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ORIGINAL ARTICLE

Three decades of vegetation change in Jabel Marra: climate drivers and post-conflict vegetation dynamics

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Abstract

Understanding long-term vegetation dynamics in semi-arid and conflict-affected environments is important for sustainable land management and climate adaptation. This study investigated vegetation change and climate variability in the Jabel Marra region of Central Darfur, Sudan, during 1994–2024 using Landsat-derived Normalized Difference Vegetation Index (NDVI), CHIRPS precipitation, MERRA-2 temperature, and the Standardized Precipitation Evapotranspiration Index (SPEI). Long-term vegetation trends were assessed using the Mann-Kendall trend test and Sen's slope estimator, whereas climate–vegetation relationships were evaluated using correlation analysis. The annual NDVI showed a significant positive trend (Mann–Kendall $Z=4.78$, $p<0.001$), with a Sen's slope of 0.00143 NDVI units year^{-1}, indicating a gradual increase in vegetation greenness. Spatial trend analysis showed that positive vegetation trends were concentrated primarily in mid-to-high elevation vegetated areas. Annual precipitation exhibited substantial interannual variability ($R^2 = 0.06$), whereas temperature increased consistently ($R^2 = 0.51$). NDVI was positively correlated with precipitation ($r=0.48$) and negatively correlated with temperature ($r=-0.57$). The SPEI identified recurrent drought episodes before 2018, followed by predominantly wetter conditions thereafter. The findings indicate that vegetation dynamics in Jabel Marra were primarily associated with climatic variability, particularly precipitation and drought conditions, while conflict-related processes were considered contextual because they were not directly analyzed. This study demonstrates the value of integrating long-term satellite observations and climate datasets to monitor vegetation changes in data-scarce dryland environments.

Keywords NDVI · Climate variability · Jabel Marra · Darfur · Remote sensing · Vegetation dynamics

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Introduction

Vegetation cover is a fundamental component of terrestrial ecosystems that influences carbon cycling, hydrological processes, energy exchange, and biodiversity conservation (Bonan 2008; Gerten et al. 2004; Piao et al. 2020). Changes in vegetation dynamics are closely linked to climatic factors, particularly precipitation, temperature, and drought conditions, which directly affect plant productivity, distribution, and resilience (Fensholt et al. 2013; Igbawua et al. 2016). Vegetation influences climate through feedback mechanisms involving evapotranspiration, surface albedo, and carbon sequestration (Forkel et al. 2015; Zhang et al. 2022). Therefore, understanding long-term vegetation responses to climate variability is essential for sustainable land management and ecosystem conservation, particularly in environmentally fragile regions.

Dryland ecosystems are particularly sensitive to climatic fluctuations because their vegetation growth is largely controlled by water availability (Nicholson et al. 2013a, 2013b). In many semi-arid regions, changes in rainfall patterns and increasing temperatures have altered vegetation productivity, drought frequency, and ecosystem resilience (Butiseacă et al. 2022; Haider et al. 2025). Drought is one of the most significant environmental stressors affecting vegetation in drylands, often resulting in reduced biomass production, land degradation, and a decline in ecosystem services. To assess drought conditions, indices such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are widely used in the literature. Because SPEI incorporates both precipitation and potential evapotranspiration, it is particularly suitable for evaluating drought dynamics under changing climatic conditions (Asadi Zarch, Sivakumar, and Sharma 2015; Vicente-Serrano et al. 2010a, 2010b).

Advances in remote sensing have greatly improved the ability to monitor vegetation dynamics over large spatial and temporal scales. Satellite-derived vegetation indices, including the Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), and Enhanced Vegetation Index (EVI), are extensively used to assess vegetation productivity and ecosystem responses to environmental changes (Huete et al. 2002; Tucker 1979). Among these indices, NDVI remains one of the most widely applied because of its simplicity, long historical record, and strong relationship with vegetation greenness and biomass (Fensholt et al. 2013; Pettorelli 2013). Recent studies in Asia, Europe, Africa, and other dryland regions have demonstrated the effectiveness of remote sensing in detecting long-term vegetation trends, evaluating climate impacts, and supporting sustainable environmental management (Haq et al. 2022; Niu, Khan, and Iftikhar 2025; Sushmitha et al. 2025). The availability of cloud-based geospatial platforms, such as the Google Earth Engine (GEE), has further enhanced the capacity to process long-term satellite archives and climate datasets efficiently (Gorelick et al. 2017). These tools are particularly valuable in regions where field-based environmental monitoring is limited by accessibility, security concerns, or a lack of long-term observational data.

The Jabel Marra region of Central Darfur represents one of the most ecologically distinctive landscapes in Sudan. Unlike the surrounding lowland Sahelian environments, Jabel Marra is characterized by mountainous terrain, cooler temperatures, higher rainfall, and greater vegetation diversity. These environmental gradients create unique ecological conditions that may influence vegetation responses to climate variability in ways that differ from those in other parts of Darfur. Simultaneously, the region has experienced prolonged socio-political instability and recurrent population displacement over the past two decades, which may have indirectly influenced land-use patterns and vegetation dynamics. However, despite its ecological and environmental significance, long-term assessments of vegetation change and climate variability in Jabel Marra remain limited. Previous studies in Darfur have primarily focused on land-use change, desertification, and vegetation dynamics in the western and southern parts of the region (Abaker et al. 2018; Ahmed et al. 2025; Ahmed and Czimber 2025; Ahmed, Rotich, and Czimber 2025; Atiem et al. 2022). A comprehensive assessment of long-term vegetation trends and their climatic drivers in Jabel Marra is still lacking. Addressing this knowledge gap is particularly important given the region's ecological importance and vulnerability to climate variability.

Therefore, this study investigated vegetation dynamics and climate variability in Jabel Marra between 1994 and 2024 using Landsat-derived NDVI, precipitation, temperature, and drought indicators. Specifically, this study aims to (1) assess long-term trends in vegetation cover using Landsat time-series data, (2) evaluate the relationships between vegetation dynamics and climatic variables, including precipitation, temperature, and drought conditions, and (3) identify spatial patterns of vegetation change across the study area. These findings contribute to a better understanding of climate-vegetation interactions in semi-arid mountainous environments and provide information relevant to environmental monitoring, land management, and climate adaptation planning in Darfur and similar dryland regions.

Methodology

Description of the study area

This study was conducted in the Jabel Marra region of Central Darfur, western Sudan, which covers approximately 914,991.55 ha. The study area is located between 12°48′–13°24′ N and 24°00′–24°48′ E (Fig. 1a–d). Jabel Marra forms part of the Sahelian ecotone, a transitional zone between the arid Sahara Desert to the north and the savanna woodlands of sub-humid Africa to the south (Ahmed 1983; Williams 2021).

