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Satellite-Derived Spatial and Temporal Trajectories Drought Analysis in Myanmar's Dry Zone

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Abstract

Drought is one of the most damaging natural hazards, affecting vast areas and creating serious ecological and economic difficulties. Unlike rapid-onset disasters, drought develops slowly, making early detection and timely mitigation essential. Monitoring drought remains particularly challenging in developing countries like Myanmar, where weather stations are limited and long-term climate records are incomplete. These limitations reduce the effectiveness of drought assessment and management, especially in vulnerable regions such as the Dry Zone. This study investigates the spatiotemporal patterns of drought persistence in Myanmar's Dry Zone from 2001 to 2023 using remote sensing and Geographic Information System (GIS) technologies. MODIS-derived Vegetation Health Index (VHI), which combines the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) to assess drought stress. The VHI is validated against the Standardized Precipitation Index (SPI), calculated from CHIRPS data which is one of the indices that commonly observed from Myanmar. Results reveal distinct seasonal drought patterns, with vegetation stress peaking during the dry season (January to May) and recovering during the monsoon. Severe drought events, particularly in 2004, 2015, 2016, and 2019 are marked by significant declines in VHI indicating widespread vegetation stress and reduced plant growth. Spatial analysis identifies Mandalay, Magway, and Sagaing regions as highly drought-prone due to high temperatures and limited water resources. The research confirms a meaningful relationship between VHI, SPI rainfall. The findings underscore the value of integrating remote sensing and GIS for cost-effective drought monitoring in data-scarce regions and provide crucial insights for developing targeted adaptation strategies in Myanmar's Dry Zone.

Keywords: *LST, MODIS, NDVI, SPI, TCI, VCI, VHI, SPI, Trajectory*

Satellite Image များအသုံးပြု၍ မြန်မာနိုင်ငံ အပူပိုင်းဇုန်၏ မိုးခေါင်မှုအခြေအနေအား လေ့လာခြင်း

စိုးမိုးကျော်၊ ဦးစီးအရာရှိ

စာတမ်းအကျဉ်း

ဤလေ့လာမှုသည် မြန်မာနိုင်ငံအပူပိုင်းဇုန်တွင် ဖြစ်ပေါ်လေ့ရှိသော မိုးခေါင်မှု အခြေအနေကို အဝေးထိန်းအာရုံခံကိရိယာ (Remote Sensing)နှင့် ပထဝီဝင်သတင်း အချက်အလက်စနစ် (GIS) နည်းပညာကိုအသုံးပြုလေ့လာထားပါသည်။ မိမိအနေဖြင့် မြေတိုင်းဦးစီးဌာနတွင် ကောင်းကင်ဓာတ်ပုံများအား အသုံးပြု၍ မြေပုံရေးဆွဲခြင်းလုပ်ငန်းများကို လုပ်ဆောင်နေသဖြင့် ကောင်းကင်ဓာတ်ပုံများအကြောင်းကို ပိုမိုသိရှိလေ့လာနိုင်ရန်အတွက် Satellite Image များကို အသုံးပြု၍ မိုးခေါင်မှုကိုလေ့လာခဲ့ခြင်းဖြစ်ပါသည်။ သုတေသနဆိုင်ရာ လေ့လာဖတ်ရှုချက်များအရ VHIနှင့် SPI မိုးရွာသွန်းမှု လေ့လာချက်များသည် မိုးရေချိန်ဒေတာမရရှိနိုင်သောဒေသများနှင့် အရေးပေါ်သုတေသန လေ့လာမှုများရှိပါက အချိန်တိုအတွင်း ကုန်ကျစရိတ်သက်သာပြီး မိုးခေါင်ရေရှားမှု အခြေအနေကို မှန်ကန်စွာ လေ့လာနိုင်ကြောင်း တွေ့ရှိရပါသည်။ MODIS Remote Satellite Image ကို အသုံးပြု၍ အပင်များ၏ ကျန်းမာရေးညွှန်းကိန်း (Vegetation Health Index - VHI) သည် မိုးခေါင်မှုဒဏ်ကို အကဲဖြတ်ရန် ပုံမှန်ကွာခြားချက်အပင်ညွှန်းကိန်း (Normalized Difference Vegetation Index - NDVI)နှင့် မြေမျက်နှာပြင် အပူချိန် (Land Surface Temperature - LST) တို့ကို ပေါင်းစပ်ထားသည်။ VHI တွက်ချက်ခြင်းကို အဓိကထား၍ လေ့လာမှုပြုလုပ်ခဲ့ပြီး ၎င်းတွက်ချက်မှုမှ ရရှိလာသော မိုးခေါင်မှုအခြေအနေများကို မြန်မာနိုင်ငံမှ သုတေသနပညာရှင်များ အသုံးပြု တွက်ချက်လေ့ရှိသော အညွှန်းကိန်းတစ်ခုဖြစ်သည့် CHIRPS Satellite Image အသုံးပြု၍ မိုးရွာသွန်းမှုညွှန်းကိန်း(SPI)တွက်ချက်၍ အတည်ပြုထားပါသည်။ ရလဒ်များအရ ရာသီအလိုက် မိုးခေါင်မှုပုံစံများကို ထင်ရှားစွာတွေ့မြင်ရပြီး အဓိကအားဖြင့် ဇန်နဝါရီလမှမေလအတွင်း ခြောက်သွေ့ရာသီတွင် အပင်ဖိစီးမှုအထွတ်အထိပ်သို့ရောက်ရှိပြီး မိုးရာသီတွင် ပြန်လည်ကောင်းမွန်လာကြောင်း တွေ့ရှိရပါသည်။ အထူးသဖြင့် ၂၀၀၄၊ ၂၀၁၅၊ ၂၀၁၆ နှင့် ၂၀၁၉ ခုနှစ်များတွင် ပြင်းထန်သော မိုးခေါင်မှုဖြစ်ရပ်များသည် VHI သိသိသာသာ ကျဆင်းခြင်းဖြင့် အပင်ဖိစီးမှုပိုမိုဖြစ်ပေါ်ခြင်းနှင့် အပင်ကြီးထွားမှုလျော့နည်းသွားခြင်းကိုညွှန်ပြပါသည်။ မြန်မာနိုင်ငံတွင် မန္တလေးတိုင်းဒေသကြီး၊ မကွေးတိုင်းဒေသကြီးနှင့် စစ်ကိုင်းတိုင်းဒေသကြီးတို့ရှိ ဒေသတော်တော်များများ၌ အပူချိန်မြင့်မားခြင်းနှင့် ရေအရင်းအမြစ်အကန့်အသတ်ရှိခြင်းကြောင့် မိုးခေါင်မှုအလွန်ဖြစ်နိုင်ခြေများကြောင်း တွေ့ရှိရ ပါသည်။

Satellite-Derived Spatial and Temporal Trajectories Drought Analysis in Myanmar's Dry Zone

1. Introduction

Drought is one of the most severe natural hazards, exerting widespread impacts on ecosystems, agriculture, and socioeconomic systems. Unlike rapid-onset disasters, droughts evolve gradually due to prolonged rainfall deficits, high temperatures, and increased evapotranspiration, often persisting for months or years. Their far-reaching consequences include water scarcity, reduced agricultural productivity, food insecurity, and economic losses [1].Globally, drought currently affects over 2.3 billion people, accounting for nearly 650,000 deaths between 1970–2019, and more than 10 million deaths over the past 100 centuries [2]. In Southeast Asia, approximately 66% of the population has been affected by drought events in the last three decades, with even a 1% increase in drought index contributing to a 0.6% decline in regional GDP [3]. In Myanmar, the 1997–1998 El Niño event caused unprecedented extremes in temperature and rainfall, severely impacting agricultural activities.

Drought severity is typically categorized into four types: (i) meteorological drought, defined by prolonged rainfall deficits; (ii) hydrological drought, associated with reduced groundwater and surface water storage; (iii) agricultural drought, resulting from insufficient soil moisture to sustain crop growth; and (iv) socioeconomic drought, where water shortages disrupt livelihoods and economic activities [4]. These categories are interlinked and collectively contribute to food insecurity, unemployment, and environmental degradation.

Traditional drought monitoring has relied on ground-based rainfall and meteorological records. However, sparse and inconsistent datasets limit their reliability, particularly in developing regions. Remote sensing (RS) offers an efficient alternative, providing large-scale, consistent, and repeatable observations with high spatial and temporal resolution. Satellite-based vegetation indices, precipitation estimates, and land surface temperature (LST) have been widely applied to characterize agricultural drought [5]. Among these, the Normalized Difference Vegetation Index (NDVI) and its derivative, the Vegetation Condition Index (VCI), are widely used to evaluate vegetation stress. The Temperature Condition Index (TCI), derived from LST, further characterizes drought severity, while their combination, the Vegetation Health Index (VHI), has been shown to outperform individual indices in agricultural drought monitoring [6]. Additionally, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) provides long-term, high-resolution rainfall estimates, commonly used with the Standardized Precipitation Index (SPI) to evaluate meteorological drought in data-scarce regions [7].

2. Objectives

This study aims to analyze the spatial and temporal trajectories of agricultural drought in Myanmar's Dry Zone between 2001 and 2023, using MODIS-derived VHI, and CHIRPS-derived SPI. By combining multiple satellite indices with Geographic Information System (GIS) techniques.

The main objectives of this research are;

(i) identify drought-prone hotspots
(ii) assess vegetation response
(iii) provide data-driven insights to support agricultural resilience and climate adaptation strategies.

3. Disaster Management and Drought Preparedness

The World Meteorological Organization (WMO) and the Global Water Partnership (GWP) define drought management as a three-pillar framework consisting of: (i) monitoring and early warning, (ii) vulnerability and impact assessment, and (iii) mitigation, preparedness, and response [18].

Monitoring and Early Warning: Real-time observation of precipitation, soil moisture, and hydrological conditions using meteorological networks and remote sensing enables proactive decision-making.

Vulnerability and Impact Assessment: GIS and remote sensing facilitate spatial mapping of drought-prone areas, helping policymakers identify populations at risk based on agricultural dependency, water resources, and socio-economic conditions [19].

Mitigation and Response: Long-term strategies include sustainable irrigation, efficient water management, and community awareness programs [20].

Southeast Asia's agricultural dependency on monsoon rainfall increases exposure to drought-related risks. Myanmar's Dry Zone, home to nearly one-third of the population, experiences high evapotranspiration and erratic rainfall [21] Conventional post-disaster relief approaches are insufficient; therefore, integrated risk management emphasizing early warning, preparedness, and adaptive land-use strategies is essential.

