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Spatiotemporal Analysis of Agricultural Drought Severity and Hotspots in Somaliland

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ABSTRACT

This study uses remote sensing data from 2005 to 2023 to analyze the spatiotemporal pattern of agricultural drought severity and hotspots in Somaliland. The Vegetation Condition Index (VCI), derived from MODIS satellite imagery, was employed to assess drought conditions, while CHIRPS rainfall data provided insights into precipitation patterns. Results revealed significant temporal and spatial variability in drought severity across Somaliland. VCI trends indicated cyclical patterns of vegetation health, with severe stress observed from 2015 to 2018, followed by recovery from 2019 to 2021. A strong positive correlation between VCI and rainfall was observed, with correlation coefficients ranging from 0.5638 in Saaxil to 0.7701 in Togdheer. Drought severity classification identified Sool and Togdheer as the most critically affected regions, with 90% and 85% of their areas under extreme drought conditions, respectively. Saaxil exhibited the lowest percentage of extreme drought at 35%. Temporal analysis of NDVI deviations confirmed prolonged vegetation stress from 2015 to 2018, with notable improvement in 2020 and 2021. The findings underscore Somaliland's vulnerability to recurrent droughts, emphasizing the urgent need for targeted interventions and adaptive management strategies to enhance resilience in this semi-arid region.

1. INTRODUCTION

Drought, a prevalent hydrometeorological hazard, is one of the least understood natural disasters, yet it is second only to floods in its impact on social and economic security [1]. The increase in weather and climate extremes, such as droughts, is inextricably linked to climate change, posing significant threats to ecosystems and human societies [2-7]. The effects of drought often manifest gradually and can persist for years, heightening the environmental risk, exacerbating water scarcity, and leading to conflicts over water resources [8, 9]. Furthermore, drought-induced social instability and economic damage are major concerns [10].

Effective drought monitoring and mitigation are crucial for enhancing resilience and preparedness [11, 12]. The success of these efforts largely depends on timely information on drought onset, progression, and spatial extent [13]. This information is typically obtained through drought monitoring using drought indices derived from station-based observations [14, 15]. However, in data-scarce regions with limited ground-based monitoring networks, such as Somaliland, station-based drought indices are insufficient to accurately characterize drought conditions [16, 17]. In such regions, meteorological drought, resulting from a significant negative deviation from mean precipitation and vegetation due to persistent high atmospheric pressure [18], can be used as an early indicator of more impactful dry events. Monitoring meteorological drought is critical for drought preparedness and mitigation, as it triggers the propagation of agricultural and hydrological droughts [19, 20].

Africa, with its vast drylands and arid and semi-arid climates, is highly susceptible to droughts and land degradation, threatening economic growth, food security, and political stability [21, 22]. The Horn of Africa (HOA), characterized by arid and semi-arid conditions, frequently experiences droughts, leading to food and water shortages that severely compromise food security, especially in rapidly growing and less developed regions [23-26]. Somaliland, in particular, is highly vulnerable to drought, experiencing moderate droughts every 3-4 years and severe droughts every 7-9 years, leading to catastrophic consequences due to factors such as conflict, pastoralism, and population density [27-29]. The country has experienced multiple drought events of varying intensities and durations, causing crop failures, reduced employment opportunities, water and pasture shortages, and livestock deaths [28, 30-33].

Despite the severe implications of droughts, related studies in Somaliland are scarce. Recent research has increasingly utilized remote sensing techniques for agricultural drought assessment in sub-Saharan Africa and the HOA addressing the limitations of traditional ground-based observations. For instance, Bayissa et al. [34] demonstrated the effectiveness of integrating multiple satellite-derived drought indices for comprehensive drought monitoring in Ethiopia. Similarly, Agutu et al. [35] employed MODIS-derived vegetation indices and CHIRPS precipitation data to assess agricultural drought patterns in East Africa, highlighting the potential of these datasets for drought characterization in data-scarce regions.

While these studies have advanced our understanding of drought patterns in the broader region, research specifically focused on Somaliland remains limited. The few existing studies in Somaliland have primarily relied on short periods and limited station data to assess meteorological droughts using the Standardized Precipitation Index (SPI). For example, Abdulkadir [36] used station observation data from 11 locations to estimate droughts in Somaliland. Bile et al. [37] explored teleconnections between climate indices and droughts but did not address the spatial variability of drought impacts. These previous studies failed to show the spatial variability of droughts across the country, largely due to their reliance on point-based data and limited spatial coverage.

The estimations were also unreliable due to low-quality observations and long periods of missing data. Additionally, all the existing studies focus solely on assessing meteorological droughts. Droughts impact Somaliland society most significantly when they affect agriculture. However, no studies have been conducted so far to characterize Somaliland's agricultural droughts. Some studies attempted to assess the impacts of droughts on agriculture in Somaliland using survey data and field observations [26, 28]. They showed that drought recurrence in Somaliland is exacerbated by slow progress in risk management, increased population, and land degradation, requiring increased efforts in drought mitigation to lessen negative impacts.

This study aims to integrate Moderate Resolution Imaging Spectroradiometer (MODIS) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) satellite-based observations to provide comprehensive and accurate agricultural drought monitoring in Somaliland, supporting drought preparedness and mitigation efforts in this vulnerable region. This study's findings will establish a foundation for developing robust drought monitoring and early warning systems and informing strategies to mitigate the adverse impacts of drought and support climate-resilient management of natural resources in this highly vulnerable region.

The structure of this paper is organized as follows: Section 1 provides an introduction; Section 2 presents the study area; Section 3 covers the Methodology; Sections 4 and 5 present the results and discussion, respectively; and Section 6 presents the conclusion and recommendations.

2. STUDY AREA

Somaliland is a self-declared, de facto independent region located in the HOA (Figure 1). It declared its independence from Somalia in 1991, following the collapse of the Somali central government, though it remains unrecognized as a sovereign state by the international community. It is situated in the northwestern part of Somalia, bordered by Djibouti to the northwest, Ethiopia to the south, the Gulf of Aden to the north, and Somalia to the east. Despite its lack of formal international recognition, Somaliland has developed its own government, political institutions, currency, and military. It operates relatively peacefully compared to the rest of Somalia, holding regular elections and maintaining a level of security and stability that contrasts with the ongoing conflict in the south of Somalia. Historically, Somaliland was a British protectorate known as British Somaliland until it gained independence in 1960 and briefly united with Italian Somalia to form the Somali Republic. Its capital is Hargeisa, and the population is primarily ethnic Somali.

