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Spatio-Temporal Analysis of Rainfall Variability and Agricultural Resilience in Nasarawa State, Nigeria: Implications for Climate Adaptation

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ABSTRACT

This study investigates the spatial and temporal variability of rainfall across the Northern, Southern, and Western zones of Nasarawa State, Nigeria, from 1997 to 2023. The analysis integrates multiple rainfall variables annual rainfall, number of rain days, rainfall onset, cessation, and growing season length (LGS) within a unified regional framework, which is a novel approach for understanding climate variability in this region. Monthly rainfall data from the Nigerian Meteorological Agency (NiMET) were analyzed using Mann-Kendall test and World Meteorological Organization (WMO) variability analysis to assess trends and variability. The results reveal significant spatial heterogeneity in rainfall, with the Northern and Western zones experiencing irregular rainfall onset, delayed cessation, and fluctuating LGS. In contrast, the Southern zone exhibited a comparatively stable rainfall distribution. These variations underscore the challenges posed to agricultural productivity, especially in the Northern and Western zones, where inconsistent rainfall and shorter growing seasons prevail. The study contributes to the literature by providing a comprehensive regional analysis that combines onset, cessation, and LGS variables to improve understanding of rainfall variability. The findings emphasize the need for region-specific climate adaptation strategies, including enhanced water management and the adoption of drought-resistant crops, to bolster agricultural resilience.

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INTRODUCTION

Rainfall variability remains one of the most critical climatic factors shaping agricultural performance in semi-arid and sub-humid environments, especially where rain-fed agriculture supports household livelihoods and regional food systems. In such settings, rainfall variability is expressed through changes in precipitation amount, frequency, seasonal distribution, onset, cessation, and the length of the growing season, all of which directly influence planting decisions, crop establishment, moisture availability, and final yields (Niang et al., 2022). Increasingly erratic rainfall patterns, often marked by alternating wet spells and dry spells within the same season, have heightened concerns about declining agricultural reliability, food insecurity, and production instability. These climatic irregularities complicate farm planning because crops are highly sensitive to both the timing and distribution of rainfall, not merely the total annual amount received.

Across Africa, recent studies have shown that rainfall variability is becoming more pronounced, with important consequences for crop production and rural livelihoods. For example, evidence from Southern Africa indicates that rainfall seasons that were once relatively stable are increasingly interrupted by irregular precipitation, thereby exposing crops to both waterlogging and drought stress within a single season (Mohammed et al., 2023). In West Africa, similar patterns have been associated with extreme rainfall events, prolonged dry periods, intra-seasonal dry spells, and rainfall deficits that reduce the productivity of major staple crops such as sorghum and millet (Olayide et al., 2024). These broader regional examples are relevant to Nasarawa State because they demonstrate that rainfall variability is not only a continental or subregional concern, but also a practical local challenge in farming systems that depend heavily on seasonal rainfall. They also show that the most serious agricultural effects of climate variability often emerge through changes in rainfall timing and distribution, which are precisely the conditions farmers in Nasarawa State must respond to each season.

Although a growing body of research has examined rainfall variability in Africa, much of it has focused on continental, regional, or national scales. While these studies provide important background, they often conceal local differences that are essential for agricultural planning and adaptation. Edao et al. (2023) note that rainfall variability can differ substantially across ecological zones and microclimates, yet many studies do not adequately capture how such differences operate at finer spatial scales. This limitation is particularly important in places like Nasarawa State, where farming decisions are made locally and where climatic conditions may vary considerably across zones within the same state. As a result, findings from broader-scale studies cannot easily be translated into location-specific recommendations for planting dates, crop selection, water management, or risk reduction.

The case of Nasarawa State is especially important because agriculture is central to livelihoods, food supply, and rural income, while the state itself is characterised by marked internal climatic contrasts across its Northern, Southern, and Western zones. These zones do not experience rainfall in the same way. Variations in rainfall onset, cessation, seasonal distribution, and growing season length can create unequal levels of agricultural opportunity and risk across the state. For farmers cultivating crops such as maize, beans, and yams, even small shifts in the timing of seasonal rains can lead to delayed planting, poor germination, moisture stress during sensitive growth stages, and lower yields. The importance of studying rainfall variability in Nasarawa State, therefore, lies not only in describing climate behaviour, but in generating practical evidence for agricultural adaptation. Without a clear understanding of zonal rainfall patterns, it becomes difficult for farmers, extension services, and policymakers to design responses such as adjusted cropping calendars, drought-tolerant crop choices, supplementary irrigation planning, and improved soil and water conservation strategies.

This study addresses that challenge by undertaking a spatio-temporal analysis of rainfall variability across the Northern, Southern, and Western zones of Nasarawa State. Specifically, it examines rainfall onset, cessation, and length of growing season as critical dimensions of climate risk that directly shape agricultural performance. In doing so, the study moves beyond broad descriptive climate analysis and adopts a climatic-agronomic framework, that is, an analytical approach that links climatic variables to agricultural implications. Within this framework, rainfall characteristics are not treated as isolated meteorological events; rather, they are analysed in terms of how they affect planting windows, crop water availability, seasonal crop suitability, and the vulnerability of farming systems in each zone. By integrating these interrelated rainfall variables into a single state-level analysis, the study provides a more practical basis for understanding how climate variability translates into agronomic challenges.

Therefore, the significance of this study lies in its ability to bridge the gap between climate analysis and agricultural decision-making in Nasarawa State. Unlike studies that aggregate rainfall conditions over large territories, this research provides zone-specific evidence that can support targeted adaptation planning. Its findings are expected to help identify which areas are more vulnerable to delayed onset, early cessation, or shortened growing seasons, and how such patterns may affect agricultural productivity. In this way, the study contributes not only to the literature on rainfall variability, but also to the design of locally relevant adaptation strategies aimed at strengthening agricultural resilience and food security under increasing climate uncertainty.

METHOD

Study Area

Nasarawa State lies between latitude 7^0 45′ N and 9^0 25′ N of the equator and between longitude 7^0 and 9^0 37′ E of the Greenwich meridian spans approximately 27,117 km^2 and is characterized by diverse topography, ranging from lowland plains in the south to undulating hills in the north and west. The state was divided into three zones Northern, Southern, and Western based on administrative considerations. These zones are predominantly agrarian, relying on rain-fed farming, which makes them highly sensitive to fluctuations in rainfall and temperature.

