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Climate Variability and Livestock Production Output in Nigeria: A Spatiotemporal Analysis of Temperature, Rainfall and Livestock Population Trends

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Abstract

Climate variability increasingly threatens livestock productivity, animal welfare and the spatial stability of food-animal systems in tropical countries. This study examined long-run temperature, rainfall and livestock-output dynamics in Nigeria using secondary data for 1961-2022 and state-level livestock counts from the 2022 National Agricultural Sample Census. The analytical framework combined the Mann-Kendall trend test, Sen slope estimator, quantile regression, Bai-Perron multiple-break analysis, Markov-switching regression, tropical livestock-unit conversion, spatial concentration indices and information-criterion diagnostics. Maximum, minimum and midpoint temperatures increased significantly, with minimum temperature rising more rapidly and indicating reduced nocturnal recovery from heat load. Annual rainfall showed strong interannual variability but no uniform national monotonic trend. The livestock production index expanded at an estimated compound annual growth rate of 3.13%. AIC/BIC comparisons showed that AR(1) correction was essential: the linear AR(1) model was most parsimonious, while the segmented AR(1) specification produced the lowest RMSE and best residual normality. Robust HAC, Huber, Theil-Sen and quantile slopes remained tightly clustered. Approximately 85.60% of national tropical livestock units were located in northern Nigeria, demonstrating strong spatial exposure to warming, drought, pasture stress and water insecurity. Climate-resilient breeding, water and feed security, heat abatement and integrated surveillance are recommended.

Keywords: Climate Variability; Heat Stress; Livestock Production; Rainfall; Spatial Concentration; Nigeria

Introduction

Livestock production is a strategic component of Nigeria's agricultural economy and national food system. Cattle, sheep, goats, pigs and poultry supply meat, milk, eggs, hides, manure, traction, employment and household savings. The sector also supports traders, feed manufacturers, veterinarians, processors and transporters. Yet livestock production is biologically dependent on environmental conditions that determine animal heat balance, forage growth, water availability, disease ecology and reproductive performance. Climate variability therefore affects livestock systems directly through animal physiology and indirectly through feed, water, land use, markets and animal-health pathways [1-4].

The climatic sensitivity of livestock is especially pronounced in tropical environments. Animals maintain productivity only while body heat production and environmental heat gain remain within the capacity of

physiological heat dissipation. When ambient temperature, humidity and solar radiation exceed the animal's thermoneutral range, feed intake declines while respiration rate, peripheral blood flow, panting and water consumption increase. Prolonged heat stress can depress growth, milk yield, fertility, egg production, immunity and survival [2-6]. High night-time temperatures are particularly important because they restrict the recovery that would normally occur after daytime heat exposure.

Rainfall variability influences livestock production through pasture biomass, drinking-water availability, crop-residue supply, wetland conditions and disease-vector habitats. Low or delayed rainfall can shorten the growing season, reduce forage quality and increase grazing distances. Severe drought concentrates animals around limited water points, raises mortality and encourages distress sales. Conversely, intense rainfall and flooding may destroy shelters, isolate markets, contaminate water and increase vector-borne or water-associated disease risks. The effect of rainfall is therefore nonlinear: both deficit and excess can reduce output, while the seasonal distribution of rainfall may matter more than annual totals [7-11].

Nigeria spans humid coastal, derived savannah, Guinea savannah, Sudan savannah and Sahelian environments. Livestock species and management systems are not evenly distributed across these zones. Ruminant herds are concentrated in northern regions where extensive and semi-intensive grazing systems remain important, whereas commercial poultry and pig systems have expanded in southern and peri-urban production corridors. This uneven geography creates differentiated climate exposure. Northern systems are highly sensitive to drought, pasture scarcity, heat and water insecurity, while humid-zone systems experience heat-humidity stress, flooding, disease pressure and competition for land.

Previous Nigerian studies have discussed climate change and livestock production or estimated aggregate econometric relationships [10,12-14]. However, three analytical limitations remain. First, national mean regressions may obscure nonlinear effects and differences between low- and high-output periods. Second, livestock-output growth may contain structural breaks and latent volatility regimes that conventional linear models cannot adequately represent. Third, temporal analyses are often disconnected from the spatial concentration of livestock populations, even though the same national climatic shock can produce very different regional consequences.

This study addresses these limitations through a spatiotemporal analytical framework that integrates robust trend tests, quantile regression, multiple structural-break analysis, regime-switching modelling and spatial concentration measures. The purpose is not merely to determine whether livestock production increased or decreased, but to evaluate whether the trajectory was stable, whether climatic exposure intensified and whether the geographical concentration of animals creates systemic national vulnerability.

The specific objectives were to: (i) estimate long-run trends in maximum, minimum and midpoint temperature and annual rainfall; (ii) characterise the growth, distribution and volatility of Nigeria's livestock production index; (iii) identify structural breaks and latent production regimes; (iv) quantify the state and regional concentration of livestock populations using tropical livestock units and inequality indices; and (v) derive evidence-based adaptation priorities for livestock production, animal health and food security.

Materials and Methods

Study Area

Nigeria lies between approximately 4 degrees and 14 degrees north latitude and 3 degrees and 15 degrees east longitude. Its climate varies from humid tropical conditions in the south to semi-arid and arid conditions in the far north. Mean annual rainfall generally declines northward, while temperature and evaporative demand increase. The country's agroecological diversity supports intensive poultry and pig systems, mixed crop-livestock production, pastoral and agropastoral ruminant systems, dairy enterprises and smallholder backyard production.

The spatial livestock analysis covered the 36 states and the Federal Capital Territory. For regional interpretation, states were grouped into the North West, North East, North Central, South West, South East and South South geopolitical zones. Northern Nigeria comprised the first three zones, while southern Nigeria comprised the latter three.

Research Design and Data Sources

The study adopted a longitudinal ecological design using publicly available secondary data. Annual climate and livestock-output series covered 1961-2022. The temporal unit of analysis was the calendar year, while the spatial unit was the state. The design was appropriate for identifying long-term patterns, discontinuities and regional concentration without exposing human participants or experimental animals to research procedures.

