorghum model achieved a root mean square error of 11.29 kilograms per hectare, equivalent to a relative error of approximately 1.2 percent. The rice model achieved a root mean square error of 9.32 kilograms per hectare, equivalent to a prediction error of about 2 percent, given the observed yield range of approximately 300 to 470 kilograms per hectare. The cowpea model achieved a root mean square error of 9.99 kilograms per hectare, equivalent to a prediction error of about 6.6 percent given the narrower observed range of 100 to 195 kilograms per hectare. Table 6 summarises the validation statistics for all four crops.

Crop	RMSE (kg/ha)	R2	Approx. Relative Error
Maize	13	0.773	~2.0%
Sorghum	11.29	0.86	~1.2%
Rice	9.32	0.892	~2.0%
Cowpea	9.99	0.87	~6.6%

Table 6: Root Mean Square Error and Predictive Accuracy of the Climate-Yield Models, Kaduna State, 2010-2025

Source: Author's Computation from NAERLS, NBS and Nigerian Meteorological Agency Data

5. DISCUSSION

Across all four crops, rainfall emerged as the single most consistent and statistically significant determinant of yield, confirming the predominantly rain fed nature of crop production in Kaduna State and aligning with the broader literature on rainfall sensitivity in West African cereal and legume systems (Lobell and Burke, 2010; Food and Agriculture Organization, 2016). Dry spell frequency was likewise a significant negative predictor for maize, sorghum and cowpea, underscoring the agronomic importance of intra-seasonal moisture distribution over total seasonal rainfall volume, a pattern also identified in the companion analysis of climatic variability in this state.

The crops diverged, however, in their sensitivity to onset timing, cessation and temperature. Sorghum showed the strongest negative response to delayed onset, reflecting its reliance on timely establishment in drier, more marginal growing environments, while maize showed a comparatively modest, non-significant onset effect. Rice was distinctively sensitive to minimum temperature, consistent with well documented evidence that elevated nighttime temperatures impair spikelet fertility and grain filling (Peng et al., 2004), a mechanism not relevant to the other three crops. Cowpea stood apart in its sensitivity to cessation timing, with delayed cessation substantially reducing yield, likely through excess moisture during pod development and elevated disease pressure (Hall, 2004).

The consistently high explanatory power of the four models, ranging from 77 to 89 percent of yield variation explained, together with root mean square errors equivalent to only 1.2 to 6.6 percent of each crop's observed yield range, demonstrates that climate-based regression models can provide a statistically robust basis for seasonal yield forecasting in Kaduna State. The comparatively higher relative error for cowpea reflects its narrower absolute yield range and its documented sensitivity to non-climatic factors such as pest pressure and input access (Food and Agriculture Organization, 2018), rather than a weakness in the underlying climatic relationship.

These findings have direct implications for agricultural advisory practice. Because the dominant climatic drivers differ by crop, a single, undifferentiated climate advisory message is unlikely to serve farmers of all four crops equally well; advisory content should instead be tailored to each crop's specific climatic sensitivities, prioritising dry spell warnings for maize, sorghum and cowpea growers, onset timing guidance for sorghum growers, and temperature-informed guidance for rice growers.

The spatial concentration of each crop within particular local government areas of Kaduna State, with cowpea concentrated in the northern-central areas of Giwa, Igabi, Soba and Zaria, sorghum in the northeastern areas of

Makarfi and Ikara, maize cultivated widely across northern, central and southern local government areas, and rice concentrated in the southern floodplain areas of Kajuru, Kachia, Zangon Kataf, Kaura and Jema'a, means that the crop-specific climatic sensitivities identified in this study map onto distinct geographic zones. This spatial correspondence strengthens the case for zonally differentiated agricultural advisory and input distribution strategies, rather than a uniform state-wide approach, and provides a practical basis for targeting limited extension resources toward the climatic risks most relevant to each zone's dominant crop.

From a food security standpoint, the comparatively high unexplained variability in cowpea yield, together with its role as a key protein and income source for smallholder households, suggests that climate-based forecasting alone will not be sufficient to stabilise cowpea output, and that complementary investment in pest and disease management, input access and post-harvest handling is required alongside climate advisory services. By contrast, the strong climatic fit obtained for maize and rice indicates that climate-informed forecasting can meaningfully strengthen planning for these two crops, which together account for a substantial share of staple food supply in the state.

6. CONCLUSION

This study has quantified the relationship between climatic variables and the production of maize, rice, sorghum and cowpea in Kaduna State over 2010 to 2025 using multiple linear regression. Rainfall and dry spell frequency were confirmed as the most consistent determinants of yield across all four crops, while onset timing, cessation and temperature exerted crop-specific effects, most notably the strong negative sensitivity of sorghum to delayed onset, the distinctive sensitivity of rice to minimum temperature, and the pronounced sensitivity of cowpea to delayed cessation. The models explained between 77 and 89 percent of observed yield variation and validated with root mean square errors within acceptable agronomic tolerances for all four crops, confirming their suitability for integration into climate-informed advisory and forecasting systems in Kaduna State.

7. RECOMMENDATIONS

i. Crop-specific climate advisory services should be developed, prioritising dry spell alerts for maize, sorghum and cowpea farmers, and temperature-informed guidance for rice farmers.

ii. Timely planting support and onset forecasting should be strengthened for sorghum growing areas, given the crop's pronounced sensitivity to delayed rainfall onset.

iii. The climate-yield regression models developed in this study should be integrated into seasonal agricultural planning and early warning systems operated by state agricultural agencies.

iv. Non-climatic constraints on cowpea production, including pest pressure and input access, should be addressed alongside climate-focused interventions, given the crop's comparatively high unexplained yield variability.

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