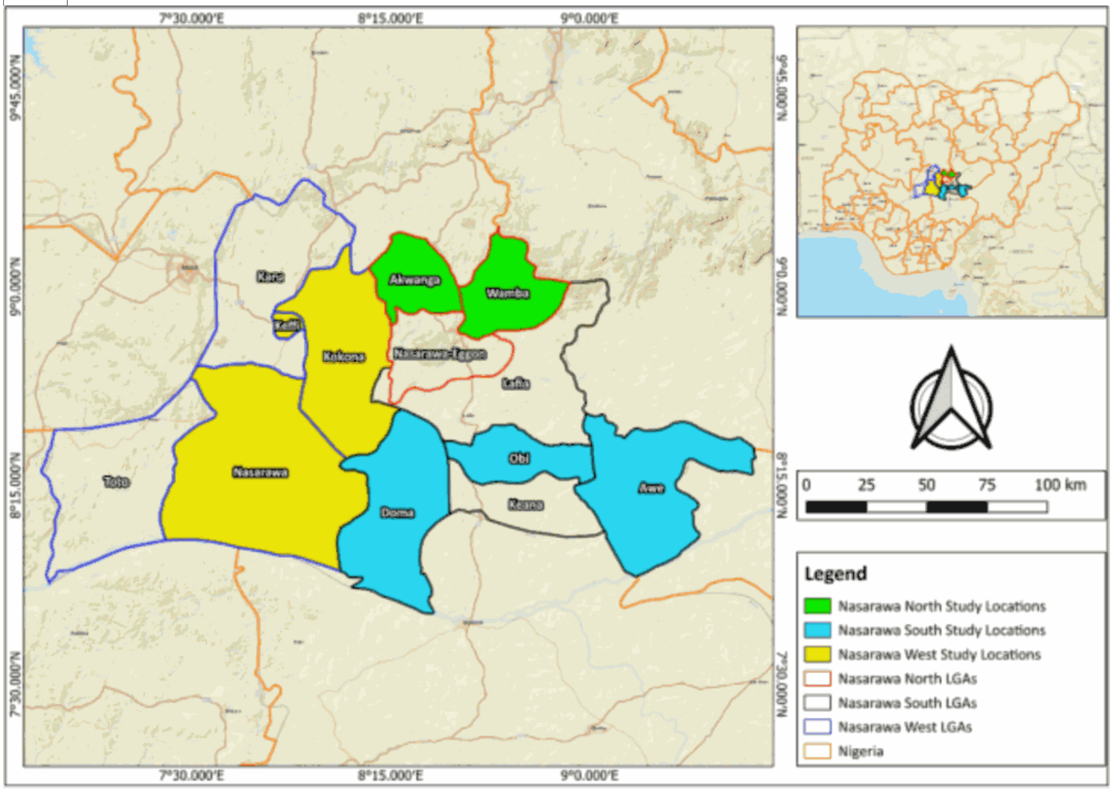

Figure 1. Showing Map of the Study Area
Source: Samson Amoga Asemanya (2025)

Data Collection and Pre-processing

The data used for this study were collected from NiMET, and include monthly rainfall records for each of the three zones in Nasarawa State. The data were pre-processed by checking for missing values, outliers, and inconsistencies. Gaps in the data were filled using linear interpolation, and outliers were addressed using a robust statistical approach to minimize their influence on the analysis.

Variability Analysis

The simple method which measures climate variability by dividing the climatic time series into two periods of equal length was, recommended by WMO (1988) cited in Lawrence (2021). The climate variability was computed by

$$Cv = \mu_1 - \mu_2 \quad (1)$$

$$Cv = \sigma_1 - \sigma_2 \quad (2)$$

Where $Cv =$ climate variability, $\mu_1 =$ mean of the first time scale, $\mu_2 =$ mean of the second time scale, $\sigma_1 =$ standard deviation of the first time scale and $\sigma_2 =$ standard deviation of the second time scale. The coefficient of variability (Cv) was computed by

$$CV = \frac{\sigma}{\mu} \times 100 \quad (3)$$

Where σ = standard deviation of the annual data series, and μ = mean of the annual data series. Higher CV values indicate greater relative variability.

Trend Analysis - Mann-Kendall Test

To complement the OLS analysis, the Mann-Kendall test is applied to detect monotonic trends in the rainfall data. The test evaluates the null hypothesis that there is no trend (i.e., the values of the data are randomly ordered over time). The test statistic SSS is calculated as follows:

$$S = \frac{n - 1}{i = 1,\ j = i + 1} sign(Yj - Yi)$$

Where:

Yj and Yi are rainfall values at times j and i, respectively,

The sign function returns +1, −1, or 0 based on whether Yj>Yi, Yj<Yi or Yj=Yi, respectively.

The Mann-Kendall statistic is used to calculate the p-value for the trend test, with a significance level of 0.05 used to determine whether a significant trend is present.

Statistical Significance and Confidence

To evaluate the statistical significance of the observed trends, both OLS regression and Mann-Kendall results are tested at the 95% confidence level. If the p-value is less than 0.05 for either the OLS or Mann-Kendall test, the null hypothesis of no trend is rejected, indicating that a significant trend exists in the rainfall data.

Additionally, a Durbin-Watson **test** is applied to check for autocorrelation in the residuals of the OLS regression, ensuring that the model assumptions are not violated. The Durbin-Watson statistic should be close to 2 to indicate no significant autocorrelation.

Climate Resilience Framework

The spatio-temporal analysis is further integrated into a framework for assessing agricultural resilience to rainfall variability. This framework examines how the variability in rainfall patterns, particularly the onset, cessation, and LGS, impacts agricultural productivity and the need for climate adaptation measures, such as improved water management systems and the adoption of drought-resistant crops.

Statistical Software

All statistical analyses are performed using R and Python programming languages, with packages like "lm" for regression analysis, "Kendall" for Mann-Kendall tests, and "dwtest" for the Durbin-Watson test. These tools ensure the robustness of the statistical tests and the accuracy of the trend analysis.

RESULTS AND DISCUSSION

Rainfall variability is one of the key indicators in climate change and agricultural sustainability studies, particularly in tropical regions that are highly dependent on seasonal rainfall patterns. Changes in rainfall distribution, number of rainy days, and Length of Growing Season (LGS) can directly affect agricultural productivity, food security, and farmers’ adaptation strategies. Therefore, the analysis of rainfall variability in Nasarawa North between 1997 and 2023 is essential for understanding the climatic dynamics occurring in the region and their implications for agricultural systems.

Table 1. Rainfall Variability in Nasarawa North (1997-2023)

Parameter	Period	Annual Rainfall (mm)	Rain Days	LGS (Days)
Mean	1997-2010	1295.5	192	189
	2011-2023	1379.8	193	187
	Variability	-84.3	-1	2
	1997-2023	1336.1	192	188
Standard deviation	1997-2010	158.5	9.9	11.1
	2011-2023	187.9	11.9	12.1
	Variability	-29.4	-2	-1
	1997-2023	175.2	10.8	11.4
Coefficient of variability	1997-2010	0.12	0.05	0.06
	2011-2023	0.14	0.06	0.07
	Variability	-0.02	-0.01	-0.01
	1997-2023	0.13	0.06	0.06

The data reveals an increase in annual rainfall in Nasarawa North from 1295.5 mm during the period 1997–2010 to 1379.8 mm from 2011–2023, representing a positive change of +84.3 mm. This increase, although significant, is relatively modest in terms of total volume. More importantly, the number of rain days only showed a slight increase, from 192 to 193, indicating that the increase in rainfall is not due to a substantial rise in the number of rainy days, but rather to fluctuations in rainfall intensity and distribution during the season. This could mean that while rainfall is available for longer periods, it may be more concentrated into shorter, heavier spells, which may not always be beneficial for crops that require consistent, evenly distributed rainfall (Niang et al., 2022).