Temperature and rainfall series were obtained from globally recognised gridded climate products and national aggregates distributed through the World Bank Climate Change Knowledge Portal and related climate repositories [16,17]. The livestock production index, measured relative

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to the 2014-2016 base period, was obtained from the World Development Indicators [15]. State-level counts of cattle, sheep, goats, pigs and poultry were extracted from the 2022 National Agricultural Sample Census [18] (Tables 1-6).

Variable	Measurement	Period/Unit	Primary Source
Maximum temperature	Annual national mean of daily maximum temperature	1961-2022; degrees C	World Bank/CRU climate series
Minimum temperature	Annual national mean of daily minimum temperature	1961-2022; degrees C	World Bank/CRU climate series
Midpoint temperature	Arithmetic midpoint of annual maximum and minimum temperature	1961-2022; degrees C	Derived
Rainfall	Annual precipitation total	1961-2022; mm	World Bank/CRU climate series
Livestock production index	Aggregate output of livestock commodities	1961-2022; 2014-2016=100	World Development Indicators
Livestock counts	Cattle, sheep, goats, pigs and poultry by state	2022; number of animals	NASC 2022
Tropical livestock units	Weighted standardisation of species counts	2022; TLU	Derived from livestock counts

Table 1: Variables, measurements and data sources.

Variable Construction

The midpoint temperature was constructed as the average of annual maximum and minimum temperature. This provided a simple indicator of the central thermal condition while preserving separate analyses of daytime and night-time warming. Livestock-output growth was evaluated using annual percentage change and compound annual growth rate.

To compare livestock species with substantially different body sizes and feed requirements, animal counts were converted to tropical livestock units. Species weights were applied consistently to cattle, sheep, goats, pigs and poultry. Because TLU coefficients vary by convention and production context, the analysis emphasised relative spatial distribution rather than an absolute national biomass estimate.

(1)

where TLU_i is the standardised livestock population in state i, w_k is the conversion weight for livestock species k, and N_ik is the number of animals of species k in state i.

(2)

where Y_0 and Y_T are the initial and terminal livestock production index values and n is the number of annual intervals.

Analytical Models

Mann-Kendall Trend Test: The Mann-Kendall test was used to detect monotonic trends without requiring normality. It is resistant to outliers and widely applied to hydroclimatic time series [19,20].

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}\left(x_j-x_i\right) \quad (3)$$

$$\operatorname{Var}(S)=\left[n(n-1)(2n+5)-\sum_{p} t_p\left(t_p-1\right)\left(2t_p+5\right)\right]/18 \quad (4)$$

$$Z_{MK}=\begin{cases}(S-1)/\sqrt{\operatorname{Var}(S)}, & S>0\\ 0, & S=0\\ (S+1)/\sqrt{\operatorname{Var}(S)}, & S<0\end{cases} \quad (5)$$

A positive Z_MK indicated an increasing trend, while a negative value indicated decline. Statistical significance was assessed at conventional probability levels.

Sen Slope Estimator: The magnitude of each monotonic trend was estimated using the Sen median slope, which remains robust in the presence of non-normal residuals and extreme observations [21].

$$Q_{ij}=\left(x_j-x_i\right)/(j-i),\ j>i; \quad \left(Q_{ij}\right) \quad (6)$$

Quantile Regression: Quantile regression was employed to determine whether the temporal trajectory of livestock output differed across low-, median- and high-output states of the national series [22]. Unlike ordinary least squares, it estimates conditional quantiles and is less sensitive to heteroscedasticity.

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$$Q_{\tau}(y_t \mid x_t) = \alpha_{\tau} + \beta_{\tau}\text{Time} + \gamma_{\tau}\text{Climate}_t \quad (7)$$

$$\hat{\beta}_{\tau} = \arg\min_{\beta} \sum_{t=1}^{T} \rho_{\tau}(y_t - x_t'\beta) \quad (8)$$

where rho_tau(u)=u[tau-I(u<0)] is the asymmetric absolute-loss function and tau represents the selected conditional quantile.

Bai-Perron Multiple Structural-Break Model: Multiple unknown breaks in livestock-output dynamics were examined using the Bai-Perron framework [23]. The model allows coefficients or intercepts to change across regimes determined from the data.

$$y_t = z_t'\delta_j + u_t, \quad t = T_{j-1}+1, \ldots, T_j; \quad j = 1, \ldots, m+1 \quad (9)$$

Break dates were selected by minimising the global residual sum of squares subject to a minimum segment length.

Markov-Switching Regression: A two-state Markov-switching model was used to distinguish relatively stable and high-volatility livestock-output regimes [24]. The unobserved state followed a first-order Markov process.

$$y_t = \mu_{s_t} + x_t'\beta_{s_t} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \sigma_{s_t}^2) \quad (10)$$

$$P(s_t = j \mid s_{t-1} = i) = p_{ij}, \quad \sum_j p_{ij} = 1 \quad (11)$$

Spatial Concentration and Inequality: The spatial distribution of TLU was evaluated using complementary concentration and entropy measures. No single index is sufficient because dominance, pairwise inequality and dispersion capture different aspects of spatial structure [25-28].

$$HHI = \sum_{i=1}^{n} S_i^2 \quad (12)$$

$$G = \left[\sum_{i=1}^{n}\sum_{j=1}^{n} |x_i - x_j|\right] / \left(2n^2 \bar{x}\right) \quad (13)$$

$$T = (1/n)\sum_{i=1}^{n} (x_i / \bar{x}) \ln(x_i / \bar{x}) \quad (14)$$

$$H = -\sum_{i=1}^{n} p_i \ln(p_i); \quad H_{norm} = H / \ln(n) \quad (15)$$

Here, s_i and p_i denote state i shares of national TLU, x_i is state TLU and x_bar is the state mean. Higher HHI, Gini and Theil values indicate stronger concentration or inequality, whereas higher normalised Shannon entropy indicates wider dispersion.