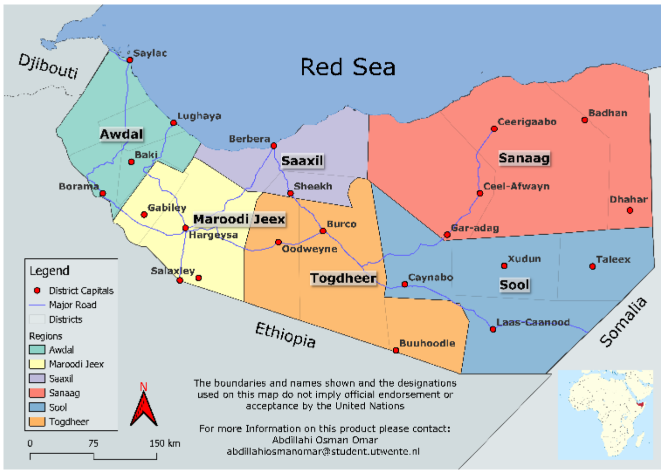

Figure 1. Study area map (Somaliland)

It occupies an area of 137,600 square kilometers [30]. Despite not being recognized internationally or by the federal government of Somalia, Somaliland has maintained peace and a functional political system. It has largely avoided the chaos and violence affecting the rest of Somalia and the HOA [38]. The region is characterized by three major agro-ecological zones: desert (northern coastal areas), arid (central regions), and semi-arid (highlands and plateau areas) [32]. These zones significantly influence land use patterns, with pastoralism dominating in arid and semi-arid areas, and agro-pastoralism and crop cultivation more common in regions with higher rainfall [39].

Somaliland exhibits a diverse climate with annual rainfall varying from 100 mm along the northern coastline to 500 mm in areas like Boorama and Gabley [26]. It experiences a bimodal rainfall pattern with two rainy seasons (Gu and Deyr) and two dry seasons (Xagaa and Jilaal), driven by the movement of the Inter-Tropical Convergence Zone [27, 32]. Temperature variations play a crucial role, with the highlands and plateau areas experiencing mean annual temperatures of 20°C to 24°C, while the coastal regions have higher temperatures of 28°C to 32°C [32]. These differences underscore the diverse climatic conditions within Somaliland.

Pastoralism remains the primary livelihood, engaging approximately 60-70% of the population [30]. The livestock sector contributes significantly to the region's GDP and export earnings [28, 40]. In areas with higher rainfall, crops such as sorghum and maize are cultivated, complementing traditional pastoralism [39]. However, over the past decades, recurrent droughts and substantial land use changes have significantly impacted fodder availability and livestock production [30].

Temperature variability significantly impacts drought occurrences, as climate change leads to more frequent and intense droughts [37]. Projected temperature increases align with global projections [41, 42] and could lower cattle prices by 4% and increase violent conflict by 58% in Somalia, highlighting the interconnectedness of climate change, temperature variability, and drought-induced conflicts [43]. The population largely depends on vegetation productivity (pasture, crops) for their livelihoods [39, 44].

Understanding temperature fluctuations is essential for assessing and mitigating drought impacts in these water-scarce regions, emphasizing the need for effective climate adaptation strategies to enhance resilience and sustainability.

3. MATERIAL AND METHODS

3.1 Gridded rainfall data

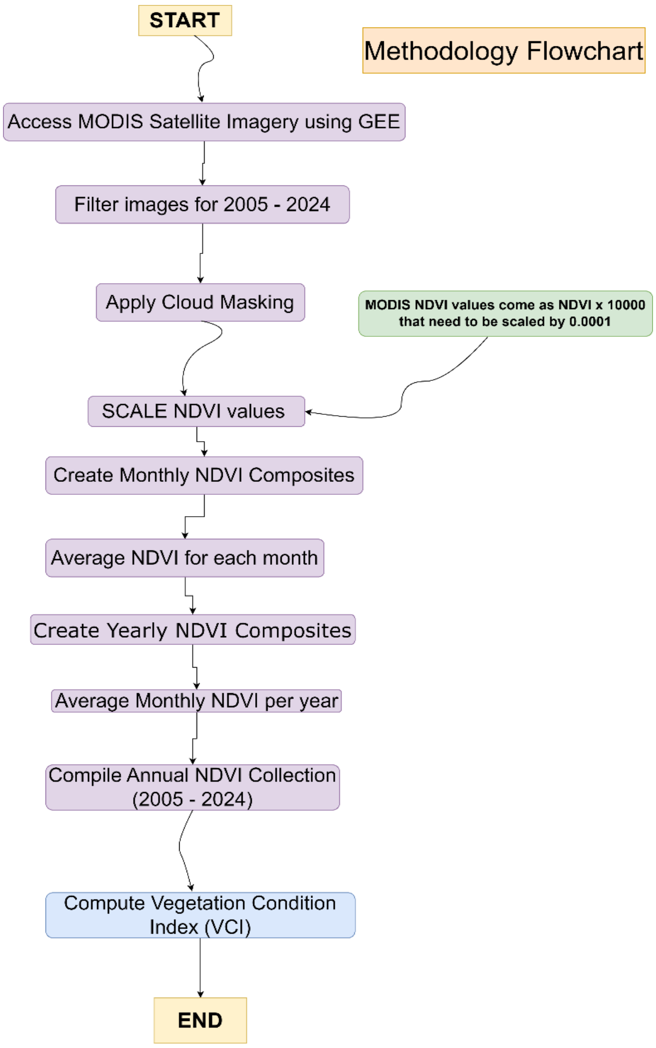

Figure 2. Methodology flowchart

The study used the Climate Hazards Group's Stationary Infrared Precipitation (CHIRPS) dataset for long-term precipitation variability and trends (Figure 2). CHIRPS gridded daily rainfall product combines observed and satellite rainfall and has low systematic bias with an extended period of record. The CHIRPS Pentad product merges high-resolution satellite imagery with in-situ station data, providing an extensive, accurate, and reliable quasi-global rainfall dataset that spans over 30 years. The data combines satellite-based infrared precipitation estimates with ground-based observational data and boasts a high spatial resolution of 0.05 degrees (~5 km) [23]. Gridded rainfall data from CHIRPS were extracted between 1981 and 2024 using Google Earth Engine to estimate long-term trends. It has also been compared with station data from the Department of Meteorology in Somaliland, but due to a big historical gap in the data, our analysis has been mainly focused on CHIRPS. The CHIRPS dataset has been widely used for rainfall monitoring and analysis in various regions of Africa due to its wide spatial coverage and long temporal record [23, 45, 46]. CHIRPS, characterized by high spatial resolution and an extensive period of record, was curated to generate monthly average rainfall, annual rainfall patterns, and seasonal analyses [47]. The curated data enabled a comprehensive examination of rainfall variability and trends over the past four decades, providing valuable insights into long-term climatic changes in the study area [48].