Despite the increase in total rainfall, the growing season length (LGS) showed a decrease from 189 days in 1997–2010 to 187 days in 2011–2023, a reduction of 2 days. This shortening of the growing season, coupled with the increase in rainfall, presents a complex scenario for agricultural productivity. On one hand, more rainfall could provide additional moisture, potentially benefitting crops during the early growing stages, which are critical for crop establishment. On the other hand, the reduced length of the growing season could result in crops being unable to fully mature, especially for long-cycle crops like maize and yams. This reduction in growing season duration may reduce the total amount of time crops have to develop, potentially impacting yields, especially in crops that are highly sensitive to the timing of rainfall (Olayide et al., 2024).

The increase in rainfall coupled with a shortening growing season could have mixed effects on agricultural productivity. While the increase in rainfall may improve soil moisture availability, especially in regions prone to dry spells, the shortened growing season may not provide enough time for crops to reach their full potential. The inconsistent distribution of rainfall may also result in waterlogging in certain periods, followed by dry spells, which could adversely affect crop health, particularly for rain-fed systems that are not supported by irrigation (Mohammed et al., 2023).

Furthermore, the coefficient of variability in rainfall, which remained relatively low at 0.12 for 1997–2010 and 0.14 for 2011–2023, suggests moderate stability in rainfall patterns. This indicates that although there is an increase in rainfall, the overall variability in rainfall from year to year is not dramatic, and farmers may not experience large swings in water availability. However, even with moderate variability, the changing rainfall patterns (increased intensity and reduced growing season length) could still pose challenges for crop scheduling, pest and disease control, and overall yield forecasting (Niang et al., 2022).

Table 2. Rainfall Variability in Nasarawa West (1997-2023)

Parameter	Period	Annual Rainfall (mm)	Rain Days	LGS (Days)
Mean	1997-2010	1174.6	185	187
	2011-2023	1208.8	190	187
	Variability	-34.2	-5	0
	1997-2023	1191.1	187	187
Standard deviation	1997-2010	145.6	10.3	14.2
	2011-2023	160.6	11.4	12.7
	Variability	-15	-1.1	1.5
	1997-2023	151.1	10.9	13.3
Coefficient of variability	1997-2010	0.12	0.06	0.08
	2011-2023	0.13	0.06	0.07
	Variability	-0.01	0.0	0.1
	1997-2023	0.13	0.06	0.07

In Nasarawa West, the mean annual rainfall increased from 1174.6 mm (1997–2010) to 1208.8 mm (2011–2023), showing a +34.2 mm rise, while the number of rain days also saw an increase from 185 to 190. Despite this increase, the growing season length (LGS) remained stable at 187 days. The stability of LGS indicates that while rainfall is increasing, it is not disrupting the growing cycle, which remains relatively stable.

The coefficient of variability remained low (0.13) for both periods, indicating consistent rainfall patterns over time. However, the increase in rain days and annual rainfall could point to shifting rainfall distribution, potentially enhancing the water availability for farming and increasing the water resource potential in the region.

Similar studies across the central and northern Nigerian regions show that rainfall variability has been influenced by climate change, leading to increased total rainfall in some regions, while other areas experience drier conditions (Ishaku et al., 2024). The increase in rain days is consistent with findings that suggest longer rainy seasons may lead to more water availability, which could support crop cultivation but also increase flooding risks (Olali et al., 2025).

Table 3. Rainfall Variability in Nasarawa South (1997-2023)

Parameter	Period	Annual Rainfall (mm)	Rain Days	LGS (Days)
Mean	1997-2010	1155.3	160	184
	2011-2023	1304.3	160	185
	Variability	-148.7	0	-1
	1997-2023	1227.0	160	185
Standard deviation	1997-2010	134.4	8.6	8.5

	2011-2023	165.4	10.1	12.8
	Variability	-31.0	-1.5	-4.3
	1997-2023	165.7	9.2	10.6
Coefficient of variability	1997-2010	0.12	0.05	0.05
	2011-2023	0.13	0.06	0.07
	Variability	-0.01	-0.01	-0.02
	1997-2023	0.14	0.06	0.06

In Nasarawa South, the mean annual rainfall rose significantly from 1155.3 mm (1997–2010) to 1304.3 mm (2011–2023), representing a +148.7 mm increase. This increase was coupled with no change in the number of rain days, which remained at 160 days. Additionally, the growing season length (LGS) increased slightly from 184 days to 185 days.

The increase in annual rainfall in Nasarawa South is substantial, though the stability in rain days and LGS indicates that the region is experiencing consistent rainfall that could benefit agriculture. However, the slight extension of the growing season may reflect increased growing potential, which can lead to higher crop yields, especially if rainfall is well-distributed over the season.

Across all three zones of Nasarawa State, annual rainfall has shown an overall increase, with Nasarawa South showing the most significant rise. However, the rain days remain relatively stable, suggesting that the increased rainfall is not necessarily a result of more frequent rainfall, but possibly of higher intensity rainfall events. The growing season length (LGS) has remained relatively consistent, with a slight shortening in Nasarawa North and Nasarawa South, while Nasarawa West experienced no changes in LGS.