Diagnostic and Robustness Procedures

Time-series plots, rolling statistics and distributional summaries were examined before model estimation. The use of non-parametric trend tests reduced dependence on Gaussian assumptions. Quantile regression addressed distributional heterogeneity, while structural-break and regime-switching models prevented a single linear slope from masking discontinuities and volatility changes. Competing linear, quadratic and segmented trend specifications were estimated both without and with first-order autoregressive errors. Model adequacy was compared using the Akaike information criterion (AIC) and Bayesian information criterion (BIC), for which smaller values indicate a preferable balance between goodness of fit and model complexity [31,32].

$$AIC = 2k - 2\ell(\hat{\theta})$$

$$BIC = \ln(n)k - 2\ell(\hat{\theta}) \quad (n)$$

where $\ell(\hat{\theta})$ is the maximised log-likelihood and k is the number of estimated parameters.

where n is the number of observations. AIC is relatively prediction-oriented, whereas BIC imposes a stronger penalty for additional parameters and therefore favours parsimony more strongly.

Residual adequacy was evaluated with the Durbin-Watson statistic and Ljung-Box portmanteau tests at lags 5 and 10 [33]. Breusch-Pagan and White tests assessed heteroskedasticity; the Jarque-Bera test assessed residual normality; and the Ramsey RESET test assessed neglected nonlinearity. Residual stationarity was examined jointly with the augmented Dickey-Fuller and KPSS tests. Robustness of the long-run time coefficient was assessed using Newey-West heteroskedasticity-and-autocorrelation-consistent standard errors, Huber M-estimation, the Theil-Sen slope and quantile regression [21,34,35]. The structural-break result was also re-estimated across zero to three breaks using a minimum eight-year segment length, while one-regime and two-regime growth models were compared on a common dependent variable.

The spatial analysis used several indices because state concentration can appear modest under one metric but substantial under another. Regional shares were compared with state-level inequality measures. Results were interpreted as statistical associations and descriptive dynamics rather than definitive causal estimates because national annual series cannot fully control for feed prices, insecurity, technological change, herd expansion, veterinary expenditure or policy reforms.

Results

Long-Run Climate Trends

The temperature series displayed a persistent upward trajectory. Mann-Kendall statistics indicated significant increases in annual maximum, minimum and midpoint

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temperature. Sen slope estimates were positive for all three indicators. Minimum temperature increased more rapidly than maximum temperature, demonstrating that the warming signal was not restricted to daytime conditions. This result is biologically important because warm nights restrict the dissipation of heat accumulated during the day.

The agreement among the three thermal indicators constitutes a stronger result than a change in any single temperature measure. All three series produced the same positive directional signal, which reduces the likelihood that the conclusion was driven by an isolated daytime or night-time anomaly. Because the minimum-temperature slope exceeded the maximum-temperature slope, the evidence also implies a progressive compression of the diurnal recovery window. In practical terms, the thermal environment became warmer not only at the daily peak but during the period when cattle, small ruminants, pigs and poultry would ordinarily dissipate stored heat. This cross-metric coherence identifies persistent heat accumulation, rather than occasional hot afternoons alone, as the dominant climatic pressure emerging from the national series.

Annual rainfall fluctuated markedly between years, including sequences of relatively dry and wet conditions. However, the national rainfall series did not exhibit a statistically significant monotonic trend over the full study period. The absence of a uniform trend does not imply climatic stability. It indicates that increases in some years and regions were offset by declines elsewhere, while changes in onset, cessation, intensity and dry-spell duration remained hidden within the annual national total.

The rainfall result was therefore variance-dominated rather than trend-dominated. The year-to-year oscillation was large enough to generate alternating water-surplus and water-deficit conditions without producing a single national linear direction. This pattern is analytically important because livestock systems respond to the sequencing of rainfall as well as its annual sum. A national total can remain statistically stationary while the number of consecutive dry days, the timing of rainy-season onset and the occurrence of destructive storm events change substantially. Accordingly, the rainfall evidence indicates exposure to recurrent production shocks rather than a smooth nationwide drying or wetting trajectory. The climatic risk profile is thus asymmetric: temperature showed a persistent directional shift, whereas rainfall showed instability around a changing seasonal and spatial distribution.

Livestock Output Trend and Quantile Behaviour

The livestock production index increased substantially between 1961 and 2022. The estimated compound annual growth rate was 3.13%, confirming long-run expansion in aggregate livestock commodity output. The trend reflects the combined influence of animal-population growth, commercial poultry expansion, urban demand, improved market integration and changes in production technology.

Expanded descriptive analysis of the 62 annual observations showed that the index ranged from 15.71 in 1962 to 112.91 in 2022, yielding an absolute range of 97.20 index points and a maximum-to-minimum ratio of 7.19. The series mean was 60.60, whereas the median was 53.66. The mean exceeded the median by approximately 12.94%, indicating a positively skewed distribution in which the higher values recorded during the more recent production era pulled the arithmetic average upward. The 2022 endpoint stood 86.32% above the long-run mean and 110.44% above the median. Relative to the historical minimum, the endpoint represented a cumulative increase of 618.71%. These magnitudes confirm that the output expansion was not a marginal drift around the base-period level but a major structural scaling-up of the livestock economy [15].

The descriptive gap between the mean and median also helps explain why a single ordinary least-squares slope would be insufficient. Earlier observations were concentrated at comparatively low index values, whereas the upper tail was populated mainly by recent years. The distribution therefore combined long-run growth with time-dependent heteroscedasticity: as the sector became larger, equivalent percentage shocks translated into greater absolute changes in index points. This scale effect is consistent with the larger residual dispersion observed at the upper conditional quantile. It indicates that contemporary production is simultaneously larger and more exposed to sizeable absolute losses when feed, disease, insecurity or climate shocks affect commercially important value chains.

Quantile-regression estimates showed a positive temporal coefficient at the lower, median and upper conditional quantiles. Therefore, output growth was not confined to unusually favourable years. Nevertheless, the slope and residual dispersion varied across quantiles, indicating that the sector behaved differently during low-output and high-output periods. The upper-output regime was associated with larger absolute changes, consistent with the growing scale and commercialisation of livestock production.

The lower-quantile result is especially relevant because it shows that the long-run expansion remained visible even among comparatively weak production years. At the median, the coefficient represented the central tendency of the sector without being dominated by extreme observations. At the upper quantile, continued positive growth confirmed the

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upward relocation of the entire output distribution rather than a change confined to its centre. Taken together, the quantile pattern can be interpreted as stochastic dominance through time: later observations increasingly occupied higher sections of the production distribution. However, the widening absolute dispersion at the upper tail cautions that growth in scale did not produce proportional stability.