3.1 Definitions and Types of Droughts

Drought is a multi-dimensional hazard with no universal definition, as its onset is slow and impacts vary across sectors [22]. Wilhite and Glantz classify drought into four categories [18].

Meteorological Drought: Sustained precipitation deficit relative to long-term norms.
Agricultural Drought: Insufficient soil moisture to support crop growth.
Hydrological Drought: Decline in surface and groundwater availability.
Socioeconomic Drought: Water shortages affecting economic activities and livelihoods.

These categories are interrelated and context-dependent, especially in rain-fed agrarian systems such as Myanmar's Dry Zone [23].Prolonged drought reduces soil moisture, vegetation cover, and groundwater recharge, often leading to cascading effects such as land degradation, erosion, and biodiversity loss [24], [25].

3.2 Spatial and Temporal Drought Monitoring

Droughts are spatially heterogeneous and temporally dynamic, requiring multi-scale analysis to capture variability in intensity, duration, and extent [26]. SPI and VHI are widely applied in integrated frameworks to monitor short-term rainfall deficits and vegetation stress [19]. Spatiotemporal assessments using MODIS-derived VHI highlight chronic drought-prone areas and seasonal vegetation responses [27].

Temporal analysis identifies drought cycles, persistence, providing critical insights for adaptive management [23]. However, studies focusing on long-term drought trajectories in Myanmar remain limited [28]. GIS-based spatial modeling and trajectory analysis can identify evolving drought hotspots, enabling risk-based resource allocation [29].

3.3 Background and Impact of Drought in Myanmar's Dry Zone

The Dry Zone, encompassing Mandalay, Magway, and Sagaing regions, is Myanmar's most drought-prone area, receiving only 500–1000 mm of annual rainfall. Climate variability, monsoon shifts, and rising temperatures exacerbate water scarcity, soil degradation, and food insecurity [30].

Agriculture in this region, dominated by rice, pulses, and sesame, is highly vulnerable to rainfall variability. Recurrent drought has caused yield declines, economic instability, and rural migration. In addition, secondary disasters such as heatwaves, dust storms, and land degradation amplify vulnerability [20].

Recent adaptation efforts include solar-powered irrigation, community-managed water storage, and watershed restoration programs [31]. Nevertheless, persistent data limitations, weak early-warning systems, and socio-economic constraints hinder comprehensive drought management. Strengthening geospatial monitoring and integrating remote sensing indices with climate modeling are essential to building resilience in this critical agricultural region.

3.4. Study Area

The study focuses on Myanmar's Central Dry Zone, encompassing 53 townships across the central parts of Mandalay, most of Magway, and the lower Sagaing region (Fig. 1). Geographically, the Dry Zone lies between 19°20′–22°50′ N and 93°40′–96°30′ E**,** covering an estimated 88,567 km² (approximately 13% of Myanmar's land area) and supporting a population of over 10 million people [8]. The region is bounded by the Rakhine Mountains to the west, the Bago Yoma to the south, and the Shan Plateau to the east.

The Dry Zone represents the most drought-prone and climate-sensitive area of Myanmar. Annual rainfall averages 500–1000 mm, significantly below the national mean, and is characterized by high temporal variability due to South Asian monsoon dynamics [9]. Evapotranspiration rates are high, and rainfall distribution is sparse and uneven, leading to frequent agricultural droughts. Seasonal climate is tropical with three distinct periods: a hot season (mid-February to mid-May), a rainy season (mid-May to late October), and a cool season (late October to mid-February) [10].Peak drought intensity typically occurs in April–May, when temperatures can reach 43 °C**,** while winter temperatures may drop to 8–10 °C.

Agriculture is the backbone of the Dry Zone economy, with major crops including rice, sesame, groundnut, chickpea, pulses, and cotton. The region contributes nearly 35% of Myanmar's rice production, despite water limitations [11]. Irrigation is scarce, leaving livelihoods highly dependent on rainfall, and frequent droughts have historically led to widespread yield reductions, economic instability, and rural migration.

Hydrologically, the area is traversed by the Ayeyarwady River and its tributaries, yet water availability remains constrained due to limited storage and high demand. Land cover is a mosaic of croplands, forest patches, shrublands, grasslands, and sparsely vegetated or degraded lands, reflecting both ecological vulnerability and human pressures such as deforestation and overgrazing. Rainfall data from the Myanmar Meteorological and Hydrological Department provide essential monitoring, though the sparse station network necessitates the integration of remote sensing for reliable drought assessment.

Despite interventions such as irrigation schemes, reforestation, and early warning systems, the Dry Zone continues to face critical challenges of water scarcity, land degradation, and poverty**.** As both a key agricultural hub and a hotspot of climate vulnerability, it is a priority region for drought monitoring and resilience planning [12].

3.5 Current Issues in Drought Monitoring in Myanmar's Dry Zone

The Central Dry Zone of Myanmar is increasingly vulnerable to drought under climate change, which alters rainfall patterns, raises temperatures, and accelerates evapotranspiration, leading to reduced soil moisture and declining groundwater levels [9], [32]. As Myanmar's primary agricultural hub, the Dry Zone faces recurrent and severe drought events that threaten food security, water resources, biodiversity, and rural livelihoods.

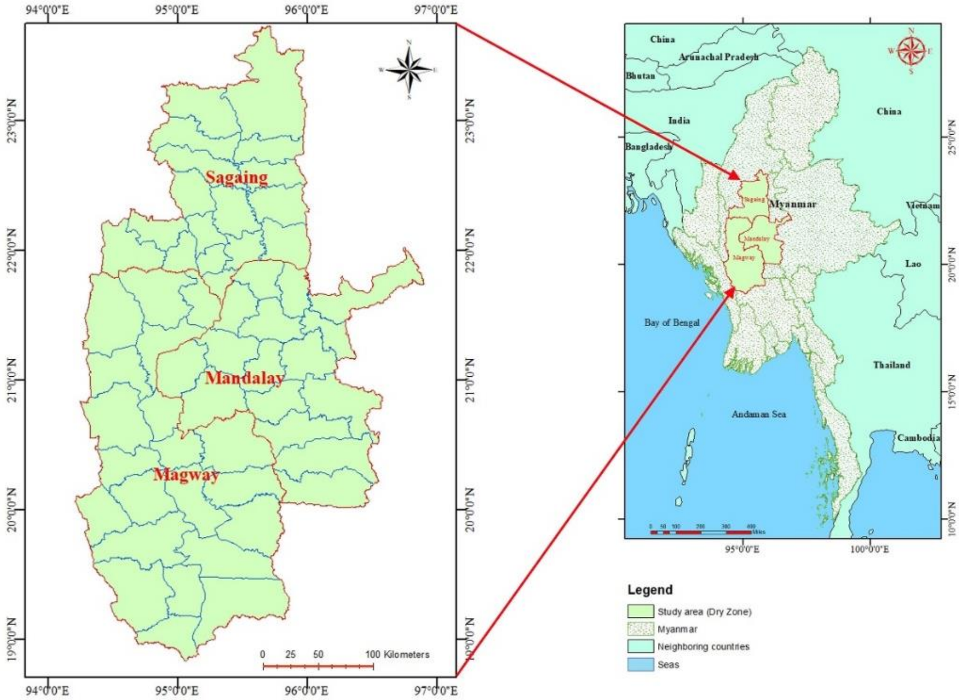


Figure 1; Study area (Myanmar Dry Zone)

Traditional drought monitoring approaches in Myanmar primarily rely on ground-based meteorological observations. While practical, these methods lack spatial coverage, real-time updates, and long-term consistency. Remote sensing has enhanced monitoring capacity, particularly through indices such as the Vegetation Health Index (VHI) and Standardized Precipitation Index (SPI)**,** which capture vegetation stress and precipitation anomalies, respectively [12], [20]. However, current applications are constrained by data availability, accuracy limitations, and weak integration with ground-based datasets.

Monitoring challenges are compounded by the gradual onset of drought, which makes early detection and response more difficult compared to rapid-onset disasters. Although Myanmar has initiated a three-pillar framework consisting of early warning systems, vulnerability assessments, and mitigation strategies, institutional capacity, financial resources, and technical expertise remain limited [8]. Moreover, adaptation strategies such as climate-resilient farming, water conservation, and reforestation have yet to achieve widespread implementation due to insufficient investment and policy support.

3.6 Literature Gaps and Research Justification

Existing studies on drought in Myanmar largely adopt single-index approaches, focusing either on precipitation anomalies (SPI) or vegetation health (NDVI or VHI). For example, R. Dutta, A.M. Tun, T.Z. Htoo, and T. Maung analyzed drought severity using rainfall anomalies or NDVI but were restricted by fragmented datasets and limited temporal coverage [4], [33], [34], [35]. Similarly, T. Yi applied SPI for drought assessment but without integration of vegetation conditions [36]. While such methods provide partial insights, they fail to capture the complex interplay between climatic drivers, vegetation stress, and ecosystem response.

Another persistent challenge is the lack of consistent, high-quality ground-based meteorological and soil data. Sparse station networks hinder validation of satellite-derived indices, while institutional and technical gaps restrict the use of advanced methods such as machine learning for drought prediction [3].This creates an urgent need for scalable, data-driven frameworks that integrate multiple indices and exploit satellite datasets for continuous monitoring.

To address these gaps, this study employs a multi-indicator framework combining VHI, and SPI over a 23-year period (2001–2023) using MODIS and CHIRPS datasets. This enables a detailed spatial and temporal analysis of drought onset and persistence. The integration of vegetation, climate, and productivity-based indices provides a holistic view of agricultural drought, surpassing the limitations of single-index methods.

Overall, this research contributes to both scientific and practical domains. Scientifically, it advances the understanding of long-term drought trajectories in tropical agricultural systems. Practically, it provides actionable insights for drought early warning, agricultural planning, and climate adaptation policies in Myanmar's Dry Zone, one of the most drought-prone regions in Southeast Asia.

4. Materials and Methods

This study integrates multi-sensor datasets to analyze agricultural drought persistence in Myanmar's Dry Zone from 2001 to 2023. The primary datasets are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) dataset.

MODIS: MODIS, onboard the Terra (1999, morning orbit) and Aqua (2002, afternoon orbit) satellites, provides multispectral observations across 36 bands with spatial resolutions of 250 m, 500 m, and 1 km, and global coverage every 1–2 days [37]. Key products include:

MOD13Q1: 16-day composites of NDVI at 250 m resolution.

MOD11A2: 8-day average land surface temperature (LST) at 1 km resolution.