Annual Rainfall Trends

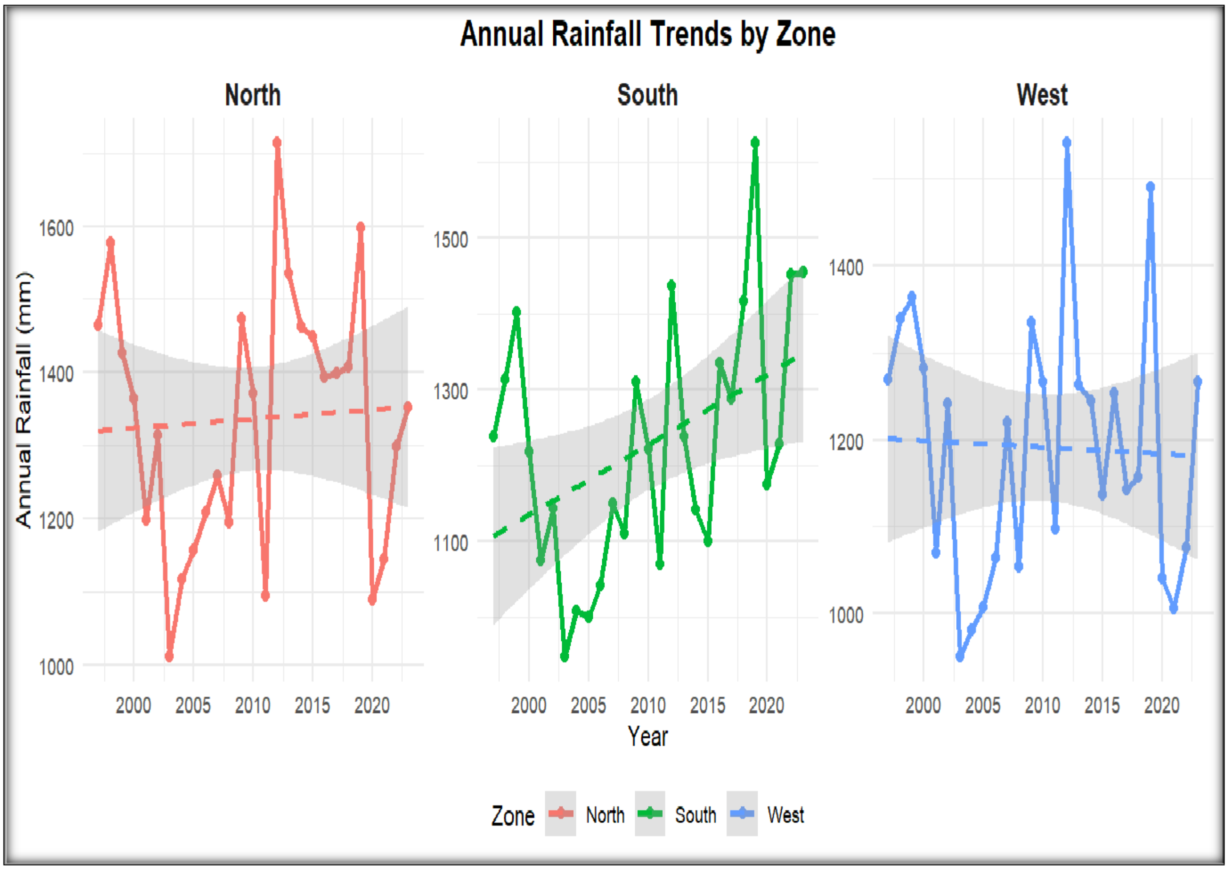

Figure 1. Combined Annual Rainfall Trends by zone

Source: NiMET (2024)

In the northern zone, rainfall exhibits significant inter-annual variability, fluctuating between approximately 1,000 mm and 1,650 mm, as shown in Figure 1. Notable years, such as 2000, 2012, and 2018, experienced exceptionally high precipitation, while the period from 2005 to 2010 saw marked deficits in rainfall. Although the trend line suggests a slight upward trajectory, this marginal increase is overshadowed by considerable year-to-year fluctuations, making it difficult to discern a consistent long-term pattern. These fluctuations imply that agricultural activities in the northern zone face considerable uncertainty. The wide variation in annual rainfall can disrupt crop planning and water resource management, which require flexible and adaptive approaches. For instance, prolonged dry periods could result in crop failure, while excessive rainfall in other years could lead to waterlogging, both of which would hinder agricultural productivity (Salami, 2024).

The confidence intervals depicted for the northern zone are relatively wide, reflecting the high variability in rainfall over time. These intervals provide an important statistical measure of the uncertainty surrounding the trend, indicating that the observed rainfall values could vary significantly from the predicted averages in any given year. The broad confidence intervals suggest that, despite the slight upward trend, the variability in rainfall remains a major concern for agricultural planning. Farmers must account for the possibility of both extreme wet and dry years, making long-term agricultural strategies more challenging to implement.

In contrast, the southern zone demonstrates more stable and consistently increasing annual rainfall, with totals ranging from 1,000 mm to 1,550 mm. The positive trend line, accompanied by a narrower confidence interval, suggests that rainfall in this zone is more predictable than in the northern zone, with relatively lower inter-annual variability. This provides more reliable conditions for rain-fed agriculture, where water availability is less prone to drastic fluctuations. However, episodic dips in rainfall, particularly in 2005 and 2015, indicate that even zones with generally favorable trends remain vulnerable to short-term climatic anomalies. These brief reductions in rainfall highlight the importance of integrating both long-term trends and short-term fluctuations in managing agricultural activities, particularly for crops that are sensitive to timing and water availability.

The western zone shows moderate rainfall variability, with annual totals ranging from 950 mm to 1,450 mm. The near-flat trend line suggests that there has been minimal long-term change in rainfall patterns in this zone. However, wide confidence intervals indicate high inter-annual variability, meaning that while the average rainfall remains relatively stable, there is considerable uncertainty from year to year. Farmers in this zone must prepare for a wide range of potential rainfall scenarios, from years of adequate rainfall to years of drought or excessive precipitation. This variability presents challenges in maintaining consistent crop yields and ensuring water availability throughout the growing season.

The observed trends in rainfall variability across the three zones underscore the importance of considering not just total annual rainfall, but also the timing and distribution of rainfall throughout the growing season, which are crucial factors for agricultural success. For example, the northern zone's rainfall fluctuations could lead to periods of insufficient moisture during critical crop growth stages, while the southern zone's more stable rainfall offers a better foundation for predictable planting and harvesting schedules (Fayose, 2025). Therefore, farmers in the northern and western zones may need to implement more robust water management strategies, such as irrigation or water storage systems, to mitigate the impact of drought years.

Moreover, the integration of satellite-derived precipitation data can complement sparse ground-based observations, providing higher-resolution, spatiotemporal insights that are vital for precision agriculture. These insights enable farmers to better predict rainfall patterns, adjust planting schedules, and optimize water use, which are essential for enhancing agricultural productivity and resilience. The use of advanced data technologies can also support the development of more tailored climate-smart policies, addressing the unique hydro-climatic vulnerabilities of each zone (Olayide et al., 2024). These policies could include the promotion of drought-resistant crop varieties in areas with unpredictable rainfall, as well as targeted water conservation measures.

Ultimately, understanding the variability in rainfall and the associated risks across Nasarawa State is crucial for enhancing food security and agricultural sustainability. By addressing the specific challenges posed by each zone’s rainfall pattern, policymakers and farmers can develop strategies that ensure agricultural resilience in the face of a changing climate (Awode et al., 2025; Kabo-Bah et al., 2025).

