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Climate Change and the Future of Cereal Production in Niger: Projections to 2050 Using SARIMA and PLS-SEM Analysis

Issaka Saidou ISMAILLA[1]*, Haydar ŞENGÜL[1], Şinasi AKDEMIR[1], Seyit HAYRAN[1]

ABSTRACT

Climate change in the Sahel is a challenge for the agriculture sector in Niger, which is mainly based on rain-fed cereal production, of an existential demand. The relationship between stressors and future crop performance is highlighted, despite the historical evidence of increasing temperatures and erratic rainfall. This study projects production trends until 2050 and the effects of climate change on the major cereals of Niger: millet, sorghum, and maize. A dual modelling approach is applied in this study, with the integrated seasonal moving average autoregressive models (SARIMA) used to predict the performance up to 2050 and the partial least squares structural equation modelling (PLS-SEM) used to investigate causal relationships among climatic variables (temperature and precipitation) and agricultural indicators (area and yield). The climate analysis shows that over the past 30 years, there was a warming trend of 0.04°C per year, which is equivalent to a warming of approximately 1.3°C. The PLS-SEM model results show that cereal production appears to be strongly influenced by climatic conditions, as well as by the cultivated area (0.737) and the yield (0.695) of sorghum, which underlines the particularly high sensitivity of this crop. Note that the production of total sorghum and millet is projected to rise 69.1% and 47.4%, respectively, by 2050, but this is because of land extensification (increase in area), and not an increase in productivity. Moreover, unstable rainfall and heat stress are expected to lead to stagnation, or even a decline, in yields for all three crops. Based on these findings, Niger's current food security strategy is based on an unsafe expansion of cultivated land, both horizontally and environmentally. To prevent a systemic collapse of the cereal sector by the middle of the century, a shift from reactive land expansion to proactive, climate-adaptive intensification is essential.

Keywords: Niger, climate change, cereal production, SARIMA, PLS-SEM, food security.

1. INTRODUCTION

Challenged with increasingly unpredictable environmental changes, climate change represents a fundamental threat to international food security, making it a major global concern of the 21st century (Vos and Bellù, 2019). Agriculture is the mainstay of

economic development in West Africa, and is particularly vulnerable due to its geographical constraints and socio-economic context, but also faces increasing systemic threats (Sultan and Gaetani, 2016). Smallholder farmers and marginalized groups, in both rural and urban areas, are severely affected by food supply problems (Abdulai, 2022). Knowing the long-term climate trajectories is essential for Niger's resilience, as cereal crops are the main source of calories and livelihoods in rural areas. In the Sahel, temperatures are rising 1.5 times faster than the global average, seriously threatening agricultural production in the area (Eboreime et al., 2025).

The climbing trend and irregular seasonal cycles are associated with high temperature volatility and a brief rainy season, which in turn often goes beyond the physiological limits of basic food crops like millet and sorghum, contributing to considerable yield volatility (Adam and Matta, 2025). The impact of the environmental shocks is immediately translated into socio-economic vulnerability in Niger, where the majority of the population relies on rain-fed agriculture more than 80% (Shah et al., 2026). There have been no integrated long-term forecasting models, which has meant that strategic foresight has been lacking. Based on the present assessments, by 2050, Niger has a potential yield reduction of up to 25%, unless climate-smart agriculture (CSA) is implemented immediately, especially through drought-tolerant varieties and solar irrigation (Surekha et al., 2025). This would seriously affect the country's food security. According to MacCarthy et al., (2021) and Zenda, (2024), despite progress made in understanding climate stressors and producer adaptation in the Sahel, our knowledge remains insufficient regarding the specific structural vulnerabilities of cereal production. Cereals form the caloric basis of Sahelian diets; previous research has largely neglected the specific sectoral dynamics that transform climate shocks into severe food insecurity for smallholder farmers. This research aims to understand the complex relationship between seasonal variability and agricultural yield through an integrated approach that combines long-term climate projections and a comprehensive analysis of the agricultural sector. Our analysis delivers the evidence that the Republic of Niger's policymakers need to implement sustainable adaptation policies and secure the nation's food systems through 2050.

2. THEORETICAL & PRACTICAL FRAMEWORK OF ADAPTATION TO CLIMATE CHANGE

2.1. Conceptual foundations of adaptation

The adaptation is theoretically grounded in evolutionary biology, defined as the capacity of systemic entities to alter their behaviors to survive and prosper within changing environments (Socorro Márquez et al., 2026). This concept applies directly to human-induced climate change. Mehla et al. (2026) note that adaptation to these anthropogenic changes requires proactive responses to variations in temperature, precipitation, and soil integrity. The idea has shifted from reactive ecological responses to a proactive strategic framework expected to reduce the sensitivity and vulnerability of socio-ecological systems through progress made in this area (Wang et al., 2026). This requires a major renovation of the Niger Republic's agricultural policy and infrastructure to take advantage of the country's new climate rather than passively adapting to it.

2.2. Distinction between variability and change

The distinction between climate variability, or short-term interannual fluctuations, and climate change, which is a continuous and directional modification of the state of the atmosphere, is crucial in the Sahelian context (Gole et al., 2026). Although seasonal fluctuations have been manageable for Nigerien producers, the current acceleration of climate change is creating dangers of a completely different magnitude (Oyewola et al., 2026). To move from reactive adaptation to proactive planning and to cope with both current seasonal shocks and anticipated structural changes by 2050, it’s important to understand how these two phenomena interact.

2.3. Adaptive behavior of smallholder systems

In Niger, the farmers are adopting adaptive management in real time to stabilize shocks and maximize their performance over time. The outline in econometric modelling of the importance of accounting for these adjustments, the indifferent farmer scenario is obtained, which overestimates the negative effects of climate change and omits the role of human action (Assan, 2026; Aroyehun et al., 2025; Antle and Capalbo, 2010).

2.4. Institutional Response: 3N Initiative

Niger has institutionalized its resilience in “Les Nigériens nourrissent les Nigériens (3N)”, a promising framework for agricultural development that mobilizes climate finance and supports tools such as drought-resistant seeds, agroforestry, and rural credit World Agroforestry (ICRAF, 2016). Though a persistent gap in its adoption remains, due to financial constraints and gender inequalities.

Hidrobo et al., (2024) identified the need for a shift to locally available and gender-responsive agricultural extension services to ensure that policies are put into action and have tangible impacts on the resilience of the 80% of people dependent on the land.

3. MATERIALS AND METHODS

3.1. Choice of study area

Niger was chosen as the study area for several reasons. First, the country is exposed to the increasing instability of the West African monsoon and the major impacts of climate change, with agriculture being the primary sector of its economy and the primary source of income for over 80% of the population (Vogel et al., 2021). High degree of exposure, which allows for a comprehensive assessment of the effects of climate change on a sector essential to national GDP and rural stability, largely explains the choice of Niger for this study. Secondly, this research offers an overview of the national territory by prioritizing national statistics. Atalla et al., (2026) found that the method makes it possible to understand the considerable impact of desertification and environmental degradation, particularly the advance of the Sahara, on cereal production in different agro-ecological zones, from the semi-arid Sahelian strip to the more humid regions of southern Sudan. Also, given the main cereals grown in Niger (millet, sorghum, and maize), this research is of particular importance. In addition to their widespread cultivation (over 10 million hectares), these crops constitute the staple food for the vast majority of Nigeriens (Toffa et al., 2023; Kamara et al., 2023; Adamou et al., 2021). The research provides exact and relevant information on production dynamics in the face of recurring climate threats such as droughts and locust invasions. In addition to its strong dependence on rain-fed agriculture, its high vulnerability to food insecurity induced by climate change, and the strategic importance of its staple cereals for its survival, Niger represents an ideal study area. This study provides an essential macro-level perspective on the national agricultural sector. Figure 1 shows the geographic scope of the research across the entire territory of Niger.