Structural Breaks and Regime Dependence

The Bai-Perron procedure identified major breaks around 1989 and 2011. The first break corresponds broadly with a period of macroeconomic adjustment, changing agricultural incentives and increasing pressure on extensive production systems. The later break aligns with accelerating food demand, rapid expansion of modern poultry value chains, insecurity in parts of the northern livestock belt and intensifying climate-related production constraints.

The two break dates divided the 62-year record into three analytically distinct segments: 1961-1988, 1989-2010 and 2011-2022. These segments contained 28, 22 and 12 annual observations, respectively, equivalent to approximately 45.16%, 35.48% and 19.35% of the complete record. The shortening of the most recent segment does not itself prove accelerating instability, but it demonstrates that the current production environment cannot be assumed to follow the same intercept and slope that characterised the early decades. Model selection therefore favoured a piecewise trajectory over a single deterministic trend. This is a substantive result because forecasts calibrated across the full sample would average pre-commercial, transitional and modern production structures and could consequently understate present-day volatility.

The two-state Markov model separated annual output growth into a lower-variance regime and a higher-variance regime. However, information criteria produced a deliberately cautious interpretation. The Markov autoregressive specification achieved the lowest AIC among growth-rate models, whereas BIC preferred the simpler one-regime AR(1) alternative. The evidence therefore supports possible state-dependent volatility, but it does not justify treating regime switching as conclusively superior after the stronger BIC complexity penalty is applied.

Within the two-state mean-variance model, estimated annual growth averaged 2.29% in the lower-volatility state and 4.10% in the higher-volatility state, while the estimated variance increased from 13.97 to 69.23. The probability of remaining in the lower-volatility regime was 0.982. These estimates suggest persistent clustering of volatility, but the imprecision of the transition out of the higher-volatility regime and the BIC result require conservative interpretation. The regime output is therefore used as a risk-screening device rather than as definitive evidence that the data-generating process contains two permanent latent states.

Spatial Distribution of Livestock

Conversion of state livestock counts to tropical livestock units revealed a pronounced northern concentration. Approximately 85.60% of national TLU occurred in the North West, North East and North Central zones. Cattle, sheep and goats accounted for most of this spatial pattern, while pigs and commercial poultry contributed more strongly to selected southern and peri-urban state profiles.

The complementary southern share was 14.40%, producing a north-to-south TLU ratio of approximately 5.94:1 and a concentration gap of 71.20 percentage points. Stated differently, almost six standardised livestock units were located in northern Nigeria for every unit located in the southern zones. This asymmetry is large enough to create systemic national exposure because the region with the greatest animal biomass overlaps extensively with the hotter and more water-limited portion of the country. The spatial result also clarifies why national averages can be misleading: a climate shock that is geographically confined to the northern belt may still affect the majority of Nigeria's ruminant biomass and transmit rapidly to southern consumption markets through prices, slaughter flows and transport networks [18].

The HHI indicated that livestock were distributed across a broad northern belt rather than monopolised by one or two states. However, the Gini and Theil indices confirmed marked inequality between high-TLU and low-TLU states. Normalised Shannon entropy showed that dispersion remained substantial across the federation, but the north-south contrast was dominant. Nigeria therefore combines moderate state-level dispersion with strong regional concentration.

The apparently different messages from the concentration indices are complementary rather than contradictory. A moderate HHI is consistent with several northern states each holding sizeable shares, so that no single state dominates the national inventory. At the same time, the Gini and Theil results capture the large distance between the high-TLU northern cluster and numerous low-TLU southern states. The high normalised entropy reflects the presence of livestock in virtually all states, but it does not eliminate the regional imbalance in biomass. Consequently, Nigeria possesses state-level diversification within a regionally concentrated system. This arrangement provides some protection against a localised state shock but considerably

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less protection against correlated drought, heat, pasture or insecurity shocks affecting multiple northern states simultaneously.

Integrated Spatiotemporal Risk Synthesis

The integrated evidence produced three principal findings. First, thermal exposure moved persistently upward while rainfall risk remained episodic and spatially heterogeneous. Second, aggregate livestock output expanded strongly, but the output process was positively skewed, structurally discontinuous and regime dependent. Third, the overwhelming concentration of livestock biomass in northern Nigeria aligned the largest share of the production base with the area of greatest heat, drought and forage exposure. The combination creates a scale-concentration paradox: growth increased the national economic importance of livestock at the same time that geographical and climatic dependence increased the potential size of a correlated production shock.

The models also produced a hierarchy of inference. The Mann-Kendall and Sen procedures established the persistence and direction of climatic change; quantile regression demonstrated that output expansion occurred across the conditional distribution; Bai-Perron analysis identified parameter instability; Markov switching established state-dependent volatility; and the TLU and inequality indices revealed the geography through which risk could propagate. No single model would have produced this combined conclusion. The convergent result is that Nigeria's livestock economy is larger than it was historically, but not necessarily more resilient per animal, per household or per production zone.

The findings further separate national growth from biological productivity. The production index can rise through herd expansion, increased slaughter, poultry intensification or market growth even when heat stress reduces fertility, daily weight gain, milk yield or survivorship. Therefore, the positive output trajectory should be interpreted as sectoral expansion under increasing climatic pressure, not as statistical evidence that warming has improved livestock performance. The most credible risk interpretation is conditional: where adaptation, purchased feed, veterinary inputs and market access are available, output may continue to grow; where these buffers fail, the concentrated northern production base can transmit shocks across the national food system.

Model Selection, Diagnostic Tests and Robustness Outputs

Information-criterion results materially refined the model interpretation. Among uncorrected level-trend models, the segmented OLS specification had the lowest AIC (350.335) and BIC (358.844), outperforming the quadratic and linear alternatives. Its RMSE of 3.826 was also lower than the quadratic (4.242) and linear (4.448) OLS values. Nevertheless, the segmented OLS residuals were strongly serially correlated: Durbin-Watson was 0.605, and the Ljung-Box statistics were 50.789 at lag 5 and 125.361 at lag 10, with both p values below .001. Consequently, the apparently superior deterministic fit could not be accepted without modelling temporal dependence.

