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Spatiotemporal dynamics of vegetation in response to climate variability in the Borana rangelands of southern Ethiopia

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In this paper, we analyze the spatiotemporal dynamics of vegetation and its association with climate variables in the Borana rangelands of southern Ethiopia. Moderate resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data, namely, MODIS/TERRA, MOD09Q1 16-day L3 Global 250 m Version 6 from National Aeronautics and Space Administration (NASA) United States Geological Survey (USGS), and climate data from 2000 to 2018 obtained from the National Meteorological Agency (NMA) of Ethiopia are used to determine the vegetation dynamics both at annual and seasonal timescales. The results indicate that the NDVI varies between .31 and .41, and the study area is dominated by sparse vegetation, especially shrubs and grasslands. The Borana rangelands were previously dominated by open grasslands, perennial herbaceous and woody vegetations, and some encroaching woody vegetations. The NDVI revealed poorer vegetation growth than the vegetation condition index (VCI) between 2000 and 2018, although variations were observed spatiotemporally. Rainfall was more highly variable both at annual and seasonal scales than the temperature during the studied years. The climate variables significantly determined the condition of vegetation, particularly during the growing seasons compared to other periods. A significant strong positive correlation was observed between the NDVI, VCI, and climate variables during the main (*Belg*) and short (*Meher*) rainy seasons in the Borana rangelands. The results of this study are beneficial for the development of proper intervention policies and provide information for sustainable rangeland management.

KEYWORDS

MODIS, NDVI, VCI, NASA USGS, rainfall, temperature, Borana rangelands

Abbreviations: AppEEARS, Application for Extracting and Exploring Analysis Ready Samples; DJF, December, January, and February; JJA, June, July, and August; LPDAAC, Land Processes Distributed Active Archive Center; MAM, March, April, and May; mm, millimeter; MODIS, moderate imaging spectroradiometer; NDVI, normalized difference vegetation index; NIR, near infrared; NMA, National Meteorological Agency; SON, September, October, and November; VCI, vegetation condition index; °C, degrees centigrade.

1 Introduction

Vegetation dynamics are controlled both by natural and anthropogenic factors that comprise climate variability and change, grazing pressure due to the increased number of livestock, bush fires (both natural and human-made), and agricultural land expansion driven by population growth (Cheikh et al., 2014). Climate change is primarily caused by the increased concentration of greenhouse gases in the Earth's atmosphere, which is significantly caused by human activities, as reported by the Intergovernmental Panel on Climate Change (IPCC, 2014). Different economic sectors, such as agriculture, forestry, energy end-use sectors (industry, transportation, and buildings), and many others, are contributing disproportionately toward this increase. The agriculture, forestry, and other land uses (AFOLU) sector is the major factor contributing to the emission of greenhouse gases in Ethiopia, contributing nearly 80% of the total emissions (Ethiopia's Climate-Resilient Green Economy Strategy (CRGE), 2011; Worku, 2020). Agricultural practices that include both growing crops and livestock raising form the major economic basis in Ethiopia. The population of the country is growing at an alarming rate, which has resulted in the demand for additional agricultural land. This extra land for farming purposes is converted from previously forested and grassland areas, and bushfires are currently commonly observed.

In addition, the lowland areas of Ethiopia dominated by shrubs and grasslands are inhabited by pastoral and agropastoral communities. These areas, on one hand, are overgrazed by the huge number of livestock in the region, while on the other hand, they are threatened by woody plant encroachment. Therefore, it is extremely important to understand how the vegetation dynamics respond to any of these factors in order to address problems associated with them.

There have been different approaches adopted to analyze land cover dynamics. Since the 1970s, numerous studies have used satellite-based land observations to monitor and analyze land surface dynamics. Remotely sensed data provide a synoptic view of the land and a spatiotemporal context (Gu et al., 2007; Cheng, Nnadi & Liou, 2015). Geospatial techniques are used to derive various vegetation indices for the effective analysis of vegetation dynamics using various image processing methods (Dutta et al., 2015). Remotely sensed vegetation indices are effective and suitable for the spatial and temporal monitoring of vegetation conditions (Rousta et al., 2020). According to Liu et al. (2020), commonly used indices for monitoring vegetation conditions include, among others, the normalized difference vegetation index (NDVI), vegetation condition index (VCI), and temperature condition index (TCI) (Liu et al., 2020).

Several studies have been conducted on the dynamics of vegetation using satellite-based remotely sensed data and linked to climate parameters in different areas. To highlight a few papers conducted in Ethiopia, Getahun and Shefine (2015) analyzed climate variability and vegetation dynamics in the north-central areas of the country (Gojjam) from 2000 to 2008 and observed a highly variable NDVI and rainfall during the growing season. Zewdie et al. (2017) also studied the long-term trends in dryland vegetation variability in northwestern Ethiopia (Kaftahumera) from 2000 to 2014 and revealed a significant reduction trend in vegetation until 2009. Similarly, Tadesse et al. (2020) analyzed the long-term dynamics of woodland vegetation in the northwestern lowlands of Ethiopia using Landsat data from 1984 to 2014, finding precipitation to be a significant key factor for

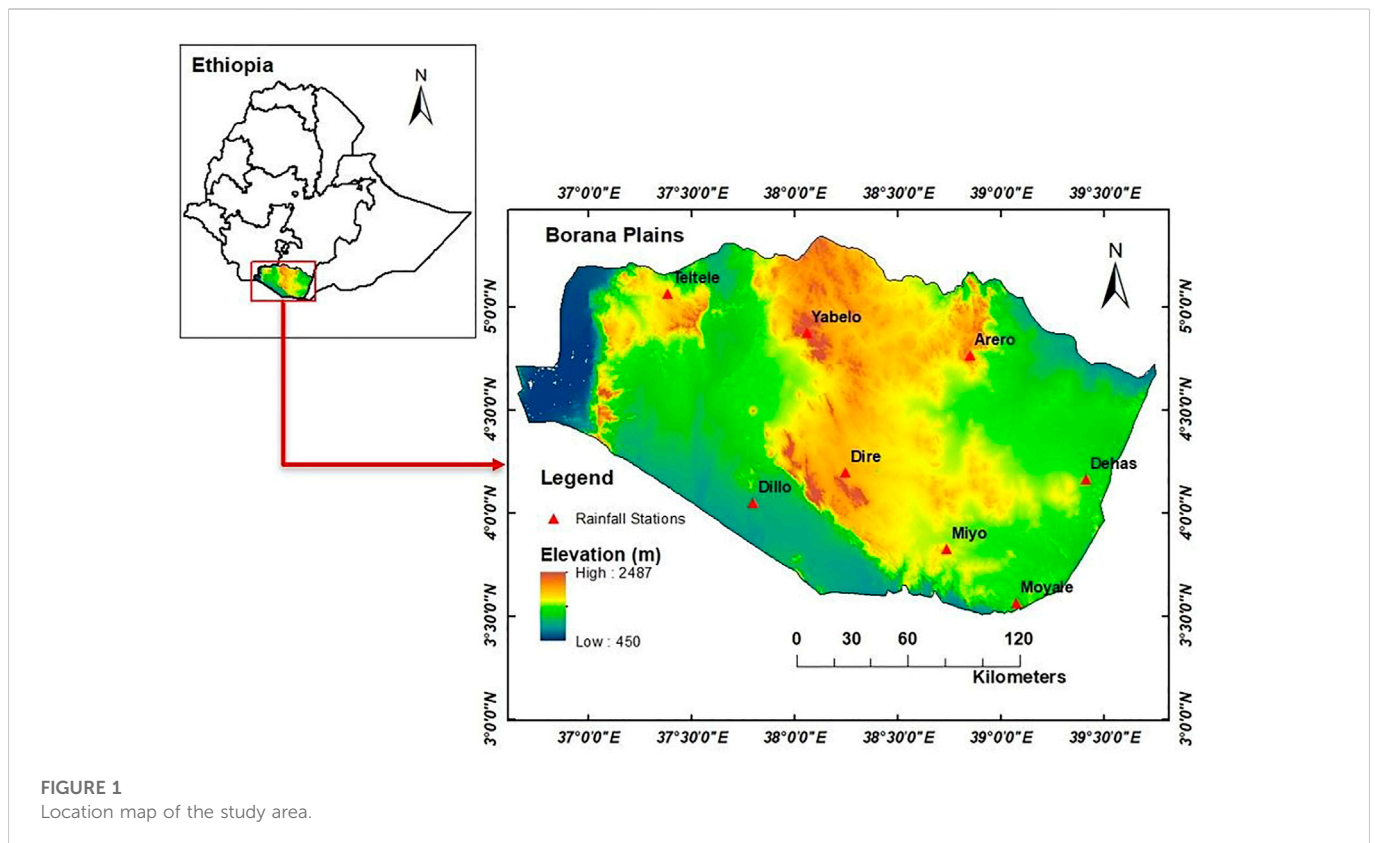
woodland vegetation and that the NDVI significantly contributes to climate variability. Wedajo et al. (2019) and Melku et al. (2020) further studied the nexus between climate and vegetation change over the Dhidhessa River and Gojeb River catchments. A strong interaction was found between the climate variables and vegetation greenness in the case of Dhidhessa, while a strong positive increment of the NDVI, which is attributed to rainfall, was observed in the Gojeb River catchment.