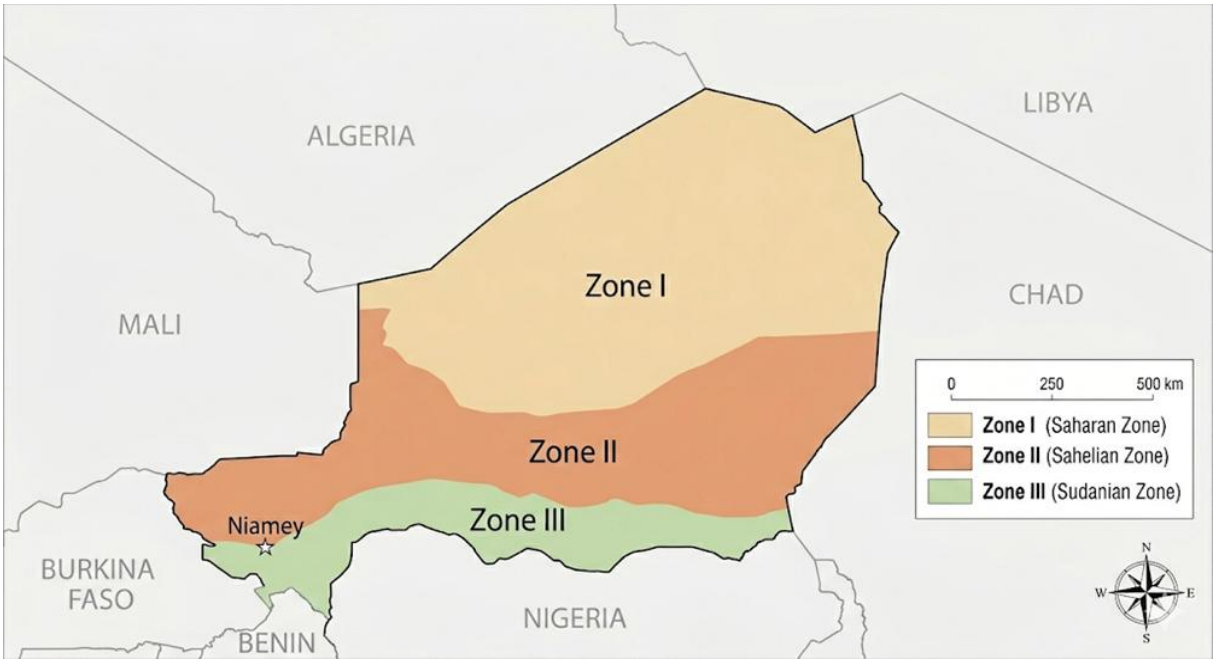

Figure 1. Map of the Republic of Niger showing the three main agro-ecological zones: zone I (Saharan zone), zone II (Sahelian zone) and zone III (Sudanian zone).

3.2. Data Used

The National Meteorological Directorate of Niger (DMN) provided climate data, including average annual temperatures and rainfall. The data covers a period of 30 years (1990-2020). This approach method is supported by the study of Nunes (2022) and Akumaga and Tarhule (2018), who underline the need for long-term data series to examine variations in climate parameters such as rainfall and temperature. To assess the variability of agricultural production, Dossa et al., (2025) and Nkosi et al., (2024), have focused on the harvested area and the average annual cereal yield (kg/ha), in addition to these two meteorological variables: temperature and precipitation. The statistics for this research include indicators such as yield per hectare, total area harvested annually, and total annual cereal production. Considers total production as a crucial indicator of the state of a crop and its contribution to food security (OECD,

2022). The FAOSTAT is the source of this agricultural data, which covers the period from 1990 to 2020 (Table 1). In the context of Niger, the FAO was chosen to collect data accessible for each criterion considered in this study.

Table 1. Summary of variables used for the model

Variables	Description	Sources	Period
Precipitation	Mean annual and monthly precipitation (mm)	DMN	1990–2020
Temperature	Mean annual and monthly average temperature (°C)	DMN	1990–2020
Area Harvested	Annual area harvested for millet, sorghum, and maize (ha)	FAO	1990–2020
Yield	Average annual yield for millet, sorghum, and maize (kg/ha)	FAO	1990–2020
Total Production	Total quantity of grain harvested for millet, sorghum, and maize (t)	FAO	1990–2020

3.3. Analysis Method

Time series analysis techniques were used to assess the temporal evolution of the parameters, which show how variables change over time, and are the most suitable method for a longitudinal study (Lee et al., 2024). Structural equation modeling (SEM), and more specifically the partial least squares (PLS) approach, made it possible to illustrate the impact of climatic conditions on the three indicators, such as harvested area, yield, and total production, for the three target crops (millet, sorghum and maize). Other, Tama et al., (2023), illustrated that data analysis methods, such as factor analysis or classical linear regression, are often less effective than structural equation modeling. Richter & Tudoran, (2024), indicate the capability to develop latent variables, to account for errors in the model, to test the theoretical hypotheses by data from the empirical world, and to simultaneously evaluate complex models with several dependent variables. Based on PLS-SEM, a linear model is developed, whose general form is mathematically presented below:

$$Y = XB + E \qquad (1)$$

Where:

- Y is a matrix of n observations by m response variables: harvested area, yield, and total production for each crop.
- X is a matrix of n observations by p predictor variables, such as an average annual temperature and rainfall.
- B is a matrix of regression coefficients p by m.
- E is the error term of the model, maintaining the same dimensions as Y.

The external models (Equation 2) are the relationships between each latent variable and its manifest indicators, while the internal models (Equation 3) are the relationships between the latent variables.

$$X_{kj} = \pi_{kj}\,\delta_i + \varepsilon_k \qquad (2)$$

Where:

Xkj is the vector for the manifest variable of the latent variable δ_k; π_{kj} is a loading or structural coefficient associated with X_{kj} and ϵ_{kj} is the measurement error of the manifest variables. This research relates to the relationships between the climate parameter and their specific indicators (average annual temperature and precipitation), as well as between each crop: millet, sorghum, and maize, and its production indicators: area, yield, and total production.

$$\delta_k = \sum_{i=\delta_i}^{\delta_k} \beta_{ki}\,\delta_i + \varepsilon_k \qquad (3)$$

Where:

β_{ki} symbolizes the structural value connected to the path between latent variables δ_k *and* δ_i; ε_k is the error term related to the endogenous latent variable. These represent the direct correlations of the underlying climate variables with the latent response variables for the cereal crops. The measurement model was evaluated first, as structural model estimations can be severely confounded by measurement errors and poor indicator reliability if left unaddressed (Abreu-Ledón et al., 2025). Therefore, internal consistency, discriminant validity, and extracted mean variance (EMV) were used to assess the accuracy and reliability of the measures (Dinç et al.,

2025). Variance inflation factor (VIF), used to verify collinearity, the coefficient of determination (R^2), and the path coefficients were then used to evaluate the structural model (Ibrahim et al., 2026). The thresholds established for each of these criteria are presented in Table 2.