The region experiences a semi-arid climate, with mean annual temperatures ranging from 23 °C to 26 °C and annual rainfall between 520 mm and 672 mm (FAO 2015). Rainfall is highly seasonal and concentrated between June and September, defining a short but ecologically important growing season in the region. Surface runoff is conveyed through a network of seasonal streams (wadis), including Wadi Elku, Wadi Ibra, and Wadi Azum, which form part

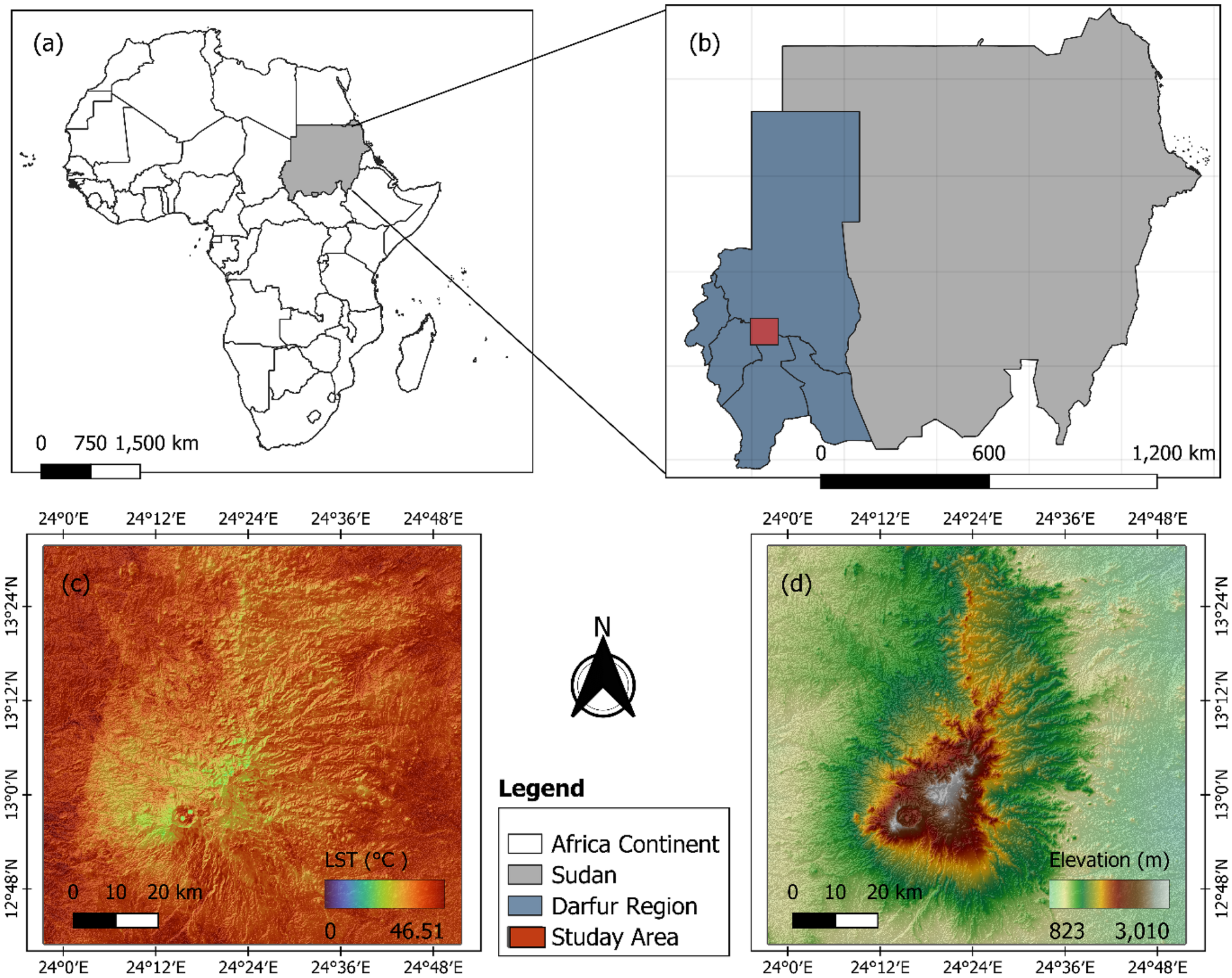


Fig. 1 Study area; (**a**) depicts the location of Sudan in Africa (**b**) location of Darfur region in Western Sudan, (**c**) land surface temperature, and (**d**) the elevation

of the larger Lake Chad drainage system (Hamid Ali 2014; Knight 2023).

A distinguishing characteristic of Jabel Marra is its mountainous topography. The region consists of a volcanic massif rising to elevations exceeding 3,000 m above sea level, creating pronounced altitudinal gradients in temperature, precipitation, and vegetation distribution (Hegazy et al. 2018a, b). These topographic controls generate localized microclimatic conditions that support relatively denser and more diverse vegetation than the surrounding lowland plains. The landscape comprises rugged highlands, sandy clay plains, seasonal watercourses, and valley systems that create considerable environmental heterogeneity (Hegazy, Hosni, et al. 2018a, 2018b).

The vegetation is dominated by dryland savanna species, including *Acacia senegal*, *Albizia amara*, *Anogeissus leiocarpus*, *Balanites aegyptiaca*, and *Eucalyptus spp*. Several of these species possess strong regenerative capacity through coppicing and basal resprouting, enabling persistence under recurrent disturbances such as grazing, fuelwood collection, and fire (Ahmed et al. 2025).

In addition to its ecological significance, Jabel Marra has experienced prolonged socio-political instability since the early 2000 s, resulting in population displacement and changes in land-use practices (Abdul-Jalil and Unruh 2013; UNEP 2024). Although conflict-related processes were not directly assessed in this study, they provided an important contextual background for interpreting long-term environmental changes. The combination of strong climatic gradients, complex topography, and limited long-term environmental monitoring makes Jabel Marra a particularly valuable region for investigating vegetation dynamics and climate variability in semi-arid environments.

Climate data source, processing and analysis

This study integrated long-term climate and vegetation datasets to investigate vegetation dynamics in the Jabel Marra region between 1994 and 2024. The analysis combined precipitation, temperature, and drought indicators derived from the SPEI and satellite-derived vegetation indices to evaluate climate-vegetation relationships over the study period. Elevation data were incorporated to examine the influence of topographic variability on vegetation distribution.

Temperature and precipitation

Long-term precipitation and temperature datasets were obtained from satellite-based and reanalysis products owing to the limited availability and discontinuity of ground-based meteorological observations in the Darfur region.

Precipitation data were acquired from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (https://www.chc.ucsb.edu/data/chirps3), which integrates satellite imagery within situ station data, offering daily precipitation estimates at a ~ 0.05° spatial resolution (~ 5.6 km) (Funk et al. 2015). CHIRPS has been widely applied and validated in semi-arid and sub-Saharan African environments due to its high spatial resolution and long-term temporal coverage (Lameck et al. 2025; Ngoma et al. 2021).