3.2 MODIS data

The study also used MODIS satellite imagery to analyze vegetation health in Somaliland from 2005 to 2023 (Figures 3 and 4). The study utilized Google Earth Engine to process and analyze the data, beginning with filtering the MODIS collection to include only images within the specified date range. Cloud masking was applied to the images to ensure data quality, using a bitwise extraction technique to remove pixels affected by clouds and snow. The selected images were then scaled to obtain accurate normalized difference vegetation index (NDVI) values, as MODIS NDVI values are provided as NDVI x 10000 and need to be scaled by 0.0001. Figure 3 depicts the procedure used to characterize droughts in Somaliland.

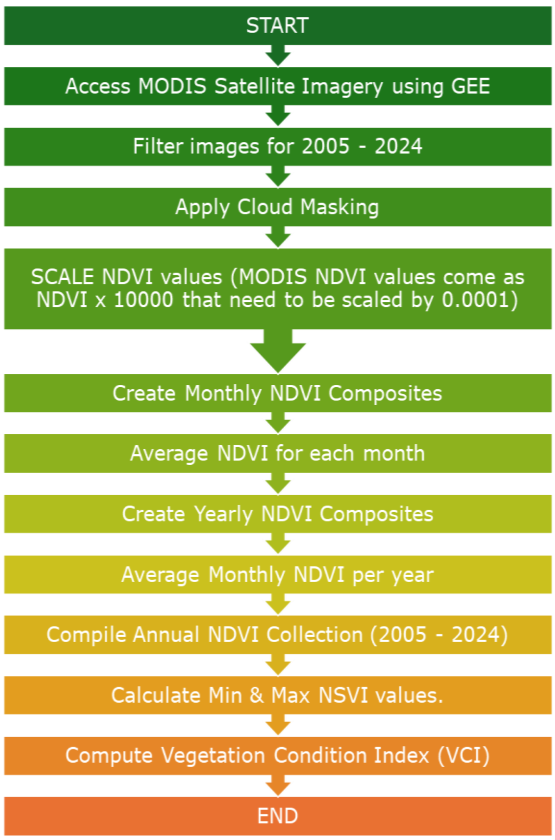

Figure 3. The procedure used to characterize droughts in Somaliland

The scaled NDVI images were aggregated into monthly and yearly composites to create a comprehensive NDVI dataset. Monthly composites were generated by averaging the NDVI values for each month across the entire study period, resulting in a collection that captures seasonal variations in vegetation health. Yearly composites were created by averaging the monthly NDVI values for each year, providing a broader overview of annual vegetation trends. After compiling an image collection of annual mean NDVI images, the overall minimum and maximum NDVI values are calculated across all years to establish a range. These values are then used to compute each year's Vegetation Condition Index (VCI). The VCI is calculated by expressing the annual NDVI relative to the range, scaled to a 0-100 index, indicating vegetation health, where higher values represent better vegetation conditions for each district in Somaliland (Table 1).

$$\text{NDVI} = \frac{Visible - NIR}{Visible + NIR} \quad (1)$$

$$\text{VCI} = \frac{NDVIcurrent - NDVIminimum}{NDVImaximum - NDVIminimum} * 100 \quad (2)$$

Table 1. Vegetation condition classification based on VCI percentages

VCI (%)	Condition
60-100	Good
40-60	Fair
0-40	Poor

4. RESULTS AND DISCUSSION

4.1 Dynamics of VCI in Somaliland

Figure 4 presents a comprehensive analysis of the dynamics of the VCI in Somaliland from 2005 to 2020. The VCI, a widely used indicator of vegetation health and productivity, is categorized into three classes: low vegetation cover (VCI < 40%, depicted in red), moderate vegetation cover (VCI 40-60%, shown in yellow), and high vegetation cover (VCI > 60%, represented in green) as indicated Table 2. The series of maps illustrates the temporal and spatial variations in vegetation cover across the region.

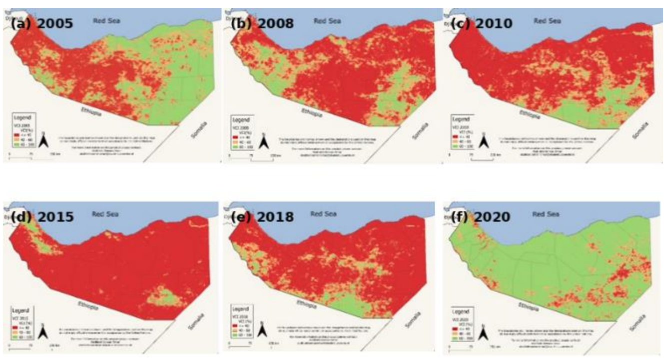

Figure 4. Dynamics of VCI in Somaliland from (a) 2005, (b) 2008, (c) 2010, (d) 2015, (e) 2018, to (f) 2020, showing low (red), moderate (yellow), and high (green) vegetation cover

In 2005, extensive red areas dominated the map, indicating that a substantial portion of Somaliland experienced low vegetation cover and significant vegetation stress. This condition could be attributed to various factors, including drought, overgrazing, or deforestation. By 2008, the red areas had further expanded, signifying a continued decline in vegetation cover and a worsening of vegetation stress conditions across the country. However, in 2010, there was a noticeable increase in green areas, representing a recovery in vegetation cover. This improvement could be linked to favorable climatic conditions, such as increased rainfall, or successful implementation of vegetation restoration efforts. Nevertheless, some red areas persisted, suggesting that the recovery was not uniform across the region. Alarmingly, the situation deteriorated again in 2015, with a dominance of red areas, implying a significant reduction in vegetation cover and a return to severe vegetation stress conditions. This regression could be due to drought, land degradation, or insufficient vegetation management practices.

Table 2. Correlation coefficient between VCI and rainfall

Region	Correlation Coefficient (r)
Awdal	0.6048
Maroodi Jeex	0.7067
Saaxil	0.5638
Sanaag	0.5887
Sool	0.6344
Togdheer	0.7701

By 2018, the map showed a marked increase in green areas, indicating a substantial improvement in vegetation cover compared to 2015. This positive change may reflect effective conservation efforts, improved land management practices, or favorable climatic conditions supporting vegetation growth. Finally, in 2020, the map displayed the highest proportion of green areas throughout the observed period, suggesting a significant recovery in vegetation cover across Somaliland. The reduction in red areas implies that the region experienced favorable conditions for vegetation growth, possibly due to consistent rainfall, successful vegetation restoration projects, and reduced anthropogenic pressure on the land.

