International Journal of Research in Environmental Science (IJRES)
Volume 11, Issue 3, 2025, PP 1-15
ISSN No. (Online) 2454-9444
DOI: http://dx.doi.org/10.20431/2454-9444.1103001
www.arcjournals.org

From Deficit to Dysfunction: Rethinking Drought through a Multi-Index Functional Framework for Ecologically Vulnerable Systems

Dr. M.N. Pius[1*], Prof. S.A. Yelwa[2], Prof. T.O. Adewuyi[3]

[1]*Department of Geography Usmanu Usmanu Danfodio University, Sokoto Nigeria,*

[2]*Department of Environmental Resources Management, Usmanu Danfodio University, Sokoto Nigeria*

[3]*Department of Geography, Nigerian Defence Academy Kaduna, NIGERIA*

Received: 24 September 2025 *Accepted: 1 October 2025* *Published: 5 October 2025*

***Corresponding Authors: Dr. M.N. Pius,** *Department of Geography Usmanu Usmanu Danfodio University, Sokoto Nigeria.*

Abstract: *Traditional definitions of drought have over time focussed on total rainfall deficits over a given period, often overlooking important intra-seasonal variations and ecological sensitivities. This paper offers a refined definition of drought that considers not only precipitation amounts but also vegetation responses and atmospheric demand, considering it a climatic cancer. This approach is based on findings from a 16-year mixed-methods study conducted in Kaduna State, Nigeria, combined with a broader review of drought patterns in semi-arid regions. Using MODIS-derived indices such as the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Water Satisfaction Index (WSI), validated with community-level field observations, the study shows that drought can occur even when annual precipitation appears stable. This can result from factors such as delayed rainfall onset, early cessation of rainfall, uneven distribution, and increased evapotranspiration. The study further identifies five common drought scenarios that highlight how drought arises not only from a lack of rainfall but also from mismatches in timing, ineffective rainfall, and elevated atmospheric moisture loss. These scenarios include: first, sudden shock events, second, gradual cumulative deficits, third, intra-seasonal dry spells, fourth, excessive rainfall with limited usefulness, and lastly, drought driven by high evaporative demand. Each of these scenarios leads to crop failures, ecosystem stress, and disruptions in agricultural planning, even in years with near-normal Standardised Precipitation Index (SPI) values. Consequently, the study proposed the following definition: Drought is an initial or cumulative precipitation deficit that causes an imbalance between moisture availability and the needs of ecosystems and human activities in a region, resulting in ecological degradation and functional disruption. This definition more accurately reflects the complex nature of drought and facilitates its integration with satellite monitoring tools and early warning systems. Among other things, it also supports the development of adaptive agricultural practices and climate-resilient policies. This represents a shift in focus from simply measuring rainfall volumes to understanding moisture availability and system functioning.*

keywords: *Deficit, drought, precipitation, dry spells, wet spells, degradation, cessation.*

1. INTRODUCTION

The understanding of drought as a complex and multidimensional phenomenon that affects ecosystems, agriculture, hydrology, and human livelihoods across diverse climatic regions have over time gained the understanding of my researchers (Wilhite and Glantz, 1985; Mishra and Singh, 2010). However, traditionally, drought has been classified into four types meteorological, agricultural, hydrological, and socio-economic with each one defined by specific variables, metrics and temporal scales (WMO, 2012; Tallaksen and Van Lanen, 2004). Meteorological drought typically has been referred to as a reduction in precipitation over a specified period, while agricultural drought has always emphasized the impact on crop production vis-à-vis soil moisture (FAO, 2019). Hydrologically, drought focuses on declining water levels in rivers and aquifers, whereas socio-economic drought relates to water supply's impact on society, livelihood and economy (Wilhite *et al*., 2007).

In the last three decades, accelerated changing climates suggest that these classifications may inadequately capture the dynamic interactions between climate variability and land surface processes, particularly in rainfed systems (Trenberth *et al*., 2014; Seneviratne *et al*., 2012). In many regions, especially in sub-Saharan Africa, drought-related impacts have in recent times showed a decoupling fashion from annual precipitation totals, the corner stone of drought definition (Van Lanen *et al*., 2016; Ayalew *et al*., 2020). Accelerated climate change have shown intra-seasonal anomalies such as delayed rainfall onset, early cessation, and prolonged dry spells during sensitive phenological stages which are now recognized as critical drought drivers (Lyon and Barnston, 2005; Dinku *et al*., 2007; Ingram *et al*., 2002).

In Nigeria, studies have shown increasing variability in rainfall patterns, which significantly affect food security and water availability (NIMET, 2020; Odekunle *et al*., 2007; Adefolalu, 2007). However, national drought monitoring systems primarily depend on indices such as the Standardized Precipitation Index (SPI), which focus on cumulative rainfall rather than its alignment with the specific needs of agro-ecological zones (McKee *et al*., 1993; Zargar *et al*., 2011). Satellite-based indicators like the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Water Satisfaction Index (WSI) have shown greater effectiveness in detecting vegetation stress and hydrological imbalances (Rojas *et al*., 2011; Tucker *et al*., 1985; Peters *et al*., 2002).

Recent developments in drought early warning systems suggest moving toward multi-index dimensional frameworks that combine biophysical, climatic, and socio-ecological factors (Naumann *et al*., 2014). The increasing impacts of changing climate patterns highlight the need to conceptualize drought in terms of system functionality rather than solely precipitation deficits, providing a more accurate reflection of actual conditions as it affects man and its environment (Vicente-Serrano *et al*., 2010; Zhang *et al*., 2017). This approach supports climate resilience objectives outlined in the Sendai Framework and the UNFCCC adaptation strategies (UNDRR, 2015; IPCC, 2021).

Building on this literature, this paper critiques conventional drought definitions and presents an empirically derived, operationally grounded redefinition. Drawing from a 16-year dataset in Kaduna State, Nigeria, as a result, the study explore how drought manifests in the absence of rainfall decline, emphasizing instead the role of timing, distribution, evapotranspiration, and vegetation response. The study proposes a revised drought definition that reflects functional water imbalance, system sensitivity, and ecological consequences, enabling improved early warning, policy design, and climate-adaptive planning strategies.

2. Study Area and Methods

2.1. Study Area

Kaduna State, located in northwestern Nigeria, lies between latitudes 9°03′ and 11°32′N and longitudes 6°05′ and 8°38′E. Kaduna State is located in northwestern Nigeria and shares boundaries with seven states. To the north, it borders Katsina and Kano States, primarily through LGAs such as Ikara, Makarfi, Soba, Kubau, and Lere. To the northeast, Zaria and Sabon Gari LGAs link Kaduna to Kano State. Kaduna shares its eastern border with Bauchi State, through Lere and Kauru LGAs, while Nasarawa State lies to the southeast, adjoining Sanga and Kachia LGAs. To the south, Kaduna borders Plateau State via Kaura, Jema'a, and Zangon Kataf LGAs, and FCT Abuja through Kagarko LGA. On the west, Kaduna shares boundaries with Niger State, especially through Birnin Gwari, Chikun, and Giwa LGAs, while to the northwest, Katsina State is again contiguous with Kudan and Ikara LGAs (Figure 1). This strategic central location, surrounded by diverse ecological and socio-political contexts, positions Kaduna as a critical climatic and agricultural transition zone in northern Nigeria. It spans approximately 46,053 square kilometers and comprises 23 Local Government Areas (LGAs), encompassing diverse agro-ecological zones ranging from the northern Guinea savanna to the Sudan savanna. The climate is characterized by distinct wet and dry seasons, with mean annual rainfall ranging between 1,000 mm in the north to 1,500 mm in the south. Rainfall is highly seasonal, typically occurring between April and October, while the dry season is dominated by harmattan winds and elevated evapotranspiration. The state's varied topography and soil types, including shallow and sandy soils in the northern LGAs, contribute to heterogeneous land use patterns and agricultural potential. Kaduna is predominantly agrarian, with a reliance on rainfed farming systems for crops such as maize, sorghum, millet, and groundnut. However, its sensitivity to rainfall variability makes it a strategic area for assessing the dynamics and impact of drought in sub-Saharan Africa.