Temperature data were obtained from the Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) dataset using the NASA POWER platform (https://power.larc.nasa.gov/data-access-viewer/). MERRA-2 provides globally consistent meteorological variables and has been extensively used for climate monitoring and environmental studies in data-scarce regions (Gelaro et al. 2017). Daily precipitation and temperature records were extracted and spatially subsetted to the study area using GEE. Subsequently, the data were aggregated to monthly and annual time scales for climate trend analysis and drought assessment. Statistical analyses were conducted using R software (version 4.3.2), including descriptive statistics, correlation analysis, and trend evaluation. The study period (1994–2024) was selected to coincide with the availability of consistent Landsat observations and climate datasets, allowing for the assessment of vegetation and climate dynamics over a continuous 30-year period. Benchmark years (1994, 2004, 2014, and 2024) were subsequently used for detailed spatial comparisons because they represent approximately decadal intervals and provide adequate image quality and temporal consistency for long-term vegetation analysis (Table 1).

Table 1 Summary of landsat datasets used for annual NDVI compositing

Benchmark Year	Sensor	Resolution (m)	Cloud Cover	Platform
1994	Landsat-5 TM	30	< 5%	GEE
2004	Landsat-7 ETM+	30	< 5%	GEE
2014	Landsat-8 OLI	30	< 5%	GEE
2024	Landsat-8 OLI	30	< 5%	GEE

Drought assessment

To evaluate drought dynamics, we applied the SPEI, which captures the balance between precipitation and potential evapotranspiration (PET) over various timescales. Unlike traditional indices, the SPEI accounts for temperature variability, making it more suitable for assessing drought impacts under climate change in arid and semi-arid regions (Asadi Zarch et al. 2015; S. M. Vicente-Serrano, Beguería, and López-Moreno 2010a, 2010b). Potential evapotranspiration (PET) was calculated using the FAO Penman–Monteith method, which is widely recommended for estimating reference evapotranspiration under diverse climatic conditions (Allen 2000). Precipitation data were obtained from the CHIRPS dataset, while temperature data were derived from the MERRA-2 reanalysis dataset. These datasets were first processed in GEE for spatial filtering and extraction of the study area.

The SPEI values were calculated using the "SPEI" package in R software (version 4.3.2) following the methodological framework proposed by (Vicente-Serrano et al. 2010a, 2010b). The log-logistic probability distribution was used to standardize the climatic water balance series, which represents the difference between precipitation and PET. SPEI was computed at three temporal scales to capture drought dynamics affecting different environmental processes: SPEI-3, representing short-term drought conditions that primarily affect soil moisture and agricultural productivity, SPEI-6, representing intermediate-term drought conditions, and SPEI-12, representing long-term hydrological drought patterns that influence groundwater and reservoir storage. The calibration period used for standardizing the SPEI series was 1994–2024, corresponding to the full temporal coverage of the climate datasets used in this study. Positive SPEI values indicate wetter-than-normal conditions, while negative values represent drought conditions of varying intensity.

All drought analyses and visualizations were performed using R statistical software, and spatial pre-processing and data extraction were conducted in GEE.

NDVI and vegetation analysis

Vegetation dynamics were assessed using the Normalized Difference Vegetation Index (NDVI) derived from

Landsat imagery acquired from Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI sensors. Four benchmark years (1994, 2004, 2014, and 2024) were selected for a detailed spatial analysis. These years were chosen based on (i) the availability of high-quality imagery with minimal cloud contamination, (ii) approximately decadal intervals that facilitate long-term comparisons while minimizing short-term climatic variability, and (iii) their representation of different socio-environmental phases within the study period.

To reduce seasonal and phenological effects, annual NDVI composites were generated using all cloud-free observations available within each benchmark year in the GEE. Annual compositing provides a more representative measure of vegetation productivity than single-date imagery and reduces the influence of transient atmospheric conditions and short-term disturbances (Boschetti et al. 2013; Detsch et al. 2016).

Image pre-processing includes radiometric and atmospheric correction, cloud and cloud-shadow masking using the CFMask algorithm (Foga et al. 2017), mosaicking, and clipping to the study area boundary. To ensure consistency among Landsat sensors, surface reflectance products from the Landsat Collection 2 archive were used, which provide standardized radiometric processing across sensors and improve the comparability of NDVI estimates through time. NDVI was calculated using Eq. 1.

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

where:

NIR is the Near-Infrared reflectance,

Red is the reflectance of the red band.

NDVI values range from −1 to +1, with higher values indicating greater vegetation greenness and photosynthetic activity (Mohiuddin and Mund 2024; Tiwari and Kanchan 2024)Elevation data were derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at a 30-m spatial resolution to assess the topographic influences on vegetation distribution (Eisenlohr et al. 2013; Jarvis 2008). All spatial analyses were performed using GEE and QGIS 3.34, whereas statistical analyses were conducted using R software (version 4.3.2).

NDVI trend analysis (mann-kendall and sen's slope)

Long-term vegetation trends were assessed using annual mean NDVI values derived from Landsat observations from 1994 to 2024. The non-parametric Mann-Kendall (MK) trend test was applied to detect monotonic trends in vegetation dynamics over time. The MK test is widely used in environmental studies because it does not require assumptions regarding data normality and is relatively robust to outliers.

The magnitude of the NDVI change was quantified using Sen's slope estimator, which calculates the median rate of change over the study period. Positive Sen's slope values indicated increasing vegetation greenness, whereas negative values indicated declining vegetation conditions (Zhang et al. 2025). In addition to the temporal analysis, a pixel-based Mann-Kendall trend analysis was conducted to map the spatial distribution of significant vegetation trends across the study area. The resulting trend classes were categorized as a significant increase, a significant decrease, or no significant trend.

Correlation analysis

Pearson's correlation analysis was used to evaluate the relationships between annual NDVI, precipitation, temperature, and elevation (Hou et al. 2015; Pei et al. 2019). Prior to the analysis, the variables were standardized and assessed for normality to ensure the suitability of the parametric statistical methods. Elevation was analyzed as a spatial variable derived from SRTM DEM. Because elevation is a static topographic characteristic, it was used to examine the influence of terrain on vegetation distribution rather than temporal changes in vegetation.

Although correlation analysis provides valuable insights into climate-vegetation relationships, the results should not be interpreted as evidence of causality. Vegetation dynamics in dryland ecosystems are influenced by multiple interacting factors, including antecedent rainfall conditions, soil properties, land use history, and ecological disturbances. Furthermore, vegetation responses to climatic variability may exhibit lag effects that are not captured by contemporaneous correlation analysis. Therefore, future studies should explore lagged correlations and time-series modeling approaches to better understand the delayed vegetation responses to climate variability.