CHIRPS: CHIRPS is a quasi-global precipitation dataset (0.05° resolution, ~5 km) integrating infrared satellite observations with ground-based rain gauge data [38]. It provides daily to monthly records from 1981 to the present, supporting precipitation anomaly analyses.

4.1 Drought Indicators

Three drought indicators were employed to capture vegetation stress, precipitation anomalies, and ecosystem productivity.

Normalized Difference Vegetation Index (NDVI):

$$\mathbf{NDVI} = \frac{\mathbf{NIR-RED}}{\mathbf{NIR+RED}} \quad \textbf{where } (0<\mathbf{NDVI}>1) \tag{1}$$

where *NIR* and *RED* represent near-infrared and red reflectance, respectively.

Vegetation Condition Index (VCI)

VCI measures how healthy vegetation is compared to its historical minimum and maximum NDVI (Normalized Difference Vegetation Index) values

$$\mathbf{VCI} = 100 * \frac{\mathbf{NDVI - NDVI\ min}}{\mathbf{NDVI\ max - NDVI\ min}} \tag{2}$$

Land Surface Temperature (LST)

Converts the raw satellite digital number (DN) for temperature into actual temperature in Celsius.

$$\mathbf{LST} = (\mathbf{LST_{DN}} * 0.02) - 273.15 \tag{3}$$

Temperature Condition Index (TCI)

TCI shows how hot the land is compared to its historical hottest and coldest values.

$$\mathbf{TCI} = 100 * \left(\frac{\mathbf{LST\ max - LST}}{\mathbf{LSTmax - LSTmin}}\right) \tag{4}$$

Vegetation Health Index (VHI)

Combines vegetation condition (VCI) and temperature stress (TCI) into a single index.

$$\mathbf{VHI} = \mathbf{a} * \mathbf{VCI} + (1-\mathbf{a}) * \mathbf{TCI} \tag{5}$$

where a=0.5, producing values from 0 (extreme drought) to 100 (no drought) [90]. Drought classes are presented in **Table IV**.

Table 1:Drought classification based on VHI

No	VHI value	Drought severity
1	0–10	Extreme drought
2	10–20	Severe drought
3	20–30	Moderate drought
4	30–40	Mid drought
5	>40	No drought

Standardized Precipitation Index using CHIRPS Data

The CHIRPS dataset uses high-quality, satellite-derived precipitation data to calculate annual precipitation and the Standardized Precipitation Index (SPI) to validate the reliability of the VHI drought conditions. The SPI is a commonly recognized drought indicator that quantifies precipitation variations across several time intervals (e.g., three months, six months, and One year). The CHIRPS data provide high-resolution global precipitation estimates by integrating satellite imagery. It can be available from 1981 to the present and provides temporal resolution for daily, pentanal, and monthly precipitation. CHIRPS is particularly valuable in developing countries where ground-based observations are unavailable [39].

The Standardized Precipitation Index (SPI) is a useful tool for drought monitoring and rainfall analysis. The severity of drought is assessed using SPI values (<-2) as Severe drought, (-2.0 < SPI <= -1.5) as Moderate drought, (-1.5 < SPI <= -1.0) as Mild drought, and (-1.0 < SPI) as No drought. It measures rainfall variability over different time scales and provides insight into short- and long-term drought conditions. Its spatial coverage and temporal resolution make it suitable for regions with limited ground-based surveys. A comparative analysis was conducted between VHI and SPI results to determine the consistency between satellite-derived drought indices and ground-based precipitation records.

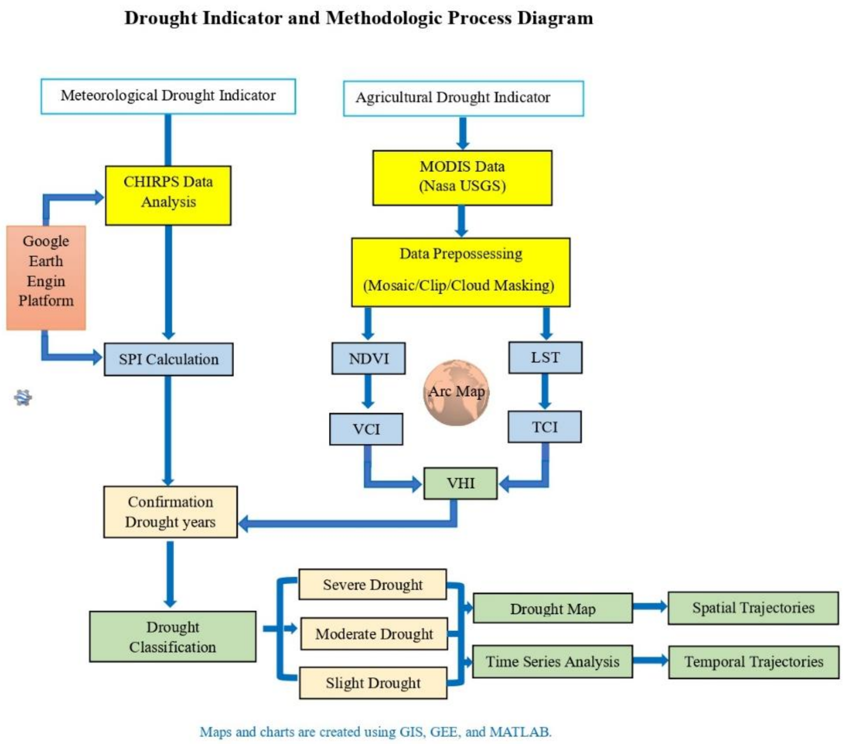


Figure 2: Methodological work flow

5. Result

5.1. Vegetation Health Index (VHI) Analysis

The Vegetation Health Index (VHI), derived from NDVI and LST, effectively characterizes vegetation stress induced by water deficits and high temperatures. NDVI values in the Dry Zone ranged between 0.1–0.6 during 2001–2023, with seasonal minima (<0.3) observed in the dry months (March–May) and recovery following monsoon onset (August–October). Years such as 2001, 2010, 2015–2016, and 2019–2021 recorded significant NDVI declines, consistent with reported drought events.

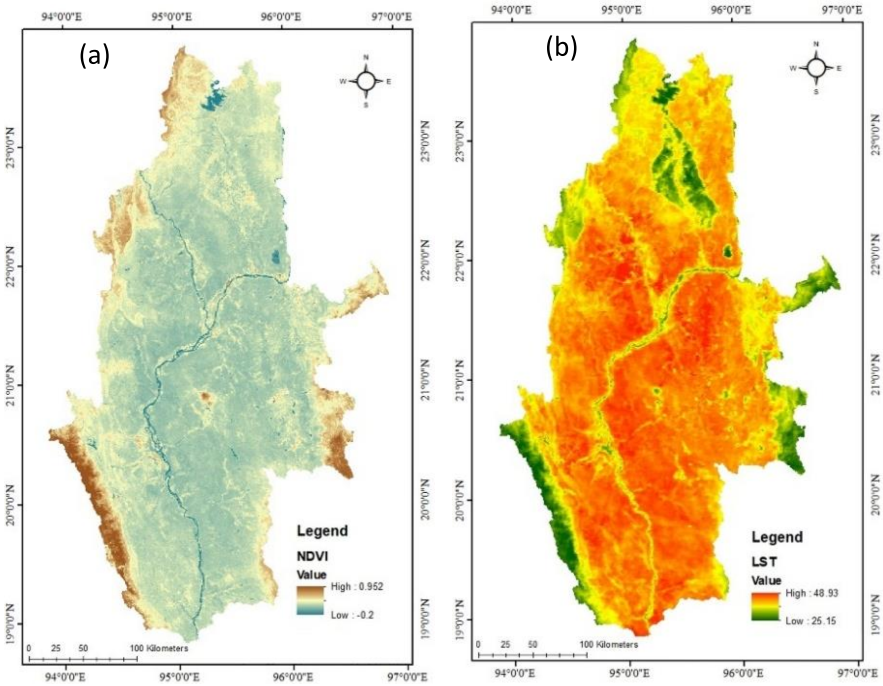


Figure 3: NDVI and LST Calculation

Land Surface Temperature (LST) exhibited strong seasonal variability, with maxima exceeding 40–45°C in April and May, coinciding with vegetation stress. Cooler LST values (30–35°C) were consistently observed along the Ayeyarwady River corridor, demonstrating the buffering effect of riparian vegetation. Long-term trends indicate a gradual increase in dry-season temperatures after 2010, consistent with regional warming.

The Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) provide complementary perspectives on vegetation greenness and heat stress, respectively. VCI values declined by approximately 5% per decade, reflecting progressive vegetation stress, particularly during dry seasons. In contrast, TCI values fell by ~6% over the 23-year study period, reflecting intensifying thermal stress. Severe TCI anomalies (<30) were concentrated in Magway and central Sagaing, highlighting hotspot regions of vulnerability.

The integration of VCI and TCI into VHI provided a multidimensional representation of drought. Seasonal cycles were evident, with VHI minima during March–May (often <20, severe drought) and recovery in September–November (>60, no drought). These findings confirm VHI's utility for capturing both climatic and ecological drought signals in data-scarce environments.