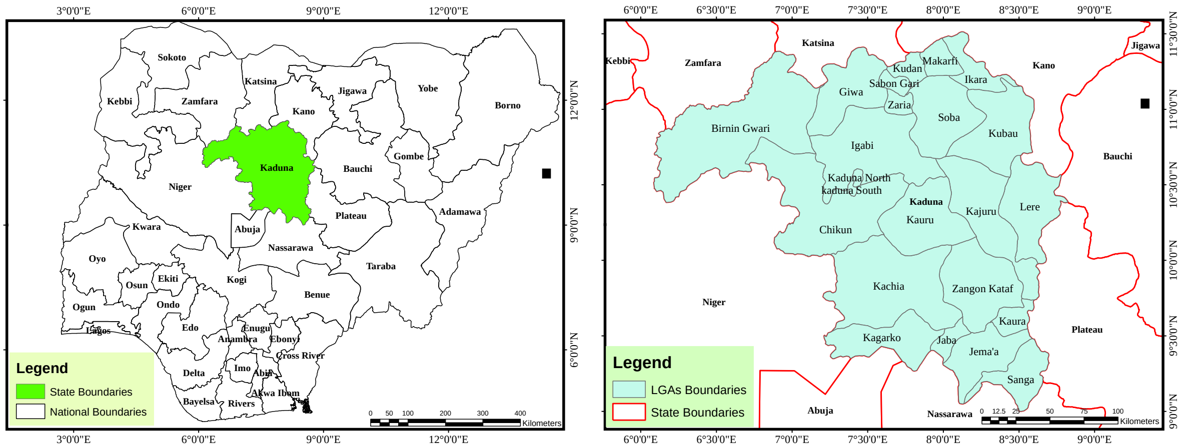


Figure1. *Kaduna State (Study Area) Map*

2.2. Remote Sensing and Geospatial Indices

The study utilized satellite-derived vegetation and moisture indices, including the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Water Satisfaction Index (WSI), all sourced from MODIS (Moderate Resolution Imaging Spectroradiometer) archives (Figure 2). These indices enabled temporal and spatial monitoring of vegetative stress and water deficit across 576 dekadal time steps (10-day periods). SPIRITS (Software for Processing and Interpretation of Remotely sensed Time Series) was used for temporal anomaly detection and drought onset tracking.

2.3. Precipitation Analysis

Standardized Precipitation Index (SPI) values were generated for multiple timescales using rainfall data obtained from the European Commission Joint Research Centre (EC-JRC) and corroborated with national meteorological datasets where available. Rainfall onset, cessation, and intra-seasonal distribution were analysed using both climatic time series and farmer-informed phenological calendars.

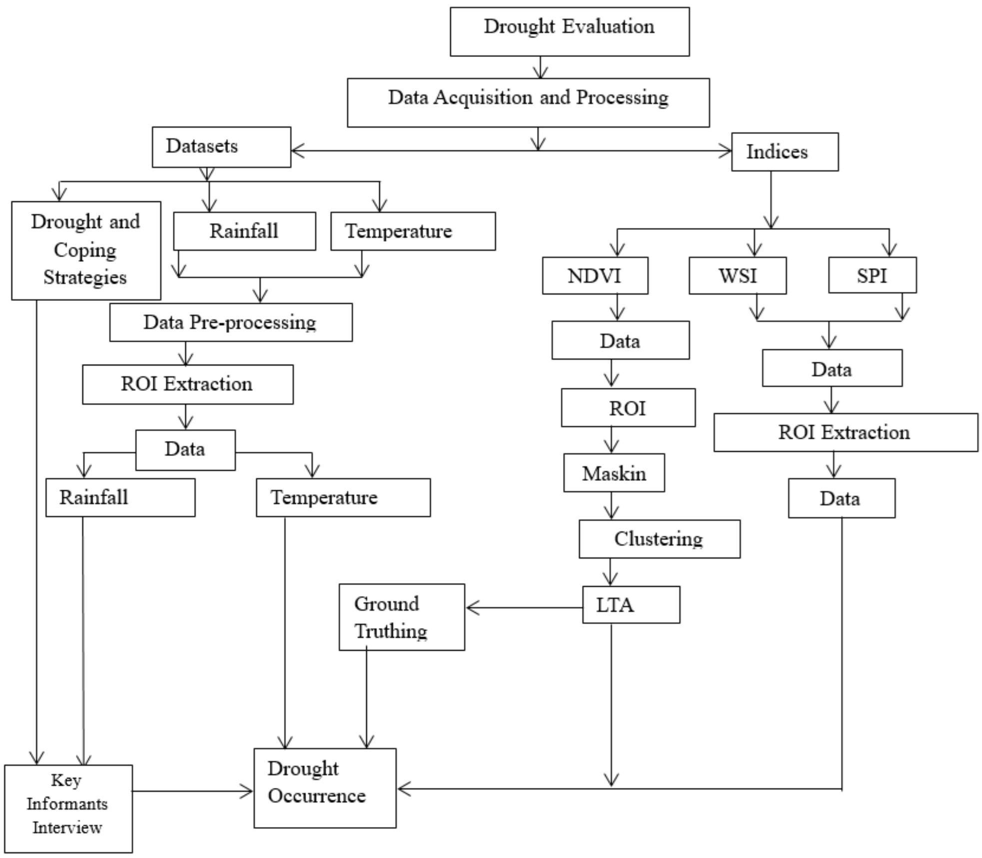


Figure2. *Flow Chart of Data Acquisition and Processing*

2.4. Field Surveys and Ground Validation

To ensure accuracy and local relevance, satellite-based findings were validated through semi-structured interviews with 48 key informants and farmer groups in 12 (Jaba, Kachia, Jemaa, Sanga, Chikun, Kaduna South, Kaduna North, Igabi, Soba, Sabon Gari, Kudan and Makarfi) Local Government Areas (LGAs) of Kaduna State. Respondents provided detailed insights on crop planting delays, yield loss, and perceived shifts in rainfall behaviour, which were triangulated with remote sensing anomalies.

2.5. Analytical Integration

Findings from all data sources were synthesized to identify functional drought events, which were not always aligned with meteorological definitions. Emphasis was placed on detecting moisture stress episodes that disrupted cropping systems and ecosystem functions, even in years classified as "normal" by SPI. The triangulated dataset provided the empirical foundation for proposing a revised drought framework grounded in functional water balance, timing sensitivity, socio-economically useful and ecological outcomes.

3. Results and Discussion

3.1. Rainfall Quantity vs. Rainfall Functionality

During the study period (2003–2018), Kaduna State recorded an average annual rainfall of about 1200 mm, with no significant downward trend over the years (Figure 3). However, vegetation indices consistently showed signs of stress, especially in the early to mid-growing seasons. Both NDVI and VCI dropped below 0.2 and 35%, respectively, during the core agricultural months (May–July) in 10 of the 16 years, indicating moderate to severe drought stress despite normal total rainfall.