Furthermore, Muir et al. (2021) investigated vegetation change using MODIS satellite data over the entire country of Ethiopia, observing declines in the NDVI, with the greatest change during the dry season and concentrated in the northern semi-arid regions of the country. Similarly, Measho et al. (2019) noted a decreasing NDVI at 57.15% and 58.74% of all the pixels, respectively, for the annual main growing seasons in the semi-arid region of Eritrea. Fenetahun et al. (2022) recently estimated the yearly dynamics of biomass production and carrying capacity of the Borana rangelands of southern Ethiopia using NDVI and field-based data, revealing a significant decrease in the biomass production ($R^2_{adj} = .67$) and the NDVI value ($R^2_{adj} = .47$) from 1990 to 2019. Therefore, most of the papers conducted previously in the country, particularly in a similar environment (Wedajo et al., 2019; Melku et al., 2020; Tadesse et al., 2020; Fenetahun et al., 2022), have captured and applied NDVI data from advanced very high-resolution radiometer (AVHRR) sensors. This source can extend data back to the 1980s and hence provide an adequate length of year, but its spatial resolution (8 km by 8 km) is coarser, which makes the observation of detailed land cover challenging. In this study, we intend to analyze vegetation dynamics on a monthly, seasonal, and annual basis, ranging from 2000 to 2018, using relatively high-resolution (250 m x 250 m) multi-temporal MODIS satellite data. We also examine the response of vegetation conditions in relation to local climate variability over the same period. Apart from these few papers, no study has been conducted in the region, even though the information on the nexus between vegetation dynamics and climate variability is crucial to policymakers, practitioners, and the community at large. It is believed that the findings of this paper may provide a basis for developing proper intervention policies and provide information relevant to the sustainable management of rangeland resources in the study area and similar environments.

2 Materials and methods

2.1 Study area

The Borana rangelands are located in the southern parts of the country, stretching approximately from 3°30' N to 5°25' N latitude and 36°40' E to 39°45' E longitude. The average elevation range is between 450 m in the west and 2,487 m above mean sea level in the north-central and central areas, as shown in Figure 1. The mean annual temperature of the study area, as reported by Fenetahun et al. (2022), varies between 28°C and 33°C with little seasonal variation, whereas the average annual rainfall is estimated as between 350 mm and 900 mm (Debela et al., 2019), which was later reported between to be 285 mm and 741 mm by Worku et al. (2022). The rainfall received is distributed among the two rainfall periods, namely, *Belg* (March to May), which accounts for nearly 60%, and *Meher* (September to November), which accounts for 27% of the total rainfall with high



spatial and temporal fluctuations (Gemedo et al., 2006). In between *Belg* and *Meher*, constituting the seasons in a year, there exist dry seasons, namely, *Bega* (December to February) and *Kiremt* (June to August) (Korecha & Barnston, 2007; Riche et al., 2009).

The main landcover types of Borana include shrubland, grassland, woodland, cultivated land, exposed surfaces, or bare land. The Borana rangelands are dominated by tropical savanna vegetation, with varying proportions of open grasslands and perennial herbaceous and woody vegetation (Pratt & Gwynne, 1977). The dominant encroaching woody species include *Senegalis mellifera*, *Vachellia reficiens*, and *Vachellia oerfota* (Coppock, 1993; Gemedo et al., 2006), and the bushlands are dominated by *Acacia* and *Commiphora* species (Haugen, 1992). Furthermore, the most frequent grass species in the study area include *Chrysopogon aucheri* (45%), *Eragrostis papposa* (30%), and *Sporobolus pellucidus* (25%), as previously reported by Gemedo (2004) and Gemedo et al. (2006).

The population inhabiting the region has long been exclusively pastoral and has recently started practicing small-holder farming. The start of farming practices is a means of coping with climate-related risks, particularly drought. The region is a drought-prone area, and in some cases, this climatic event causes deleterious impacts on the community, livestock, and farm fields.

2.2 Data types and sources

Monthly rainfall and maximum and minimum temperature data for all the stations in the Borana rangelands for the period 2000–2018 were collected from the Ethiopian National Meteorological Agency (NMA) to calculate annual and seasonal

means for the climate variables considered. Since station observations are not free from missing values, gridded data with a spatial resolution of 4 km x 4 km were used to fill the data gaps both for rainfall and temperature. The latter data types were also obtained from the NMA and were developed through the enhancing national climate services (ENACTS) initiative that integrates satellite-based data with station observations; hence, the data were made complete and used in the analysis.

Moderate resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data were used in this study. The data exist in various spatial resolutions of 250 m, 500 m, and 1,000 m. It is believed that the data improve our understanding of global dynamics and the processes occurring on the land, in the oceans, and in the lower atmosphere. MODIS is playing a vital role in the development of validated, global, interactive Earth system models able to predict global change accurately (Rousta et al., 2020).

Therefore, the MODIS data product, MOD13Q1, was used for the NDVI. The MODIS-NDVI data from 2000 to 2018 were downloaded from the Land Processes Distributed Active Archive Center (LP-DAAC), which can be accessed from USGS Global Visualization Viewer (<http://earthexplorer.usgs.gov>).

2.3 MODIS vegetation indices

2.3.1 Normalized difference vegetation index (NDVI)

The NDVI is the most common and useful index for investigating vegetation status. It has been used in different studies in the modern era (Mushore et al., 2019). The basic concept of the NDVI is based on

TABLE 1 Specification of the MODIS NDVI product used in this study.

Item	MODIS NDVI product
File name	Vegetation Indices 16-Day L3 Global 250 m Version 6
Spatial resolution	250 m
Input image	MODIS/TERRA MOD09Q1
Composition	16-day
Projection	Sinusoidal projection
Data (years)	2000–2018

TABLE 2 NDVI classification and land cover and/or drought associated with this study.

NDVI range	Landcover associated
<0.1	Water surfaces, human-made structures, rocks, clouds, and snow
.1–0.2	Bare soil
.2–0.4	Sparse vegetation including shrubs and grasslands
.4–0.6	Moderate vegetation
>0.6	Dense vegetation or crops at the peak growth stage

the fact that the internal mesophyll of healthy green leaves highly reflects near-infrared (NIR) radiation, whereas the leaf chlorophyll and other pigments absorb a large proportion of the visible (red) radiation (Broge & Leblanc, 2001). This function of internal leaf structure becomes reversed in the case of unhealthy or water-stressed vegetation. The NDVI is calculated using the following Eq. 1 (Dutta et al., 2015):

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

where *RED* and *NIR* represent spectral reflectance measurements acquired in the visible (red) and near-infrared regions of the spectrum, respectively. Because the pigment in plant leaves (chlorophyll) strongly absorbs visible light (from .4 to .7 μm) for use in photosynthesis and the cell structure of the leaves strongly reflects near-infrared light (from .7 to 1.1 μm), the greener leaves a plant has, the more these wavelengths of light are affected, and hence the higher the NDVI. The NDVI has been used for analyzing changes in vegetation that have been affected by the surrounding environment (Wang et al., 2001).