Rain Days Trends

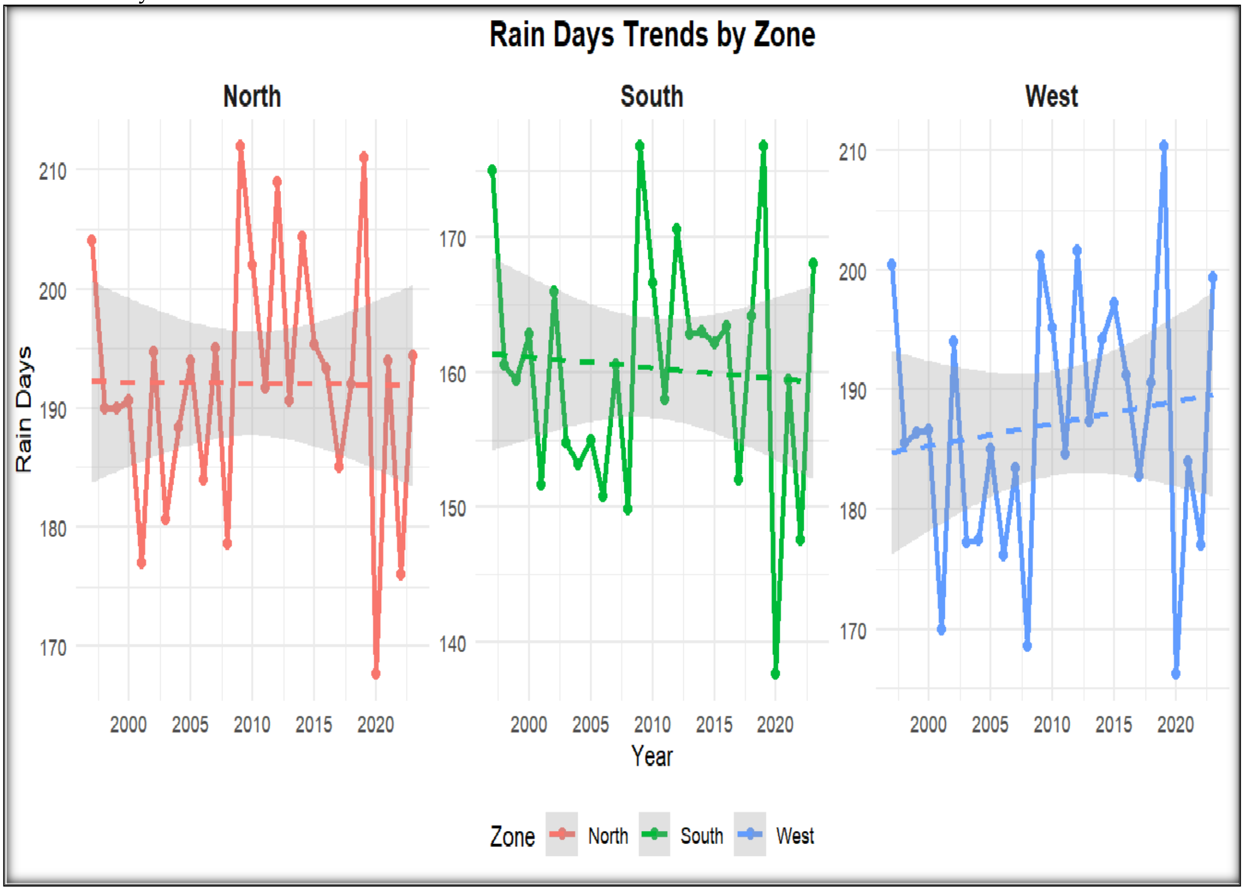

Figure 2. Combined Rain Days Trends by Zone

Source: NiMET (2024)

In the northern zone, the number of rain days exhibits considerable inter-annual variability, fluctuating between approximately 170 and over 210 days. The trend line is relatively flat, indicating minimal long-term change despite pronounced year-to-year fluctuations. Sharp peaks are observed around 2010 and 2018, while significant declines occur near 2020, underscoring the erratic nature of precipitation occurrence. This unpredictability highlights the challenges for agricultural activities in the northern zone, as farmers must contend with an unreliable rainy season. Consequently, flexible management strategies, such as the use of drought-tolerant crop varieties, water conservation practices, and supplemental irrigation systems, are essential to adapt to the unpredictable nature of rainfall patterns (Salami et al., 2025; Okafor et al., 2024).

Projections for the future suggest that, if current trends continue, the variability in the number of rain days may persist, with the potential for increasingly erratic rainy seasons. Prolonged dry spells followed by intense wet periods could further disrupt planting and harvesting schedules, making the need for adaptive water management systems even more urgent. These future trends necessitate more robust risk management strategies and the development of region-specific crop varieties that can withstand unpredictable rainfall patterns.

In contrast, the southern zone exhibits more consistent rainfall patterns, with rain days varying roughly between 140 and 180 annually. The trend line is essentially flat, with minor fluctuations, including a notable dip around 2020. The narrower confidence intervals suggest more predictable precipitation frequency compared to the northern zone. This relative stability may allow for improved planning in rain-fed agriculture, offering opportunities for longer-term agricultural strategies that are less vulnerable to short-term rainfall anomalies. However, even in the southern zone, adaptive measures such as optimizing planting schedules and integrating traditional and scientific forecasting methods remain important to mitigate the occasional rainfall shortfalls that have been observed (Umar et al., 2021; Tegegn et al., 2024).

Projections for the southern zone suggest that while rainfall variability may remain moderate, future trends may still be influenced by broader climatic shifts. The occurrence of rainfall dips, such as those seen in 2020, may increase in frequency, requiring farmers to adopt strategies that can accommodate these fluctuations. Improved forecasting techniques, including the use of both satellite-derived data and traditional knowledge systems, will be critical to maintaining agricultural productivity in the face of potential future variability.

The western zone shows moderate variability in rain days, ranging from about 170 to 210 days, with the trend line displaying a slight upward slope. Peaks in specific years, such as 2010 and 2016, suggest sporadic increases in precipitation frequency, while sharp declines near 2020 highlight ongoing uncertainty. The relatively high variability in rain days underscores the need for localized climate adaptation measures, such as decentralized water storage and irrigation systems, to buffer agricultural production against the impacts of unpredictable rain day occurrences. Farmers in this zone will need to stay prepared for both wetter and drier years, adjusting their crop management strategies accordingly (Olayide et al., 2024; Salami et al., 2025).

Projections for the western zone indicate that the upward trend in rain days may continue, albeit at a moderate rate. However, the fluctuations observed in specific years, like those in 2010 and 2016, suggest that while the frequency of rain days may increase slightly, the distribution of rainfall will remain highly variable. The uncertainty around rainfall timing and frequency means that agricultural planning in the western zone should incorporate flexible scheduling and water management systems that can adapt to these fluctuations. Over the long term, as rainfall patterns become more erratic, it will be critical to integrate more resilient agricultural practices, including water storage and climate-resilient crop varieties, to ensure sustained productivity.

The analysis of rain day trends across the northern, southern, and western zones of Nasarawa State underscores the importance of understanding not only the total amount of rainfall but also its frequency and distribution over time. While the southern zone benefits from relatively stable rain days, the northern and western zones are more prone to erratic precipitation patterns that pose significant risks for agricultural productivity. Given the observed variability and future projections, adaptive strategies such as improved irrigation systems, drought-tolerant crops, and better water management practices will be critical in enhancing the resilience of agricultural systems to climate change. Additionally, integrating satellite-derived precipitation data and improving forecasting accuracy will be essential for optimizing agricultural planning in each zone.