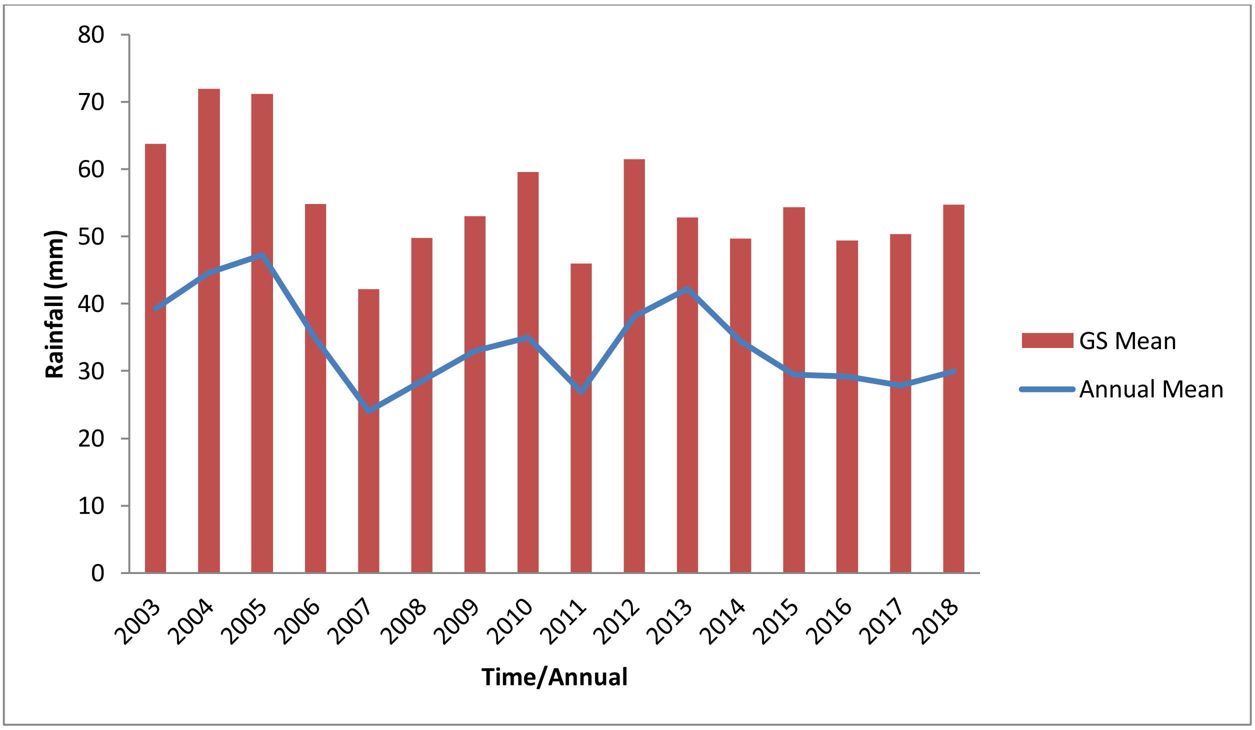


Figure3. *Annual versus Growing Season Rainfall Change*

This pattern points to a key mismatch between rainfall timing and crop water requirements. In years like 2010, 2012, and 2015, SPI values remained within normal limits, yet functional indicators such as WSI and VCI revealed moisture stress events that were not captured by traditional meteorological measures (Figure 4). These results suggest that total rainfall amount alone does not adequately reflect drought onset or intensity.

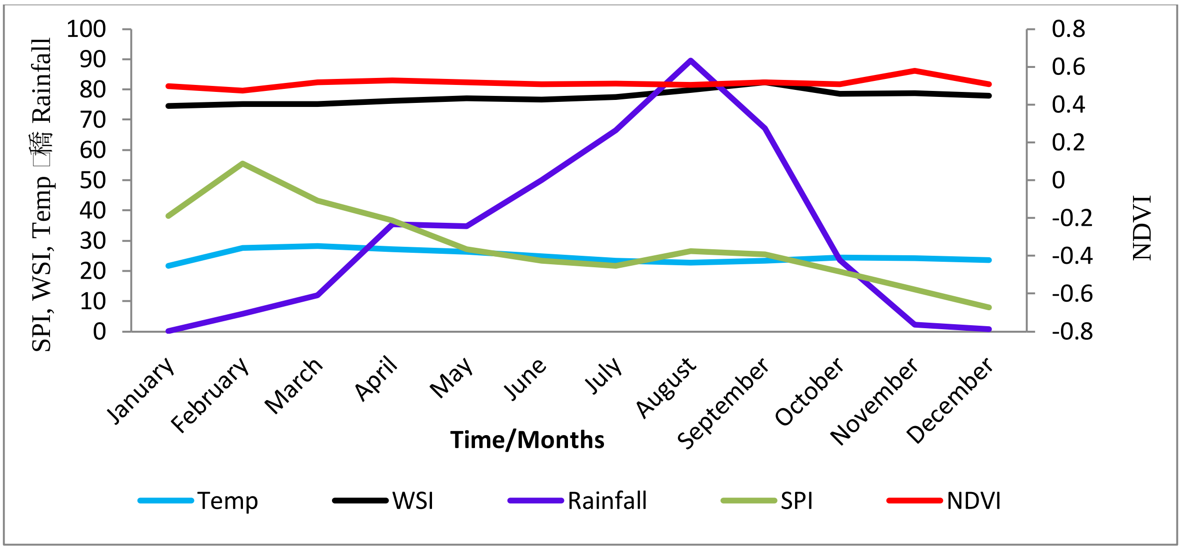


Figure4. *Temporal Changes in Temperature, Rainfall, SPI, WSI and NDVI*

3.2. Sub-Seasonal Variability and Vegetation Stress

Sub-seasonal disruptions in rainfall timing were common. Dekadal analysis using SPIRITS data showed rainfall onset was delayed by 20 to 40 days (2 to 4 dekads) in at least nine years. Additionally, in ten years, rainfall decreased greatly by late August to early September, shortening the growing season considerably (Figure 5). These shifts exposed crops to water stress during crucial phases like flowering and grain filling. The raining season was interspersed with frequent and prolonged dry spells.

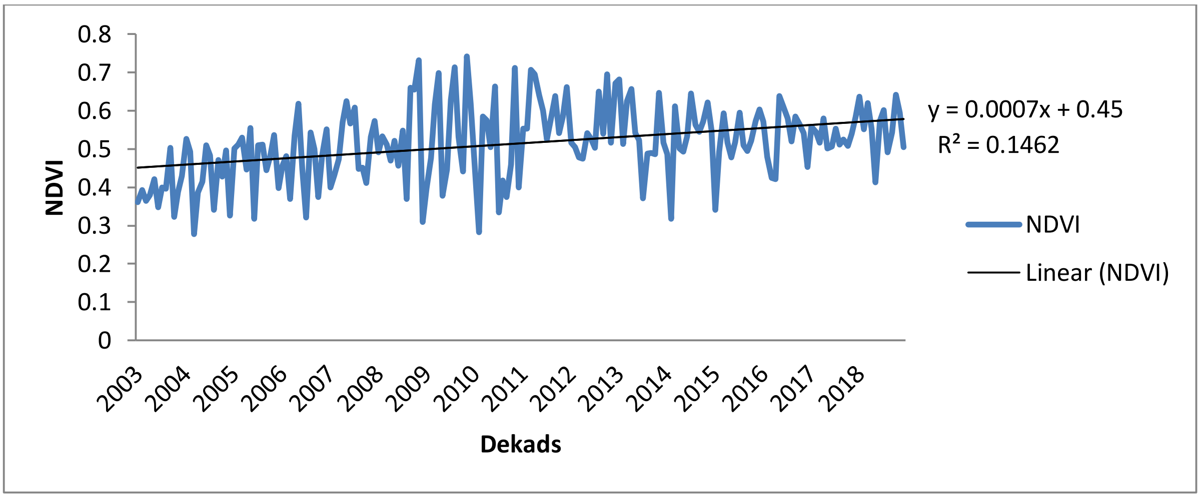


Figure5. *Dekadal NDVI Change 2003-2018*

Consequently, vegetation responses were suppressed. NDVI values fell below critical thresholds early in the season, reflecting reduced biomass productivity, while VCI values indicated vegetation stress consistent with agricultural drought. Even in years when SPI indicated neutral conditions, NDVI and WSI pointed to drought impacts caused by the misalignment of rainfall timing, confirming that functional drought can occur without a substantial drop in cumulative rainfall. For instance, in 2010 and 2013, despite SPI values hovering around zero (indicating normal cumulative rainfall), WSI indicated severe soil moisture deficits, particularly in the Soba, Sabon Gari, Kudan and Makarfi.

3.3. Ground-Level Evidence from Farmers

Field surveys with 48 farmers across 12 local government areas corroborated the remote sensing findings on functional drought dynamics. Farmers reported irregular rainfall patterns, missed planting windows, experienced mid-season crop failures, and reduced yields, particularly for maize, sorghum, and groundnut. For example, in 2013 and 2016, although SPI suggested normal rainfall, many farmers experienced premature harvesting due to dry spells mid-season (Figure 6).