Results

Climate variability

Climate records from 1994 to 2024 showed interannual variability in precipitation and temperature in the Jabel Marra region. Precipitation fluctuated throughout the study period, whereas the mean annual temperature followed an overall increasing trend.

Precipitation trends

Annual precipitation varied between years during the study period (Fig. 2a). A positive linear trend was observed (R^2 = 0.06). The highest annual precipitation occurred in 2018 (>800 mm), followed by 2019 and 2003 respectively. Lower annual precipitation totals (<500 mm) were recorded in 1995, 2002, 2008, and 2016.

Temperature trends

The mean annual temperature increased during the study period (Fig. 2b), with an R^2 value of 0.51. Mean annual temperature increased from approximately 23.0 °C in 1994 to 24.5 °C in 2024. Lower annual temperatures were recorded in 2000 (23.3 °C), 2011 (23.6 °C), and 2022 (23.8 °C), whereas the highest temperatures occurred in 2023 (24.7 °C) and 2009 (24.5 °C). The annual minimum and maximum temperatures also increased over the study period.

Drought analysis

Temporal variations in drought conditions derived from SPEI-3, SPEI-6, and SPEI-12 are presented in (Fig. 3). Negative SPEI values correspond to dry conditions, whereas positive values correspond to wetter-than-normal conditions.

Dry periods occurred during 1996–1999, 2001–2003, 2009–2011, and 2015–2017. Wetter periods occurred during 1994–1996, 1999–2001, 2004–2008, 2011–2015, and 2018–2024. The SPEI-3 and SPEI-6 series showed greater temporal variability than the SPEI-12 series. Positive SPEI values were more frequent after 2018 across all three timescales.

Vegetation cover changes

NDVI trend analysis

The Mann–Kendall analysis of the annual mean NDVI for 1994–2024 showed a significant positive trend (Table 2; Fig. 4). The Mann-Kendall test produced a Z statistic of 4.78 ($p < 0.001$), and Sen's slope estimated an annual increase of 0.00143 NDVI units.

Spatially, the pixel-based Mann–Kendall analysis identified heterogeneous NDVI trends across the study area (Fig. 5). Significant positive trends occurred mainly in the central and northeastern parts of the study area, whereas localized significant negative trends occurred in the southwestern region. However, large areas showed no statistically significant trends.

Spatial and temporal patterns of NDVI

The spatial distributions of the annual NDVI for the benchmark years 1994, 2004, 2014, and 2024 are presented in (Fig. 6). Higher NDVI values occurred primarily in mid-to-high elevation vegetated areas, whereas lower NDVI values occurred in lowland areas and sparsely vegetated mountain summits.

The monthly NDVI time series (Fig. 7) showed a recurring seasonal pattern during all benchmark years. NDVI values

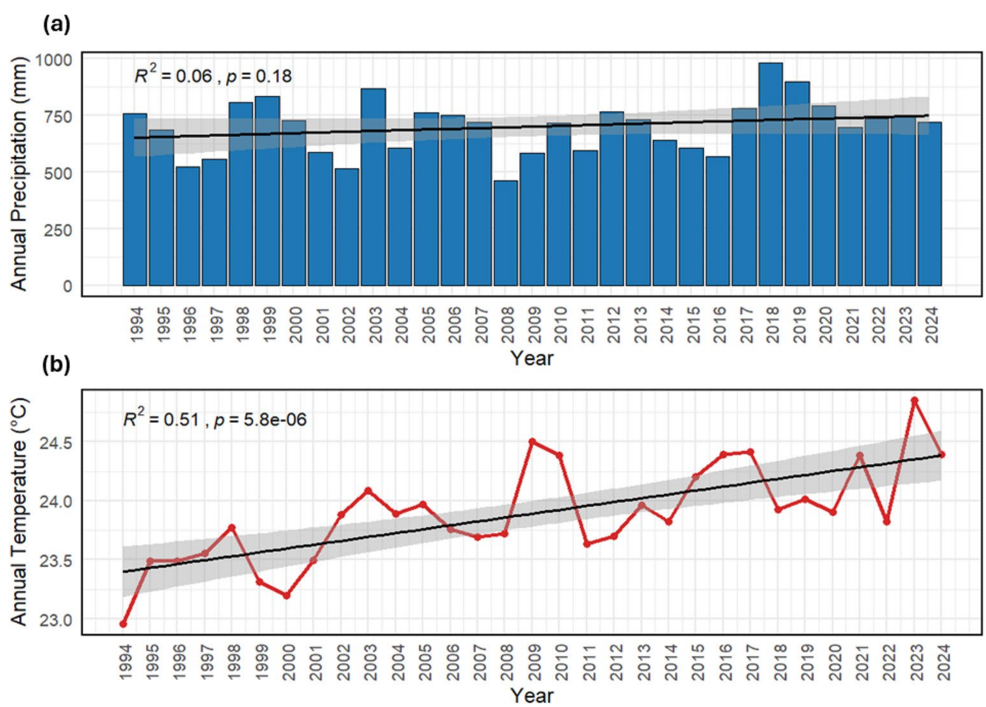


Fig. 2 (**a**) Annual precipitation trends, and (**b**) annual mean temperature in Jabel Marra from 1994 to 2024