Rainfall Onset Trends

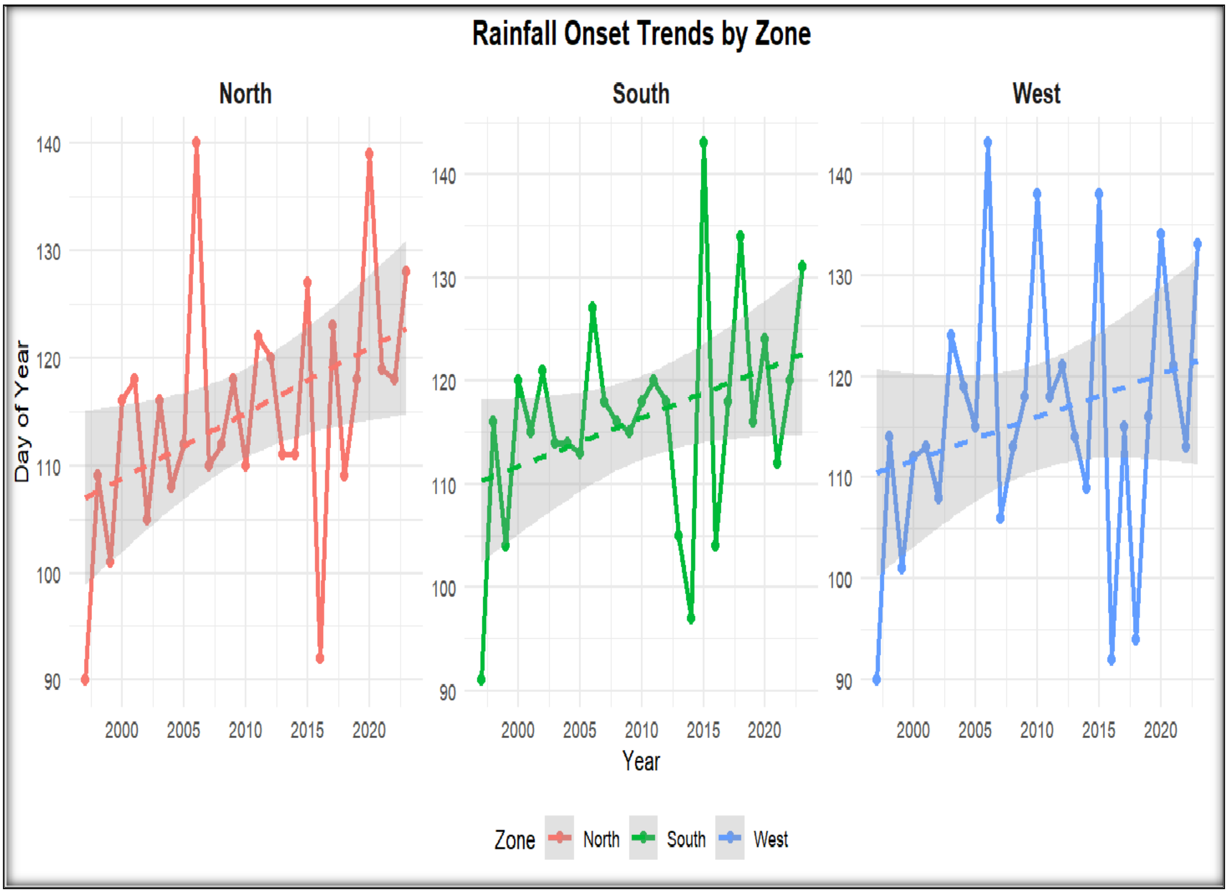

Figure 3. Combined Rainfall Onset Trends by zone

Source: NiMET (2024)

Figure 3 reveal a gradual shift toward later rainfall onset across the Northern, Southern, and Western zones of Nasarawa State, highlighting significant spatial and temporal variability in climatic conditions. The upward trend lines observed in all three zones suggest that the commencement of the rainy season has increasingly shifted to later days of the year, indicating a potential alteration in the region's seasonal rainfall dynamics. Such delays in rainfall onset have important implications for agricultural activities, particularly in predominantly rain-fed farming systems where the timing of precipitation determines the success of crop establishment.

In the Northern zone, the data show pronounced inter-annual fluctuations in rainfall onset dates, although the general trend indicates a gradual delay over time. Early years recorded rainfall onset close to day 90–105, whereas more recent years frequently show onset occurring after day 115, with some extreme cases approaching day 140. These irregular variations highlight the growing uncertainty surrounding seasonal rainfall patterns in the northern part of the state. The delayed onset effectively reduces the time available for land preparation and planting, which may lead to shorter growing periods and lower crop productivity. Studies have noted that such shifts in rainfall timing narrow the window for optimal agricultural operations, potentially resulting in declining crop yields and heightened vulnerability of farming communities (Abdullahi et al., 2025).

Similarly, the Southern zone demonstrates a moderate but consistent upward trend in rainfall onset dates. Although the variability here appears less extreme than in the northern zone, the increasing delay in seasonal rainfall initiation still poses challenges for agricultural scheduling. The progressive shift toward later rainfall onset indicates a contraction of the early growing season, limiting soil moisture availability during critical crop germination stages. According to Fayose (2025), delayed rainfall onset can significantly constrain planting periods and disrupt established cropping cycles.

The Western zone presents a slightly different pattern characterized by greater inter-annual variability compared with the northern and southern zones. Although the trend line also suggests a delayed onset of rainfall over time, the fluctuations between years are more pronounced. Several peaks and sharp declines indicate alternating episodes of early and late rainfall onset, suggesting that the western region may be more sensitive to localized climatic influences.