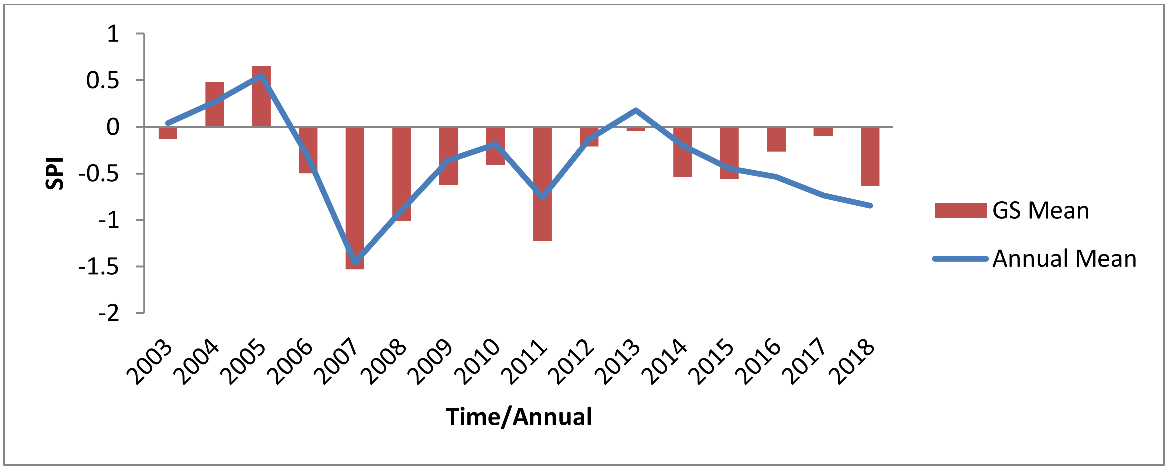


Figure6. *Annual versus Growing Season SPI Change*

Farmers' accounts supported satellite-based drought indicators. Their observations of delayed planting, shortened growing periods, and wilting after the rainy season highlighted discrepancies between actual drought conditions and SPI classifications. Many adapted to the emerging climatic conditions by shifting to drought-resistant crops like millet or cowpea, adjusting planting schedules, or foregoing the second cropping season entirely. In Kaura and Zaria LGAs, some farmers cited shifting planting dates and crop types as a necessary response to climate instability. Their testimonies reinforced the findings from NDVI and VCI metrics, further validating the existence of drought impacts beyond what SPI reflects.

3.4. Multi-Year and Spatially Uneven Impacts

Drought effects were unevenly distributed across Kaduna State. Northern LGAs such as Kudan, Soba, and Makarfi frequently experienced VCI values below 20% and notable WSI anomalies, often associated with shallow soils and higher evaporation rates (Figure 7). Central and southern LGAs including Kajuru, Kachia, and Jaba showed more intermittent stress but still faced yield reductions during seasons with rainfall timing disruptions.

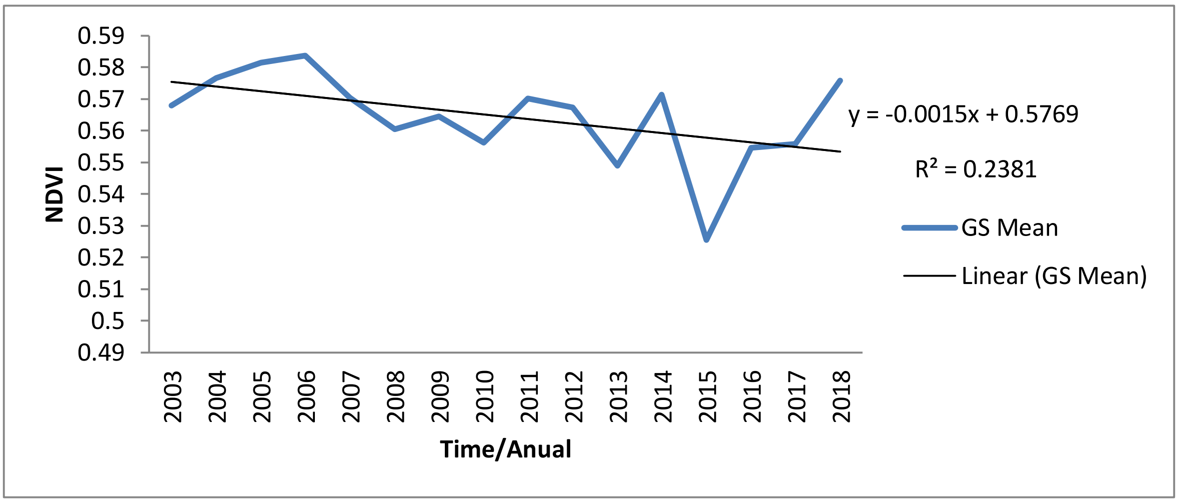


Figure7. *Growing Season NDVI Trend*

Years such as 2009, 2011, and 2015 exhibited overlapping stressors: delayed onset, early cessation, prolonged dry spells, and increased radiation amplifying the overall drought severity. These compound effects suggest that drought recurrence is often underestimated when metrics focus solely on rainfall quantity, instead of rainfall quality and timing.

3.5. Rainfall Quality: Intensity, Duration, and Ineffectiveness

Even in years with above-average rainfall (e.g., 2012 and 2017), rainfall often occurred in intense but short-lived bursts, followed by extended dry spells. These patterns led to high runoff and limited infiltration, failing to replenish soil moisture effectively (Figures 8 and 9). Consequently, crops experienced moisture stress despite "wet" classifications based on annual rainfall totals.

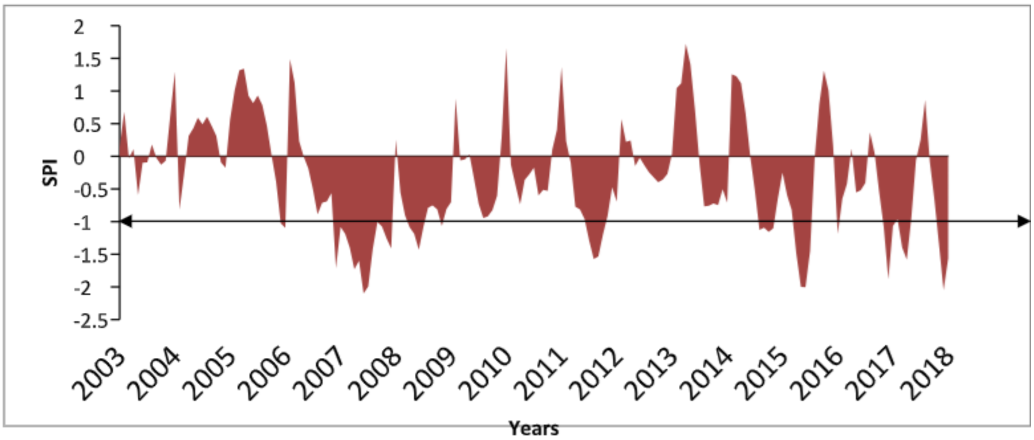


Figure8. *Annual SPI Pattern*

Field observations indicated that the flash flood (wet spells) - dry spell combination led to crop root damage, erosion, and seedling loss. In shallow soil zones of the northern LGAs of Soba, Sabon Gari, Kudan and Makarfi poor rainfall retention capacity compounded the impact, making even high rainfall years functionally equivalent to drought. The functional impact was like drought, as crops failed to absorb sufficient moisture for growth (Figure 9).