The analysis reveals a cyclical pattern of vegetation cover changes in Somaliland, with periods of significant vegetation stress followed by recovery phases. This cyclical nature underscores the vulnerability of the country's ecosystems to climatic variability and human activities, highlighting the importance of sustained efforts in vegetation conservation and land management to promote ecosystem resilience. The findings emphasize the need for proactive measures, such as implementing sustainable land-use practices, promoting reforestation and afforestation initiatives, and developing drought mitigation strategies to ensure Somaliland's vegetation resources' long-term health and productivity.

4.2 Vegetation condition index in Somaliland in 2022

Figure 5 illustrates the spatial distribution of the VCI across Somaliland in 2022, providing a comprehensive assessment of vegetation health and drought conditions. The map employs a color-coded scheme, where red areas (VCI < 40) depict regions experiencing poor vegetation health, likely indicative of severe drought stress. Yellow areas (VCI 40-60) indicate moderate vegetation health, suggesting some stress levels, while green areas (VCI 60-100) represent healthy vegetation conditions.

A striking observation from the map is the predominance of red zones across large swaths of Somaliland, signaling widespread poor vegetation health and potential drought conditions. This pattern is particularly concerning as it suggests that a significant portion of the region's vegetation resources are under severe stress, which could have far-reaching implications for local ecosystems, agricultural activities, and pastoral livelihoods. However, scattered patches of green and yellow zones are also present, indicating localized areas where vegetation health is relatively better. These pockets of healthier vegetation may be attributed to favorable microclimatic conditions, effective land management practices, or variations in soil moisture availability. The inset maps, providing zoomed-in views of key areas like Hargeisa and Sanaag, offer valuable insights into the spatial heterogeneity of vegetation health conditions at a finer scale.

Figure 6 depicts the spatial distribution of the VCI across Somaliland in 2023, providing valuable insights into the state of vegetation health and productivity throughout the region. The map categorizes VCI into three distinct classes: low vegetation cover (VCI < 40%, represented in red), moderate vegetation cover (VCI 40-60%, shown in yellow), and high vegetation cover (VCI 60-100%, illustrated in green).

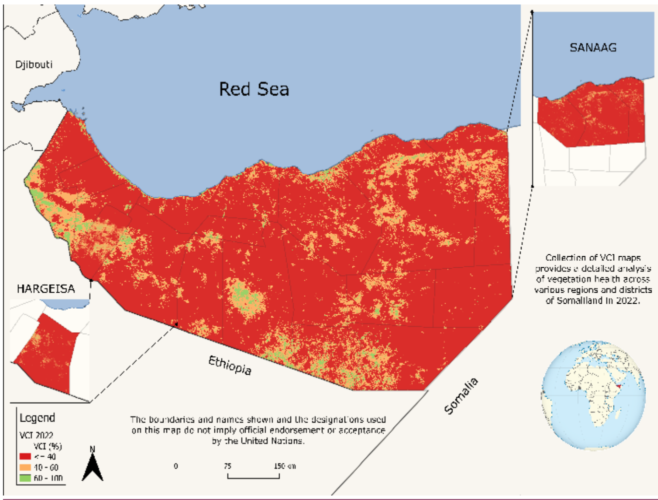

Figure 5. Dynamics of VCI in Hargeisa and Sanaag 2022

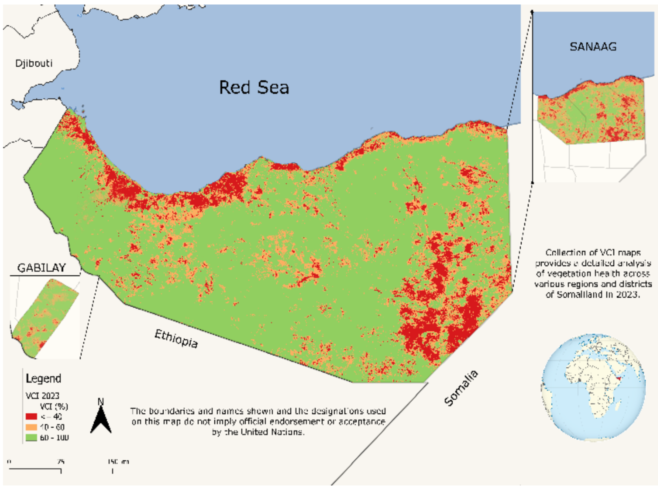

Figure 6. Dynamics of VCI in Gabilay and Sanaag in 2023

A prominent observation from the map is the extensive presence of green areas, indicating that a significant portion of Somaliland experienced high vegetation cover in 2023. This distribution suggests favorable environmental conditions and effective land management practices, contributing to robust vegetation growth across the region. However, the map also reveals notable variations in vegetation cover, highlighting the spatial heterogeneity of environmental and anthropogenic factors influencing vegetation health. Moderate vegetation cover, represented by yellow areas, is scattered throughout the region, suggesting localized areas where vegetation health is moderately stressed. These regions may be experiencing varying degrees of environmental or human-induced pressures, impacting vegetation growth and productivity. Conversely, areas with low vegetation cover, depicted in red, are predominantly concentrated in the eastern and southeastern parts of Somaliland and certain districts highlighted by the inset maps of Gabilay and Sanaag. These red zones indicate significant vegetation stress, likely attributable to drought, overgrazing, deforestation, or other forms of land degradation.

The inset maps provide a closer examination of specific districts, revealing intricate patterns of vegetation cover within these areas. In Gabilay, while some parts exhibit high vegetation cover, substantial red areas indicate severe vegetation stress, suggesting a heterogeneous distribution of environmental conditions or land use practices within the district. Similarly, Sanaag displays a combination of high and low vegetation cover areas, with extensive red regions indicating considerable vegetation stress in certain parts of the district.

The VCI map for Somaliland in 2023 as shown in Figure 6 highlights the spatial variability in vegetation health and productivity across the region. While some areas demonstrate thriving vegetation conditions, others are experiencing varying degrees of stress, underscoring the need for targeted interventions and sustainable land management strategies to address the specific challenges different regions and districts face.

4.3 Yearly variability in NDVI from 2005 to 2024

Figure 7 presents a comprehensive analysis of the yearly variability in the NDVI across the study area from 2005 to 2024. The box plot effectively illustrates the distribution of NDVI values for each year, providing valuable insights into the fluctuations in vegetation health and productivity over the two-decade period.