More recently, MODIS data have been widely used in order to monitor vegetation dynamics (Gu et al., 2007; Swain et al., 2011; Wu et al., 2015). In this study, 439 images from Terra MODIS 16-day composite NDVI with 250 m resolution (MOD09Q1, collection v006), as shown in Table 1, for the period 2000 to 2018 were downloaded from the NASA USGS website by using the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) software (<https://lpdaacsvc.cr.usgs.gov/appeears>) (Didan, 2015).

The main advantage of using MODIS data is the high temporal resolution (availability of daily images) and the composite image technology, which enables the creation of 8-day or 16-day composites from the highest quality pixels, that is, free of atmospheric effects such as cloud cover and shadow. The

disadvantages of MODIS data are the moderate geometric resolution (250 or 500 m) and the fact that the data are from 2000, so we do not have data for more than two decades (Gulacsi & Kovacs, 2018; Rousta et al., 2020).

The standard values for the NDVI are between -1 and $+1$. However, the NDVI range for MODIS data was standardized by multiplying with a scale factor of $1/10,000$ or $.0001$, and accordingly, various NDVI scales for different land cover types were determined in this study. The yearly and seasonal average NDVI were then obtained, and the corresponding maps were produced for the Borana rangelands. The NDVI values were categorized into five classes, as shown in Table 2.

2.3.2 Vegetation condition index (VCI)

There have been several NDVI-based vegetation indices that have been proposed with vegetation condition monitoring (Yang et al., 2011). The VCI compares the current NDVI to the range of values observed in the same period in previous years. It is expressed as a percentage and gives an idea of where the observed value is situated between the extreme values (minimum and maximum) in the previous years. Hence, the VCI contains both real-time and historical information about the NDVI. Using the formula to calculate the VCI in Equation (2) results in a number between 0 and 100, where smaller VCI values indicate worse vegetation growth and higher degrees of vegetation dryness (Kogan, 1990; 1995a; b), as the scale indicates in Table 3. Therefore, the formula to calculate the VCI, as given and applied by Kogan (1990), Kogan et al. (2004), Ghaleb et al. (2015), and Wei et al. (2021), is

$$VCI = \frac{(NDVI_i - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \times 100, \quad (2)$$

where $NDVI_i$ is the NDVI value of the pixels during a specified time period, and $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum NDVI values, respectively, during a specified time period.

The VCI assesses changes in the NDVI signal through time due to weather conditions, reducing the influence of geographic (Kogan, 1990) or ecosystem (Kogan, 1995c) variables, including climate, soils, vegetation type, and topography. Lower and higher VCI values indicate bad and good vegetation state conditions, respectively.

2.4 Correlation analysis

In this study, the Pearson's correlation coefficient (r) was applied in order to determine the linear association between the vegetation indices (NDVI and VCI) and the climate variables on an annual and seasonal basis at the 95% level of confidence. Pearson's correlation coefficient (r) is given by

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 (y_i - \bar{y})^2}}, \quad (3)$$

where n is the number of observations; x and y are the variables; and \bar{x} and \bar{y} are the means, respectively. The correlation coefficient (r) takes a value between $+1$ and -1 , where a value of $+1$ indicates a perfect positive correlation, while -1 indicates a perfect negative correlation and a value of 0 signifies no correlation. In the present study, we classified the correlation into several categories: very weak

TABLE 3 VCI classification scale.

S.N.	VCI value (%)	Degree of the vegetation condition (dryness)
1	<10	Extremely dry
2	10–20	Severely dry
3	20–30	Moderately dry
4	30–40	Mild (light) dryness
5	>40	Normal

Source: Kogan (1995); Kogan et al. (2003).

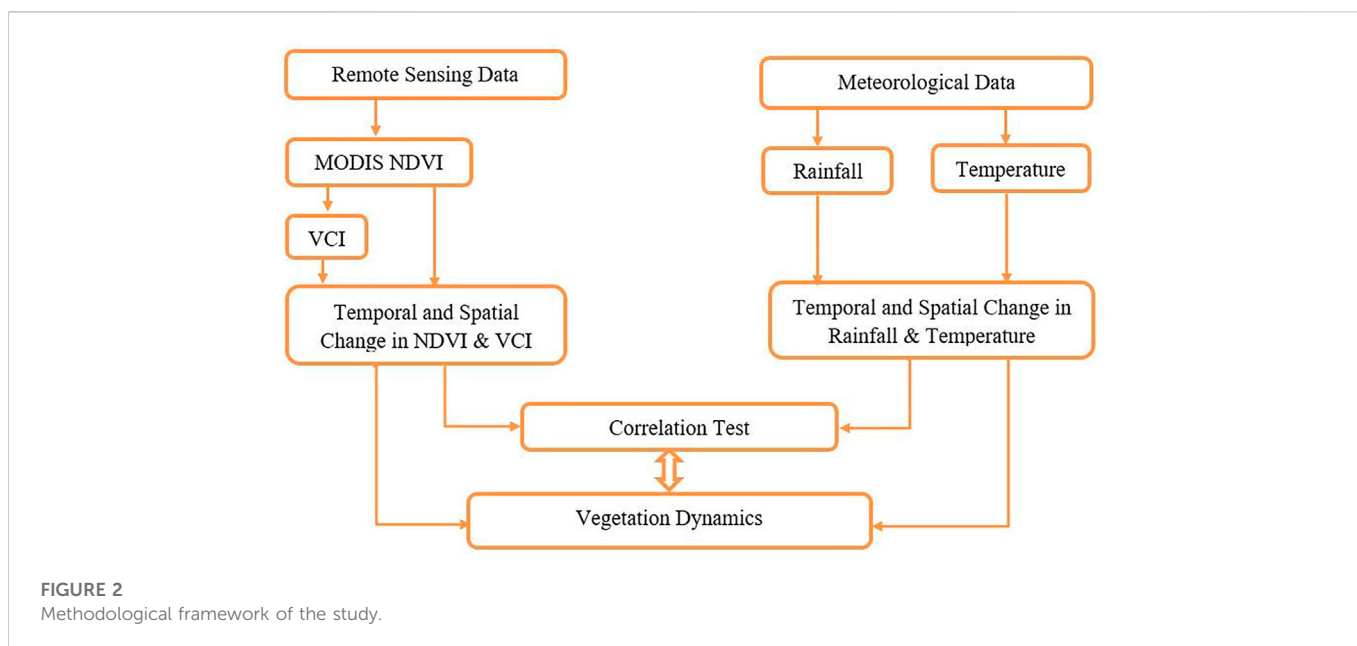


FIGURE 2 Methodological framework of the study.

TABLE 4 Annual and interannual mean values of vegetation indices and climate variables (2000–2018).

Mean value	Annual	Bega	Belg	Kiremt	Meher
NDVI	.36	.35	.42	.32	.39
VCI (%)	40.65	40.67	46.05	35.45	42.80
Rainfall (mm)	517.40	39.49	233.10	36.35	208.69
Temperature (°C)	22.36	23.70	22.22	21.33	22.18

positive/negative correlation (0 to ±.19); weak positive/negative correlation (±.2 to ±.39); moderate positive/negative correlation (±.4 to ±.59); strong positive/negative correlation (±.6 to ±.79); and very strong positive/negative correlation (≥±.8).

Overall, in this study, both spatial and non-spatial data from different sources were used in order to analyze the dynamics in vegetation and also to see the nexus between vegetation growth and climate variables, particularly rainfall and temperature. Therefore, the correlation of vegetation-based indices and the climate variables was seen, and their significance was also tested in this study. The methodological framework applied in this paper is indicated in Figure 2.