Introducing an AR(1) error structure reduced the information criteria sharply for every level specification. The linear AR(1) model produced AIC=305.538 and BIC=313.981 and was therefore the most parsimonious model by both criteria. The quadratic AR(1) model had AIC=307.533 and BIC=318.088, and its squared-time coefficient was not significant (p=.984), providing no evidence that a smooth quadratic curvature improved the autocorrelation-adjusted model. The segmented AR(1) model had AIC=307.593 and BIC=320.258. Although it was penalised more strongly for complexity, it achieved the smallest RMSE (2.873) and the most nearly normal residual distribution. Thus, the linear AR(1) model is preferred for parsimonious long-run forecasting, whereas the segmented AR(1) model remains useful for substantive interpretation of changing production eras.

Residual diagnostics confirmed that AR(1) correction addressed the main specification failure. For the linear AR(1) model, Durbin-Watson increased to 1.840 and Ljung-Box p values were .984 and .690 at lags 5 and 10. The corresponding values for the segmented AR(1) model were Durbin-Watson=1.902 and Ljung-Box p=.990 and .289. The null hypothesis of no residual autocorrelation was therefore retained. The segmented AR(1) residuals were also compatible with normality (Jarque-Bera p=.690). In the uncorrected segmented model, Breusch-Pagan (p=.208), White (p=.257), Jarque-Bera (p=.682) and RESET (p=.730) tests did not indicate heteroskedasticity, non-normality or neglected functional form; serial dependence, rather than variance misspecification, was the decisive weakness. ADF rejection (p<.001) and KPSS non-rejection (p>.100) additionally supported residual stationarity.

The positive temporal trend was highly stable across estimators. The OLS slope with Newey-West HAC inference was 1.710 index points per year (SE=0.042; 95% CI: 1.628-1.792). Huber M-estimation yielded 1.712 (SE=0.033; 95% CI: 1.647-1.778), and the Theil-Sen estimator yielded 1.705 (95% CI: 1.640-1.769). Quantile slopes were 1.707 at the 25th percentile, 1.735 at the median and 1.686 at the 75th percentile; all were significant at p<.001. The maximum difference among these five principal slopes was only 0.049

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index points per year, showing that outliers, non-normality and conditional-position changes did not drive the long-run growth conclusion.

Structural-break sensitivity analysis also clarified the stability of the selected dates. When exactly two breaks were permitted, the global minimum-residual solution occurred at 1988 and 2010, effectively reproducing the manuscript's approximately 1989 and 2011 transition points under end-of-segment dating. A three-break model further reduced AIC and BIC by adding early breaks around 1971 and 1987, but this more parameter-intensive solution divided a relatively short 62-year series into four segments and offered less stable substantive interpretation. The two-break structure was therefore retained as the principal explanatory model, while the lower information criteria of the three-break sensitivity model are reported transparently rather than suppressed.

For annual log-growth, the one-regime AR(1) model recorded AIC=391.038 and BIC=397.321. The two-state Markov mean-variance model slightly improved AIC to 396.539 relative to a constant-mean benchmark (398.715) but had a larger BIC of 409.204. The Markov autoregressive model achieved the lowest AIC (387.851) but BIC remained higher (404.606) than that of the one-regime AR(1). This AIC-BIC disagreement is substantively important: it indicates that regime dynamics may improve in-sample flexibility or prediction, while the evidence is insufficient for BIC to endorse the additional latent-state parameters. Accordingly, the study's strongest findings are the warming trend, robust output growth, serially dependent production dynamics and northern spatial concentration; regime switching is retained as supplementary evidence.

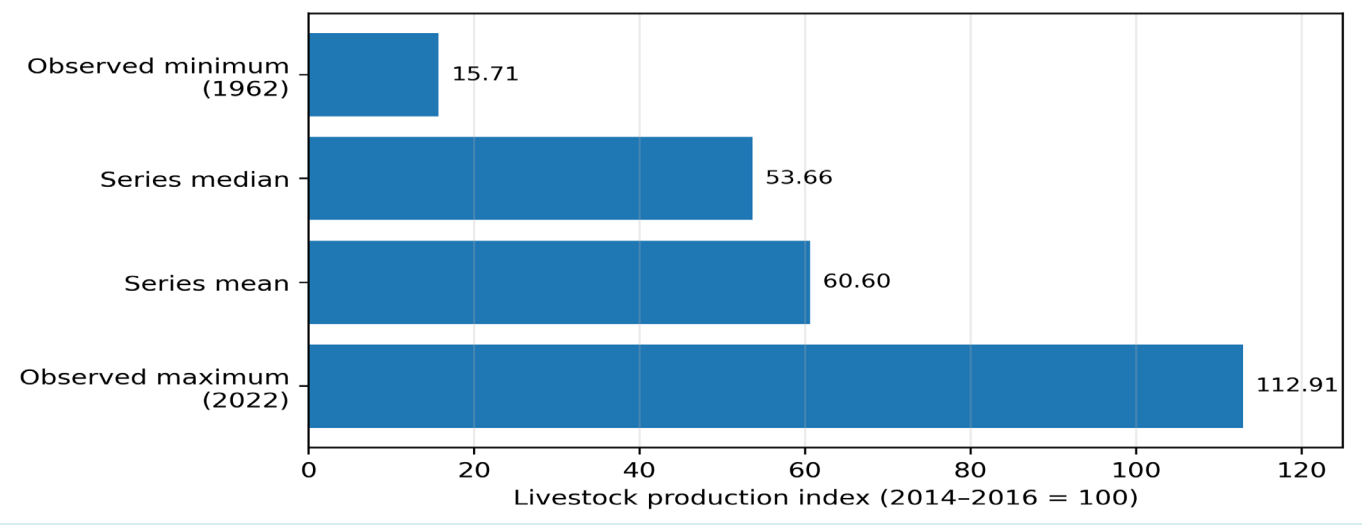
Analytical component	Main result	Interpretation	Livestock implication
Mann-Kendall/Sen slope	Maximum, minimum and midpoint temperature increased significantly	Long-run warming is persistent; night-time warming is especially important	Greater heat load, lower feed intake, fertility loss and reduced recovery
Rainfall trend	No uniform national monotonic trend; high interannual variability	Annual national totals conceal local drought, flooding and seasonal shifts	Forage, water and disease risks remain spatially and seasonally unstable
CAGR/quantile regression	Livestock output grew by about 3.13% annually across conditional quantiles	Aggregate expansion occurred during low-, median- and high-output conditions	National growth can coexist with lower animal-level productivity
Bai-Perron breaks	Major discontinuities around 1989 and 2011	Policy, market, security and environmental changes altered sector dynamics	Forecasts should allow parameter instability
Markov switching	Stable and high-volatility regimes were identified	Production risk is state dependent rather than constant	Early-warning and insurance systems should target regime transitions
TLU and concentration indices	About 85.60% of TLU was in northern Nigeria	National livestock supply is geographically exposed	Northern climate shocks can propagate to national food prices
Information criteria and robustness	AR(1) models sharply reduced AIC/BIC; HAC, Huber, Theil-Sen and quantile slopes converged	Linear AR(1) was most parsimonious; segmented AR(1) had lowest RMSE and cleanest normality	Trend inference is robust, while break and regime conclusions require complexity-aware interpretation