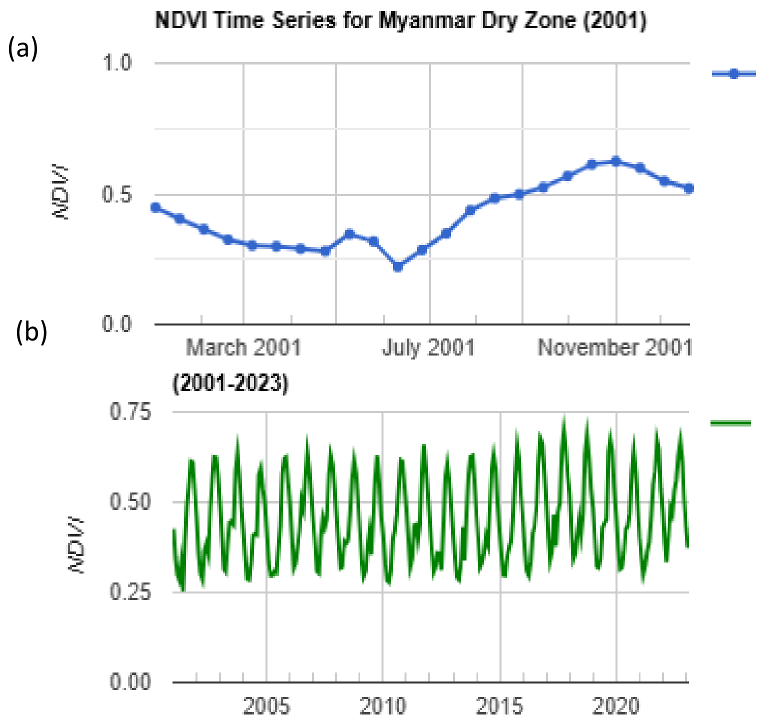


Figure 4: Time Series of NDVI: (a) Month, (b)Years

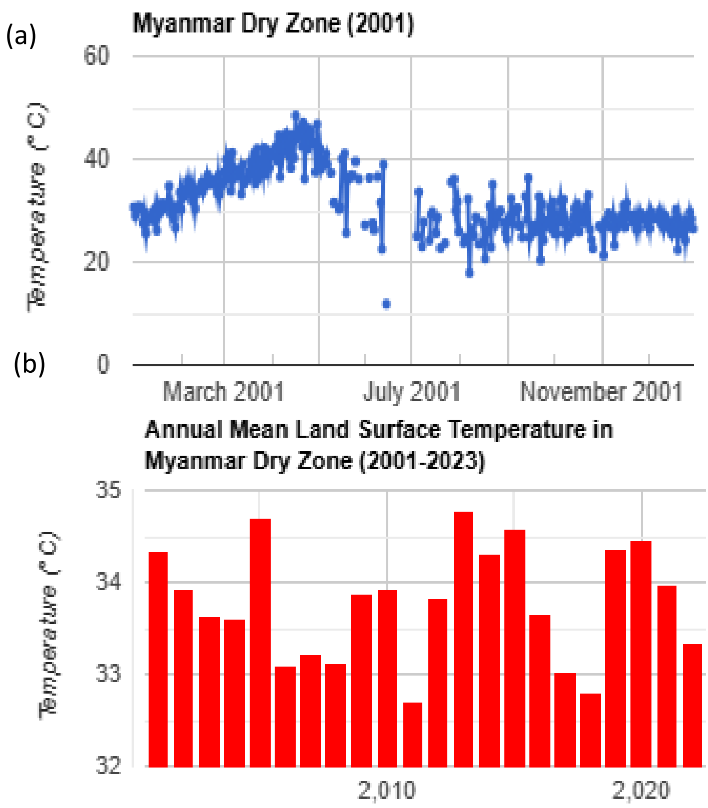


Figure 5: Time Series of LST: (a) Month, (b)Years

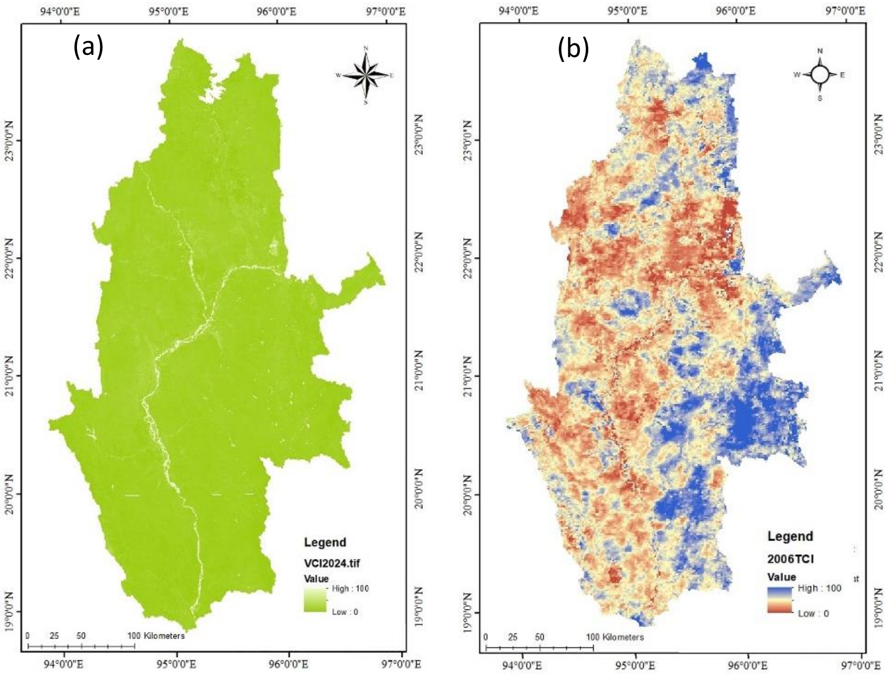


Figure 6: Calculated result of VCI(a) and TCI(b)

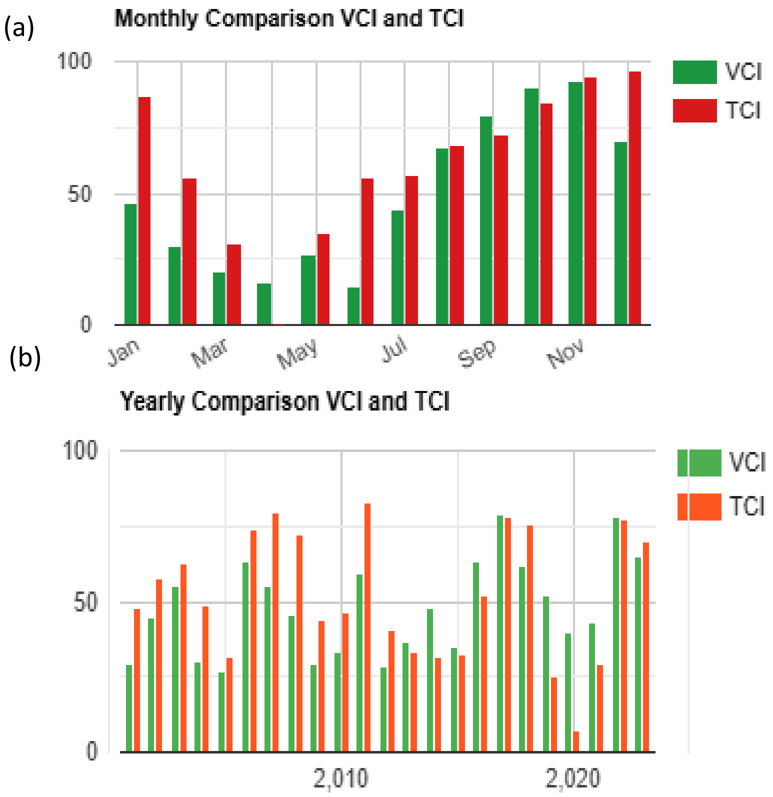


Figure 7: Time Series Analysis of VCI and TCI: (a) Month, (b)Years

The spatial distribution of VHI classified droughts into five categories: extreme (0–10), severe (10–20), moderate (20–30), mild (30–40), and non-drought (>40). Central Myanmar, particularly Mandalay, Magway, and Sagaing, consistently fell into the severe and extreme categories, while coastal and delta regions exhibited higher VHI values, indicating resilience.

Irrigated zones along the Ayeyarwady maintained relatively high VHI (>60) even during drought years.

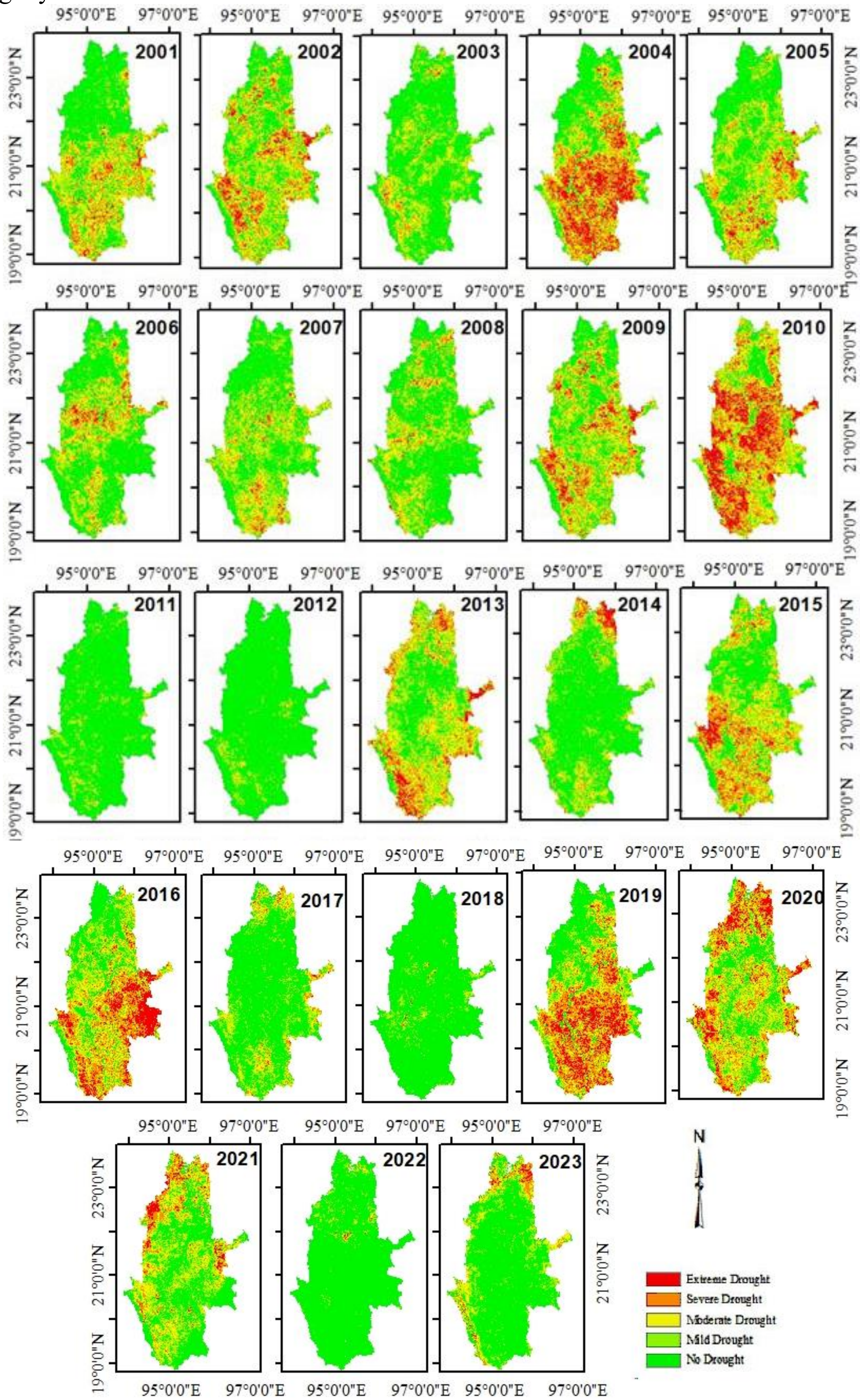


Figure 8: Calculated result of VHI from 2001 to 2023

Severe droughts were observed in 2001, 2010, 2015–2016, and 2019–2020, with VHI values falling below 20 across 40–50% of the Dry Zone. Moderate drought years included 2002, 2005, and 2012. Temporal analysis revealed that delayed monsoon onset often triggered early-season VHI declines, while post-monsoon recovery highlighted vegetation resilience in certain sub-regions.