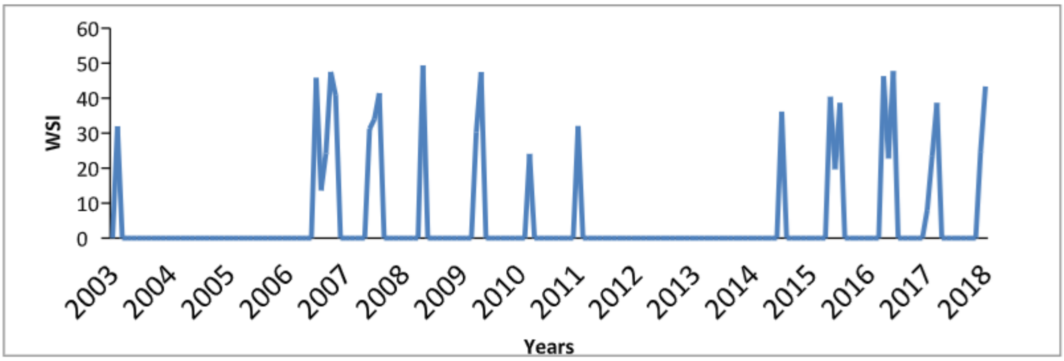


Figure9. *Duration and Frequency of WSI below Plants Satisfaction Level*

3.6. Climatic Stress Amplifiers

Beyond rainfall metrics, additional climatic variables intensified drought impacts. Elevated surface temperatures, high solar radiation, persistent Harmattan winds, and reduced relative humidity contributed to increased evapotranspiration, especially between March and June. These factors accelerated soil moisture loss and weakened vegetation health. Even when rainfall volumes were adequate, crops wilted under the pressure of these atmospheric stressors as indicated in the low WSI (Figures 10 and 11). In 2015 and 2018, for instance, NDVI and VCI dropped sharply due to high pre-season radiation, despite near-normal SPI. These climatic amplifiers transformed potential meteorological normals into agricultural droughts.

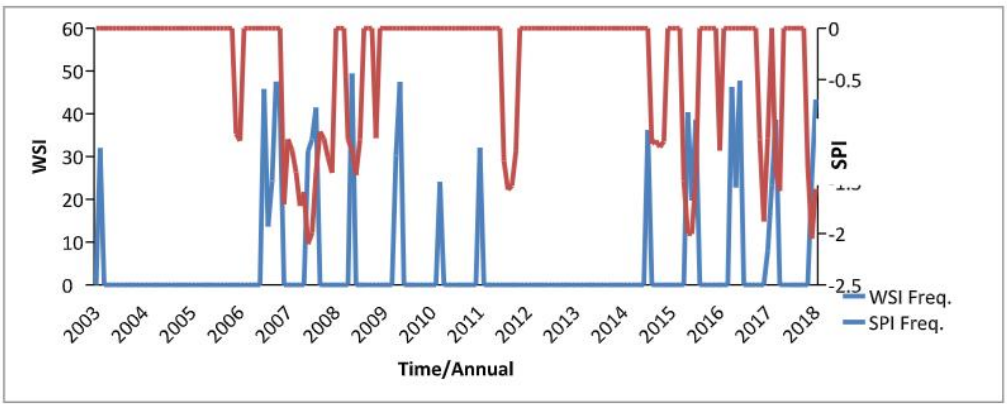
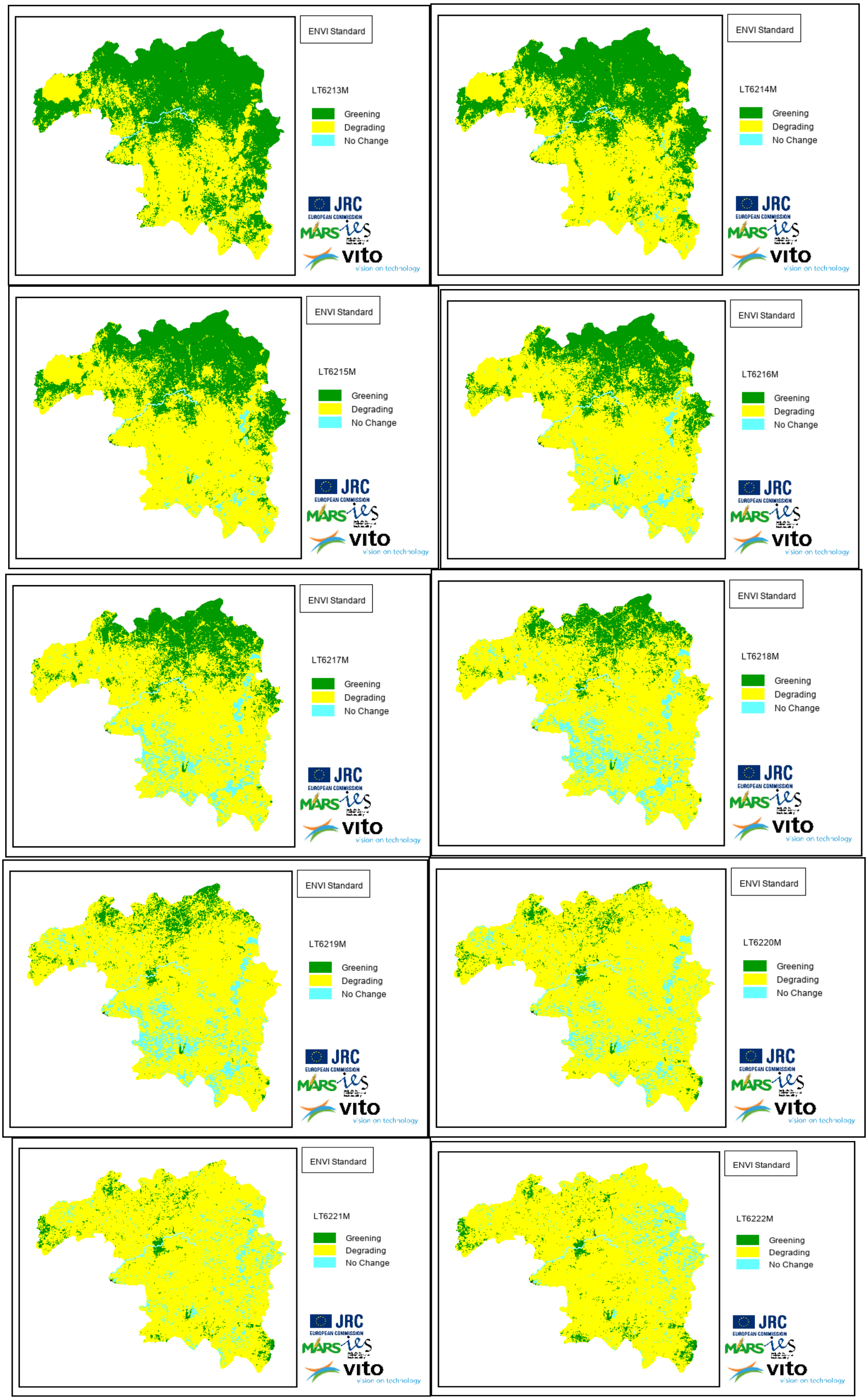


Figure10. *Drought Frequency by SPI and WSIS*


ENVI Standard
LT6213M
Greening
Degrading
No Change
JRC
EUROPEAN COMMISSION
MARS
vito
vision on technology
ENVI Standard
LT6214M
Greening
Degrading
No Change
ENVI Standard
LT6215M
Greening
Degrading
No Change
ENVI Standard
LT6216M
Greening
Degrading
No Change
ENVI Standard
LT6217M
Greening
Degrading
No Change
ENVI Standard
LT6218M
Greening
Degrading
No Change
ENVI Standard
LT6219M
Greening
Degrading
No Change
ENVI Standard
LT6220M
Greening
Degrading
No Change
ENVI Standard
LT6221M
Greening
Degrading
No Change
ENVI Standard
LT6222M
Greening
Degrading
No Change