Rainfall Cessation Trends

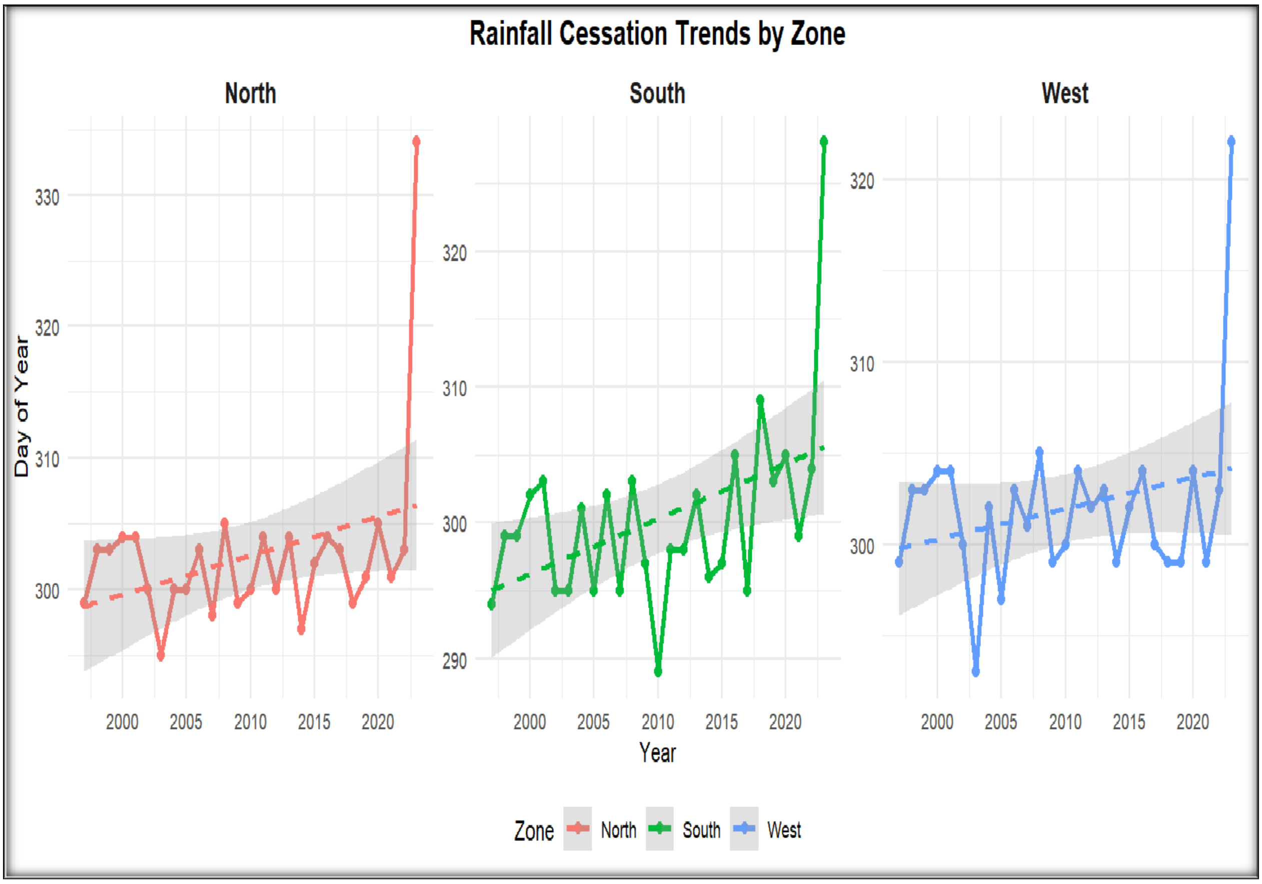

Figure 4. Combined Rainfall Cessation Trends by zone
Source: NiMET (2024)

Figure 4 provides a comprehensive overview of how the termination of the rainy season has evolved over the study period across the Northern, Southern, and Western zones. The temporal patterns in cessation dates, quantified by day of the year (DOY), reveal both gradual shifts and notable interannual variability, reflecting the dynamic nature of seasonal rainfall in the region.

In the Northern zone, rainfall cessation typically occurs between DOY 300–305, roughly corresponding to late October. The regression trend indicates a slight upward movement over time, signaling a tendency for the rainy season to end later. While most years align with this general pattern, notable deviations are observed: early cessation events near DOY 295 and delayed events exceeding DOY 305, highlighting interannual variability. The final observation shows an exceptional spike to DOY 335 (late November), suggesting an anomalously late cessation, possibly linked to extreme climatic events or shifts in large-scale atmospheric circulation. This pattern mirrors findings by Rwema et al. (2024), who report that extended rainy periods are increasingly evident in the region, even as seasonal onset remains relatively stable.

The Southern zone exhibits a slightly more pronounced upward trend, with typical cessation dates ranging from DOY 295–310, corresponding to late October to early November. Compared with the Northern zone, interannual variability is higher, including outliers such as an unusually early cessation around DOY 289. The upward trajectory of the trend line suggests a gradual lengthening of the rainy season, consistent with broader regional observations (Tegegn et al., 2024). The last year in the series shows a sharp increase to approximately DOY 325, indicating delayed cessation similar to the Northern zone. These fluctuations underscore the necessity for farmers to adjust planting and harvesting strategies to accommodate both the extension and unpredictability of rainfall patterns (Omay et al., 2022).

The Western zone demonstrates relative stability, with cessation mostly occurring around DOY 300–305. Early fluctuations, such as a drop near DOY 289, reflect occasional premature termination of rainfall. Overall, the regression line indicates a gradual upward shift, signaling a later end to the rainy season over time. Similar to the other zones, the final year exhibits a significant delay toward DOY 330.

All zones show a positive trend in cessation dates, indicating a gradual lengthening of the rainy season across the study area. The Southern zone has the highest interannual variability, while the Western zone is relatively stable. The simultaneous spikes in the most recent year across all zones suggest a possible regional climatic anomaly, highlighting the influence of extreme events on seasonal dynamics. These findings align with research emphasizing that localized microclimatic drivers may have stronger effects on seasonal termination than broader atmospheric patterns alone (Omay et al., 2023). Delayed rainfall cessation has important implications for agriculture and water resource management. Longer rainy seasons can extend the growing period, benefiting late-maturing crops.