Table 2. Indicators for evaluating measurement and structure models (Hair et al., 2019; Ghafourian et al., 2021)

Model Level	Criteria	Acceptance Thresholds
Measurement Model		
	Path Coefficients	≥0.7
	Cronbach's Alpha (CA)	≥0.6
	Composite Reliability ((rhoC))	≥0.6
	Average Variance Extracted (AVE)	≥0.5
Structural Model		
	Variance Inflation Factor (VIF)	<5
	Coefficient of Determination (R2)	≥0.5

Production Indicator Forecasts

ARIMA (SARIMA) models were used to develop the forecasts. Indeed, the study of simple and partial autocorrelation functions showed seasonality in the production parameters (Dossa et al., 2025). In such situations, seasonal ARIMA (SARIMA) models look to be the most suitable. When the time series has a definite seasonality and the effect is significant, SARIMA can be used to model the data, where trend, seasonality, and random components of the time series are considered (Szostek et al., 2024). The mathematical expression of the variable X_(T+h) (h≥1) can be approximated by Dinh et al., (2023) as follows:

$$\Phi_P(B^8)\Phi_P(B)\Delta_8^D\nabla^d X_t = \theta_Q(B^8)\theta_q(B)Z_t \qquad (4)$$

The components of the SARIMA model:

- (p, d, q): represents the non-seasonal part of the model (autoregressive, integration, moving average).
- (P, D, Q) s: represents the seasonal part of the model with a period s.
- B: Operator derailment.
- Z t: White noise or random error component.

Also, this research used mean absolute error (MAE), a technique that measures the average of the mean differences between the predicted and observed values, as one of the indicators frequently used to evaluate prediction performance (Khoshvaght et al., 2025; Sarwar et al., 2023). It is defined as follows:

$$MAE = \frac{\sum_{i=1}^{n}|Y_i - \hat{y}_i|}{n} \qquad (5)$$

With $\hat{y}_i$ being the predicted value and Yi being the actual value of observation i. Also, the coefficient of determination (R^2) was determined for each projection performed. All econometric and statistical estimations were executed within the R software statistical computing environment.

4. RESULTS

4.1. Impacts of climate change on millet production and projections

4.1.1. Dynamics of average annual rainfall and temperatures from 1990 to 2020

Figure 2 illustrates an average maximum temperature of 40.14°C. The hot and dry season (heat peak) is consistently the hottest period of the year, as shown by result (a), indicating that the maximum temperature follows a remarkably consistent seasonal pattern from year to year. October, a transitional month, remains very hot, with an average of 38.03 °C. The average maximum temperature drops to 35.95°C from June to September due to rainfall and cloud cover. On the other hand, the lowest daily maximum temperatures an average (33.15°C) are recorded during the cool, dry season. Throughout the year and in each season, a clear warming trend is emerging.

An annual increase of approximately 0.04°C to 0.045°C, each season is warming at a nearly identical rate. The average maximum temperature has increased by approximately 1.2°C to 1.35°C over a period of 30 years. Average maximum temperature of 41.17°C, the hot and dry season of the 2010s, was the most severe. In the multi-seasonal dataset, 1992 stands out as the coldest year on record. The average temperature during its hot, dry season was 39.03 °C, while the average temperature during its cool, dry season was 32.25°C. In 2016, the warmest dry season and cool season were 34.15°C. This suggests that, compared to the coldest months of the early 1990s, even the coldest months of recent years have warmed.

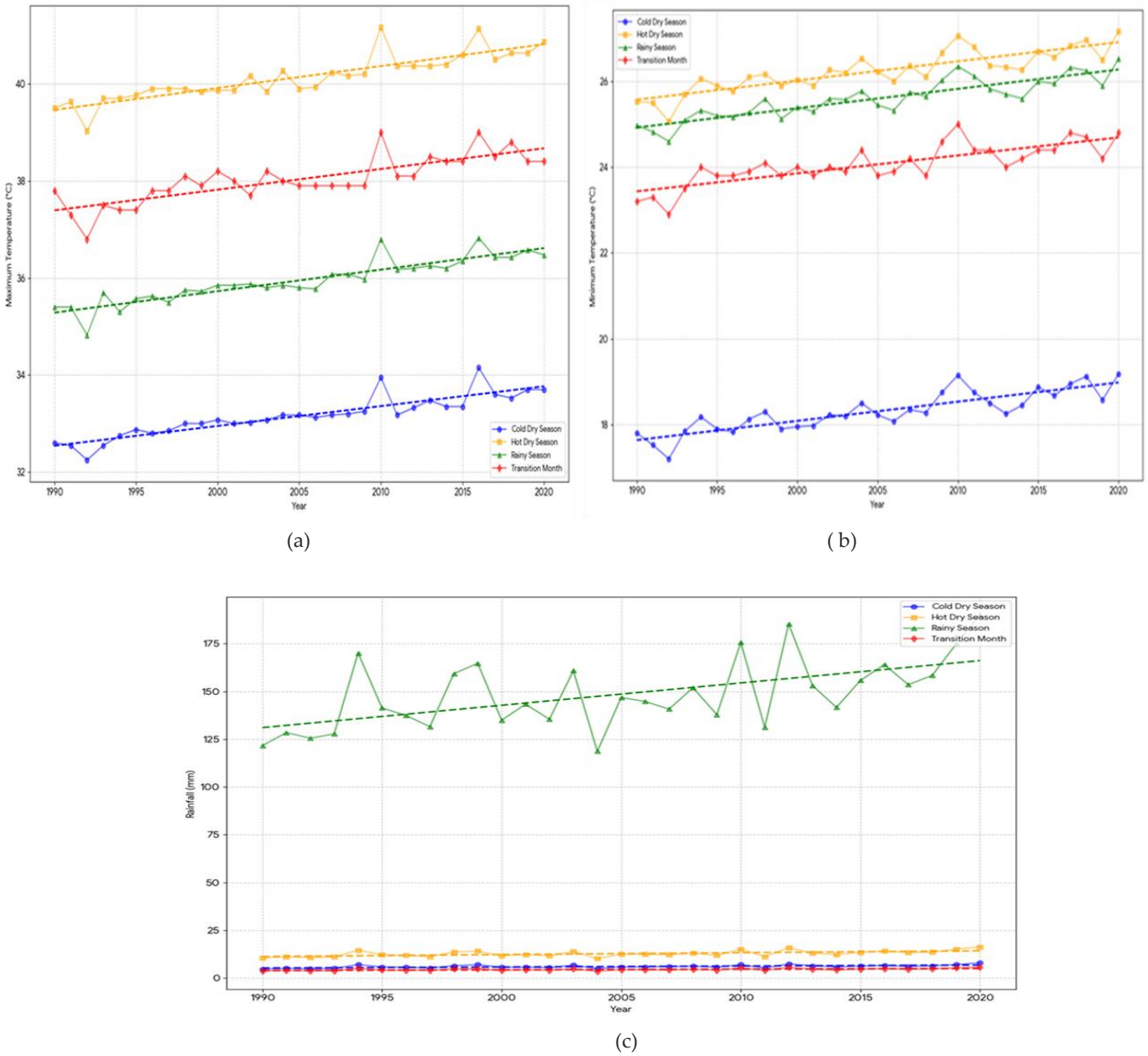

Figure 2. Chronological evolution of maximum temperatures (a), minimum temperatures (b), and rainfall (c) in Niger (1990–2020).