3 Results

3.1 Annual temporal variations in the NDVI, VCI, and climate variables

The mean NDVI value for the Borana rangelands during the entire period was .36 (Table 4). The mean values vary between .31 between the years 2000 and 2007, when it was the smallest, and .41 in 2003 and 2013, which revealed the highest NDVI values (Figure 3A). The results revealed that the study area is covered by sparse vegetation, while the dominant vegetation types are shrubs and grasslands. Regarding the VCI, an NDVI-based vegetation index, the study area exhibited a mean VCI value of 40.65% (Table 4), which signifies normal vegetation conditions. However, some years (including 2000, 2001, 2005, 2007, 2008, 2009, and 2016) showed light dryness of vegetation. The period after 2009 showed better vegetation conditions than the period ahead. A relatively poor vegetation condition (VCI = 30%) was observed in 2007, while on the contrary, a better vegetation condition was observed in 2013 in the Borana rangelands, as shown in Figure 3B.

Average annual rainfall of 517.40 mm was observed in the study area over the studied years, with the year 2000 found to be the driest (366.22 mm) and 2011 the wettest, with a mean rainfall close to 720 mm. Hence,

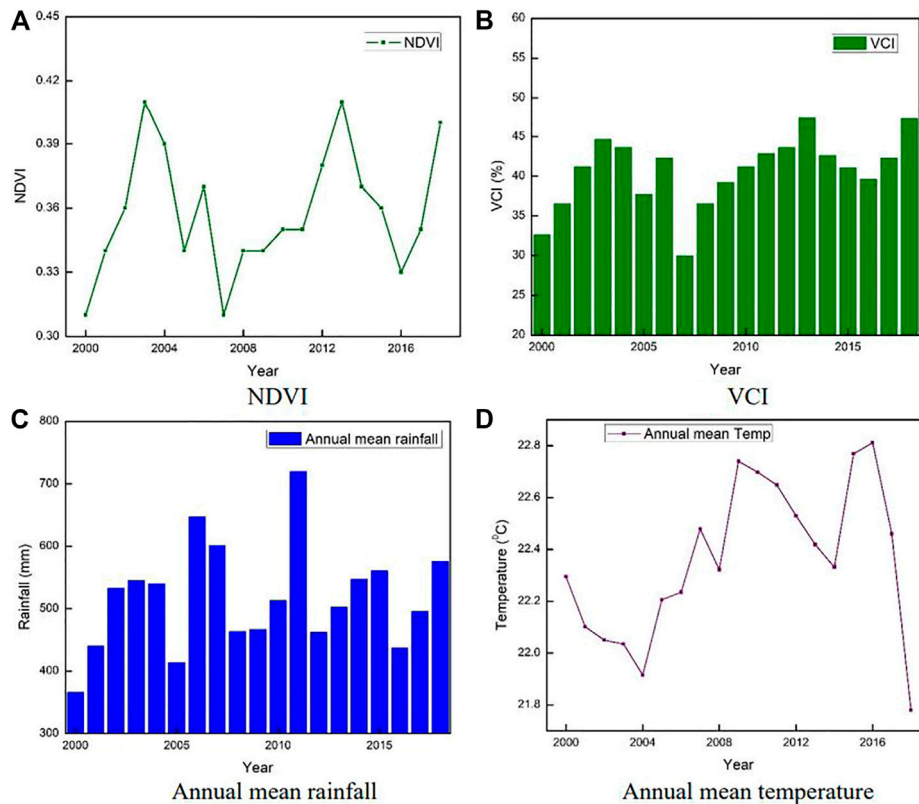


FIGURE 3
Annual mean variations in (A) the NDVI, (B) the VCI, (C) rainfall, and (D) temperature (2000–2018).

2011 received rainfall equivalent to almost twice that of the driest year (2000) (Figure 3C). Unlike rainfall, the temperature was characterized by low-level variability in the Borana rangelands over the studied period, with a mean of 22.36°C and a range of 1.03°C. Therefore, a more or less similar temperature condition has prevailed over the study area and a slight variation was observed in the latter years, as shown in Figure 3D.

3.2 Interannual temporal variations of the NDVI, VCI, and climate variables

Table 4 provides the seasonal summary of all variables considered in this study. Regarding the NDVI, its mean value is smaller during *Kiremt* (June to August), which is 0.32, followed by *Bega* (December to February), with an NDVI equal to .35. The mean value becomes relatively better during *Belg* (March to May), which is the main rainy season, when the NDVI = 0.42. The other index, VCI, shows that the vegetation condition is characterized by mild (light) dryness during *Kiremt* (VCI = 36.35%), whereas during the remaining seasons, it looks normal and even better during *Belg*.

The climate variables, particularly rainfall and temperature, were also seen at a seasonal scale in the Borana rangelands. *Belg* is the wettest season with a mean rainfall of 233 mm, followed by *Meher* with 209 mm, which favors vegetation greenness during these seasons. On the other hand, the *Kiremt* and *Bega* seasons were the driest seasons, where the mean rainfall observed was 36 mm and 39 mm, respectively. Rainfall is highly variable on a seasonal basis, and the deviation between the wettest and driest season was 197 mm. Contrary to the rainfall, the seasonal variation of