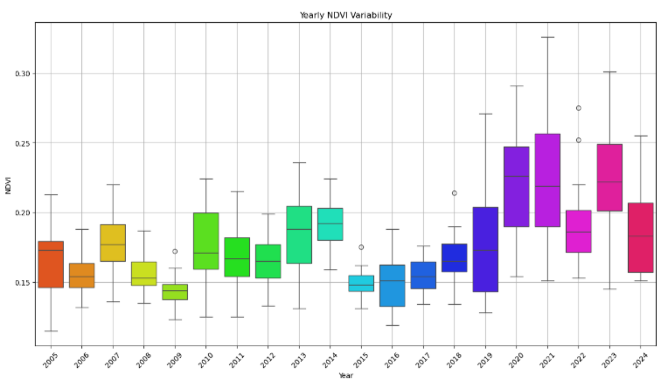

Figure 7. Time series of mean NDVI

The figure reveals distinct phases characterized by varying NDVI values and associated vegetation conditions. From 2005 to 2008, the NDVI values were relatively low, with limited variability and median values around 0.15, indicating consistent vegetation stress during this period. This could be attributed to adverse environmental factors like drought or land degradation. However, a noticeable improvement in vegetation health was observed between 2009 and 2014, as evidenced by the increase in median NDVI values and a more considerable range of variability. This period likely experienced more favorable conditions for vegetation growth, potentially due to improved precipitation patterns or the implementation of effective conservation measures.

Alarmingly, the subsequent years from 2015 to 2018 witnessed a decline in NDVI values, with medians dropping below 0.15 in some years and reduced variability. This phase represents a period of renewed vegetation stress, which could be attributed to adverse climatic conditions, such as prolonged drought or increased anthropogenic pressures on the landscape.

A remarkable recovery in vegetation health is evident starting from 2019, with a marked increase in NDVI values and substantial variability observed in the following years. The years 2020 and 2021 are particularly notable, exhibiting exceptionally high NDVI values and substantial variability, indicating significant vegetation growth and recovery across the study area. This positive trend suggests the presence of favorable environmental conditions and the implementation of effective vegetation management practices during these years.

It is worth noting that the presence of outliers in recent years implies the existence of localized areas with either exceptionally high or low vegetation health compared to the overall trend as shown for time series in Figure 7. These outliers may indicate microhabitats or specific regions that exhibit unique environmental characteristics or management practices, highlighting the importance of targeted interventions and site-specific strategies. The yearly NDVI variability analysis reveals a cyclical pattern of vegetation health, with periods of stress followed by recovery phases. This underscores the need for continuous monitoring and adaptive management strategies to mitigate the impacts of adverse conditions and promote sustainable vegetation growth and ecosystem resilience across the study area.

4.4 Correlation between VCI and rainfall across different regions

Table 2 presents the correlation coefficients (r) between the VCI and rainfall for six regions in the study area. The VCI is a widely used indicator of vegetation health, while rainfall is a critical environmental factor influencing vegetation growth and productivity. The correlation coefficient measures the strength and direction of the linear relationship between these two variables.

In the Awdal region, the correlation coefficient between VCI and rainfall is 0.6048, indicating a moderately strong positive correlation. This suggests that higher rainfall amounts are associated with increased vegetation health and productivity in this region. Maroodi Jeex exhibits a stronger positive correlation, with a correlation coefficient of 0.7067. This value implies that the relationship between VCI and rainfall is more pronounced in this region, where increased rainfall is closely tied to improved vegetation conditions.

The correlation coefficients for Saaxil (0.5638) and Sanaag (0.5887) are moderate, indicating a positive but relatively weaker association between VCI and rainfall in these regions than in others. The soil region has a correlation coefficient of 0.6344, suggesting a moderately strong positive relationship between VCI and rainfall, similar to Awdal. Notably, the Togdheer region exhibits the strongest positive correlation, with a correlation coefficient of 0.7701. This value indicates a robust linear relationship between VCI and rainfall, implying that rainfall patterns highly influence vegetation health in Togdheer.

The positive correlation coefficients across all regions highlight the importance of rainfall as a key driver of vegetation health and productivity. However, the varying strengths of the correlations suggest that other environmental factors, such as temperature, soil characteristics, and land management practices, may also play significant roles in influencing vegetation conditions in different regions.

4.5 Relationship between annual rainfall and VCI across different regions

Figure 8 presents the relationship between annual rainfall and the VCI across six regions in the study area: Awdal, Maroodi Jeex, Saaxil, Sanaag, Sool, and Togdheer. The scatter plots effectively illustrate the correlation between these two variables, with fitted regression lines and confidence intervals providing insights into the strength and reliability of the relationships.

In the Awdal region, the scatter plot reveals a positive correlation between annual rainfall and VCI, indicating that higher rainfall amounts are associated with improved vegetation health and productivity. However, the relatively wide confidence interval suggests moderate variability in the data, implying that factors other than rainfall may also influence vegetation conditions in this region. A stronger positive relationship is observed in Maroodi Jeex, where the regression line shows a clear upward trend, and the narrow confidence interval indicates a consistent and reliable association between rainfall and VCI. This suggests that vegetation health in Maroodi Jeex is highly dependent on rainfall patterns. The scatter plots for Saaxil and Sanaag also exhibit positive correlations between annual rainfall and VCI, with higher rainfall generally leading to better vegetation health. However, the broader confidence intervals in these regions suggest greater variability in the data, indicating that factors beyond rainfall may play a more significant role in shaping vegetation conditions.

In the Sool region, the relationship between annual rainfall and VCI is moderately strong and positive, with the regression line showing an upward trend and a relatively narrow confidence interval, implying a consistent association between the two variables. Notably, the Togdheer region displays the strongest positive correlation between annual rainfall and VCI. The steep regression line and narrow confidence interval indicate a robust and reliable relationship, where increased rainfall significantly impacts vegetation health. The tightly clustered data points further reinforce the strong dependence of vegetation conditions on rainfall patterns in this region. The positive correlations observed across all regions highlight the critical role of rainfall as a key driver of vegetation health and productivity. However, the varying strengths of the relationships and the differences in confidence intervals suggest that other environmental factors and regional characteristics, such as temperature, soil properties, and land management practices, may moderate the influence of rainfall.