Results (b) show that the hot, dry season from March to May has the highest average minimum temperatures. During this period, the nights are the warmest. Followed by the rainy season (June to September), whose average minimum temperatures are similar to those of the hot season. During these months, humidity is frequently constant with high nighttime temperatures. The nighttime temperature begins to drop slightly in October, a transitional month. As expected, the coldest nighttime temperatures are noted during the cool, dry season from November to February. The results show that minimum temperatures have increased gradually and significantly throughout the year. The last ten years have recorded the highest minimum temperatures. The hot, dry 2010 season set a

record for the lowest average temperature. It was much colder in the early 1990s. The lowest average minimum temperature recorded during a cold, dry season dates back to 1992. An analysis of maximum temperatures indicates that the trend lines are remarkably parallel, suggesting that warming is an annual phenomenon that affects nights as much as days.

Result (c) demonstrates that the rainy season from June to September is the period when rainfall is most concentrated. It has a balanced sheet for more than 85% of annual rainfall, with an average of 148.56 mm. The dry and cold season is the driest with, only 6.00 mm, followed by the dry and hot season from March to May, with a significantly lower average of 12.75 mm. The transition month (October), with an average of 4.46 mm, remains relatively dry. Rainfall has increased over the last 30 years for all four (4) seasons. An annual growth rate of approximately 1.17 mm, the rainy season saw the most significant increase. This suggests that the rainy season is becoming wetter over time. While the hot dry season is increasing by about 0.10 mm per year, the cool dry season and the transition period are showing very slow growth, showing that some periods of the year remain dry despite the overall increase in annual rainfall. It was observed that 2020 was the wettest year with the highest rainfall total of 190.10mm during the rainy season. The driest rainy season was 2004, with only 118.60 mm of rainfall. The early 1990s (121.6 mm) was very close behind. The results reveal that, overall, the maximum rainfall totals over the past decade (2010-2020) are, on average, higher than the quantities recorded in the 1990s, reflecting an increase in the intensity of the rainy seasons.

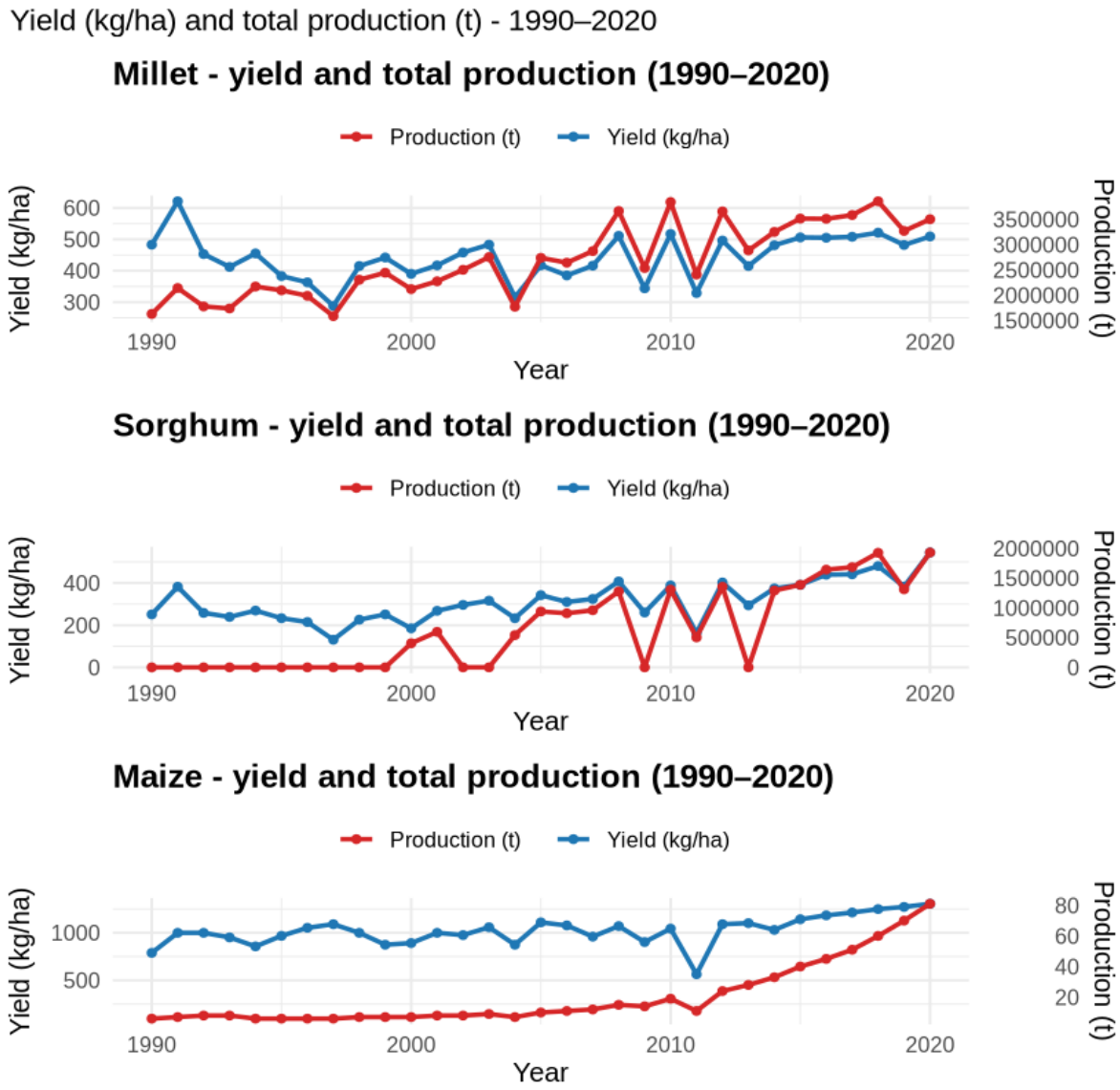

Figure 3. Dynamics of yields and total production of millet, sorghum and maize in Niger from 1990 to 2020.