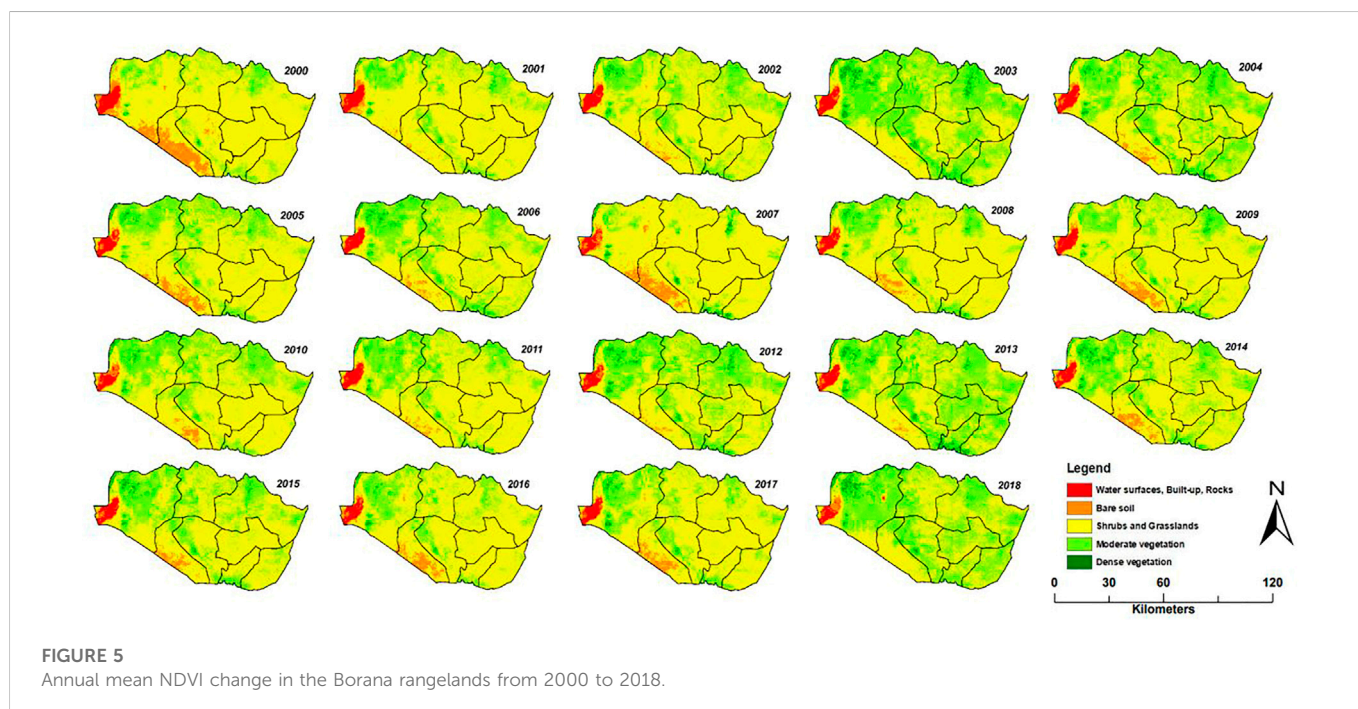
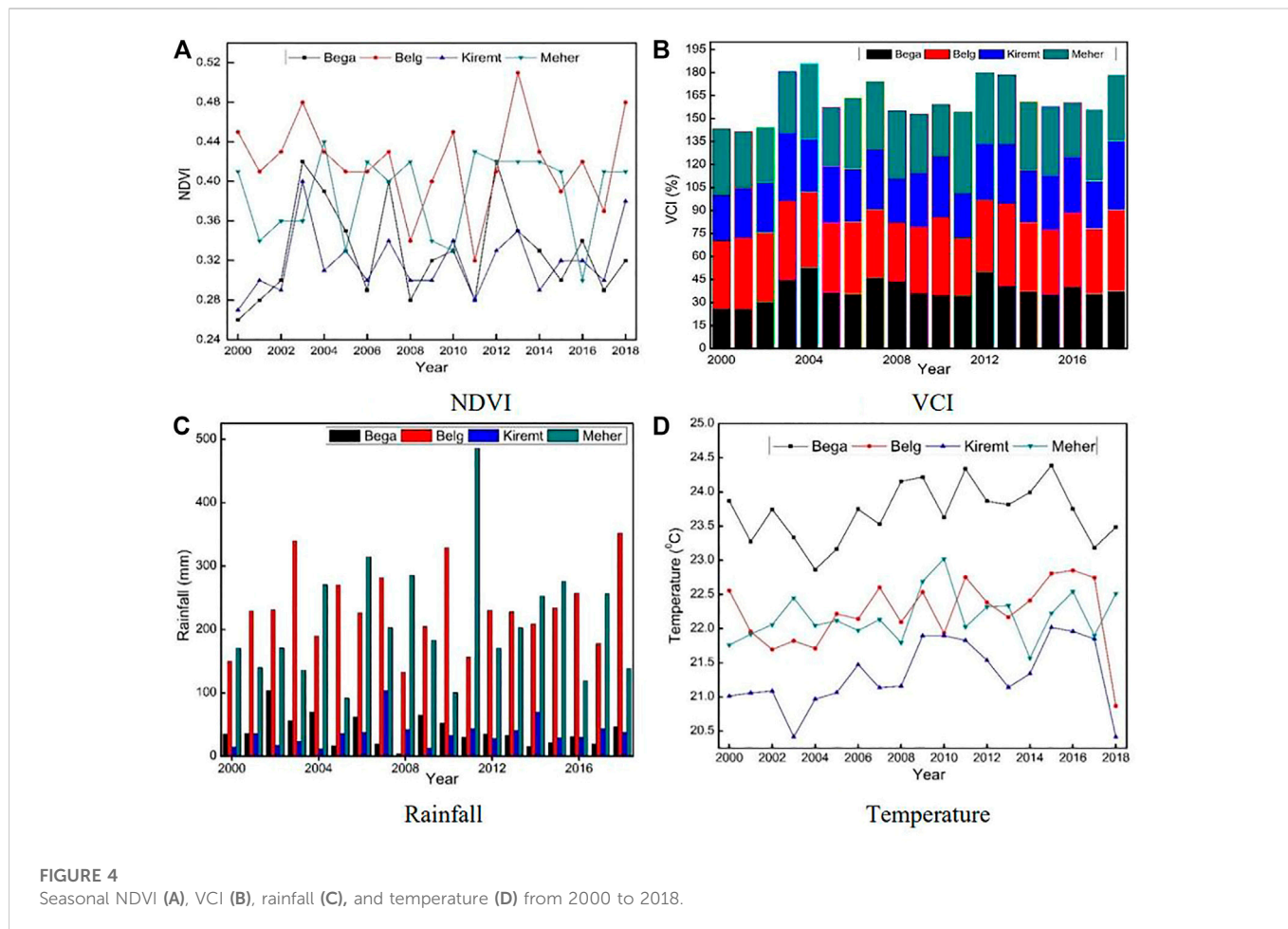
mean temperature was lesser. The *Bega* season was warmer (23.7°C), followed by *Belg* (22.22°C), whereas *Kiremt* was relatively cooler (21.33°C) than the rest of the seasons. The seasonal temperature deviation between the extreme values in the Borana rangelands was 2.37°C, which is much higher than the annual deviation.

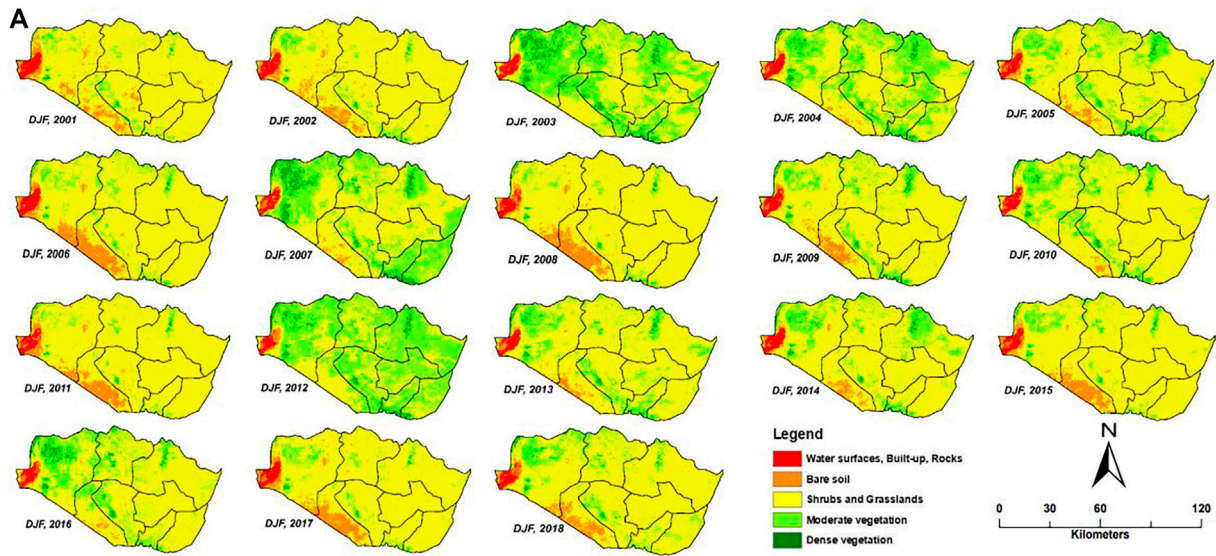
The seasonal trends of the NDVI, VCI, and climate variables are also depicted in Figure 4A. The NDVI varies from one year to the other: the *Belg* NDVI is the highest, followed by the *Meher* NDVI. Keeping in mind some exceptional years, the NDVI during *Kiremt* falls below the NDVI during the other seasons. The *Belg* VCI is better than other seasons, followed by *Meher*, while *Kiremt* relatively exhibits lesser VCI values (Figure 4B). Although the *Meher* rainfall exceeds that of *Belg* in some years, in summary, *Belg* rainfall is the highest in the Borana rangelands (Figure 4C). However, the mean rainfall during *Kiremt* and *Bega* in the study area remains among the lowest during all the individual years. Finally, as shown in Figure 4D, the mean temperature trend for *Bega* is the highest over the studied years, followed by *Belg*. For the entire study period, the mean temperature during *Kiremt* is the lowest compared to the other seasons, which implies seasonal temperature variability.