Fig. 3 Temporal variation of SPEI-3, SPEI-6, and SPEI-12 between 1994 and 2024

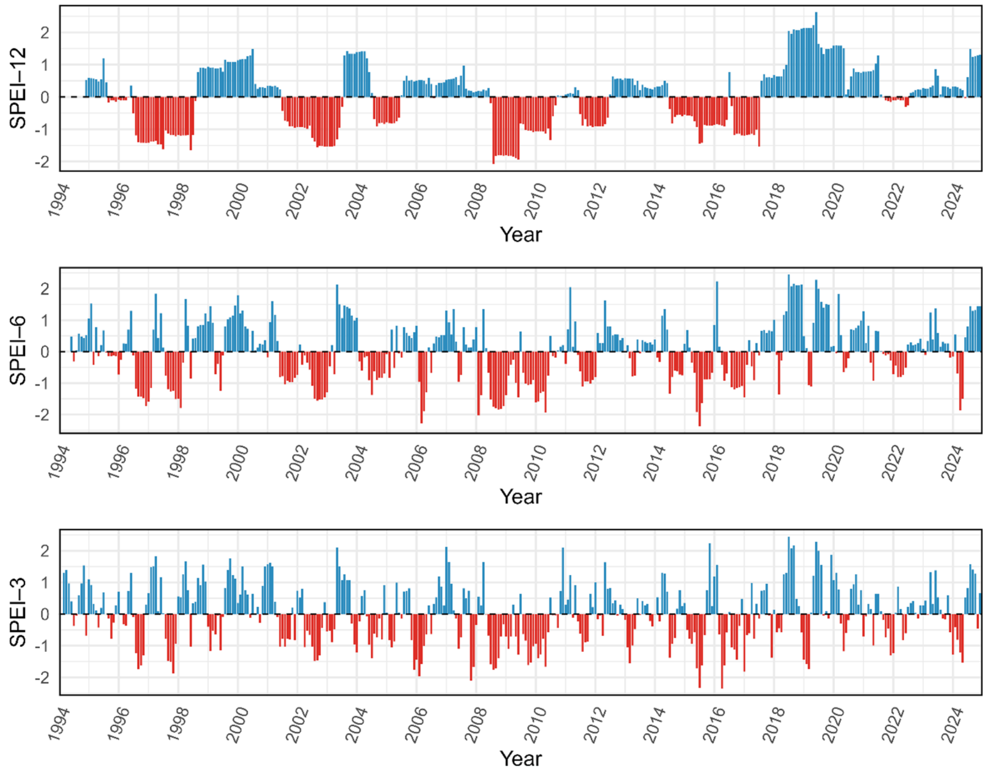


Table 2 Mann-Kendall trend analysis results for annual NDVI (1990 to 2024)

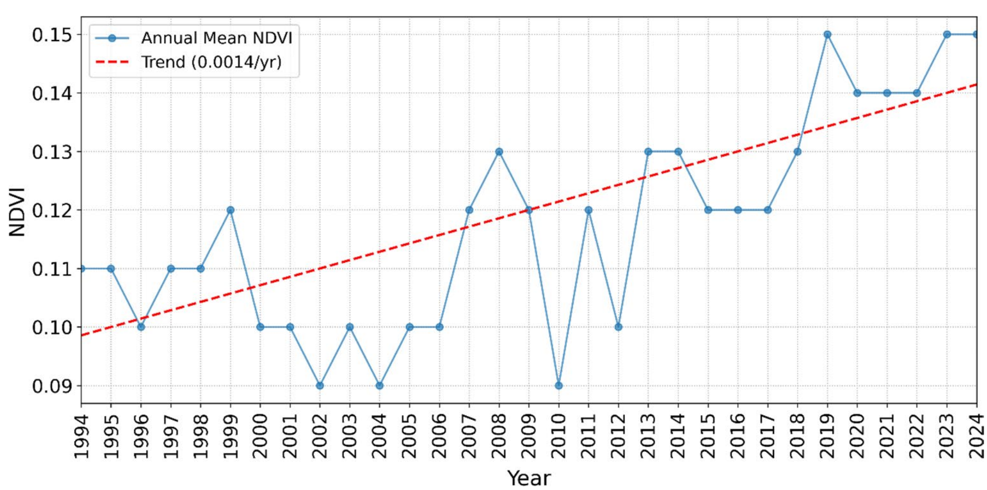
Metric	Value
Trend	Increasing
Mann-Kendall Z	4.7832
p-value	1.73×10^{-6}
Sen's Slope (Annual Rate)	0.00143
Significance (alpha = 0.05)	Significant
S-statistic	332

increased between June and October and decreased between November and May. Peak monthly NDVI values were higher in 2014 and 2024 than in 1994 and 2004 respectively.

Correlation analysis

The Pearson correlation coefficients between NDVI and the environmental variables are presented in (Fig. 8). NDVI was positively correlated with precipitation ($r = 0.48$, $p < 0.001$), negatively correlated with temperature ($r = -0.57$, $p < 0.001$), and positively correlated with elevation ($r = 0.39$, $p < 0.001$). Precipitation was positively correlated with elevation ($r = 0.87$, $p < 0.001$), whereas temperature was negatively correlated with precipitation ($r = -0.56$, $p < 0.001$) and with elevation ($r = -0.66$, $p < 0.001$).

Fig. 4 The Mann-Kendall trend analysis results of annual NDVI from 1990 to 2024



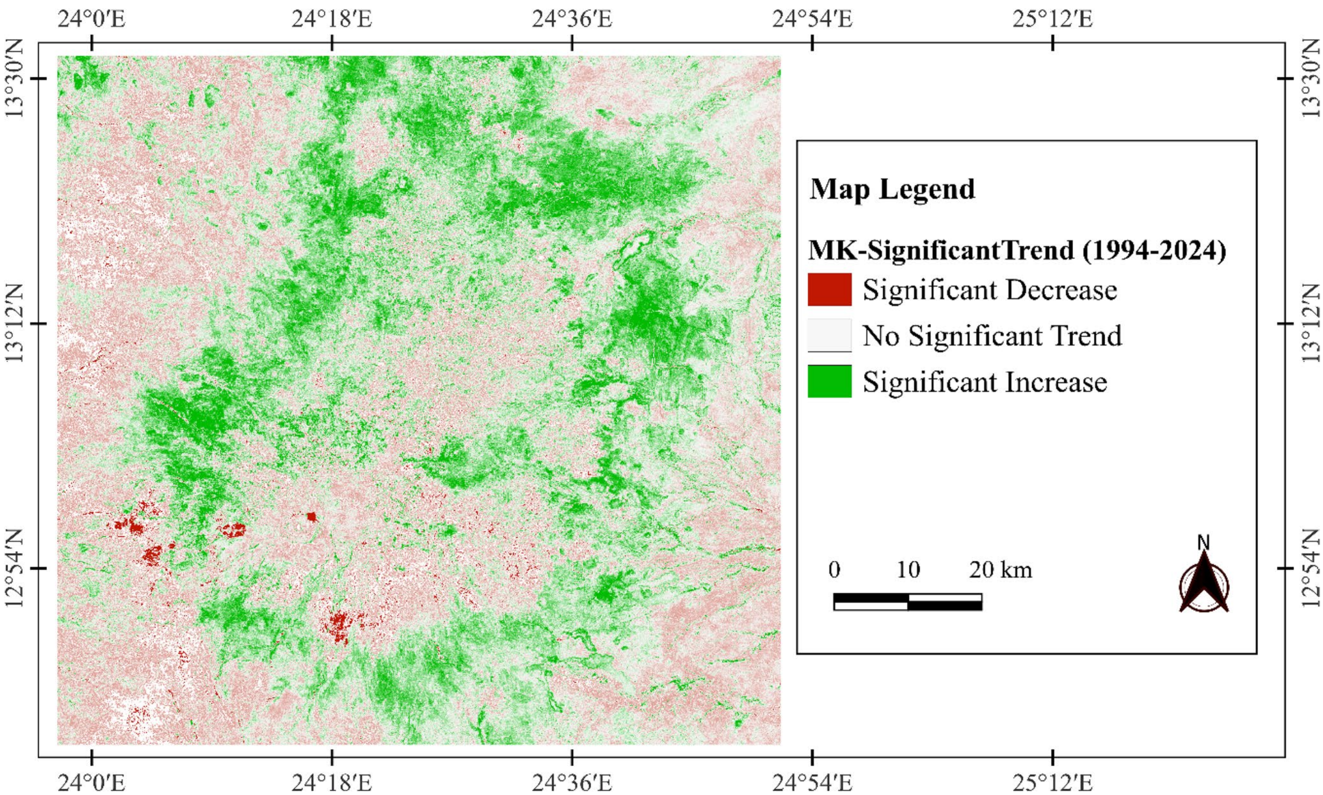


Fig. 5 Spatial distribution of significant Mann-Kendall NDVI trends (1994–2024)

Discussion

Climate drivers of vegetation change

The present study identified significant associations between long-term vegetation dynamics and climatic variability in the Jabel Marra region from 1994 to 2024. Annual NDVI was moderately positively correlated with precipitation and moderately negatively correlated with temperature, while precipitation exhibited considerable interannual variability and only a weak long-term trend. These findings indicate that vegetation dynamics are associated with multiple climatic factors rather than changes in annual precipitation alone.