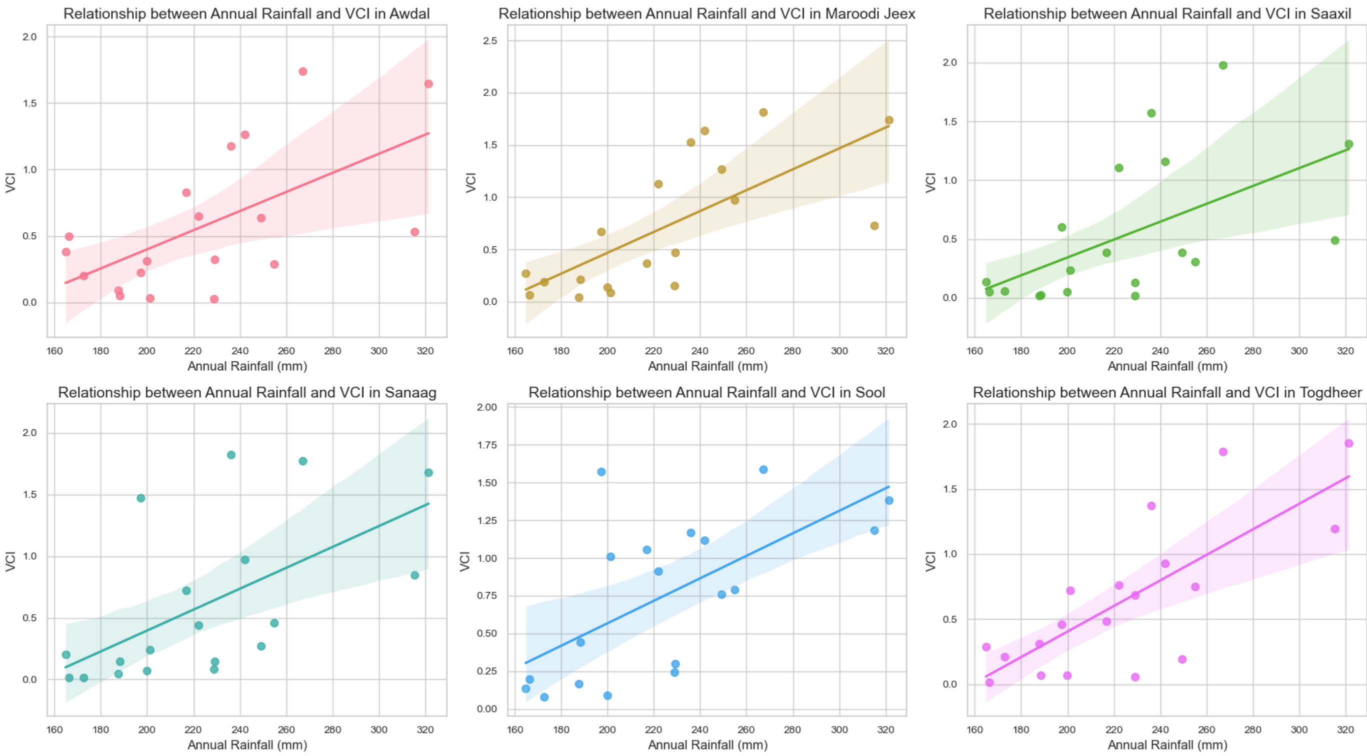

Figure 8. Scatter plots with regression lines showing the relationship between annual rainfall and VCI across the six regions of Somaliland

4.6 Temporal and spatial variability in VCI deviations

Figure 9 provides a comprehensive analysis of the deviations in the VCI across different regions and years, offering insights into the temporal and spatial variations in vegetation health. The figure comprises two bar plots: the left plot illustrates the seasonal VCI deviations for six regions in Somaliland (Awdal, Maroodi Jeex, Saaxil, Sanaag, Sool, and Togdheer), while the right plot presents the annual VCI deviations from 2005 to 2023 for the entire study area.

The seasonal VCI deviation plot reveals distinct patterns among the regions. Regions like Maroodi Jeex and Sool exhibit consistent positive deviations, particularly in recent years, indicating prolonged periods of above-average vegetation health. In contrast, regions such as Awdal and Togdheer show a mix of positive and negative deviations, suggesting fluctuations in vegetation conditions over time. Saaxil and Sanaag display relatively fewer deviations, implying relatively stable vegetation health, with some improvements in recent years. The annual VCI deviation plot provides a broader perspective on the temporal variations in vegetation health across the entire study area. The early years, from 2005 to 2014, show a mix of positive and negative deviations, with a general trend towards negative deviations around 2010-2014, indicating a phase of below-average vegetation health. This period was followed by predominantly negative deviations from 2015 to 2018, suggesting a prolonged phase of below-average vegetation conditions across the region.

Nevertheless, a remarkable shift is observed from 2019 onwards, with a noticeable trend towards positive deviations. The years 2020 and 2021 stand out with significant positive deviations, indicating a substantial improvement in vegetation health and above-average conditions across the study area during this period. This positive trend could be attributed to favorable environmental conditions, effective vegetation management strategies, or a combination of both. The observed patterns in VCI deviations highlight the dynamic nature of vegetation health and productivity, influenced by various environmental and anthropogenic factors. The divergent regional patterns underscore the importance of localized analyses and targeted interventions to address region-specific challenges and promote sustainable vegetation management practices.

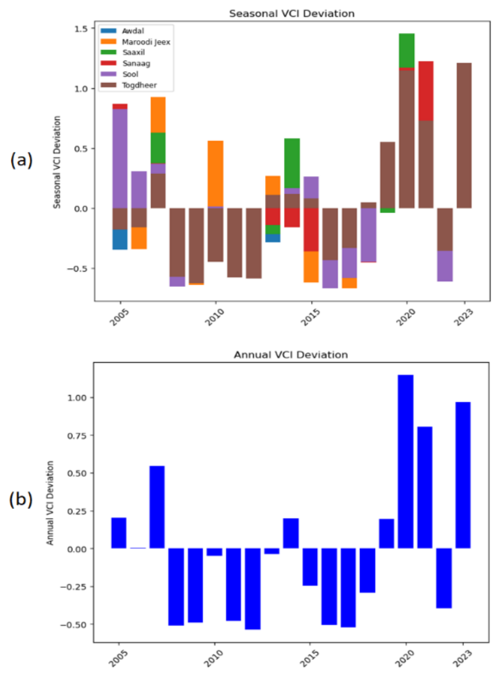

Figure 9. Annual and seasonal VCI deviation across Somaliland

4.7 Drought hotspots

Figure 10 depicts the spatial distribution of drought conditions and hotspot areas across Somaliland based on analysis of the VCI derived from MODIS satellite imagery. The map employs a color-coded system to represent varying degrees of drought severity, with deep red areas indicating extreme drought conditions and green areas signifying regions free from drought. The most striking features of the map are the dark circular overlays highlighting drought hotspots. These hotspots, centered on key districts such as Borama, Gebiley, Hargeisa, Burco, Ceerigaabo, Xudun, Las Caanood, and Buuhoodle, represent areas experiencing the most severe drought impacts. Within these hot spots, vegetation health is critically low, suggesting acute water stress and high vulnerability to agricultural failure and livestock loss.