3.3 Spatial annual and interannual variability in the NDVI and climate variables

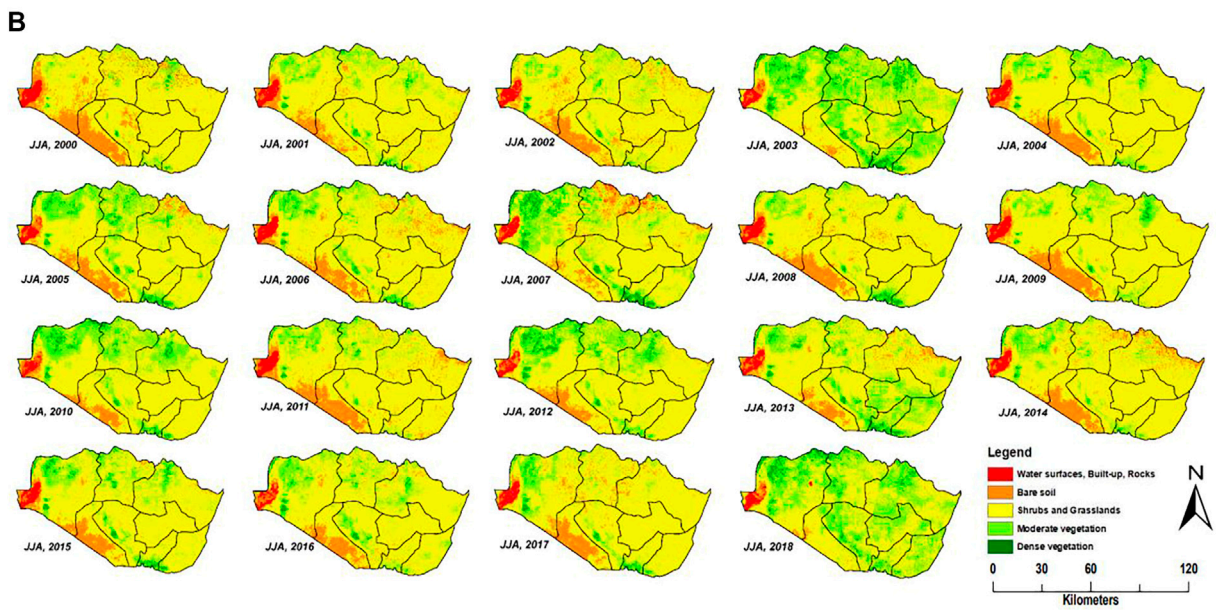
3.3.1 Annual NDVI change

Figure 5 shows the annual spatial change of the NDVI from 2000 to 2018 in the study area. The land cover is classified into five classes: surface





Bega season (DJF – December, January & February)



Kiremt season (JJA – June, July & August)

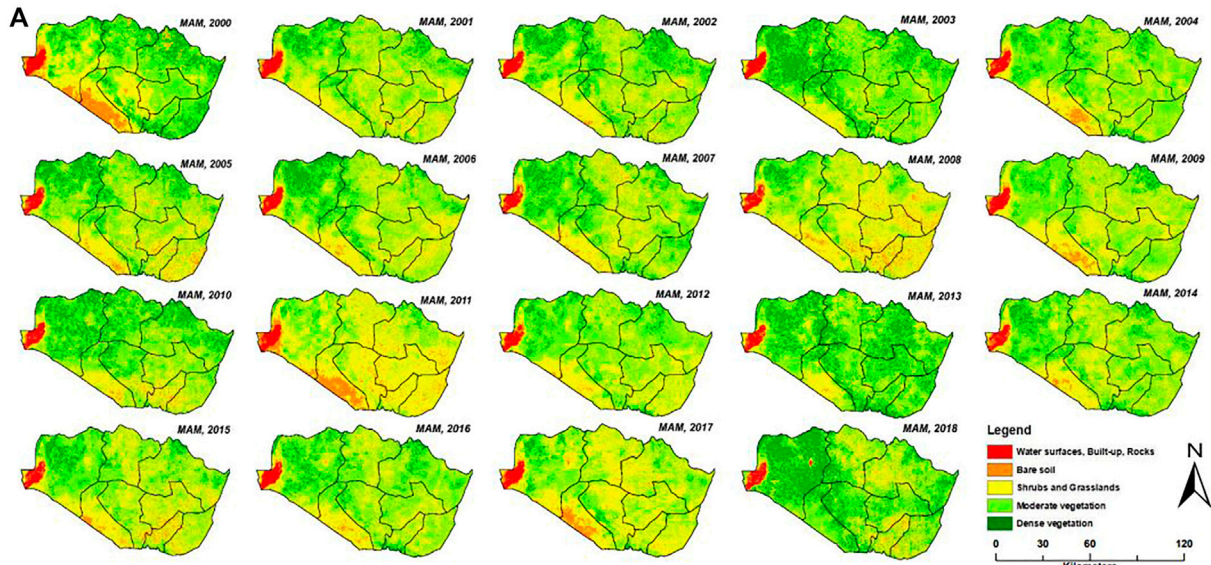
FIGURE 6
Dry season NDVI change from 2001 to 2018: (A) *Bega*; (B) *Kiremt*.

water, barren land, sparse vegetation (shrubs and grasslands), moderate vegetation, and dense vegetation. The western extreme region of the study area (“*Lake Chew Bahir*,” the southern extension of the Ethiopian Rift Valley) is characterized by its lower vegetation cover (NDVI < .1) during the entire period. The second lowest level of NDVI (.1–.2) was seen in the southwestern areas along the Ethiopia–Kenya border, particularly in 2000, 2005, 2007, 2009, 2014, 2016, and 2017. On the other hand, dense vegetation is only found in some pockets or very remote areas, as can be seen in [Figure 5](#). The region is dominantly covered with sparse

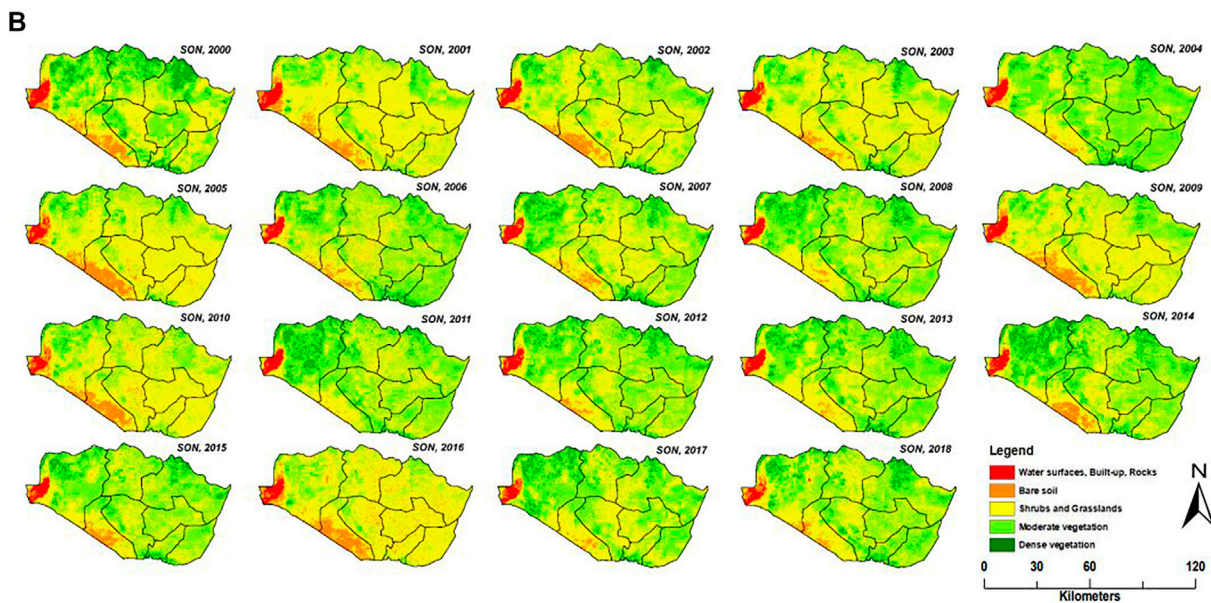
vegetation, especially shrubs and grasslands, during almost all of the years. However, in some years, including 2003, 2004, 2012, 2013, and 2018, vegetation greenness increased and the region’s areas were covered with moderate vegetation, where the mean NDVI ranges between .4 and .6.

3.3.2 Seasonal (wet and dry) NDVI change

The mean NDVI maps for two dry seasons, namely, *Bega* (December to February) and *Kiremt* (June to August), were



Belg season (MAM – March, April & May)



Meher season (SON – September, October & November)

FIGURE 7
Wet season NDVI change from 2000 to 2018: (A) *Belg*; (B) *Meher*.

produced for the entire period. The *Bega* season is characterized by a low NDVI, as expected, since the study area and the entire area of Ethiopia, except for smaller areas in the northeastern region, remain dry during this season. Some years, including 2003, 2007, 2012, and 2016 (Figure 6A), show vegetation greenness, and the vegetation types observed during these years were not of a woody kind but rather temporary (herbaceous) plants that last for only a few months. The dominant land cover type is shrubs and

grasslands in the areas of the study region. Similar to the annual case, the western and southwestern areas are characterized by water features, as well as barren land during the *Bega* season. During *Kiremt*, the region is characterized by a low NDVI, especially in the western and southwestern areas, in an almost regular pattern. There were also some years (2003 and 2018) during which sparse and moderate vegetation dominated the region (Figure 6B).