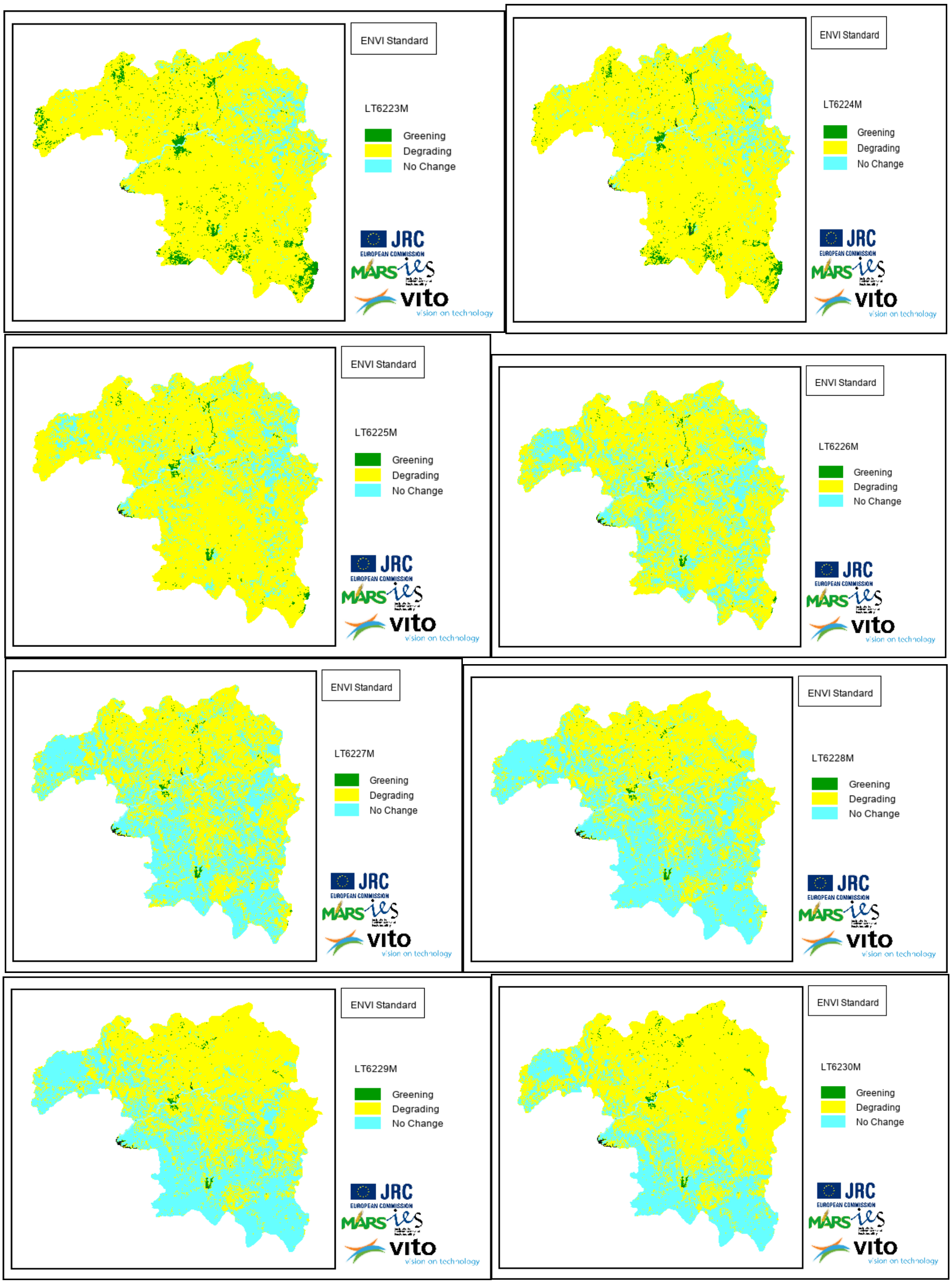


Figure11. *Long Term Average (LTA) Images of Vegetation Change*

4. Discussion

The findings of this study challenge long-standing assumptions in drought monitoring by revealing that conventional rainfall-based indices like SPI can fail to capture ecologically and agriculturally significant moisture stress events. The observed disconnect between stable annual precipitation and widespread vegetation stress in Kaduna State corroborates findings by Vicente-Serrano *et al*. (2010), who argue that cumulative rainfall is an insufficient proxy for functional drought in warming climates where there is poor water management system in place. Similarly, Peters *et al*. (2002) demonstrated that NDVI-based indices often detect vegetation stress in the absence of meteorological drought, a pattern confirmed across the SPI-neutral but ecologically stressed years (e.g., 2010, 2013) in this study. These findings are also consistent with Naumann *et al*. (2014), who emphasized the rising incidence of short-term dry spells and rainfall burstiness as the key risk factors for agricultural drought in sub-Saharan Africa. In the results, delayed rainfall onset and early cessation compressed the growing season, exposing crops to dry conditions during critical phenological stages outcomes similarly documented by Dinku *et al*. (2007) and Ingram *et al*. (2002).

Furthermore, the inadequacy of SPI in detecting drought severity, particularly in cases where atmospheric demand overwhelmed available moisture, aligns with the conclusions of Seneviratne *et al*. (2010) and Trenberth *et al*. (2014), who advocate for drought indices that incorporate evapotranspiration and radiation. In Kaduna State, high pre-season radiation, dry winds, and low humidity consistently exacerbated moisture stress, leading to vegetation degradation even in years with normal rainfall. The critical insight emerging from this research is that drought, in functional terms, is better understood as a disruption in moisture continuity and timing, rather than total quantity. This conceptual approach is echoed by Zhang *et al*. (2017), who proposed integrated drought assessment models incorporating land surface and atmospheric interactions. The current findings reinforce this by showing how timing anomalies such as a 2–4 dekads delay in rainfall onset could lead to cascading stress responses that SPI alone failed to signal. Moreover, this study advances the operational relevance of indices like WSI and VCI, which detected moisture deficits missed by SPI. Rojas *et al*. (2011) argue that incorporating these indices into early warning systems significantly improves drought forecasting accuracy a recommendation validated by the functional drought cases documented across Kaduna State diverse agro-ecological zones.

Finally, farmer reports provide a crucial dimension to the discourse. Like the participatory findings in Lyon and Barnston (2005), local knowledge in Kaduna State revealed adaptive responses including crop switching, altered planting calendars, and abandonment of second cropping, which were often in tension with official forecasts based solely on SPI. Taken together, these insights call for a reorientation in drought conceptualization, policy, monitoring and reporting. The revised definition proposed in this paper, grounded in system response and functional water deficits, aligns closely with calls by the IPCC (2021) and UNDRR (2015) for resilience-based drought frameworks tailored to ecologically sensitive and rainfed regions.

5. PROPOSED REVISED DEFINITION OF DROUGHT

Traditional definitions of drought often focus narrowly on total rainfall deficits, overlooking critical factors like timing, distribution, and ecological demand. However, evidence from both satellite data and field observations in Kaduna State reveals that drought impacts frequently occur even under near-normal rainfall conditions. To address these functional realities, a revised definition is proposed that better reflects the ecological and systemic disruptions caused by precipitation imbalances.

Drought is an initial or cumulative deficit in precipitation that results in an imbalance between moisture availability and the needs of a region's ecosystems and human systems, leading to ecological degradation and functional disruption.

This revised definition integrates a decade of empirical observations from Kaduna State, where drought effects were evident despite near-average annual rainfall. Two distinct drought pathways informed this formulation:

1. Shock Onset: A sudden, extreme reduction in rainfall within a critical window (e.g., 70% loss in a year out of 10 years single season) caused severe immediate impacts on crop failure, reduced groundwater recharge, and hydrological stress with long-lasting legacy effects.
2. Cumulative Deficit: A slow but steady decline in effective rainfall over 10 years (50% deficit total deficit), often unnoticed until systemic ecosystem degradation emerged.

These scenarios illustrate that drought can originate from both abrupt failures and prolonged underperformance of rainfall. Importantly, both cases result in moisture imbalances that ecosystems and human systems cannot buffer or recover from without long-term planning.