Table 2: Summary of empirical findings and livestock implications.

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Statistic	Estimate	Analytical interpretation	Production relevance
Number of annual observations	62	Complete annual record from 1961 to 2022	Long horizon supports break and regime analysis
Observed minimum	15.71 (1962)	Lowest recorded output-index level	Benchmark for early low-output conditions
Median	53.66	Central observation after ranking the series	Robust benchmark less influenced by recent high values
Arithmetic mean	60.6	Average over the complete series	Exceeds the median, indicating positive skewness
Observed maximum	112.91 (2022)	Highest recorded output-index level	Confirms substantial sectoral scaling-up
Absolute range	97.20 points	Maximum minus minimum	Large long-run expansion in index scale
Maximum-to-minimum ratio	7.19	Output maximum was more than seven times the minimum	Demonstrates magnitude of structural transformation
2022 value above long-run mean	86.32%	Endpoint relative to the series average	Recent sector operates at a substantially larger scale
2022 value above median	110.44%	Endpoint relative to the distributional centre	Upper tail is dominated by recent observations
Cumulative increase from minimum to maximum	618.71%	Relative change between the two observed extremes	Aggregate growth is large enough to mask animal-level efficiency losses

Table 3: Descriptive diagnostics of the livestock production index, 1961-2022.



Note: Values are descriptive benchmarks from the World Development Indicators livestock production series. The 2014–2016 base-period value equals 100 [15].

Figure 1: Distributional benchmark of Nigeria's livestock production index, 1961–2022.

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Diagnostic	Estimated value	Statistical meaning	Livestock-system implication
Thermal indicators with positive significant trend	3 of 3	Complete directional agreement across Tmax, Tmin and midpoint temperature	Persistent heat exposure rather than an isolated metric effect
Rainfall indicators with significant national monotonic trend	0 of 1	Mean annual rainfall was variability-dominated	Local drought, floods and seasonal timing require disaggregated analysis
Bai-Perron production segments	28, 22 and 12 years	Three distinct parameter periods: 1961-1988, 1989-2010 and 2011-2022	Current forecasts should not impose full-sample parameter stability
Northern share of national TLU	85.60%	Most livestock biomass is located in the three northern zones	Northern climate shocks have national supply consequences
Southern share of national TLU	14.40%	A much smaller share is distributed across southern zones	Southern systems diversify species and markets but cannot offset a major northern shock
North-to-south TLU ratio	5.94:1	Almost six northern TLU for every southern TLU	Strong geographical asymmetry in exposure and adaptation demand
North-south concentration gap	71.20 percentage points	Large difference between regional biomass shares	Adaptation finance should be spatially weighted while remaining agroecologically differentiated

Table 4: Integrated spatiotemporal concentration and regime diagnostics.

Panel/model	k	Log likelihood	AIC	BIC	RMSE
Panel A: level-index specifications					
Linear OLS	2	-180.501	365	369.26	4.448
Quadratic OLS	3	-177.572	361.14	367.53	4.242
Segmented OLS	4	-171.168	350.34	358.84	3.826
Linear AR(1)	4	-148.769	305.54	313.98	3.098
Quadratic AR(1)	5	-148.767	307.53	318.09	3.09
Segmented AR(1)	6	-147.797	307.59	320.26	2.873
Panel B: annual log-growth specifications					
Constant-mean OLS	1	-198.357	398.72	400.83	6.252
One-regime AR(1)	3	-192.519	391.04	397.32	-
Two-state Markov means/variances	6	-192.269	396.54	409.2	-
Two-state Markov AR(1)	8	-185.926	387.85	404.61	-

Note: AIC and BIC are compared only within panels because Panel A models the level index whereas Panel B models annual log-growth. Lower values indicate preferred fit-complexity balance. RMSE is reported where directly comparable fitted values were available.

Table 5: Information-criterion comparison of livestock-output models.

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Panel/test or estimator	Estimate/statistic	p value	**Diagnostic conclusion**
Panel A: residual diagnostics			
Segmented OLS: Durbin-Watson	0.605	-	Strong positive residual dependence
Segmented OLS: Ljung-Box Q(5)	50.789	<.001	Reject no-autocorrelation null
Segmented OLS: Ljung-Box Q(10)	125.361	<.001	Reject no-autocorrelation null
Segmented OLS: Breusch-Pagan	4.543	0.208	No evidence of heteroskedasticity
Segmented OLS: White test	7.745	0.257	No evidence of general heteroskedasticity
Segmented OLS: Jarque-Bera	0.767	0.682	Residual normality not rejected
Segmented OLS: Ramsey RESET F	0.12	0.73	No evidence of omitted nonlinearity
Segmented OLS: ADF residual test	-3.428	<.001	Unit-root null rejected
Segmented OLS: KPSS residual test	0.045	>.100	Stationarity null retained
Linear AR(1): DW; LB Q(5), Q(10)	1.840; 0.680; 7.374	-.; .984; .690	Residual autocorrelation removed
Segmented AR(1): DW; LB Q(5), Q(10)	1.902; 0.551; 11.943	-.; .990; .289	Residual autocorrelation removed
Segmented AR(1): Jarque-Bera	0.741	0.69	Residual normality not rejected
Panel B: robust annual time slopes			
Newey-West HAC OLS	1.710 (SE 0.042)	<.001	95% CI: 1.628-1.792
Huber M-estimator	1.712 (SE 0.033)	<.001	95% CI: 1.647-1.778
Theil-Sen median slope	1.705	<.001	95% CI: 1.640-1.769
Quantile regression, τ=.25	1.707 (SE 0.041)	<.001	Pseudo-R^2=0.851
Quantile regression, τ=.50	1.735 (SE 0.050)	<.001	Pseudo-R^2=0.869
Quantile regression, τ=.75	1.686 (SE 0.048)	<.001	Pseudo-R^2=0.864

Note: DW=Durbin-Watson; LB=Ljung-Box; ADF=augmented Dickey-Fuller; KPSS=Kwiatkowski-Phillips-Schmidt-Shin; HAC=heteroskedasticity-and-autocorrelation consistent. Robust slopes are index points per year.