4.1.2. Comparative dynamics of annual yield (kg/ha) and total production (t) of millet, sorghum, and maize in Niger (1990–2020)

Figure 3 shows the complex interactions among environmental stressors and productivity of Niger's three key cereal crops from 1990 to 2020. The finding shows that the two staple crops, millet and sorghum, are closely related with yield (kg/ha) and total production (t), indicating that the total production of these two staple crops are more driven by land productivity rather than the widening of cultivated areas at national level. Sorghum exhibits a sawtooth pattern in the period from 2005 to 2015, with production decreasing even as base yields remained fairly constant, indicating significant localized shortages or reporting issues. The millet variety, on the other hand, shows a trend that has been stabilized, as more than 500kg/ha was registered in 2020. Maize, however, has a decoupling effect, with the total production rising exponentially since approximately 2010, despite reasonably stable yields. This would imply a strategic change towards the extensification of agriculture or special irrigation, among other programs such as the 3N. Most importantly, the synchronized decline of yields for all three crops over the 2011 growing season is indicative of the high sensitivity of the sector to climate shocks, especially the Sahelian drought of 2011-2012. This is another reminder that the focus needs to shift from crisis management to proactive food security prevention modeling to ensure food security for the future.

Niger's agricultural shows a marked hierarchy, as illustrated in Figure 4, with millet maintaining the largest cultivated area. Between 2010 and 2018, its area nearly doubled, increasing from 3.37 million hectares in 1990 to approximately 7.4 million hectares. Despite slight subsequent fluctuations, it remains the most widespread crop. Similar results and consistent growth have been observed for sorghum, with the area under cultivation increasing from 1.06 million hectares in 1990 to over 4 million hectares in 2018, before experiencing a slight decline. The area of maize planted is much less than that of millet or sorghum, but after 2010, there is a clear upward trend that indicates increased use. The trends of their cropping systems confirm the dominance of millets and the sustained increase in sorghum and the rapid increase in maize, likely due to changing farming methods and increased food demand.

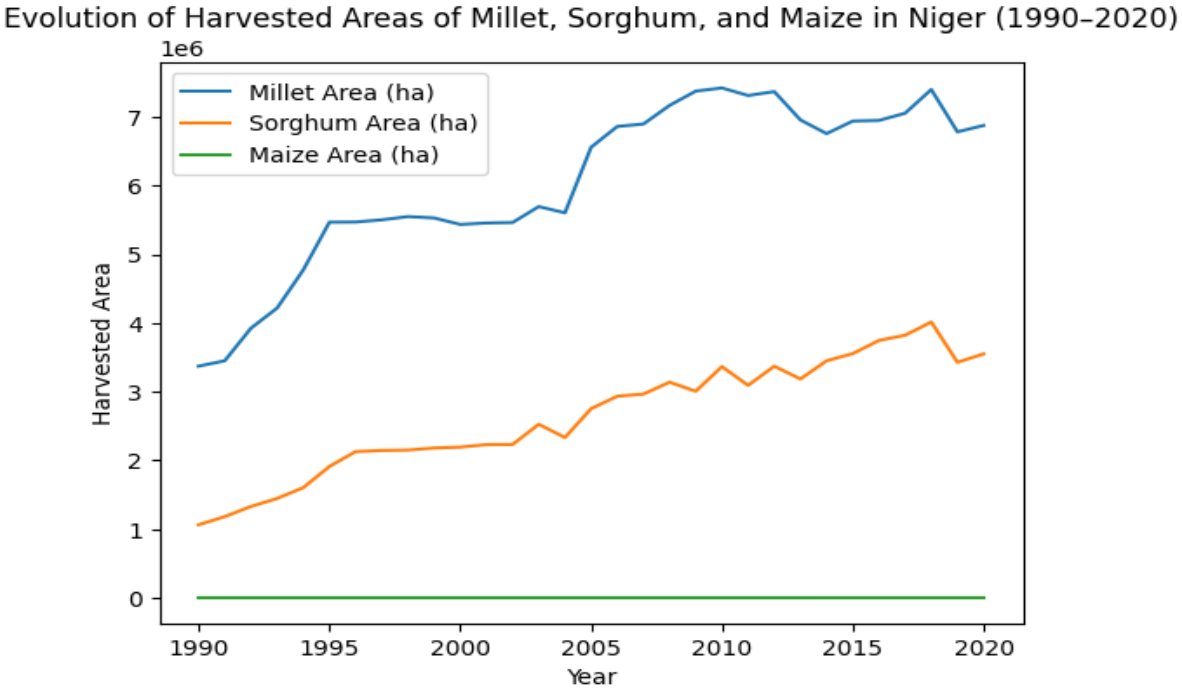

Figure 4. The evolution of harvested areas of millet, sorghum and maize in Niger from 1990 to 2020.

4.1.3. Evaluation of the Influence of Climatic Factors on Cereal Production Indicators Using the Partial Least Squares Method (PLS-SEM)

Table 3 indicates that the reliability and convergent validity of the constructs were assessed using Cronbach's alpha coefficient, composite reliability (rhoc), and extracted mean variance (AVE). All constructs have shown AVE values between 0.623 and 0.865, well above the minimum threshold of 0.50. The composite reliability values ranged from 0.768 to 0.950, exceeding the recommended threshold of 0.70, indicating satisfactory internal consistency. However, Cronbach's alpha values remained below the standard threshold of 0.70 for all constructs. An indicator (millet yield) was removed from the millet construct due to low external factor

loadings (0.578), below the reference threshold of 0.708. After its removal, the millet construct achieved a rhoc of 0.848 and an AVE of 0.660.

Table 3. Measurement Model Evaluation

Construct	Indicators	Coefficients	Cronbach's α (CA)	Composite Reliability (rhoC)	AVE	Number of indicators Deleted
Climate	Temperature (°C)	0.789	0.019	0.768	0.623	0
	Rainfall_(mm)	0.789				
Maize	Maize_production (t)	0.982	0.394	0.950	0.865	0
	Maize_area (ha)	0.959				
	Maize_yield (kg /ha)	0.844				
Millet	Millet_production (t)	0.998	0.619	0.848	0.660	1(millet yield (kg/ha))
	Millet_area (ha)	0.806				
Sorghum	Sorghum_production (t)	0.965	0.677	0.943	0.847	0
	Sorghum_area (ha)	0.900				
	Sorghum_yield (kg /ha)	0.894				