Length of Growing Season (LGS) Trends

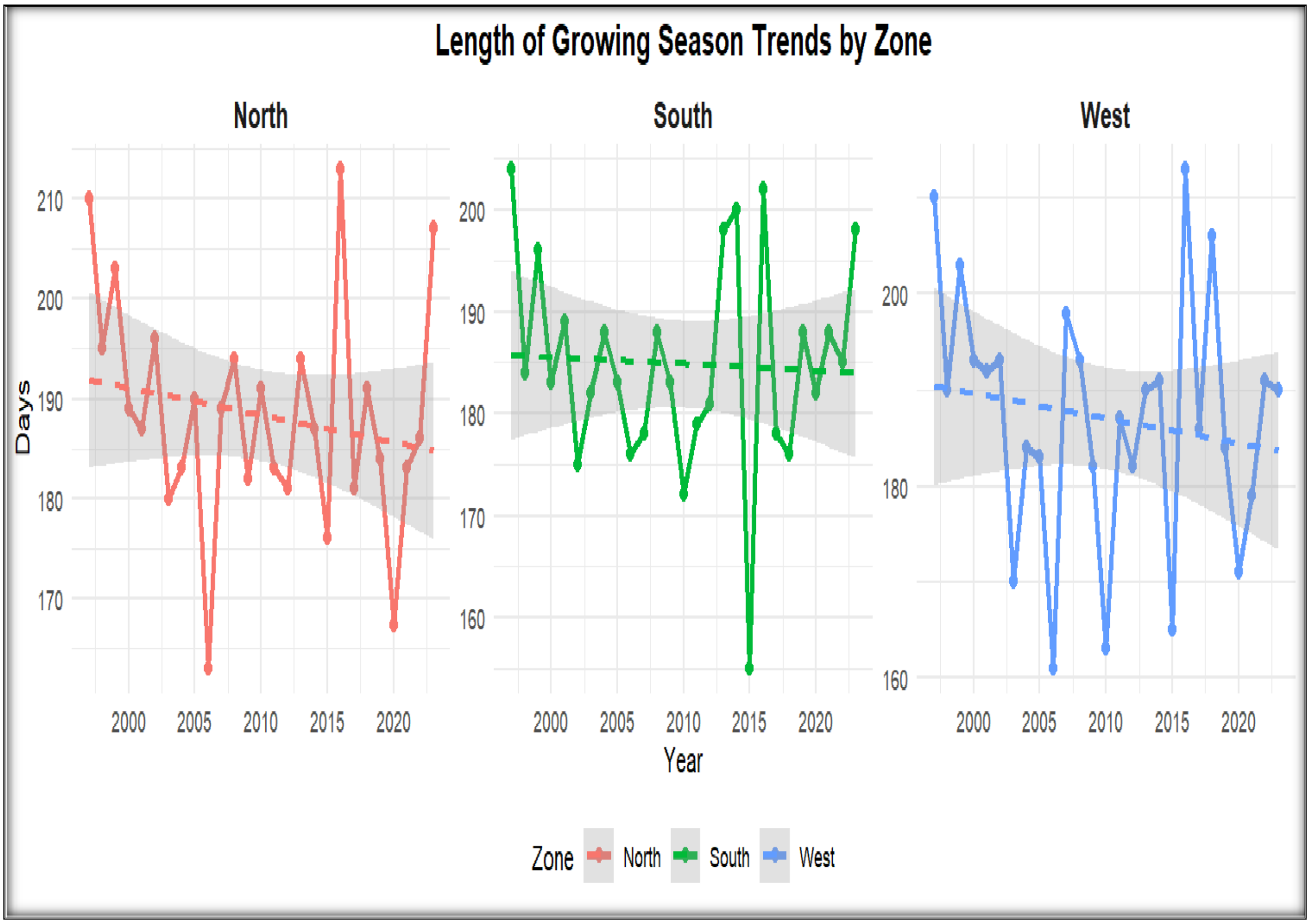

Figure 5. Combined Length of Growing Season Trends by zone
Source: NiMET (2024)

In the Northern zone, the length of the growing season fluctuates between roughly 170 and 210 days, with a general slight downward trend over the study period (fig. 5). Although most years show values near 180–190 days, pronounced spikes and dips occur, indicating substantial interannual variability. For instance, the growing season peaked near 210 days in certain years, while in other years, it dropped below 170 days, reflecting years with shortened or extended rainfall periods. Such variability emphasizes the uncertainty farmers face in planning crop cycles and managing agricultural production.

The Southern zone displays similar fluctuations, with growing season lengths mostly between 170 and 200 days. While the overall trend appears relatively stable, occasional extreme deviations are evident, including a sharp drop below 160 days around 2015. These deviations are consistent with findings that hydroclimatic oscillations can produce divergent phenological responses even in geographically proximate regions (Lara et al., 2021; Xu et al., 2025). The trend line shows a slight upward movement, suggesting a modest extension of the growing season over time. This indicates that while the Southern zone may benefit from longer growing periods for certain crops, the interannual variability necessitates adaptive strategies and improved phenological monitoring, such as multi-sensor satellite integration, to account for uncertainties inherent in ground-based observations (Tran et al., 2023).

In the Western zone, the length of the growing season ranges broadly between 160 and 210 days, with notable peaks and troughs throughout the time series. Compared with the Northern and Southern zones, the Western zone exhibits more pronounced fluctuations, particularly during the years 2005, 2010, and 2015, where the season shortened to near 160 days. Despite this variability, the dashed trend line suggests a slight downward tendency, indicating a possible contraction in the length of the growing season over the long term. These patterns reflect the non-linear interactions between early-season vegetation activity and large-scale atmospheric circulation patterns, which can dictate the magnitude of phenological fluctuations (Wu, 2021).

Comparatively, all three zones exhibit significant interannual variability in growing season lengths, with extreme peaks and troughs reflecting irregular rainfall patterns and local climatic influences. The Southern zone shows the least extreme short-term contractions, while the Western zone experiences the most pronounced oscillations. The Northern zone, although variable, generally maintains moderate season lengths.

Agriculturally, variations in growing season length have direct implications for crop selection, planting schedules, and yield outcomes. Shortened seasons may reduce the feasibility of cultivating long-duration crops, while extended seasons could benefit certain crops but increase exposure to late-season rainfall risks. The observed variability emphasizes the importance of integrating standardized onset and senescence metrics in future studies to improve comparability and reliability across regions (Panwar et al., 2023).

CONCLUSION

This study examined rainfall variability and its impact on agricultural productivity across the Northern, Southern, and Western zones of Nasarawa State. The analysis highlights significant trends in rainfall patterns, growing season length (LGS), and rain days, each with critical implications for farming activities. In the Northern zone, despite an increase in annual rainfall, high inter-annual variability presents challenges for agricultural planning. The variability, combined with a shortened growing season, complicates crop scheduling and yields. To mitigate these challenges, farmers must adopt drought-resistant crops, implement improved irrigation systems, and enhance water management practices to cope with fluctuating rainfall and the shorter growing period.

The Southern zone shows more stable rainfall patterns with a consistent increase in both rainfall and growing season length. These predictable conditions are favorable for rain-fed agriculture, yet occasional dips in rainfall still pose risks. Farmers in this zone should optimize planting schedules and integrate small-scale irrigation systems to safeguard against short-term rainfall deficits and maintain consistent productivity.

In the Western zone, moderate rainfall variability, combined with sporadic increases and decreases in rain days, presents challenges for crop consistency. The zone's reliance on decentralized water storage and effective irrigation systems is essential to buffer the impacts of erratic rainfall and ensure consistent crop water availability.

Ultimately, the study underscores the need for zone-specific strategies to address the unique climatic challenges faced by each region. A one-size-fits-all approach is inadequate. By tailoring agricultural practices, irrigation techniques, and climate-resilient crop varieties to the specific needs of each zone, Nasarawa State can enhance agricultural productivity, improve food security, and increase resilience to climate change impacts, ensuring sustainable agricultural development across the state.

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AUTHOR CONTRIBUTIONS STATEMENT

GC, conceptualized and designed the study, conducted data collection and analysis, and prepared the original manuscript draft. OE, contributed to research supervision, interpretation of findings, and methodological refinement. BE, contributed to data validation, manuscript editing, and final review of the article prior to publication

AI USAGE STATEMENT

The authors declare that Artificial Intelligence (AI) tools were used in a limited capacity to assist with language improvement, academic editing, and enhancement of manuscript readability. All analyses, interpretations, and scientific arguments presented in this article remain the sole responsibility of the authors.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the research and publication of this article.

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