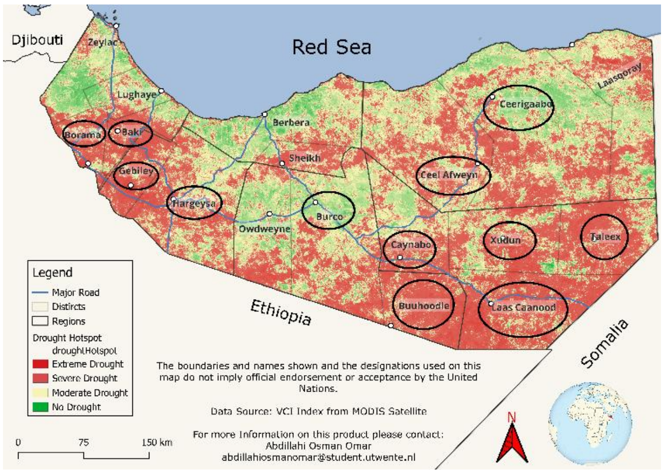

Figure 10. Spatial distribution of drought conditions and hotspot areas

Table 3 illustrates the distribution of drought severity across six regions. Notably, Sool exhibits the highest percentage of areas (90%) under extreme drought conditions, followed closely by Togdheer (85%) and Maroodi Jeex (75%). Conversely, Saaxil has the lowest extreme drought percentage, with 35% coverage, and the highest proportion of areas (40%) experiencing no drought. Regions such as Awdal and Sanaag display moderate extreme drought levels, with 65% and 55% drought coverage areas, respectively. The result underscores significant regional disparities in drought severity, highlighting areas that may require prioritized intervention.

Table 3. Drought hotspot classification

Region	Areal Coverage (%)			
	Extreme Drought	Severe Drought	Moderate Drought	No Drought
Awdal	65	15	5	15
Maroodi Jeex	75	10	5	10
Saaxil	35	15	10	40
Sanaag	55	15	10	20
Togdheer	85	5	5	5
Sool	90	5	3	2

4.8 Regional classification of drought hotspots

Figure 11 presents a comprehensive classification of drought hotspots across six regions in Somaliland: Awdal, Maroodi Jeex, Saaxil, Sanaag, Togdheer, and Sool. This bar chart offers a comparative analysis of the percentage distribution of areas experiencing extreme, severe, and moderate drought conditions and areas with no drought. The data reveals stark regional disparities in drought severity. Sool and Togdheer emerge as the most critically affected regions, with 90% and 85% of their areas under extreme drought conditions, respectively. Maroodi Jeex follows closely, with 75% of its area experiencing extreme drought. In contrast, Saaxil stands out with the lowest percentage of extreme drought at 35% and, notably, the highest proportion of drought-free areas at 40%.

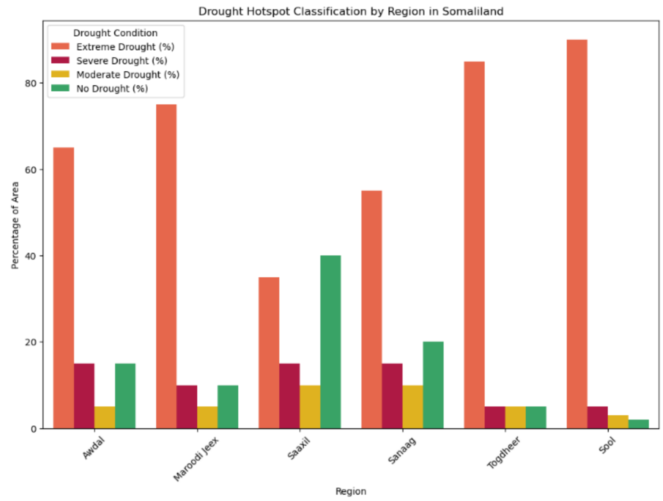

Figure 11. Drought hotspot classification by region

Interestingly, severe drought conditions remain consistently low across all regions, ranging between 5% and 15%. Similarly, moderate drought conditions are limited, with Saaxil showing the highest occurrence at 10%. This pattern suggests that most areas fall into extreme or no drought categories, with fewer intermediate conditions.

5. DISCUSSION

The study's findings highlight the critical role of remote sensing techniques and satellite-derived indices in monitoring and assessing droughts in Somaliland. By integrating MODIS and CHIRPS data with vegetation indices such as NDVI and VCI, the study provides a comprehensive spatial and temporal analysis of drought patterns across the region.

Recent studies have demonstrated the efficacy of using NDVI and VCI to assess agricultural droughts across various regions. For instance, a study in the Indian subcontinent utilized NDVI and VCI derived from MODIS data to map drought-affected areas and found a strong correlation between these indices and ground-based drought indicators, proving their reliability in identifying drought intensity and duration [49]. In Sub-Saharan Africa, researchers integrated NDVI with rainfall data to assess the impact of drought on crop productivity, revealing a consistent decline in NDVI values corresponding to periods of low precipitation [50]. Similarly, in the Mediterranean region, VCI was used to monitor vegetation stress, showing that VCI values effectively captured the spatial extent and severity of drought conditions [51].

The cyclical nature of vegetation health observed through

NDVI and VCI dynamics is a striking reflection of Somaliland's vulnerability to recurrent droughts, corroborating previous studies that have documented the susceptibility of the region to such events [23, 52]. The prevalence of low VCI values, particularly in eastern regions, means severe drought conditions and significant vegetation degradation, posing serious threats to agricultural production, pastoral livelihoods, and food security [53]. The strong positive correlation between VCI and precipitation in the semi-arid regions of Somaliland highlights the essential role of precipitation as a key factor in vegetation health and productivity. This aligns with previous studies that established the strong link between precipitation regimes and vegetation dynamics in arid and semi-arid environments [54, 55]. variations between regions suggest that other environmental factors, such as temperature, soil characteristics, and land management practices, may also exert an influence on vegetation conditions.