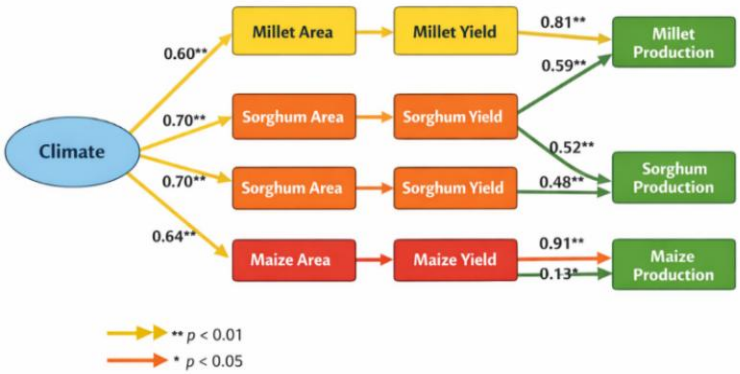

Figure 5. Impact of climate on cereal production in Niger

The structural relationship between climate and millet, sorghum, and maize production was illustrated in Figure 5. Cultivated area and yield act as mediating variables for the final endogenous production outcomes of millet, sorghum, and maize production, while climate is considered an exogenous variable. The structural robustness of the model was indicated by the statistical significance of each variable ($p < 0.05$) and then the high significance ($p < 0.01$) observed for the majority of relationships. PLS-SEM structural path model illustrates the influence of Niger's climate on cereal production. Cultivated areas and millet, sorghum, and maize yields are strongly impacted by climate, an exogenous variable that also influences crop production. Path coefficients are shown by arrows; Significance is indicated by a color code (**$p < 0.01$ in yellow) and (*$p < 0.05$ in orange). The results show that an area (0.806) and yield (0.587) have a significant impact on millet production. Also, area (0.523) and yield (0.483) both impact sorghum production, while area (0.905) is the main determinant of maize production, with yield contributing only (0.132). The direct and indirect effects of climate on cereal production, via agricultural sectors, are highlighted by the statistical significance of all correlations ($t > 1.96$). Climate has a major impact, both in terms of cultivated area and yield, as shown by the PLS-SEM structural model. Climate (0.737) and yield (0.695) are the most sensitive to sorghum area and yield, respectively. The area under cultivation is the most important factor for millet and maize, while yield is a secondary factor, especially in maize (0.132). Indirect effects emphasize the critical role of adaptive management strategies for reducing the implications of climate change on productivity; they indicate that the effect of climate on productivity is

strongly dependent on management practices in agriculture. The direction of all the coefficients is globally significant, which shows the capability of the model and the importance of climate in cereal production.

Figure 6 illustrates the strong persistence of land use for the three cereals, with an autocorrelation function (ACF) between 0.85 and 0.88 at lag 1 and remaining high at lag 2 (0.71–0.80). This highlights the evolving nature of agricultural decisions, indicating that cultivated area changes continuously rather than through a series of random fluctuations. These results indicated that structural factors such as land availability, technology adoption, population pressure, and long-term household strategies, which generally evolve gradually, determine land use. Therefore, once a land-use change occurs, this pattern is generally maintained in the following years, reflecting the stability of the main political and socioeconomic indicators. All crops have shown a significant positive autocorrelation with total production, with values at lag 1 being moderate to high (0.55 to 0.82) and values at lag 2 remaining significant (0.67 to 0.73). This finding is consistent with expectations, as yield and area are mechanically associated with production, and area exhibits particularly strong persistence. The yield shows a significantly weaker autocorrelation than area and production, especially with a year lag of 1. The cereal millet yield had only a mild 2-year lag (0.34) and a weak 1-year lag (0.13) of autocorrelation, implying relatively low interannual persistence. Sorghum yield is highly persistent and highly correlated with lag 2, while the autocorrelation at lag 2 of maize yield is weak (0.31) at lag 1. The ACF analysis shows that cultivated areas exhibit strong time dependence in spatial persistence, with high positive short-term autocorrelation. This suggests that land use changes are slow and path- or direction-dependent. There was significant autocorrelation of total production, which is consistent with the inherent inertia of land area and suggests that production is partly a function of multi-year structural dynamics. Yield, by contrast, shows a decline in autocorrelation (interannual sensitivity), expected to be related to climate variability and other transient factors. The results highlight the critical role of taking serial dependence into account when simulating the interaction between climate and crops over time.

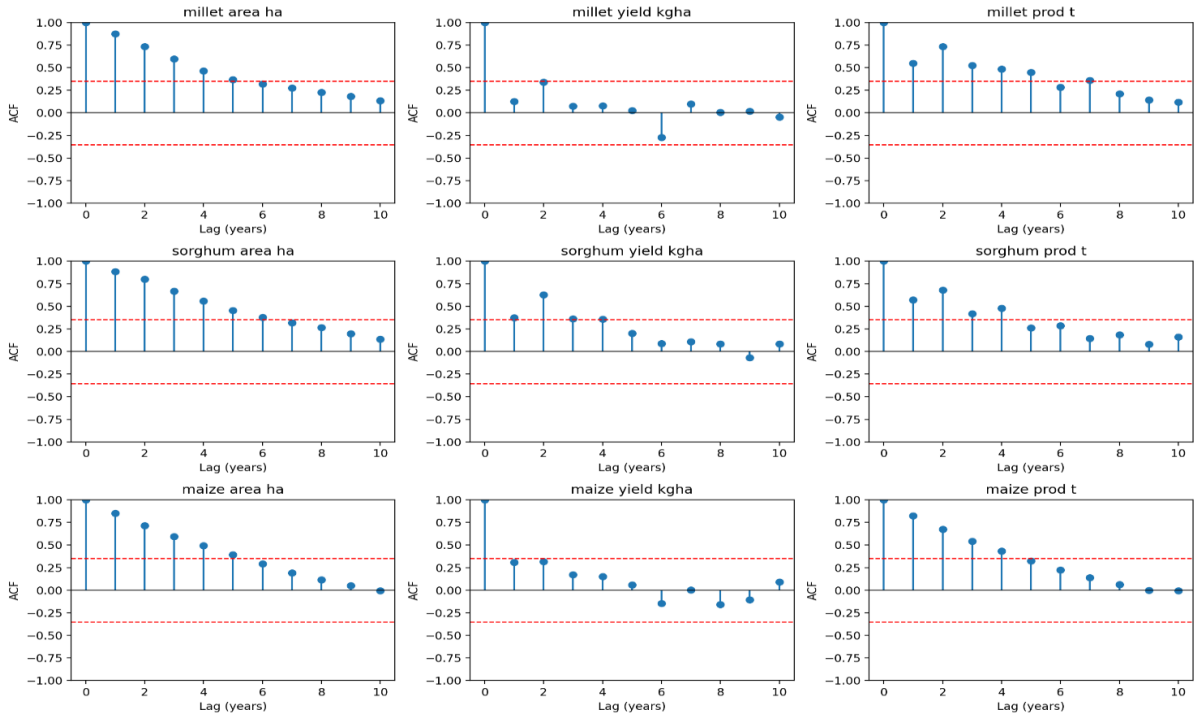

Figure 6. Autocorrelation function for area, yield and total production of millet, sorghum and maize.

4.1.4. Projected Trends for Cultivated Area, Crop Yield, and Total Production of Millet, Sorghum, and Maize (1990–2050)

Figure 7 illustrates data from 1990 to 2020 and ARIMA projections from 2021 to 2050 for millet, sorghum, and maize production indicators in Niger. The results clearly show that the projected increases in total production are almost entirely attributable to the expansion of cultivated areas, with yields of the three cereals expected to stagnate or decline relative to 2020 baseline levels. The 95% forecast intervals further reveal increasing climate volatility and uncertainty as the projections approach 2050.

For millet, the cultivated area increased from 3.37 million hectares in 1990 to 6.88 million hectares in 2020, representing a 104% increase. The ARIMA reference scenario projects a further expansion to 10.38 million hectares by 2050, +51% compared to 2020, 95% forecast interval: 7.12–13.64 million hectares. Millet yields increased slightly, from 483 kg/ha in 1990 to 509 kg/ha in 2020(+5.4%), but are projected to decrease to 443 kg/ha by 2050, -13% compared to 2020, 95% forecast interval: 301–585 kg/ha. The trend observed in the areas, millet crop increased from 1.63 million tonnes (1990) to 3.50 million tonnes (2020) (+114.9%) and is expected to reach 5.16 million tonnes by 2050, +47.4% compared to 2020, 95% forecast interval: 3.25–7.07 million tonnes.