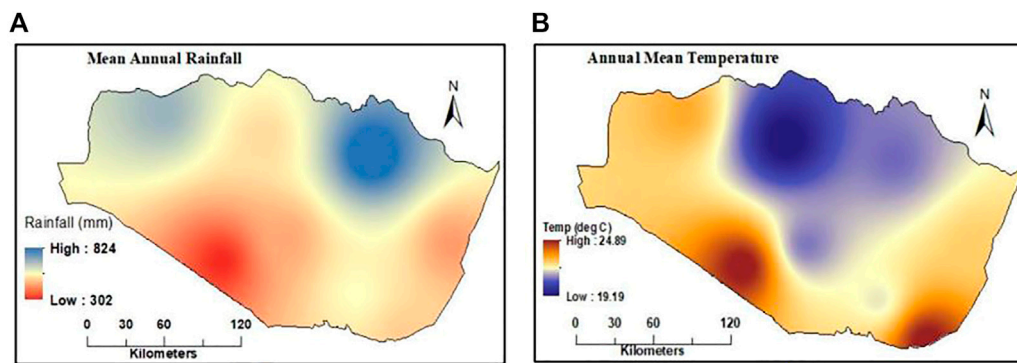


FIGURE 8

Spatial variability of mean annual rainfall (A) and temperature (B): the spatial maps produced were the result of the inverse distance weighted interpolation technique derived from the data source points (station) both for rainfall and temperature.

During the wet seasons, particularly *Belg* (March to May), the region receives much of the rainfall, and vegetation greenness increases, except for some areas in the extreme western and southwestern areas, as shown in Figure 7A. The green vegetation that dominantly covers the entire rangeland does not last long and begins to fade away as the intensity of rainfall decreases in the area. These vegetations are herbaceous plants that start to dry when the rain stops. A similar kind of vegetation greenness, but with a lesser level, was observed in the study area during the other short rainy season, *Meher* (September to November). In the *Meher* season, moderate to dense vegetation is mainly observed for most of the years, following the rain received in this part of the country, as observed in Figure 7B. Therefore, climate variables determine the condition of vegetation, which can either be greenness or dryness in a particular region.

3.3.3 Climate variability

The mean annual rainfall varies significantly across the study region, with the northeastern areas receiving better rainfall (exceeding 800 mm), while the southwestern areas are drier, and only about 300 mm per year is received in the areas along the Ethiopia–Kenya border (Figure 8A). The rest of the places obtained an average rainfall. Concerning the mean annual temperature, the southeast and southwest areas were warmer than the northern, north-central, and northeastern areas (Figure 8B). Hence, a temperature range of about 5.7°C was noted between these extreme temperature zones in the Borana rangelands. Overall, both rainfall and temperature vary spatially at an annual scale during the studied years in the Borana rangelands, but the degree of variability is higher for rainfall.

Rainfall also varies from one season to the next in a year. The *Belg* rainfall dominantly falls over the northeastern and the northwestern areas (>300 mm) and drops toward the southwest (~130 mm). However, during the shortest rainfall season, *Meher*, much of the rain occurs over the northeastern region. Therefore, the northeastern regions received relatively excess rainfall during both the *Belg* and *Meher* seasons. *Bega* is the driest season in the region, as well as in the entire country, and the region received only a minimum seasonal rainfall that occurs over the northwest parts. On the contrary, *Kiremt* rainfall (June to August) occurs in the northeast and decreases toward the south, southwest, and southeast. However, during this particular

season, most parts of the country, except the study region and the far northeast areas of Ethiopia, obtain their maximum rainfall in the year.

Unlike rainfall, the spatial distribution of temperature during all seasons shows similarity. The northern, north-central, and northeastern areas were characterized by average minimum temperature, and the southwestern and southeastern regions were characterized by maximum temperature. Low-level variability was observed where the *Bega* was warmer than the rest of the seasons, as shown in Figure 9.

3.4 Nexus between the vegetation indices and climate variables

We tested the correlation between the NDVI and VCI with the two important climate variables, i.e., rainfall and temperature, using Pearson's correlation coefficient, and the significance was tested at the 95% confidence level. The results revealed that the mean annual rainfall has a weak positive correlation both with NDVI and VCI, whereas the mean annual temperature has a moderate positive correlation with the NDVI and a weak positive correlation with the VCI. In both cases, the correlation was not statistically significant (p -value > 0.05). Seasonally, *Bega* rainfall has a weak positive correlation with both vegetation indices, while *Kiremt* rainfall has a very weak positive correlation. Since both the *Bega* and *Kiremt* seasons are identified as dry seasons, vegetation greenness and an increase in the NDVI and VCI values were not expected in the study area. However, the wet seasons, *Belg* and *Meher*, had a strong positive correlation with the NDVI and VCI that was statistically significant (p -value < 0.05), as shown in Table 5. This implies that the Borana rangelands are characterized by considerable vegetation greenness only during the rainy seasons, while one does not observe better a vegetation condition when the dry period takes over.

The correlation coefficient again indicates that the vegetation indices have a moderate positive correlation with the *Kiremt* temperature and a very weak positive correlation with the *Bega* season temperature, and this shows highly similar characteristics with rainfall. The temperature during *Belg* and *Meher* is significantly correlated (p -value < 0.05) with the NDVI and VCI, showing in all cases a moderate positive correlation (Table 5). The