This formulation:

a. Frames drought as a functional failure of precipitation, shifting the focus from absolute rainfall totals to how precipitation aligns with the biological and environmental needs of life-support systems

b. Expands the drought paradigm beyond meteorology to include agricultural, ecological, and human dimensions while acknowledging that drought occurs even during climatologically “normal” years
c. Captures sub-seasonal anomalies, such as delayed rainfall onset, early cessation, prolonged dry spells, and erratic distribution, which are key drivers of crop failure and ecological stress especially in dryland environments
d. Accommodates both water scarcity and rainfall excess that fails to infiltrate or retain, highlighting the functional irrelevance of short, intense rainfall events to land productivity
e. Unifies all vulnerable systems; crops, livestock, ecosystems, and human water uses, under the umbrella of “life-support systems,” promoting integrated drought management approaches
f. Supports dynamic thresholding, allowing drought classification to vary with land use type, seasonality, or ecosystem vulnerability, socio-economic needs rather than using rigid precipitation cutoffs
g. Enables integration with multi-source geospatial tools, including NDVI, VCI, SPI, WSI, CHIRPS, and evapotranspiration models, enhancing early warning accuracy and spatial resolution
h. Strengthens the link to climate adaptation policy, especially in the Global South, where rainfall timing and intensity are increasingly decoupled from agricultural viability
i. Frames drought as a functional failure of precipitation to meet ecological and livelihood requirements
j. Incorporates vegetation health, soil moisture, and evapotranspiration processes into drought analysis
k. Captures intra-seasonal rainfall irregularities, phenological sensitivity, and systemic impacts on life-support systems
l. Enables integration with satellite-based and locally validated drought monitoring systems

5.1. Case Scenarios Informing the Revised Definition for Drought

Drought, in its emerging complexity, behaves like a climatic cancer, slowly eroding the resilience of ecosystems and livelihoods through both visible and hidden pathways sometimes fast but mostly slowly without immediate concern. Its impact is systemic, progressive, and, if undiagnosed early, capable of inflicting irreversible damage on land-use systems.

The proposed definition is grounded in a multi-dimensional conceptualization of drought; one that emerged from both empirical field observations in Kaduna State, Nigeria, and a broader synthesis of climatic, ecological, and agricultural dynamics observed across semi-arid and rainfed systems. While Kaduna State served as a core case study, the definition reflects a 3-dimensional (3-D) understanding of drought as a complex interaction of precipitation anomalies, vegetation response, and timing mismatches vis-à-vis extent, frequency and duration. These scenarios illustrate how drought manifests through various patterns of precipitation failure, often beyond traditional cumulative rainfall metrics:

a. Acute Onset Scenario (Year 1 Shock in 10 years): In the first scenario, an abrupt and extreme 70% reduction in rainfall occurred in the first year of a 10-year period. This sharp moisture deficit triggered widespread crop failure, disrupted planting calendars, and compromised soil moisture recharge. Even though rainfall conditions improved in subsequent years, the initial shock had residual effects on ecosystem resilience and hydrological systems.
b. Cumulative Moisture Deficit Scenario (a cumulative 50% rainfall deficit in 10-Year). In the second scenario, the region experienced a gradual but persistent shortfall in rainfall in a 10-year period, cumulatively amounting to a 50% deficit. This chronic moisture stress progressed unnoticed by conventional drought monitoring indicators, yet vegetation health indicators (NDVI, VCI) revealed ongoing degradation. Farmers observed declining productivity, shortened growing seasons, and increased reliance on drought-resistant crops, all of which reflected long-term ecological stress and shifting land use patterns.
c. Intra-Seasonal Timing Mismatch: Several years recorded near-average total rainfall but experienced major disruptions in timing delayed rainfall onset, early cessation, and critical frequent and

prolonged dry spells during the flowering and yield-formation stages of staple crops. Such temporal mismatches between precipitation and phenological requirements led to agricultural drought even in the absence of annual rainfall decline.

d. Ineffective Rainfall Scenario (Excess Rainfall with Low Utility): In several observed seasons, regions received above-normal total rainfall. However, this rainfall occurred in short, intense bursts interspersed with extended dry spells, leading to flash floods, low infiltration, loss of crops, environmental degradation, and runoff-dominated conditions. Despite exceeding normal annual totals, moisture was not retained in the soil profile, resulting in poor crop yields and vegetative stress functionally equivalent to drought.

e. Atmospheric Demand Scenario (Evapotranspiration-Dominated Losses): In certain semi-arid zones, average rainfall levels were rendered ineffective due to high evapotranspiration rates driven by elevated temperatures, increased solar radiation, and persistent dry winds. These atmospheric conditions intensified soil moisture loss, reducing water availability for crops and stressing natural vegetation. This form of 'invisible drought' eluded traditional precipitation variables and metrics but manifested clearly in vegetation health indicators.

These case scenarios affirm that drought can arise from sudden shocks, accumulated deficits, ineffective rainfall, excessive atmospheric demand and poor water management strategies. Timing, pattern, management systems and ecological response not just total precipitation are decisive in defining and managing drought. Thus, the revised definition captures drought as a hydrometeorological and ecological imbalance, not simply a meteorological anomaly.

6. Implications for Monitoring and Policy

The reconceptualization of drought presented in this study carries profound implications for both monitoring systems and policy frameworks, particularly in regions where agriculture and livelihoods are heavily rainfall dependent. By decoupling drought from absolute precipitation decline and instead linking it to a functional imbalance on ecological and human systems, the revised definition facilitates earlier, more accurate, and context-specific drought detection and management.

6.1. Enhancing Monitoring and Early Warning Systems

Traditional drought monitoring tools particularly those relying solely on precipitation indices like the Standardized Precipitation Index (SPI) are often inadequate in capturing the timing, spatial distribution, and hydrological utility of rainfall. As shown in Kaduna State, NDVI, VCI, and WSI detected vegetation stress even when SPI remained neutral. Incorporating multi-index systems enables the detection of:

- Early-season onset delays
- Early-season cessation
- Mid-season dry spells
- Rainfall intensity vs. infiltration discrepancies
- Vegetation stress before yield loss manifests

This shift enhances the predictive power of Early Warning Systems (EWS), improves the spatial resolution of vulnerability mapping, and enables localized advisory dissemination. It also aligns with the WMO's Integrated Drought Management Programme (IDMP) and enhances synergies with Sendai Framework and UNFCCC adaptation mandates.

6.2. Reinterpreting Intensity, Duration, and Frequency in Functional Drought Analysis

The proposed redefinition of drought introduces a conceptual and practical shift in how intensity, duration, and frequency are interpreted and measured. Traditional drought metrics primarily depend on rainfall deficits over fixed time frames, often using precipitation-only indicators such as the Standardized Precipitation Index (SPI). While such indices are useful, they can overlook critical dynamics that determine drought severity in ecological and livelihood terms. These dynamics are discussed as follows:

- Intensity is commonly assessed by how far rainfall falls below long-term averages. Under the functional approach, intensity reflects the extent to which moisture deficits impair vegetation health, soil water availability, and atmospheric moisture balance. For example, severe vegetation stress or soil moisture depletion during a brief but critical growth phase may represent greater drought intensity than a prolonged but moderate rainfall reduction.

- Duration under this framework is not limited to how long precipitation remains below a threshold, but how long ecological and human systems remain stressed. A short-term dry spell during the flowering stage of crops can cause long-term functional disruption, especially in sensitive agro-ecological zones. Conversely, gradual ecological degradation from persistent misalignment between rainfall timing and moisture demand may extend the drought impact far beyond its meteorological window.
- Frequency in this context is broadened to include recurrent functional drought events that may not qualify as meteorological droughts. These include repeated delays in rainfall onset, increased dry spells during active growing periods, or early cessation of rains. These events, though not always reflected in SPI thresholds occur frequently in rainfed systems and are critical drivers of vulnerability.

This reconceptualization ensures that drought assessments are grounded on biophysical impact rather than rainfall quantity alone. It calls for integrated monitoring tools that capture not just how much it rains, but when, how effectively moisture is retained, and how systems respond. By redefining drought through the lens of system functionality, planners and researchers gain a more precise and actionable understanding of drought dynamics across vulnerable landscapes.