For sorghum, the cultivated area increased from 1.06 million hectares in 1990 to 3.55 million hectares in 2020 (+234.4%), and baseline forecasts indicate continued growth to 6 million hectares by 2050, +69.1% compared to 2020, 95% forecast interval: 4.54–7.46 million hectares. Sorghum yield increased from 251 kg/ha in 1990 to 544 kg/ha in 2020(+116.7%), but is anticipated to decrease to 474 kg/ha by 2050 (-12.9% compared to 2020), with a very wide 95% forecast interval (47–901 kg/ha), reflecting considerable uncertainty. Sorghum crop increased from 0.27 million tonnes (1990) to 1.93 million tonnes (2020) (+624.8%) and is expected to reach 3.02 million tonnes by 2050, +56.2% compared to 2020, 95% forecast interval: 1.73–4.30 million tonnes.

For maize, the data available is less extensive than for millet and sorghum, and baseline forecasts indicate a gradual increase in production until 2050. By 2050, an average ARIMA forecast reaches around 123,092 tonnes, with a projected yield of around 1,434 kg/ha and an area of 85,853 ha, as shown in the 2046-2050 forecast trajectory. The maize crop represents a relatively small share of total cereal production in this starting point scenario, and its projected production growth is modest compared to millet and sorghum.

As can be seen in all of the graphs, the spread of the forecast intervals grows with increasing forecast horizon, as is expected with the limitations of long-term forecasts. The overall base case scenario is not altered by this growing divergence. Growing land area will continue to be the main contributor to the expected production increase. In the medium-term projections, however, the yield growth trend slows down, suggesting that yield growth will rely almost exclusively on agricultural extensification if there are no major technology or policy programs.

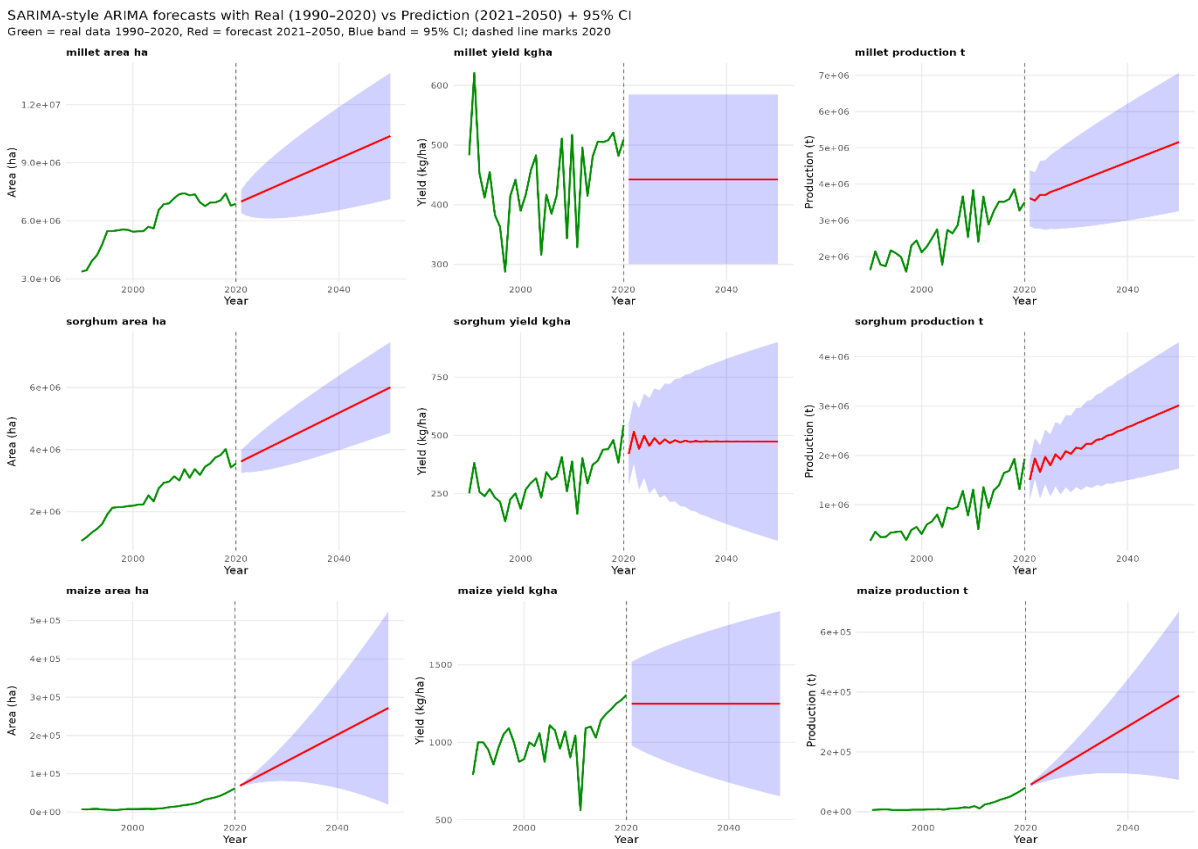

Figure 7. Long-term predictions of cereal production dynamics in Niger until 2050: trajectories of area, yield, and production.

5. DISCUSSION

The rise in minimum temperatures far exceeds historical levels and is consistent with the measured warming rate of approximately 0.04°C/year, representing an increase of 1.3°C since 1990. These results are consistent with broader regional studies (IPCC, 2021) that highlight the crucial role of the Sahel in climate change. Dike et al., (2020) show that continued thermal intensification has been recorded in West Africa. Also, Bichet and Diedhiou (2018) observed that the rebound in rainfall in the Sahel is correlated with the intensification of rainy seasons, characterized by record rainfall totals over the past decade. These findings noted that rainfall is increasingly concentrated in less frequent but more intense events, despite the increase in annual totals. Lin et al., (2022) show that a deviation from 20th century climatic norms in the region is confirmed by the transformation of the cold dry season, shifting from a period of constant cooling to a period marked by significantly higher minimum temperatures.

The findings of Bichet and Diedhiou (2018), who indicate an accentuation of seasonality in West Africa, are consistent with the concentration of over 85% of annual rainfall between June and September. The recovery of rainfall patterns in the Sahel, over the last ten years, as marked by more frequent and intense extreme rainfall events, is corroborated by Dike et al., (2020), who report that the intensification of the rainy season, with an increase in rainfall of 1.17 mm per year, was observed in this study. Moreover, the distinction between the record peak of 190.10 mm reached in 2020 and the stagnation of average rainfall during the dry season, ranging from 4.46 mm to 12.75 mm, is supported by the projections of Olusegun et al., (2022) regarding a polarization of the water cycle in the region. These results confirm that while the total volume of rainfall increases, it becomes more concentrated, exacerbating the risk of seasonal flooding compared to the drought periods of the early.