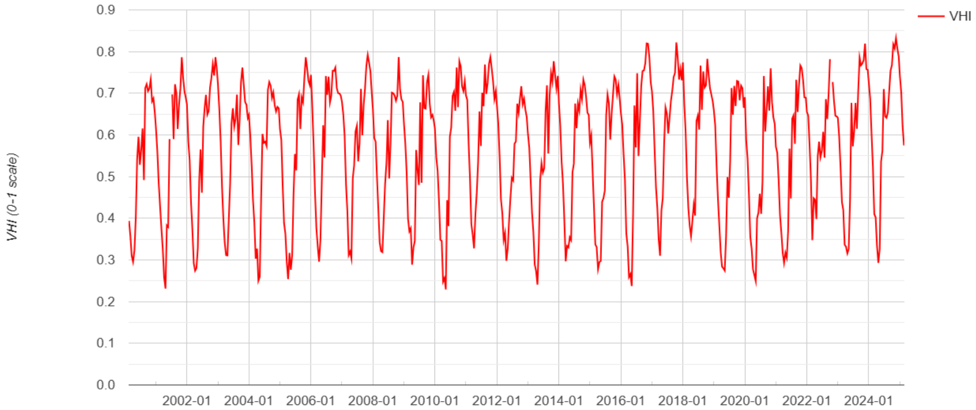


Figure 9: Time Series Analysis of Vegetation Health Index (VHI)

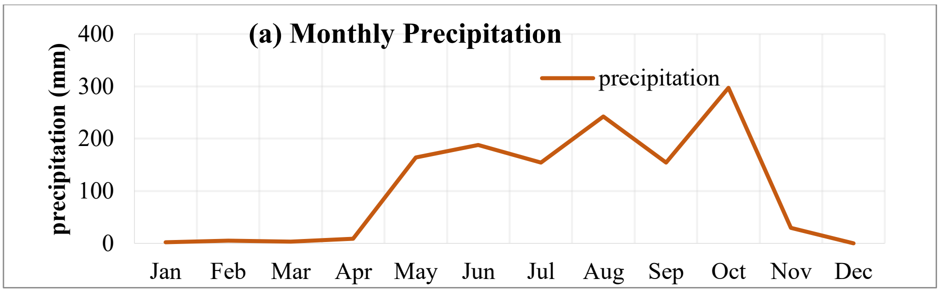
Time-series analysis of VHI from 2001–2023 confirmed recurrent droughts, with extreme events in 2001, 2004, 2010, 2013, 2016, and 2020. These episodes corresponded with below-average rainfall and elevated LST, resulting in widespread vegetation stress. Moderate drought years (2009, 2015, 2019, and 2021) reflected partial vegetation recovery, though VHI remained below 0.4.

The cyclic pattern of decline during dry seasons and recovery during monsoons underscores the monsoon's central role in ecosystem resilience. However, the persistence of low VHI in degraded soils and rainfed agricultural lands highlights chronic vulnerability.

5.2 Meteorological Validation Using SPI

Using the Standardized Precipitation Index (SPI) derived from CHIRPS data provides critical insights into drought conditions across Myanmar. CHIRPS' high spatial and temporal resolution allows for precise identification of drought-prone areas and monitoring of drought onset, duration, and recovery. SPI effectively complements Vegetation Health Index (VHI) assessments by linking drought to impacts on crop production and water resources. Combined with other indices, it offers a multidimensional understanding of drought, supporting targeted mitigation and adaptation strategies.

Analysis from 2001–2023 shows that Myanmar's Dry Zone experiences consistently low rainfall, particularly during the dry season (January–March), with transitional zones showing moderate drought stress. Annual rainfall fluctuated between 1,200–1,400 mm, with significant variability and pronounced dry years in 2009, 2013–2015, 2019, 2020, and 2022. Extreme drought events, such as in 2015–2016, correspond to prolonged low rainfall and El Niño conditions. Seasonal SPI analysis reflects negative values during pre-monsoon and dry seasons, highlighting agricultural stress and water scarcity, while wet monsoon seasons bring temporary relief.



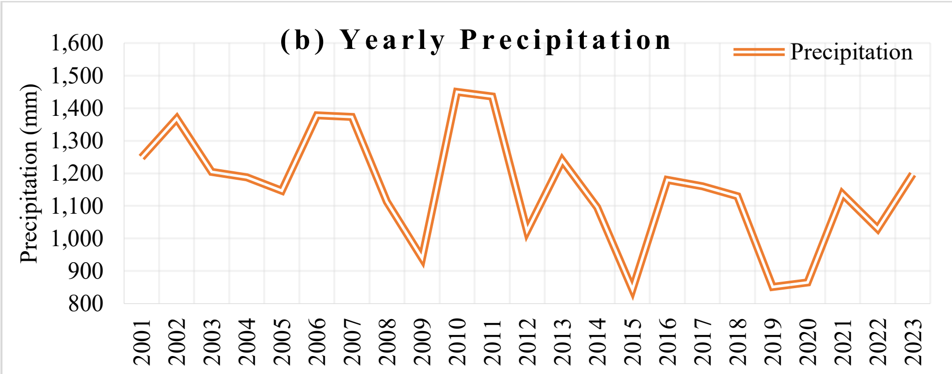


Figure 10: Time Series Analysis of precipitation (a) Month, (b) Years

SPI and rainfall analysis reveal both spatial and temporal drought dynamics, particularly severe in the central Dry Zone, emphasizing the importance of integrated drought monitoring systems that combine meteorological and ecological indicators. Such approaches are essential for climate resilience, sustainable agriculture, and water resource management in Myanmar's drought-prone regions.

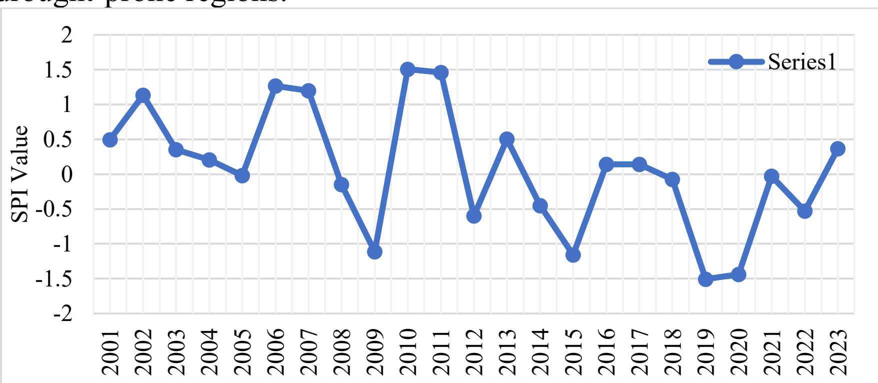


Figure 11: Time Series Analysis of 12month SPI

5.3 Confirmation of Results and Verification of Drought years

The study confirms drought conditions in Myanmar's Dry Zone by combining the Vegetation Health Index (VHI) and Standardized Precipitation Index (SPI), providing both ecological and meteorological perspectives. VHI captures vegetation stress influenced by soil moisture and temperature, while SPI reflects rainfall deficits; together, they show how vegetation responds to drought. Severe droughts occurred in 2001, 2004, 2009, 2015, 2016, and 2019 with the most prolonged impacts in 2015, significantly reducing crop yields. Spatial analysis highlights the central and western Dry Zone as most drought-prone, while riverine and irrigated areas remain more resilient.

The integration of VHI and SPI enables accurate identification of drought years and hotspots, emphasizing the need for proactive water resource management, sustainable agriculture, and strategies to enhance vegetation resilience. This combined approach supports tailored drought mitigation, reduces climate change impacts, and promotes sustainable development in Myanmar's vulnerable regions.

5.4. Drought Trajectories in Myanmar's Dry Zone

Drought trajectory analysis is a modern method that examines how droughts evolve across space and time. Unlike traditional approaches that view drought as a static event, this technique tracks how droughts begin, intensify, shift locations, merge, or break apart. Using the Vegetation Health Index (VHI) which combines vegetation, moisture, and temperature stress, researchers can identify changing drought severity, cluster patterns, and long-term trends. By observing monthly and yearly VHI patterns, drought clusters reveal how conditions overlap, expand, or recover.

This method helps identify both **spatial patterns** (hotspots and cold spots) and **temporal dynamics** (seasonal and annual variability). Hotspots represent districts with persistent or increasing drought stress, while cold spots show improving conditions. Because drought conditions fluctuate with seasonal climate patterns, trajectory analysis provides a more complete understanding of environmental behavior and supports climate-resilient planning.

5.4.1 Spatial Trajectory of VHI Values

Spatial analysis of VHI across Myanmar's Dry Zone (2001–2023) shows consistent drought concentration in central Myanmar especially Mandalay, Magway, and Sagaing Regions**.** These districts repeatedly record the lowest VHI values, indicating long-term water stress. In contrast, areas close to the Ayeyarwady River Basin show higher VHI due to better moisture availability.

Seasonal patterns reveal that February to May is the most severe drought period. Magway, Mandalay, and Sagaing each experience over 20,000 to 30,000 km² of drought-affected area during the late dry season. After May, drought severity gradually decreases and is minimal by July.

Long-term analysis shows increasing drought intensity in several districts, influenced by deforestation, land-use change, and climate variability. Severe drought years such as 2004, 2005, 2009, 2015, 2016, and 2021 show extremely large affected areas across all three regions. Although conditions slightly improved after 2021, drought continues to pose major risks to agriculture, water supply, and livelihoods across the Dry Zone.