The positive relationship between NDVI and precipitation is consistent with previous studies demonstrating that water availability is the principal constraint on vegetation productivity in semi-arid ecosystems (Fensholt et al. 2012; Mbow et al. 2015). Although annual precipitation fluctuated substantially throughout the study period, wetter conditions became more frequent after 2018, coinciding with higher NDVI values and reduced drought occurrence. Similar findings were reported by (Ahmed & Czimber, 2026a, 2026b), who showed that vegetation dynamics in the Jabel Marra Highlands were more strongly associated with drought variability and multi-temporal moisture conditions than with annual rainfall totals alone.

In contrast, NDVI exhibited a moderate negative correlation with temperature, suggesting that increasing temperature is unlikely to be the primary driver of the observed increase in vegetation greenness. Higher temperatures may increase atmospheric evaporative demand and reduce soil moisture availability, thereby limiting vegetation growth despite periods of adequate rainfall. Similar climate–vegetation relationships have been reported across the Sahel and the Horn of Africa, where increasing temperatures partially offset the beneficial effects of precipitation on vegetation productivity (Measho et al. 2021; Nicholson et al. 2013a, 2013b).

Topography also influenced the vegetation distribution across the study area. Elevation was strongly positively correlated with precipitation and negatively correlated with temperature, indicating distinct climatic gradients within the Jabel Marra region. Consequently, mid-to-high elevation vegetated areas generally supported higher NDVI values than the surrounding lowlands, reflecting cooler and wetter environmental conditions. Comparable topographically controlled vegetation patterns have been documented in other mountainous environments in East Africa and the Sahel (Dagar, Sileshi, and Akinnifesi 2020; Gebrehiwot et al. 2013; Tefera et al. 2024).

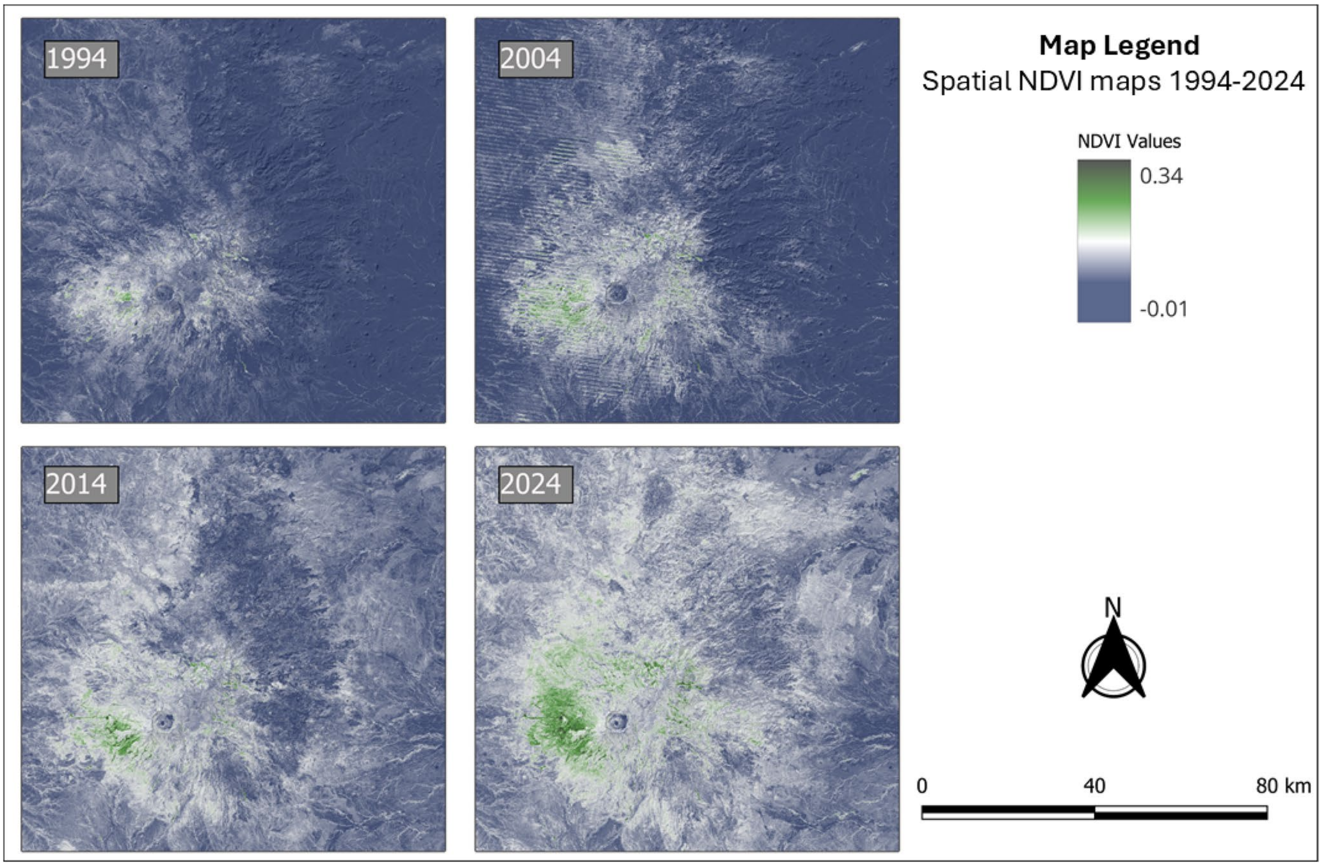
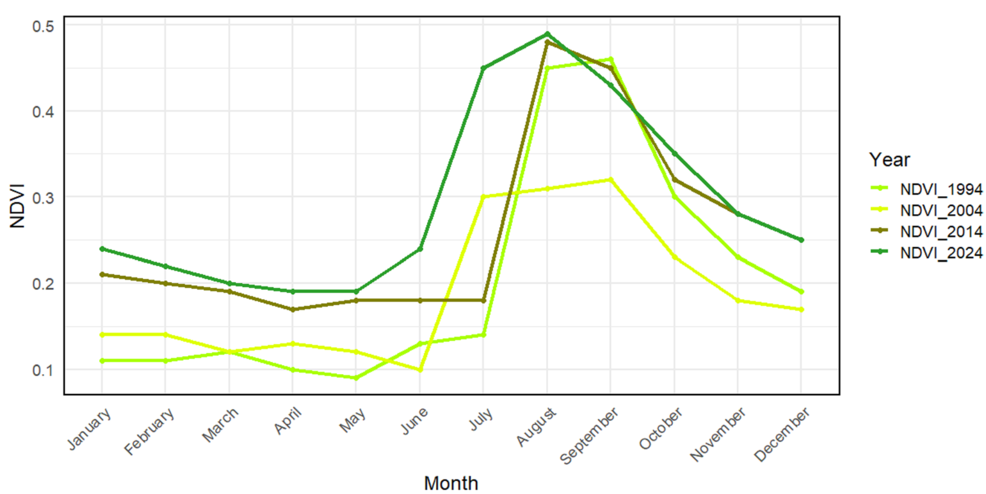