The drought severity analysis reveals that Sool and Togdheer are the most critically affected regions, with 90% and 85% of their areas classified as experiencing extreme drought, respectively, underscoring the severe water stress and vulnerability in these regions. Maroodi Jeex also faces significant drought challenges, with 75% of its area under extreme drought, indicating a high risk of agricultural and livestock losses similar to the conditions in Sool and Togdheer. In contrast, Saaxil demonstrates a more varied drought profile, with 35% of its area under extreme drought but also containing the highest proportion of drought-free areas at 40%, highlighting a region where interventions could be tailored to its diverse conditions. This spatial analysis of drought severity aligns with findings from recent studies on regional climate patterns in the HOA [56, 57] and underscores the importance of satellite-based vegetation monitoring for effective drought management in arid regions [58, 59].

The analysis of the temporal variability of the NDVI and VCI deviations reveals periods of prolonged stress in the vegetation, as demonstrated by the negative deviations observed between 2015 and 2018, potentially attributable to climatic conditions or pressures. Unfavorable anthropogenic impacts on the landscape. In contrast, the notable recovery in vegetation health from 2019, with significant positive variances in 2020 and 2021, suggests the presence of favorable environmental conditions and potentially effective vegetation management practices during these years [60]. These results highlight the need for continued monitoring and adaptive management strategies to mitigate the impacts of adverse conditions and promote sustainable vegetation growth and ecosystem resilience throughout the study area, as highlighted in previous studies [61, 62]. Furthermore, historical analysis of vegetation and precipitation patterns in Somaliland is consistent with projections of more frequent and intense droughts due to climate change [26, 63, 64]. This underscores the urgent imperative that climate adaptation strategies and natural resource management be climate resilient to build resilience and sustainability in this highly vulnerable region.

The increasing frequency and intensity of agricultural droughts in Somaliland have severe implications for the region's food security, economic stability, and social well-being [57]. As drought conditions worsen, crop yields are expected to decline significantly, leading to food shortages and potential famine conditions, particularly in rural areas heavily dependent on rain-fed agriculture [29]. This situation may trigger large-scale migration from rural to urban areas, putting additional pressure on already strained urban resources and infrastructure. Furthermore, the livestock sector, a crucial component of Somaliland's economy, will likely suffer substantial losses due to reduced pasture and water availability, potentially devastating pastoral livelihoods and exacerbating poverty [39]. These factors could increase social tensions, conflicts over scarce resources, and political instability, threatening the region's fragile peace and development progress [43]. A multi-faceted approach is necessary to adapt to the increasing threat of agricultural droughts. Firstly, improving irrigation management by adopting water-efficient technologies and practices, such as drip irrigation and water harvesting, is crucial for enhancing agricultural resilience [65]. Secondly, raising awareness among farmers and pastoralists about climate change impacts and adaptive strategies is essential, which can be achieved through community-based education programs and extension services. Thirdly, promoting alternative agriculture practices, such as drought-resistant crop varieties and diversified farming systems, can help mitigate the impacts of drought on food production [11].

The findings of this study have significant policy implications for drought risk reduction and resilience-building in Somaliland. While the suggested adaptation strategies of improving irrigation management, promoting alternative agriculture practices, and raising awareness are important, there is a need for more concrete and context-specific interventions. For instance, the successful implementation of water-efficient technologies in Jordan's arid regions, where drip irrigation increased water use efficiency by up to 60% [12], could serve as a model for Somaliland. Similarly, Ethiopia's Productive Safety Net Programme (PSNP), which combines cash transfers with community-based watershed management projects, has shown promising results in building resilience to droughts [66]. These examples highlight the importance of integrating social protection measures with ecosystem-based adaptation approaches. Furthermore, strengthening institutional capacity for drought management, as demonstrated by Kenya's National Drought Management Authority (NDMA), which coordinates early warning systems and response mechanisms across sectors, could significantly enhance Somaliland's drought preparedness [67]. These evidence-based interventions, adapted to the local context, could form the basis for a comprehensive drought resilience strategy in Somaliland, addressing the multifaceted challenges revealed by our spatial and temporal analysis of agricultural droughts.

6. CONCLUSIONS

The study investigates the spatial and temporal aspects of agricultural drought in Somaliland from 2005 to 2023 using VCI and assessing the relationship between NDVI and rainfall in semi-arid regions in Somaliland. Kagon's drought classification threshold was employed to identify agricultural drought events. Drought Monitoring Recommended Practice (UN-SPIDER, 2014) recommends that a VCI value of less than 40% can be considered a drought.

Despite the high vulnerability to droughts in Somaliland due to poverty and large dependency on rain-fed agriculture, the impact and intensity of extreme droughts vary with time. Furthermore, there is a strong correlation between rainfall and VCI in the region, which shows that water scarcity is caused by aridity and recurrent droughts. Though the indicators applied are similar to most of the analysis, this paper has assessed the drought in the region and/or district level (our case), and it can help to quantify agricultural impact assessment in the future. Still, the main challenge is collecting and analyzing relevant reference data on drought outcomes. The study has also noted that the capacity of Somaliland people to face these recurrent droughts, compounded by shortcomings in the government's capacity to install long-term and actionable drought mitigation measures, has been weakened as the population resilience mechanism has reduced. Therefore, the study recommends the following:

1. The Ministry of Agriculture (MOA), the Ministry of Environment and Climate Change (MOECC) of Somaliland, and the Somaliland National Disaster Preparedness and Food Reserve Authority (NADFOR), the institutions responsible for providing meteorological services and Early Warning Systems (EWS), should ensure that farmers and pastoralists receive weather forecast information that is simple, understandable (in Somali), timely, localized, and reliable, enabling early intervention by the government and its partners. It is recommended that the National Meteorological Agency (NMA) be established to document and disseminate climate information promptly to stakeholders, helping them prepare for imminent droughts and other climate patterns.

2. The government of Somaliland is strongly advised to increase investment in community infrastructure and social services, focusing on improving rural communities to enhance the population's resilience. This includes training farmers and pastoralists in techniques such as soil and water conservation and water harvesting, which are crucial for drought disaster mitigation.

3. More importantly, there is an urgent and dire need to progress on various fronts of drought mitigation, such as early warning and forecasting, long-term planning, and capacity building to adapt to climate change in the HOA.

4. Future research could focus on advancing remote sensing satellite observation data integration with ground-based data from drought recall surveys and longitudinal studies in the affected societies. The combined approach will enhance the accuracy of drought damage assessments, improving the effectiveness of prevention and mitigation strategies.

5. Government agencies, relief organizations, and related stakeholders should prioritize targeted drought relief efforts in the identified hotspot districts. These regions, highlighted by the study, exhibit significant drought severity and require urgent intervention. Focused and rapid response initiatives in these critical areas can substantially mitigate the severe impacts of drought on the affected populations, reducing potential damage and enhancing resilience.

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