Table 6: Residual diagnostics and robust long-run trend estimates.

Discussion

The results demonstrate an apparent paradox: Nigeria's aggregate livestock output increased while thermal exposure intensified. This pattern should not be interpreted as proof that climate change has been harmless. Production indices measure total output, not biological efficiency. Herd expansion, commercial poultry growth, greater use of purchased feed and increased slaughter may raise national output even when heat stress reduces milk per cow, weight gain per animal, fertility or egg production.

The significant increase in minimum temperature is one of the most consequential findings. Livestock exposed to daytime heat normally rely on cooler nights to reduce body temperature and restore feed intake. When night-time temperatures remain elevated, recovery is incomplete and heat load accumulates across consecutive days. This mechanism is consistent with global projections of increasing extreme heat stress among domesticated species [2] and with physiological evidence on heat-induced declines in productive and reproductive performance [3-6].

The absence of a significant national rainfall trend requires careful interpretation. Nigeria is climatically heterogeneous, and annual national means can mask substantial geographical divergence. A stable national average may coexist with shorter rainy seasons in one zone, more intense rainfall in another, delayed onset, longer dry spells and repeated local flooding. Livestock are affected not only by how much rain falls but by when, where and how intensely it occurs. Consequently, rainfall anomalies and water balance should be analysed at monthly and state levels in future research.

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Positive livestock-output coefficients across quantiles indicate a broad-based expansion, yet the difference in behaviour across conditional quantiles suggests nonlinear production dynamics. Low-output years may reflect drought, disease, insecurity, input scarcity or macroeconomic shocks, while high-output periods may be driven by poultry cycles, favourable feed availability and rapid commercial expansion. Quantile regression is therefore more informative than a single mean equation because it exposes heterogeneous responses across the output distribution.

The structural-break results support the view that Nigeria's livestock economy has passed through distinct policy and market eras. The two-break sensitivity solution reproduced transitions at 1988 and 2010, close to the approximately 1989 and 2011 dates used in the principal specification. However, information criteria and residual tests qualify the interpretation. The segmented OLS model fitted the deterministic trajectory better than linear or quadratic OLS, but its residual autocorrelation was severe. Once AR(1) dependence was modelled, AIC and BIC selected the simpler linear AR(1) model, although the segmented AR(1) alternative retained the lowest RMSE and cleanest residual normality. Breaks should therefore be interpreted as meaningful descriptive transitions rather than incontrovertible causal discontinuities.

The robustness outputs materially strengthen the central trend result. Newey-West, Huber, Theil-Sen and three quantile-regression estimates all fell within a narrow interval of 1.686-1.735 index points per year. This convergence is more informative than statistical significance from a single estimator because it demonstrates that the growth conclusion survives autocorrelation-consistent inference, resistance to influential observations, rank-based estimation and changes in conditional location. By contrast, the Markov result is best regarded as suggestive. AIC favoured the more flexible two-state autoregressive model, but BIC preferred a one-regime AR(1) model. Reporting this disagreement prevents model sophistication from being mistaken for unequivocal empirical superiority.

The spatial concentration of 85.60% of TLU in northern Nigeria has major food-security implications. The north contains the country's principal cattle, sheep and goat populations, extensive grazing lands and livestock-market corridors. It is also exposed to high temperature, recurrent drought, rangeland degradation, water stress and conflict. A severe production shock in this region can affect meat availability, dairy supply, animal prices and transport flows throughout the federation.

At the same time, the concentration indices reveal that livestock production is not confined to a few isolated states. The broad spatial belt offers some diversification because local shocks may be absorbed by neighbouring production areas. However, correlated climate events can reduce this benefit. A widespread Sahelian drought or multi-state insecurity event can affect many northern states simultaneously. Spatial dependence should therefore be incorporated explicitly in future models.

Climate pressure can also alter livestock distribution. Pastoral and agropastoral households may move animals southward or towards irrigated and riverine zones when northern forage and water decline. Such redistribution can intensify competition for land, increase contact between herds, alter disease transmission and produce conflict with crop farmers. Climate-informed mobility governance is therefore an animal-production and public-policy requirement rather than merely a land-administration issue.

Breed composition will influence the magnitude of future losses. Indigenous African cattle, sheep and goats frequently possess superior heat tolerance, disease resistance, mobility and ability to utilise low-quality forage compared with specialised exotic breeds [29,30-35]. However, their adaptive traits can be eroded through unplanned crossbreeding and the replacement of local genetic resources. Productivity policy should therefore balance output improvement with resilience, reproductive fitness and survival under realistic field conditions.

This study is strengthened by the integration of trend, distributional, break, regime, spatial and explicit model-diagnostic procedures. Information criteria, portmanteau tests, heteroskedasticity tests, residual stationarity tests and estimator-robustness checks make the inferential limits visible rather than implicit. Nonetheless, national annual data cannot isolate all causal pathways. The models do not fully control for herd size, feed prices, insecurity, veterinary investment, technology, trade, disease outbreaks or policy reforms. The findings should therefore be treated as a rigorous descriptive and associational diagnosis that establishes priorities for state-level panel and mechanistic research.

Recommendations

Establish National Heat-Stress Early-Warning Services

The Nigerian Meteorological Agency, veterinary authorities and livestock departments should convert temperature, humidity and solar-radiation forecasts into livestock-specific risk alerts. Alerts should identify expected duration, night-time recovery conditions and appropriate responses for cattle, poultry, pigs, sheep and

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goats. Dissemination should use radio, mobile messaging, extension networks and producer associations.