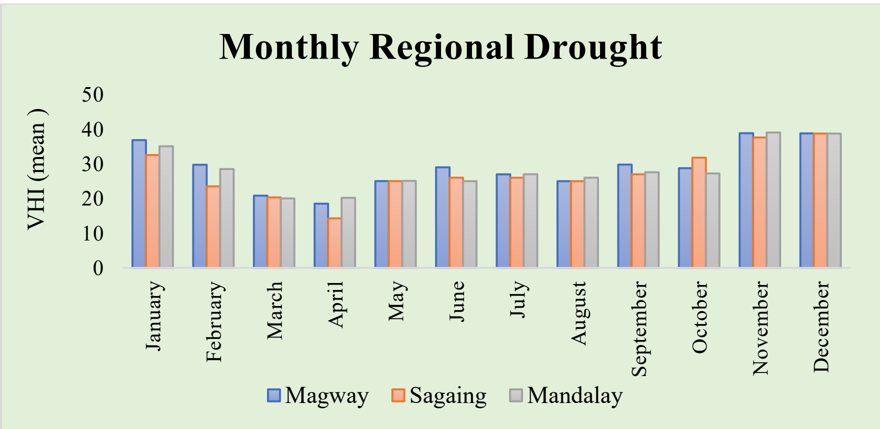


Figure 12: Monthly Variations in Drought Severity in Magway, Sagaing, and Mandalay

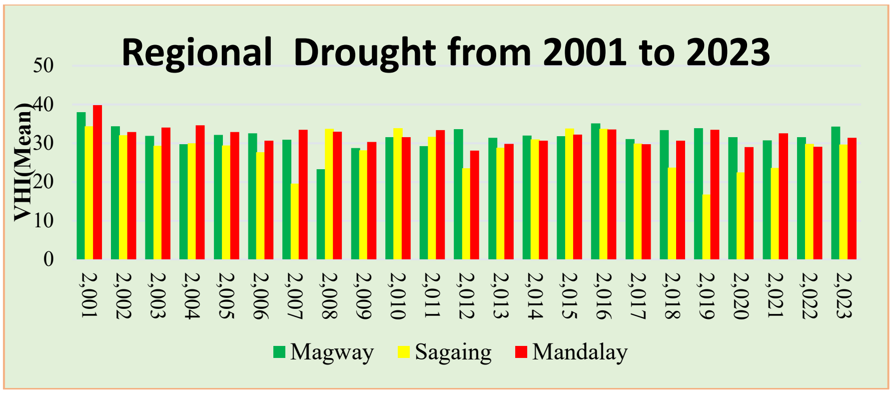


Figure 13: Yearly Variations in Drought Severity in Magway, Sagaing, and Mandalay

5.4.2 Temporal Dynamics of VHI Values

Temporal VHI analysis shows strong seasonal cycles. **January-April** repeatedly show the lowest VHI values (often below 20), reflecting extreme heat, lack of rainfall, and high vegetation stress. April represents the peak of drought intensity every year. the onset of the **monsoon season (May-October)**, VHI values rise sharply due to improved rainfall and soil moisture. The highest VHI values occur between **September and November**, representing the best environmental conditions. Values stabilize or decline slightly in December as the region transitions back into the dry season.

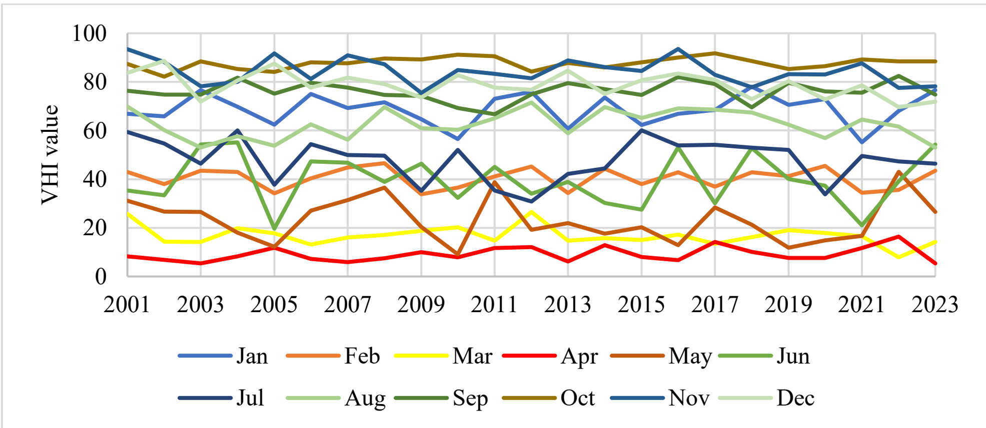


Figure 14: Monthly and Yearly Variations in Drought Intensity (2001-2023)

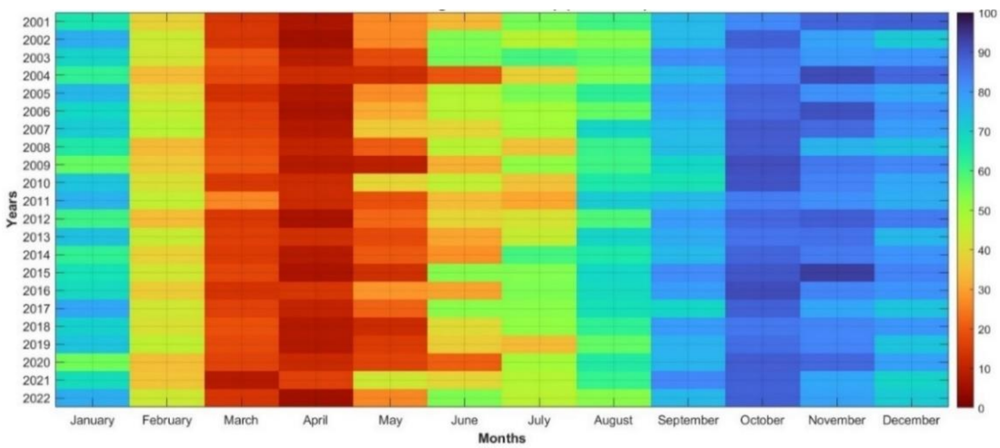


Figure 15: Annual Changes in Drought Severity Across Myanmar's Dry Zone

Year-to-year fluctuations show notable drought intensification in **2004, 2009, 2015, 2016, 2019, and 2020**, all of which recorded sharp drops in VHI. The years 2011–2020 display higher variability due to climate extremes. By 2023, VHI patterns appear more stable, suggesting partial recovery but no long-term reduction in drought recurrence.

5.5 Long-Term Trajectories

Long-term drought conditions are expected to significantly affect both ecosystems and human livelihoods. Reduced rainfall and higher evaporation increase pressure on agriculture, livestock, and domestic water supplies. Crop yields may decline, food insecurity may rise, and economic losses could intensify among rural households. Ecological impacts include habitat degradation, loss of biodiversity, and growing desertification risks. Socio-economic challenges such as water conflicts, health impacts, and strain on infrastructure will intensify without corrective action.

VHI (Vegetation Health Index) trajectories shows a clear long-term decline in vegetation health across Myanmar's Dry Zone from 2001 to 2023. Linear regression reveals a significant negative trend, especially during the dry season, confirming increasing drought severity and persistence. This decline aligns with broader global patterns linked to climate variability, higher temperatures, and reduced rainfall. Following major drought such as the extreme 2015,2016 event vegetation recovery was notably delayed. VHI values stayed below 30 well into the monsoon season, indicating prolonged vegetation stress and lower ecosystem resilience.

Spatial and temporal analyses further identify the most severe drought months and locations across Magway, Mandalay, and Sagaing Regions. Monthly and yearly severity patterns show that these regions consistently experience the lowest VHI values during February to April, highlighting recurrent high-risk periods for agriculture and water supply. Figures illustrate distinct drought behaviors, with Mandalay and Magway showing higher intensity while Sagaing experiences wider spatial coverage.

Drought clusters were examined using hotspot/cold-spot analysis, centroids, and peak drought months. Computations using Google Earth Engine, GIS, and MATLAB reveal significant spatial shifts in drought concentration. Monthly centroid movements demonstrate dynamic patterns driven by seasonal rainfall, temperature variations, and land surface processes. These movements emphasize the need for adaptive irrigation planning and early warning systems.

The Dry Zone experiences repeated droughts, but their severity and spatial distribution vary yearly. Cluster analysis shows drought shifting from southern areas toward northern locations over time. Lighter colors (brown and red) indicate higher severity, with drought centers frequently expanding or contracting based on monsoon timing and climatic fluctuations. Despite spatial variation, Magway, Mandalay, and Sagaing remain the most drought-affected regions. The blue centroid lines indicate a northward movement from May to July, reflecting seasonal climatic transitions. Black stars marking maximum drought intensity identify regions most susceptible to crop failure, water shortages, and vegetation collapse.

Centroid analysis shows that the drought epicenter reaches its northernmost position between August and October. Although intensity decreases toward the end of the year, spatial distribution still varies with changing weather patterns. Long-term drought cluster maps derived from ArcGIS (using IDW interpolation and area analysis) reveal persistent hotspots. Severe droughts were especially frequent in 2004, 2009, 2015, 2016, and 2019. Magway exhibited the highest intensity, while Mandalay and Sagaing showed the broadest affected areas.