Regarding the dynamics of yields and all cereal production of millet, sorghum, and maize in Niger, the findings of Mbow et al., (2021), which highlight that agricultural production in the Sahel remains largely dependent on seasonal climate productivity rather than solely on land expansion, are consistent with the observed correlation between yield and total production of millet and sorghum. The climate sensitivity analysis context developed by Moron et al. (2020), which identifies the Sahelian cereal triad as highly vulnerable to increased heat stress and rainfall variability, was validated by the high yield volatility and synchronized production collapse during the 2011–2012 drought. Additionally, the decoupling effect and exponential growth of maize after 2010 demonstrate the success of regional intensification strategies, such as the 3N Initiative, which, according to Sharma et al. (2009), is considered essential to counter the stagnation of productivity in conventional rainfed food crops. Eventually, these findings show that, despite the expansion of certain sectors, such as maize, appreciations to modern policies and irrigation outlines, the fundamental vulnerability of millet and sorghum to climatic hazards remains the main threat to the Niger's food security.

The near doubling of cultivated areas of millet and sorghum between 1990 and 2018 reflects a trend towards agricultural extensification in the region. Seppelt et al. (2022) indicate that the growing food demand is therefore met by the expansion of cultivated areas rather than by increasing yields. The highlight the need for drought-resistant food crops in the face of the polarization of the water cycle, are corroborated by the findings of Garba et al., (2024), this sustained growth, particularly by the predominance of millet-based systems. The rapid adoption of maize after 2010, despite a relatively small total area under cultivation, has occurred. The strategic shift towards crop diversification and irrigated agriculture is also corroborated by Tshilowa et al., (2025), who consider it an essential adaptation to the increasing frequency of heavy rainfall events.

The PLS-SEM analysis, the measurement model remains reliable according to the rhoc, even though the Cronbach's alpha values for several constructs, notably climate (0.019) and maize (0.394), are below the conventional threshold of 0.70. This result is supported by the finding of Haji-Othman and Yusuff, (2022). Vuković (2024) illustrates that the divergence between these two indicators can be explained by the following factors: the number of elements composing a construct has a significant impact on Cronbach's alpha coefficient. The latter tends to considerably underestimate the reliability of the climate construct, which includes only two indicators, such as precipitation and temperature. This result is consistent with those of Tavakol and Dennick (2011), who demonstrate that Cronbach's alpha coefficient is mathematically dependent on the number of items. Alpha will systematically underestimate the true reliability of a construct if it contains very few indicators. Cronbach's alpha coefficient is based on the assumption that all indicators have tau equivalence, or equal loadings. Composite reliability is a more precise and permissive measure of the internal consistency of PLS-SEM models, as it weights indicators according to their actual individual loadings (Haji-Othman and Yusuff, 2022). AVE values significantly greater than 0.50 from 0.623 to 0.865 indicate convergent validity, indicating that the constructs influence a significant portion of the variance of their indicators. Despite a low alpha coefficient, this shows that the indicators are indeed representative of the corresponding latent variables, which is also correlated by the result found by Kamranfar et al., (2023). A PLS-SEM structural model shows that crop yield and cultivated area are the main drivers of climate influence on cereal production in the Republic of Niger. This

model confirms that Niger's cereal production is strongly influenced by climate, both directly and indirectly. The millet and maize production depend more on total cultivated area than on yield gains, while sorghum shows the greatest sensitivity to climate, both in terms of area and yield. This finding is consistent with that of Mohamed et al., (2025), who found that, although sorghum in Niger is drought-tolerant, its growth cycle is extremely sensitive to temperature and rainfall variations typical in the Sahelian zone.

Regarding the ACF of total production, yield, and cultivated area of maize, sorghum, and millet, the most stable variable is cultivated area. This recommends that land use is a process, meaning that long-term structural factors, such as technology, policies, and demographics, change progressively rather than abruptly and influence agricultural decisions. Yields reveal a much lower autocorrelation than cultivated area. This suggests that yields are highly sensitive to interannual shocks, such as climate variability and short-lived environmental influences, and lack persistence from year to year. Largely due to the high stability of the cultivated area component, total production maintains a moderate to strong autocorrelation. The dynamics of previous years have a significant impact on current production levels; time series models between climate and crops must take into account lagged effects, as demonstrated by the strong serial dependence (autocorrelation) of these variables. The increase in total production of millets, sorghum and maize expected by the 2050 forecasts can be purely attributed to the increase of the areas under cultivation, without taking into account the increase in yields (Sanusi, 2023). In 2050, millet is estimated to be grown on 10.38 million ha, which represents a 51% rise from 2020; and 5.16 million tonnes of millet are expected to be produced. Sorghum is expected to be cultivated on 6 million hectares, a 69% increase compared to 2020, yielding 3.02 million tonnes. Yields of all three cereals are projected to decline compared to 2020 baseline levels. Sorghum and millet yields are expected to fall by 13% (474 kg/ha), a decrease of 443 kg/ha, indicating a significant and persistent yield deficit in sub-Saharan Africa. The results confirm the findings of Hall et al., (2017) and Mperejekumana et al., (2023). Climate uncertainty is rising (Singh et al., 2024), and the 95% projection intervals are growing considerably larger as we get close to 2050. Mperejekumana et al., (2023) reported that the vulnerability of sorghum to interannual shocks is very high, ranging from 47kg/ha to 901kg/ha. Even though maize production is expected to increase steadily to around 123,092 tonnes, it still contributes very little to total cereal production compared to more traditional staple cereals such as sorghum and millet.

6. CONCLUSION

The acceleration of climate change is a persistent reality. The cool and dry season in Niger is now warmer than the coldest months in the 1990s, due to a systemic warming trend. The main cause of fluctuations in sorghum and millet yields remains the high interannual volatility of rainfall, despite a slight upward trend. SARIMA and PLS-SEM models reveal a risky reliance on expanding cultivated areas. In the past, increased production was achieved by doubling or tripling the harvested area, which has increased since 1990. However, declining yields per hectare due to climatic constraints suggest that this process will become increasingly less profitable by 2050. The structuring sensitivity to climate change is the highest for sorghum, while maize shows a decoupling effect, namely an increase in production when specialized irrigation and crop expansion are accompanied by stable yields. Until it hits its threshold, the millet crop is the most important, but a fixed part of the system. Future risks are determined by the synchronized decline in yields observed during the year from 2011 to 2012 drought. Niger Republic faces a future where land expansion will no longer be able to compensate for productivity losses due to climate change, unless there is a major transition to CSA, including solar irrigation, drought-resistant varieties, and digital early warning systems. The 3N Initiative should take a localized, gender-sensitive approach to agricultural extension services and emphasize intensification (increased yield/ha) over extensification (land area), as a strategy to promote resilience through 2050.

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Author Contributions

ISMAILLA IS, ŞENGÜL H, AKDEMIR Ş, HAYRAN S: writing, review, and editing; ISMAILLA IS, AKDEMIR Ş: project management and fundraising; ISMAILLA IS, ŞENGÜL H: sample data collection and analysis, AKDEMIR Ş, ŞENGÜL H: project supervision.

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Conflict of interest

The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethical approval

Not applicable. This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

Not applicable.

Data availability

All data associated with this study will be available based on the reasonable request to corresponding author.

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