6.3. Policy Translation and Risk Management

The revised drought framework supports transformative changes in policy by emphasizing:

a. Impact-based Drought Classification: Enabling governments to differentiate between meteorological and functional droughts for timely intervention.

b. Localized Thresholds: Tailoring drought triggers to specific land use types, crop calendars, and ecosystem sensitivity.

c. Resilient Cropping Calendars: Reorganizing planting periods to reflect shifting rainfall onset/cessation patterns.

d. Investment in Vegetation-Based Surveillance: Scaling up national satellite data infrastructure and downscaling regional indicators for farmer use.

e. Drought Preparedness Financing: Shifting from reactive food relief to anticipatory drought planning, supported by climate finance and insurance.

6.4. Toward Integrated Drought Governance

A multidimensional definition of drought requires intersectoral coordination. Ministries of Agriculture, Environment, Water Resources, and Disaster Management must collaborate to:

- Develop integrated vulnerability assessment tools
- Create ecosystem-based adaptation plans
- Incorporate drought risk into National Adaptation Planning (NAP) and Nationally Determined Contributions (NDCs)

7. Conclusion and Recommendations

This study has demonstrated that drought, as traditionally defined by absolute precipitation shortfalls, no longer suffices in the context of increasingly erratic climate regimes and vulnerable agro-ecological systems. Drawing from a 16-year empirical study in Kaduna State and broader conceptual analyses, this study has redefined drought as a functional imbalance where rainfall fails to align with ecological and socio-economic moisture needs, irrespective of annual totals. By integrating satellite-based indicators (NDVI, VCI, WSI) with ground-level observations and farmer testimonies, the study has exposed the inadequacies of conventional indices like SPI. The revised drought framework captures critical but often overlooked phenomena such as intra-seasonal dry spells, ineffective rainfall bursts, early cessation, and evapotranspiration-induced deficits. This functional approach not only improves drought detection but also empowers policymakers to respond proactively. As drought is reinterpreted as a dynamic and systemic failure, it calls for adaptive monitoring, flexible classification systems, and context-sensitive policy mechanisms.

Key Recommendations

- Institutionalize the Functional Definition of Drought: National meteorological and disaster management agencies should adopt this revised definition and embed it in early warning protocols, agricultural advisories, and resilience plans.
- Expand Drought Monitoring Toolkits: Integrate NDVI, VCI, WSI, and related indices into national and subnational drought surveillance systems, ensuring their triangulation with community-based observations.
- Invest in Climate-Smart Agriculture (CSA) and Infrastructure: Promote cropping calendars aligned with rainfall onset trends; scale up soil moisture retention technologies, and prioritize irrigation expansion in high-risk zones.
- Reform Drought Relief Strategies: Move from reactive aid to anticipatory financing, including risk-layered drought insurance and forecast-based humanitarian action.
- Advance Cross-Sector Collaboration: Facilitate institutional coordination between environmental, agricultural, hydrological, and climate actors to harmonize drought data, modelling, and response systems.

In conclusion, reframing drought through this lens of functionality and systemic response creates an opportunity for better risk communication, more accurate forecasting, and deeper alignment between scientific evidence and policy action. It positions drought not merely as a weather anomaly but as a developmental and ecological challenge and realistically, as climatic cancer; one that must be confronted with foresight, flexibility, and resilience planning.

REFERENCES

[1] Adefolalu, D.O.A., 2007. *Climate change and economic sustainability in Nigeria*. In: International Conference on Climate Change and Economic Sustainability, 12–14 June 2007. pp.36–49.

[2] Ayalew, D., Tesfaye, A. and Taddese, A., 2020. Spatio-temporal assessment of drought using SPI and vegetation indices in Ethiopia. *Remote Sensing Applications: Society and Environment*, 17, p.100281.

[3] Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S.J. and Ropelewski, C.F., 2007. Validation of satellite rainfall products over East Africa's complex topography. *International Journal of Remote Sensing*, 28(7), pp.1503–1526. https://doi.org/10.1080/01431160600954688

[4] FAO, 2019. *Agricultural Stress Index System (ASIS): Concepts and user manual*. Rome: Food and Agriculture Organization of the United Nations.

[5] Ingram, K.T., Roncoli, M.C. and Kirshen, P.H., 2002. Opportunities and constraints for farmers of West Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agricultural Systems*, 74(3), pp.331–349.

[6] IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

[7] Lyon, B. and Barnston, A.G., 2005. ENSO and the spatial extent of interannual precipitation extremes in tropical land areas. *Journal of Climate*, 18(23), pp.5095–5109.

[8] McKee, T.B., Doesken, N.J. and Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: *8th Conference on Applied Climatology*, 17(22), pp.179–183.

[9] Mishra, A.K. and Singh, V.P., 2010. A review of drought concepts. *Journal of Hydrology*, 391(1-2), pp.202–216.

[10] Naumann, G., Barbosa, P., Garrote, L., Iglesias, A. and Vogt, J., 2014. Exploring drought vulnerability in Africa: An indicator-based analysis to be used in early warning systems. *Hydrology and Earth System Sciences*, 18(5), pp.1591–1604.

[11] NIMET, 2020. *Seasonal Rainfall Prediction (SRP) for Nigeria*. Abuja: Nigerian Meteorological Agency.

[12] Odekunle, T.O., Orinmoogunje, O.I. and Ayanlade, A., 2007. Application of GIS to assess rainfall variability impact on crop yield in Guinean Savanna part of Nigeria. *African Journal of Biotechnology*, 6(18).

[13] Peters, A.J., Walter-Shea, E.A., Ji, L., Vina, A., Hayes, M. and Svoboda, M.D., 2002. Drought monitoring with NDVI-based Standardized Vegetation Index. *Photogrammetric Engineering and Remote Sensing*, 68(1), pp.71–75.

[14] Rojas, O., Vrieling, A. and Rembold, F., 2011. Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. *Remote Sensing of Environment*, 115(2), pp.343–352.

[15] Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., et al., 2010. Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3–4), pp.125–161.

[16] Seneviratne, S.I., et al., 2012. Changes in climate extremes and their impacts on the natural physical environment. *IPCC Special Report*.

[17] Tallaksen, L.M. and Van Lanen, H.A.J., 2004. *Hydrological Drought: Processes and Estimation Methods*. Amsterdam: Elsevier.

[18] Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and Sheffield, J., 2014. Global warming and changes in drought. *Nature Climate Change*, 4(1), pp.17–22.

[19] Tucker, C.J., Vanpraet, C.L., Sharman, M.J. and Van Ittersum, G., 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. *Remote Sensing of Environment*, 17(3), pp.233–249.

[20] UNDRR, 2015. *Sendai Framework for Disaster Risk Reduction 2015–2030*. Geneva: United Nations Office for Disaster Risk Reduction. Available at: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030 [Accessed 8 Aug. 2025].

[21] Van Lanen, H.A.J., Wanders, N., Tallaksen, L.M. and Driessen, P.P., 2016. Hydrological drought across the world: impact of climate and physical catchment structure. *Hydrology and Earth System Sciences*, 20(7), pp.2697–2714.

[22] Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23(7), pp.1696–1718.

[23] Wilhite, D.A. and Glantz, M.H., 1985. Understanding the drought phenomenon: The role of definitions. *Water International*, 10(3), pp.111–120.

[24] Wilhite, D.A., Sivakumar, M.V.K. and Pulwarty, R., 2007. Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, 3, pp.4–13.

[25] WMO, 2012. *Standardized Precipitation Index User Guide*. Geneva: World Meteorological Organization (WMO-No. 1090).

[26] Zargar, A., Sadiq, R., Naser, B. and Khan, F.I., 2011. A review of drought indices. *Environmental Reviews*, 19, pp.333–349.

[27] Zhang, Y., Pan, M., Sheffield, J., Siemann, A.L., Wang, Y. and Wood, E.F., 2017. A climate data record (CDR) for the global terrestrial water budget: 1984–2010. *Hydrology and Earth System Sciences*, 21(9), pp.4861–4881.

Citation: *Dr. M.N. Pius, et.al., " From Deficit to Dysfunction: Rethinking Drought through a Multi-Index Functional Framework for Ecologically Vulnerable Systems." International Journal of Research in Environmental Science (IJRES), vol. 11, no. 3, pp. 1-15 2025. Available: DOI: http://dx.doi.org / 10.20431/2454-9444.1103001.*