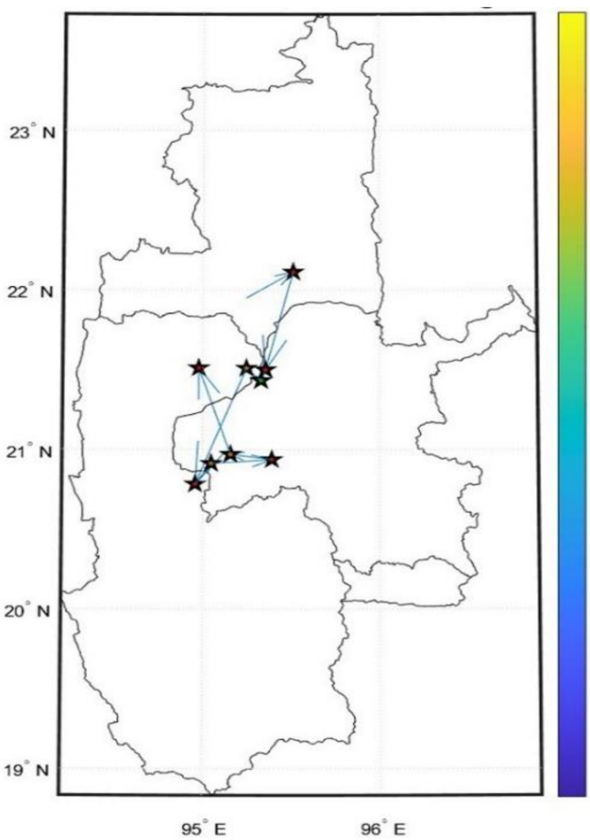
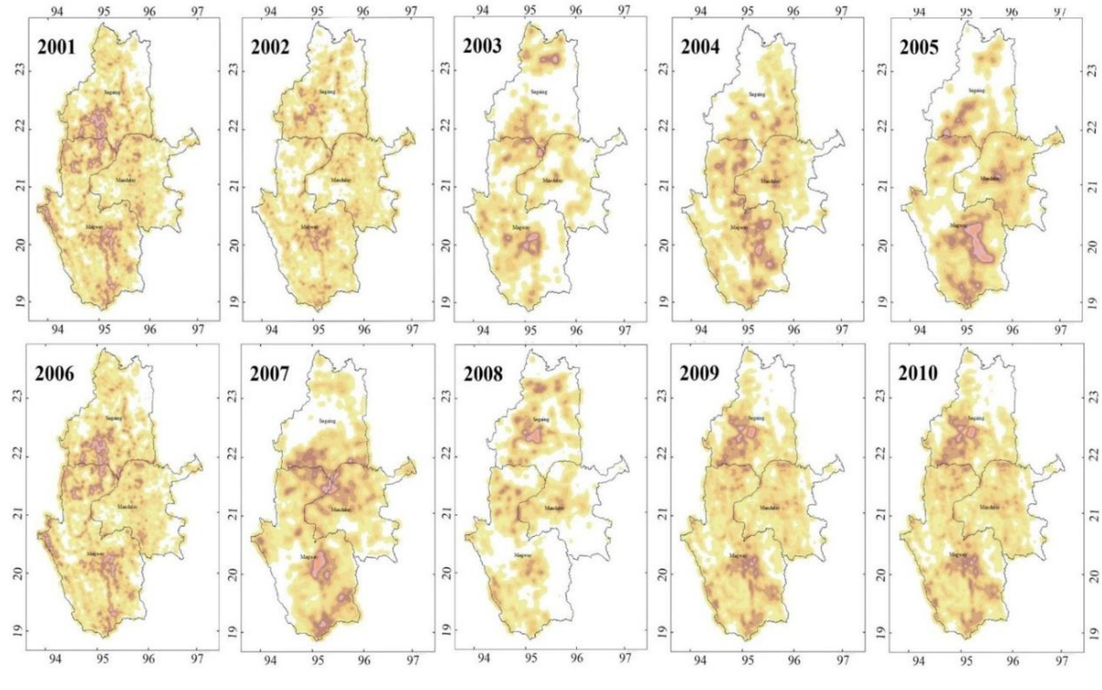


Figure 16: Centroid Moment of Severe Drought in a years



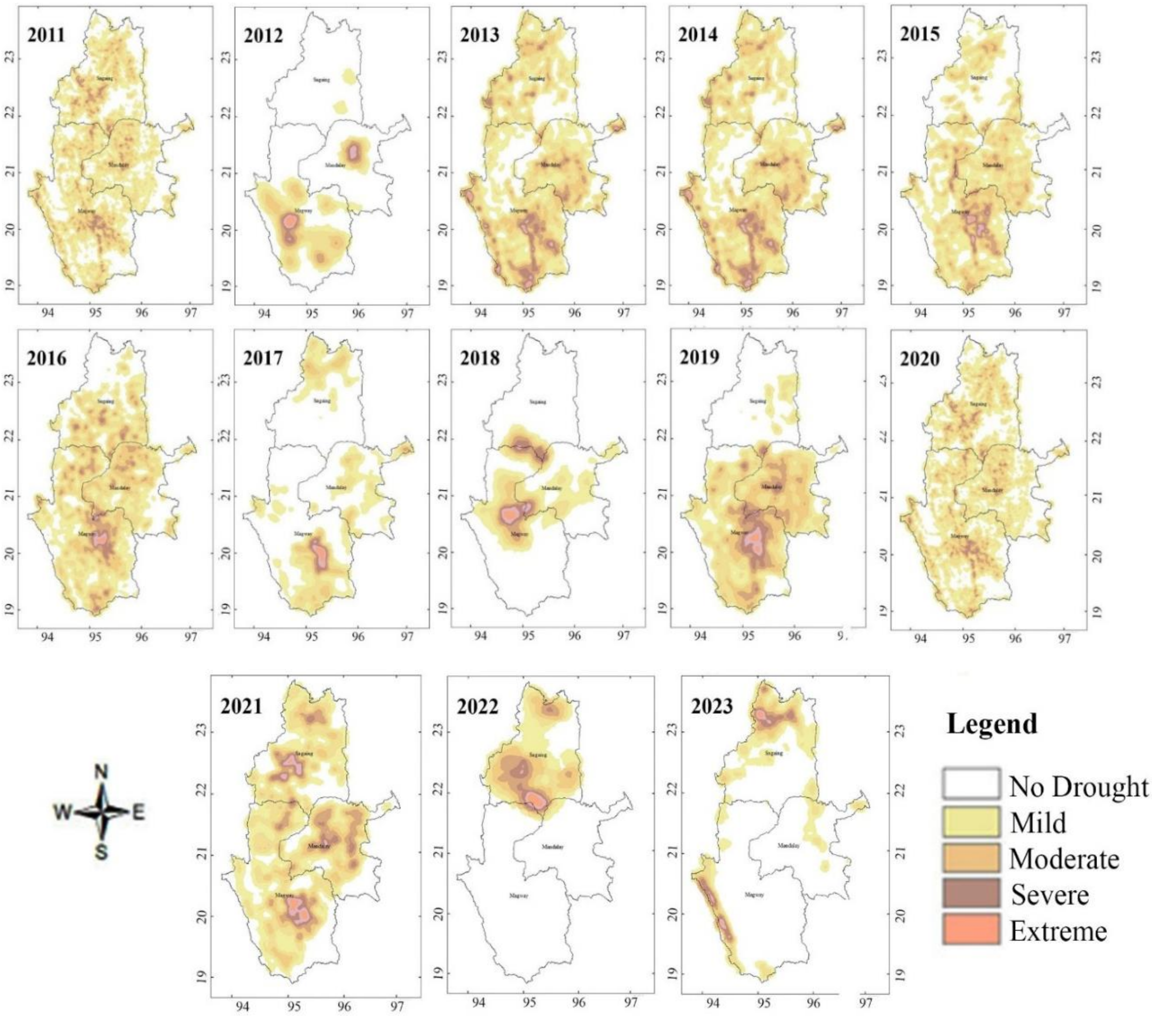
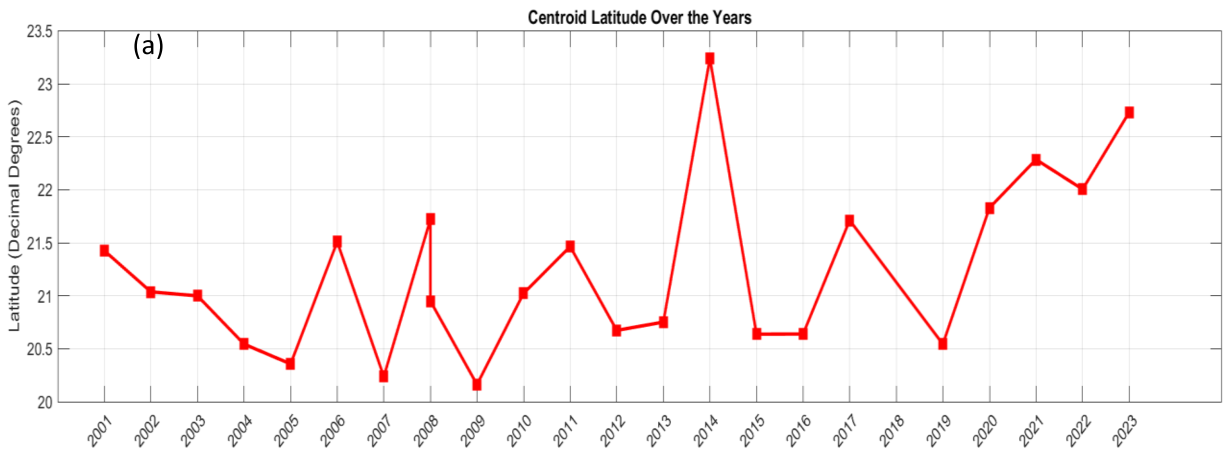


Figure 17: Cluster of Drought from 2001 to 2023

Median movement plots illustrate substantial year-to-year variability. Latitudinal trends show irregular fluctuations from 2001 to 2013 and a gradual northward shift after 2005. A sharp northward peak occurred in 2014, followed by a decrease and then recurring oscillations. Longitudinal movement shows significant east-west shifts, with noticeable peaks between 2004,2006 and again in 2015,2016. After 2016, the drought centroid shows gradual westward fluctuations. These combined patterns demonstrate that drought areas are non-stationary and strongly influenced by climate variation, rainfall anomalies, and land-use changes.



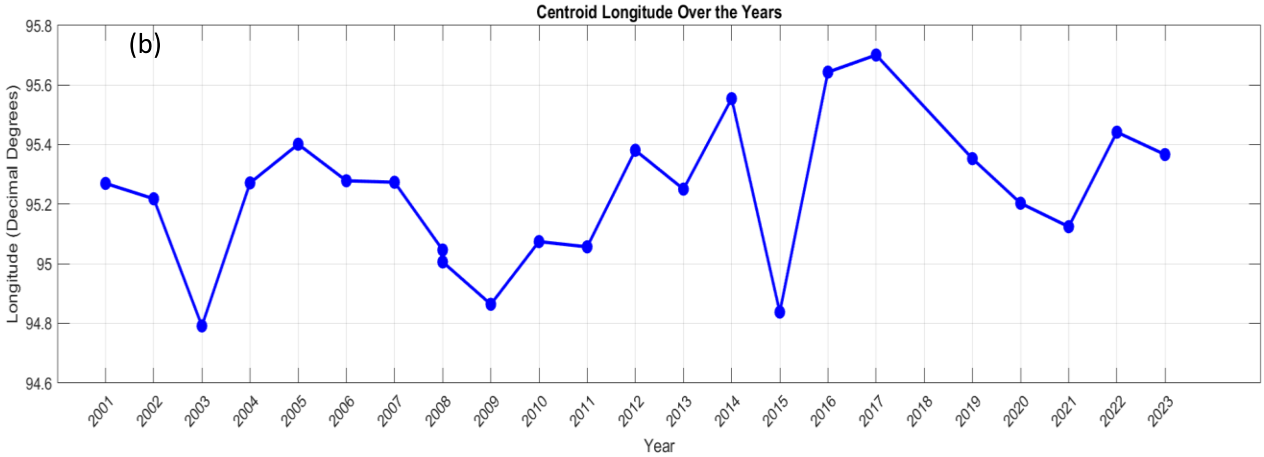


Figure 18: Yearly Centroid Moment of Latitude(a) and Longitude(b) from 2001 to 2023

Comparing intensity overlay maps for 2001,2010 and 2011,2023 highlights shifting patterns. The early period shows more stable drought zones, while the later period exhibits increased intensity and expansion into new regions, reflecting stronger climate impacts. Overall, latitudinal shifts are more pronounced than longitudinal shifts, showing a clear northward movement of drought severity after 2010. This highlights a complex, climate-driven pattern where drought hotspots cannot be assumed static.