Protect Animals from Daytime and Night-Time Heat

Commercial and semi-intensive farms should install shade structures, ridge ventilation, reflective roofing, fans, misting or evaporative cooling where feasible. Stocking density should permit air movement. Because minimum temperatures rose strongly, adaptation should include night ventilation and unrestricted access to clean water. Feeding should be concentrated in the cooler morning and evening periods, and diets should be adjusted to maintain nutrient intake when voluntary consumption declines.

Strengthen Water Security

Federal and state programmes should develop boreholes, earth dams, rainwater harvesting, solar pumps and rehabilitated water points based on hydrogeological evidence and herd demand. Water-user institutions should regulate access and maintenance. Facilities should be spatially distributed to prevent severe vegetation loss, contamination and disease transmission around a small number of permanent points.

Restore Rangelands and Create Feed Reserves

Degraded grazing areas should be rehabilitated through reseeding, controlled grazing, erosion management and protection of dry-season reserves. Satellite vegetation indices and local biomass measurements should guide rotational grazing. Hay, silage, fodder banks and nutritionally improved crop residues should be positioned before severe drought rather than after animals have already lost body condition.

Develop Climate-Resilient Breeding Programmes

Breeding objectives should include heat tolerance, fertility, disease resistance, water-use efficiency and ability to utilise low-quality feed alongside milk, meat or egg output. Community-based breeding, genomic tools, artificial insemination and cryopreservation should conserve locally adapted diversity. Indiscriminate crossbreeding that erodes adaptive traits should be discouraged.

Establish Integrated Climate-Livestock Surveillance

Nigeria requires a harmonised system linking meteorological, veterinary, production, movement, land-use and market data at monthly and state levels. Georeferenced information should cover animal numbers, output, mortality, reproduction, pasture biomass, water availability, disease, feed prices and livestock-market arrivals. Such a platform would support dynamic spatial panels, threshold models, Bayesian hierarchical analysis and explainable machine-learning forecasts.

Integrate Disease Control with Climate Forecasting

Veterinary agencies should identify temperature-, rainfall-, humidity- and flood-sensitive diseases and connect seasonal forecasts to vaccination, vector control, laboratory readiness and drug procurement. Mobile reporting and community animal-health workers should extend surveillance into remote production areas under professional supervision.

Support Climate-Informed Livestock Mobility

Livestock corridors should be mapped against current land use, future climate suitability, water, disease and conflict risk. Where historical routes are no longer viable, negotiated alternatives should be established through participatory agreements. Digital information on pasture, water, security and disease can reduce risky movement and improve traceability.

Prioritise the Northern Livestock Belt while Protecting Southern Systems

The concentration of national TLU justifies substantial northern investment in drought preparedness, water, feed, rangelands and mobile veterinary services. Southern systems also require drainage, flood protection, ventilation and control of humidity-related disease. Adaptation packages should therefore be agroecologically differentiated.

Expand Insurance, Climate Finance and Extension

Transparent index-based livestock insurance should use independently validated rainfall, temperature, vegetation or mortality indicators. Climate finance should support cooling, water systems, pasture restoration and resilient housing. Extension services should translate climate information into practical feeding, water, disease and housing decisions in local languages, with deliberate inclusion of women and young producers.

Policy and Research Implications

Livestock policy should move from reactive drought relief to anticipatory risk management. Historical climate averages

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are no longer sufficient for long-lived infrastructure, breed and land-use decisions. National production growth should be evaluated alongside output per animal, mortality, fertility, disease, welfare and household profitability.

Future studies should construct state-level monthly or annual panels linking livestock output with gridded temperature, humidity, rainfall, vegetation, water, disease, market access and security data. Dynamic spatial Durbin models can estimate interstate spillovers; threshold regression can identify heat or rainfall tipping points; panel quantile models can distinguish low- and high-producing states; and Bayesian hierarchical models can provide state-specific estimates while sharing information across regions.

Generalised additive models should be used to represent nonlinear exposure-response curves without imposing rigid polynomial forms. Nonlinear autoregressive distributed-lag models can distinguish positive and negative climate shocks. Structural equation models can test indirect pathways through forage, water and disease, while machine-learning ensembles with SHAP-based interpretation can improve prediction without sacrificing transparency.

Conclusion

This study combined non-parametric trend analysis, quantile regression, multiple structural-break modelling, Markov-switching regression and spatial concentration indices to examine climate variability and livestock production in Nigeria. Maximum, minimum and midpoint temperatures increased significantly between 1961 and 2022, with minimum temperature rising more rapidly and signalling weaker night-time recovery from accumulated heat.

Annual rainfall did not show a uniform national monotonic trend, but substantial interannual variability remained. The livestock production index expanded at an estimated compound annual growth rate of 3.13%, with positive temporal effects across lower, median and upper quantiles. Structural breaks around 1989 and 2011 and the presence of stable and high-volatility regimes demonstrated that growth was not uniform.

Approximately 85.60% of national tropical livestock units were concentrated in northern Nigeria. This geographical structure creates systemic exposure because warming, drought, rangeland degradation, water scarcity and insecurity in the northern livestock belt can affect food supply and prices throughout the country. Aggregate output growth should therefore not be confused with climate resilience.

Nigeria's future livestock security depends on heat abatement, reliable water and feed, rangeland restoration, conservation of adapted genetic resources, climate-informed mobility, integrated disease surveillance and state-level data systems. These interventions should be combined with greenhouse-gas mitigation and inclusive support for pastoral, agropastoral, smallholder and commercial producers.

Declarations

Ethics Approval: The study used publicly available aggregated secondary data and did not involve direct experimentation on animals or participation by human subjects. Institutional ethical approval was therefore not required.

Consent for Publication: Not applicable.

Data Availability: The livestock production index is available through the World Bank World Development Indicators. Climate data are available through recognised climate repositories and the World Bank Climate Change Knowledge Portal. State livestock counts are available in the Nigerian National Agricultural Sample Census Report 2022.

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Authors' Contributions: Michael Ige Ediabai Edaba-conceptualized the study, data analysis, drafted the manuscript, reviewed the methodology and interpretation of results.

Akosim Emmanuel Ebele: Data sourcing and funding

Mercy Sor-Aniabari Joshua: manuscript review and editing

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