Fig. 6 Spatial distribution of NDVI maps shows vegetation vigor across the study years

Fig. 7 Monthly mean NDVI (January–December) time series for 1994, 2004, 2014, and 2024



The observed climate–vegetation relationships should be interpreted as statistical associations, rather than direct causal relationships. Vegetation responses to climatic variability are often delayed because soil moisture storage, vegetation type, and land management influence plant growth timing. Previous studies have reported lagged vegetation responses to rainfall ranging from several months to one year in dryland ecosystems (De Keersmaecker et al. 2015; Zhao et al. 2020). Because the present analysis was based on contemporaneous annual correlations, these delayed responses were not evaluated.

Finally, NDVI should be interpreted as an indicator of vegetation greenness and photosynthetic activity rather than as a direct measure of ecosystem conditions. Although NDVI is widely used to monitor vegetation productivity, it cannot distinguish among vegetation types, species

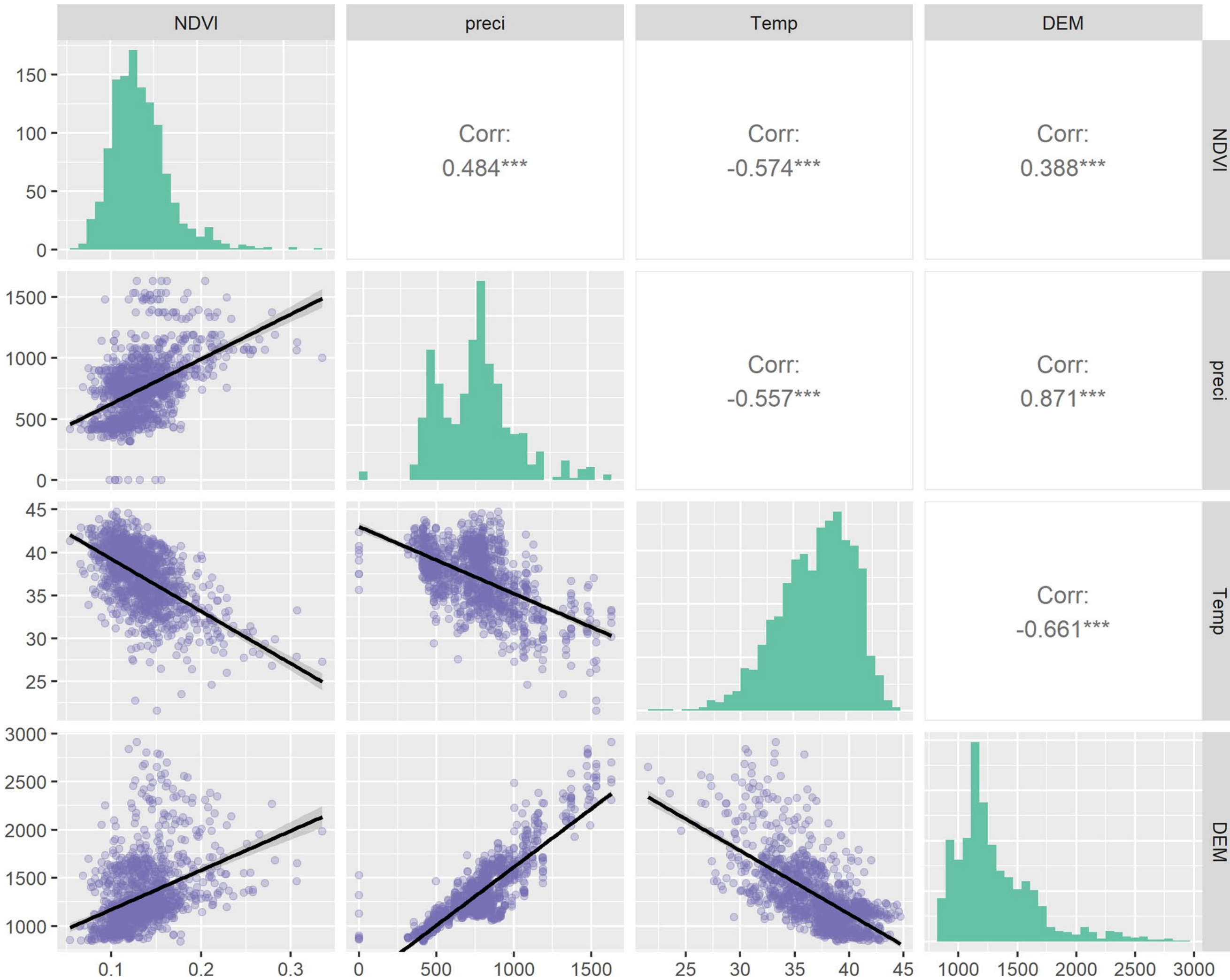


Fig. 8 Pairwise scatterplot matrix showing the correlation between NDVI and temperature, precipitation, and elevation. Note. * $p<0.05$, ** $p<0.01$, *** $p<0.001$

composition, or ecological quality (Fensholt et al. 2012; Pettorelli 2013). Therefore, the observed increase in NDVI reflects enhanced vegetation greenness but should not be interpreted as definitive evidence of ecosystem recovery or biodiversity restoration in the long term.

Drought variability and transition

The SPEI analysis demonstrated pronounced temporal variability in drought conditions during 1994–2024, with extended dry periods during 1996–1999, 2001–2003, 2009–2011, and 2015–2017, followed by predominantly wetter conditions after 2018. These wetter conditions coincided with generally higher NDVI values and widespread positive vegetation trends identified by the Mann-Kendall analysis.