The mean severe drought movement map from 2001 to 2023 further supports this trend. From 2006 onward, severe drought expanded across Magway and Sagaing. Between 2010 and 2015, drought influence increased sharply, possibly driven by land-use pressures, higher temperatures, or intensified climate anomalies. Sagaing particularly its northern division from 2014 to 2023. That became the most frequently affected area. This spatial evolution is critical for understanding long-term environmental change and planning drought-resilient development.

The VHI trajectory results emphasize the Dry Zone's high vulnerability to drought. The integration of VCI and TCI within the VHI framework enables comprehensive assessment of vegetation moisture and temperature stress. Findings show that over the last 23 years, the drought epicenter has gradually shifted northeastward with increasing frequency and intensity. As severity rises, drought movement becomes more active, indicating abnormal environmental and climatic changes.

Early detection of declining VHI values allows for timely interventions, including water-saving technologies, drought-resistant crops, and improved agricultural practices. Identifying persistent hotspots enables local governments to design targeted mitigation strategies tailored to high-risk communities.

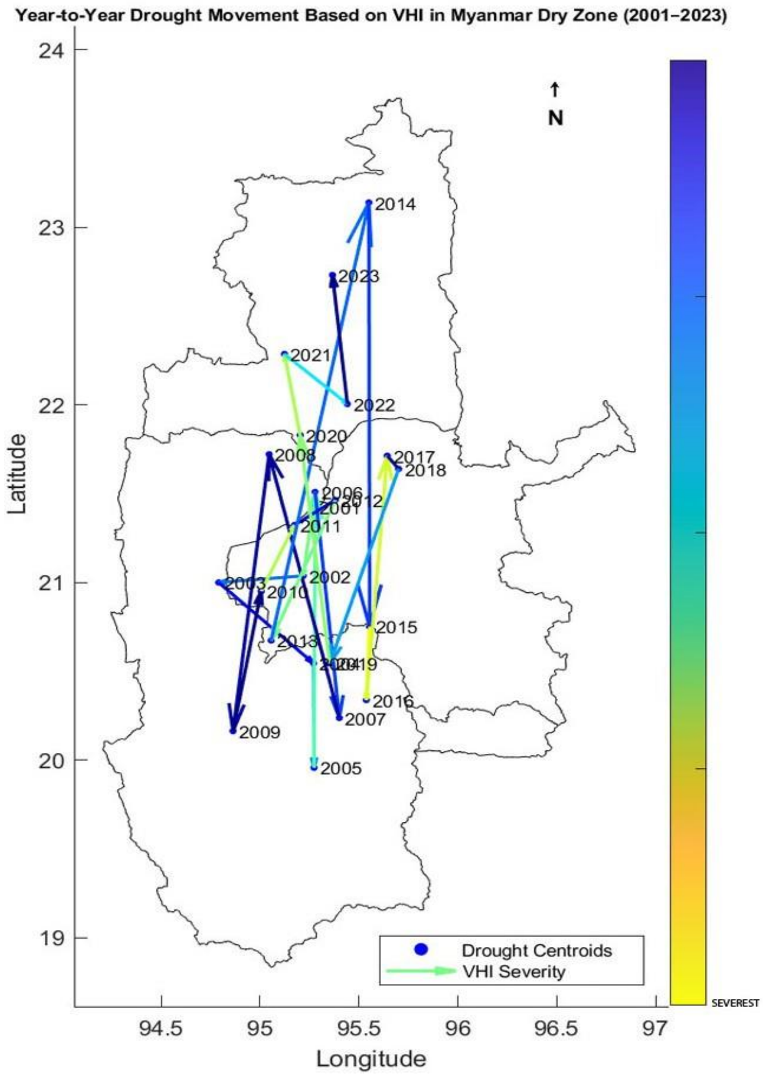


Figure 19: Mean Severe Drought Moment from 2001 to 2023

6. Discussion

6.1 Drought Severity and Identified Drought Years

The analysis combined the Vegetation Health Index (VHI), and Standardized Precipitation Index (SPI), to assess drought severity in Myanmar's Dry Zone. VHI trends derived from MODIS data revealed severe drought events in 2004, 2009, 2015–2016, and 2019, consistent with SPI-derived precipitation deficits. Moderate droughts occurred in 2001, 2006, 2013, 2017, and 2021. The strong agreement between VHI and SPI confirms the robustness of a multi-index framework for drought identification.

6.2 Severe Drought and Vegetation Response

Comparative evaluation of VHI and SPI indicated a significant positive relationship between precipitation variability and vegetation stress. Extreme negative SPI anomalies coincided with substantial VHI reductions, confirming precipitation as a primary drought driver. However, delayed vegetation responses in certain years suggest that soil moisture storage, land use practices, and elevated temperatures modulate drought impacts. Integrating VHI and SPI thus provides a comprehensive foundation for early warning systems and agricultural risk management.

6.3 Spatial and Temporal Trajectories Analysis

Spatial mapping of VHI trajectories highlighted recurrent drought hotspots in Mandalay, Magway, and Sagaing. These areas consistently recorded low VHI values, attributed to limited rainfall, high evapotranspiration, and poor soil moisture retention. Riparian zones along the Ayeyarwady River exhibited higher vegetation health but were not immune to extreme drought conditions.

Temporal patterns revealed lowest VHI values during the dry season (January–April), with partial recovery during the monsoon (May–September). Extreme drought years exhibited delayed recovery, with VHI values remaining below 30 well into the wet season. The overall declining VHI trend over 2001–2023 indicates intensifying drought frequency and severity, consistent with climate change projections for the region.

6.4 Implications for Agriculture and Water Resources

Drought trajectories directly impact rain-fed agriculture in the Dry Zone. Declines in VHI values correlate with yield losses for rice, pulses, and oilseeds. Water scarcity, reduced groundwater recharge, and increased competition for irrigation resources exacerbate vulnerability. Region-specific strategies—such as expansion of irrigation, adoption of drought-tolerant crops, and improved water storage infrastructure—are essential for safeguarding agricultural productivity.

7. Conclusion

This study investigated the spatial and temporal trajectories of agricultural drought in Myanmar's Dry Zone from 2001 to 2023 using remote sensing and GIS techniques. MODIS-derived Vegetation Health Index (VHI), and supported by Standardized Precipitation Index (SPI) from CHIRPS was applied to evaluate drought severity, persistence, and recovery. The results confirmed that drought frequency and intensity have increased over the past two decades, with hotspots consistently identified in Mandalay, Magway, and Sagaing. Temporal patterns revealed severe vegetation stress during dry seasons and incomplete recovery during subsequent monsoons, particularly in years influenced by El Niño events.

The integration of VHI, and SPI proved effective for drought assessment, enabling the detection of onset, peak, and recovery phases. Findings demonstrate the potential of satellite-based approaches for operational drought monitoring, early warning, and agricultural risk management in data-scarce regions such as Myanmar's Dry Zone.

8. Limitations and Future Research

Limitations include cloud cover during the monsoon, data gaps in ground-based measurements, and underrepresentation of socio-economic variables. Future research should integrate high-resolution satellite imagery, machine learning–based prediction models, and socio-economic data (e.g., crop yield statistics, livelihood surveys) to strengthen drought monitoring frameworks. Enhanced integration of remote sensing with ground-based data is essential for improving accuracy and operational utility.

9. Recommendations

Based on the findings, several strategies are recommended for agricultural drought mitigation:

Early Warning Systems – Implement VHI- and SPI-based real-time drought monitoring platforms to support timely interventions.

Improved Irrigation – Promote water-efficient systems such as drip and sprinkler irrigation to reduce dependence on variable rainfall.

Sustainable Water Management – Apply rainwater harvesting, groundwater recharge, and reservoir expansion to secure agricultural water supplies.
Resilient Crop Varieties – Encourage the cultivation of drought-tolerant crops, including pulses and oilseeds, adapted to the Dry Zone.
Crop Insurance – Introduce agricultural insurance schemes to protect farmers against drought-induced yield losses.
Capacity Building – Provide training programs for farmers and extension workers on climate-smart agriculture and water conservation.
These measures collectively strengthen resilience, safeguard agricultural productivity, and reduce the socio-economic impacts of drought.

10. Suggestions for Drought Mitigation in Myanmar's Dry Zone

Addressing drought challenges in Myanmar's Dry Zone requires integrated and targeted strategies. **Drought risk mapping** should incorporate biophysical indicators such as Vegetation Health Index (VHI), Standardized Precipitation Index (SPI), population density, and agricultural dependence to identify vulnerable areas. These maps can guide policymakers in resource allocation and inform regional interventions, including crop diversification, irrigation expansion, and water storage infrastructure development.

An effective drought observation and early warning system is crucial to mitigate drought impacts. Combining satellite remote sensing with ground-based meteorological data allows timely detection and forecasting. A centralized information system can quickly deliver warnings to farmers and policymakers, enabling preventive actions. Coordination among government agencies, meteorological departments, and research institutions, along with a national drought task force, strengthens planning, policy implementation, and capacity building for vulnerable communities.

Sustainable water management is vital to address regional water scarcity. Strategies such as rainwater harvesting, groundwater recharge, small reservoirs, efficient irrigation (drip and sprinkler), groundwater regulation, and community conservation programs enhance long-term water security and reduce reliance on seasonal rainfall.

Economic and agricultural support measures are essential to enhance community resilience. Crop insurance, drought-tolerant crops, agroforestry, soil conservation, and farmer training programs help sustain agricultural productivity and build local capacity for climate adaptation.

By integrating drought risk mapping, early warning systems, institutional coordination, sustainable water management, and community support, Myanmar can establish a comprehensive framework for drought adaptation and mitigation. These measures will contribute to food security, economic stability, and environmental sustainability in the Dry Zone.

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