These observations agree with previous studies showing that drought is a major determinant of vegetation productivity in semi-arid environments (Jiao et al. 2021; Schwalm et al. 2017). These findings also support the recent findings of (Ahmed & Czimber, 2026a, 2026b), who reported strong relationships between SPEI and vegetation dynamics in the Jabel Marra Highlands across multiple temporal scales. Collectively, these studies suggest that moisture availability, as represented by drought indices, provides a more comprehensive explanation of vegetation dynamics than precipitation totals alone.

The transition toward wetter conditions after 2018 may have increased soil moisture availability and prolonged favorable growing conditions, potentially contributing to the observed increase in vegetation greenness. However, vegetation responses varied spatially across the landscape, indicating that drought was not the only factor influencing vegetation dynamics. Local differences in topography, soil properties, vegetation composition, and land management practices may also have contributed to the heterogeneous vegetation trends observed in the spatial Mann-Kendall analysis. Further field-based ecological investigations are required to better understand these local-scale controls.

Vegetation dynamics in a conflict-affected landscape

Although the present study focused on climate–vegetation relationships, the broader socio-political context of Darfur provides important context for interpreting long-term environmental change. Since the early 2000 s, the region has experienced prolonged armed conflict, population displacement, and changes in land-use practices (Degomme and Guha-Sapir 2010; Depoortere et al. 2004; UNEP 2007).

Previous studies have reported that reductions in agricultural activity and grazing pressure following population displacement may contribute to localized increases in vegetation cover through natural regeneration (Broughton et al. 2021; Daskin and Pringle 2018). Similar environmental responses have been documented in other conflict-affected regions and are increasingly discussed within the framework of war ecology, which examines ecological changes associated with armed conflict and post-conflict transitions (Hanson 2018).

However, no spatially explicit information on conflict intensity, population displacement, grazing pressure, or land-use change was incorporated into the present study. Accordingly, no direct causal relationship between conflict and observed vegetation trends can be inferred. The heterogeneous spatial patterns identified by the Mann-Kendall analysis highlight the complexity of vegetation dynamics but cannot be attributed to conflict-related processes without additional evidence. Future studies integrating conflict-event datasets, land-use maps, and displacement records would provide a more comprehensive assessment of the interactions between climate variability, human activities, and vegetation change.

Localized restoration initiatives may have also influenced vegetation conditions in parts of Darfur. Programs implemented by the Forest National Corporation (FNC), UNEP, and local organizations have promoted tree planting, agroforestry, and soil rehabilitation (Ahmed et al. 2026a, 2026b; Gabay and Alam 2017; Myers et al. 2021). Similarly, recent remote sensing studies from Sudan (Ahmed & Czimber, 2026a, 2026b), have demonstrated that vegetation dynamics are influenced by the combined effects of climate variability, land management, and human activities, emphasizing the need to consider both environmental and anthropogenic drivers when interpreting long-term NDVI trends.

Study limitations and future research needs

Despite providing new insights into the long-term vegetation dynamics in Jabel Marra, several limitations should be considered when interpreting the findings.

First, annual NDVI composites provide a robust measure of long-term vegetation greenness but do not capture seasonal phenological variability or species-specific responses to environmental changes. Consequently, short-term vegetation dynamics and differences among vegetation types may not be fully represented in the data.

Second, the 30 m spatial resolution of Landsat imagery is well suited for long-term regional analyses but limits the detection of fine-scale vegetation changes associated with small agricultural fields, localized restoration activities, and settlement expansion. Future studies could benefit from integrating higher-resolution satellite data, such as Sentinel-2 or PlanetScope data, with long-term Landsat observations.

Third, the present analysis focused on climatic variables and did not incorporate spatially explicit datasets describing land-use change, grazing intensity, conflict events, or population displacement. Consequently, the influence of anthropogenic factors could not be quantified and should be regarded as contextual rather than demonstrated in this study. Integrating these datasets would improve our understanding of the combined effects of climatic and human drivers on vegetation dynamics.

Fourth, the correlation analyses identified statistical associations but did not establish causal relationships. Vegetation responses are influenced by multiple interacting factors, including soil characteristics, vegetation composition, ecological disturbances and land management practices. Moreover, vegetation responses to climatic variability often occur with temporal lags that were not explicitly evaluated in this study.

Finally, although CHIRPS and MERRA-2 are widely validated climate datasets, uncertainties remain in mountainous regions such as Jabel Marra because complex terrain can influence local precipitation and temperature patterns in these regions. These uncertainties may affect the estimates of drought intensity and climate–vegetation relationships at finer spatial scales.

Future research should integrate higher-resolution remote sensing, field-based ecological observations, and spatially explicit socioeconomic datasets to improve our understanding of vegetation dynamics in Jabel Marra. Particular attention should be given to lagged climate–vegetation relationships, pixel-level trend analyses, land-use change, conflict-related landscape dynamics, and ecological indicators beyond the NDVI, including vegetation composition, biodiversity, soil condition, and ecosystem services.

Conclusion

This study evaluated long-term vegetation dynamics and climate variability in the Jabel Marra region of Central Darfur, Sudan, during 1994–2024 using Landsat-derived NDVI, CHIRPS precipitation, MERRA-2 temperature, and SPEI. A significant positive trend in the annual NDVI was identified, indicating a gradual increase in vegetation greenness over the study period. Spatial trend analysis further showed that positive vegetation trends were concentrated primarily in mid-to-high elevation vegetated areas, while localized declines occurred in parts of the southwestern region.

The observed vegetation dynamics were significantly associated with climate variability. NDVI was positively correlated with precipitation and negatively correlated with temperature, whereas drought analysis indicated a transition toward generally wetter conditions after 2018. These findings suggest that improved moisture availability, together with topographic climatic gradients, is associated with the observed increase in vegetation greenness. However, the relatively weak long-term trend in annual precipitation and the complexity of vegetation responses indicate that no single climatic variable fully explains the observed patterns of vegetation changes.

Although the study area has experienced prolonged armed conflict and substantial socio-political changes, no conflict-related or land-use datasets were incorporated into the analysis. Consequently, the influence of conflict on vegetation dynamics cannot be quantified and is discussed only as a contextual background rather than as a demonstrated driver of the observed NDVI trends.

Overall, this study demonstrates the value of integrating long-term satellite observations, climatic datasets, and spatial trend analysis to investigate vegetation dynamics in data-scarce dryland environments. These findings provide an improved understanding of vegetation–climate relationships in the Jabel Marra Highlands and establish a baseline for future studies integrating higher-resolution remote sensing, field observations, and spatially explicit land-use and conflict datasets to better understand the interacting climatic and anthropogenic drivers of vegetation change.

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Data availability The data used in the current study are available from the corresponding author upon request.

Declarations

Ethical declaration The authors affirm that the research was carried out following ethical guidelines and regulations.

Competing interest The authors declare no competing interests.

Generative AI statement The author(s) declared that Generative AI was not used in the creation of this manuscript.

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