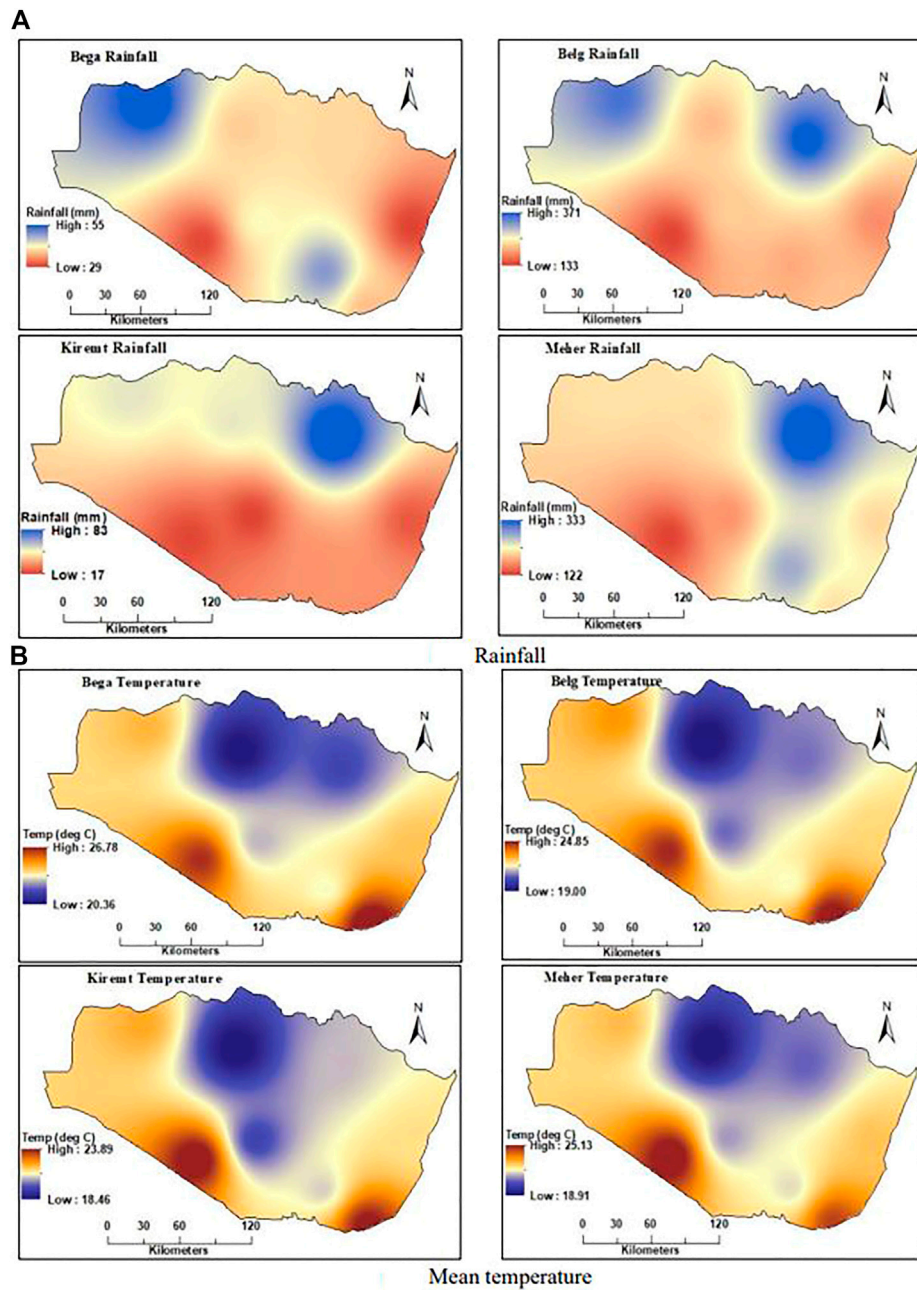


FIGURE 9 Spatial variability of rainfall (A) and temperature (B) across different seasons.

degree of association between the vegetation indices and the climate variables is higher for rainfall than temperature, which indicates that rainfall determines vegetation greenness more than temperature in the Borana rangelands.

4 Discussion

The Borana rangelands are one of the areas in the country characterized by a low NDVI, implying poor vegetation conditions. Sparse vegetation, especially bushes and grasslands, covers most parts of the region, whereas dense vegetation with better NDVI values are

confined to some pocket areas inaccessible to human interference. The NDVI value varies at temporal and spatial scales in the rangelands of Borana, and some years are characterized by better vegetation conditions, while others by worse. The VCI, unlike the NDVI, exhibited near normal conditions but only identified mild dryness during some years. On the other hand, both showed similarity in the identification of periods of dryness and greenness vegetation conditions. In a study recently conducted by Fenetahun et al. (2022), both biomass production and NDVI values decreased from 1990 to 2019 and the observed biomass production was not in a good condition in the Borana rangelands of southern Ethiopia. Kourouma et al. (2021) found overlapping years of severe dryness conditions over

TABLE 5 Correlation between NDVI, VCI, and climate variables [A] rainfall; B) temperature].

A) Rainfall										
Vegetation index	Annual		Bega		Belg		Kiremt		Meher	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
NDVI	.31	0.2	0.3	.25	.63	.004	.09	.71	.69	.001
VCI	.34	.15	.35	.17	0.7	.001	.13	.59	.81	.000
B) Temperature										
Vegetation Indices	Annual		Bega		Belg		Kiremt		Meher	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
NDVI	.44	.06	.02	.92	0.5	.03	.47	.04	.53	.02
VCI	0.2	0.4	.07	.78	.58	.01	0.4	.08	.48	.03

Ethiopia that had significant impacts on crops. Measho et al. (2019) also observed a decreasing slope of the NDVI both at annual and seasonal timescales in the semi-arid region of Eritrea, whereas Melkamu (2019) observed a dynamic change in vegetation cover from 1986 to 2016 in all seasons in the Andassa watershed of the Blue Nile Basin, Ethiopia.

The Borana rangelands are characterized by four distinct seasons, each of 3 months' duration. The NDVI maps were prepared based on the seasonal distribution observed in the study area. Bega and Kiremt are the dry seasons in the study area, and the NDVI values for these seasons were below the annual averages. During the drier seasons, the region is characterized by its poor vegetation since the shortage of rainfall and lack of soil moisture is responsible for the poor vegetation commonly observed. The western extreme area of the Borana rangelands is characterized by its very low NDVI, i.e., a proportion of a water feature (Chew-Bahir) and the southwestern areas across the Ethiopia–Kenya border was mainly uncovered by any type of vegetation (hence bare soil) for most of the years. This result is consistent with Muir et al. (2021), who observed cumulative declines in the NDVI, with the greatest change in the dry season in the arid areas of northern Ethiopia. The findings of Getahun and Shefine (2015) are consistent with the current findings in that climate variability is extremely common during the short rainy season and continues to affect the vegetation condition in Gojjam (north-central areas of Ethiopia).

The Borana rangelands are characterized by moderate vegetation conditions, particularly during Belg, the main rainy season. Most of the vegetation types are herbaceous and seasonal plants that start to dry when the rain stops. Meher is the other season when the vegetation condition looks better for the second time in a year. The degree of greenness during this time is lower than that of Belg. However, during both rainy periods, the NDVI change is observed from year to year and place to place, following the intensity and distribution of rainfall in the study area. Getahun and Shefine (2015) observed a highly variable NDVI and rainfall during the growing season in Gojjam, similar to the present study. Tadesse et al. (2020) found high spatial and temporal

dynamics of woodland vegetation in the semi-arid areas of the northwestern parts of Ethiopia. In addition, Kalisa et al. (2019) noted higher seasonal variability of the NDVI during the short compared to the long rainy season in Eastern Africa between 1982 and 2015, and this supports what we have found in the current study.

The vegetation condition of the Borana rangelands, based on the VCI during different seasons, indicates that the Kiremt season has mild dryness, while there are near normal conditions of vegetation during the rest of the seasons. Although the NDVI during Bega is below average, the VCI during the same season exhibited an above average vegetation condition. Both indices suggest the similar nature of the vegetation during the wet seasons and the dry seasons in the study area.

An inadequate amount of rainfall is obtained in the Borana rangelands, which is mainly distributed during the two wet seasons. This determines the condition of vegetation growth in the region, although internal variation exists between different geographical locations. Overall, the mean annual rainfall received in the Borana rangelands is at its maximum in the northeastern areas, followed by the northwestern areas, and decreases toward the southwestern areas on an annual basis. The areas receiving relatively better rainfall are attached to the foothills of the highlands in the north, and the influence of topography on climate variables is one of the most significant in the case of Ethiopia, among other factors. Seasonally, the rainfall received during Belg follows a similar pattern to that of the annual rainfall but the Meher rainfall is concentrated in the northeastern regions. Vegetation greenness was commonly observed during these wet seasons in most of the years under study. It should be noted that the green vegetation observed during these seasons are herbaceous plants, following the rainy periods, and these plants covering most of the areas start dying by the time the amount of rainfall obtained starts decreasing. An increase in the NDVI was supported by the observed increase in precipitation in the northern counties of Taiwan (Tsai & Yang, 2016). Measho et al. (2019) further observed a significant positive correlation between the growing season NDVI and precipitation in the semi-arid region of Eritrea from 2000 to 2017. The same characteristics were observed in Ethiopia (Liou & Mulualem, 2019), in Ningxia, China (He et al., 2020), and in Inner Mongolia between 2002 and 2019 (Hao et al., 2021).

Temperature, unlike rainfall, is less variable in the Borana rangelands. The mean annual temperature observed is more or less similar to that observed during *Belg* and *Meher*. However, relatively, *Bega* and *Kiremt* are seasons of extreme temperature conditions, with *Bega* being the warmest season and *Kiremt* being the coolest season. The mean temperature at an annual scale is the lowest in the north-central region and increases toward the southeastern and southwestern regions. These regions are characterized both by lower elevation and being devoid of vegetation, which likely contributes to the warmer conditions prevailing. The reason is that vegetation regulates the warmer temperature of a place through sequestering carbon. With minor variations, the spatial distribution of seasonal temperature looks similar to the annual pattern in the Borana rangelands. Hence, the response of vegetation cover toward temperature fluctuation is not higher, unlike rainfall in this semi-arid region. [Hao et al. \(2021\)](#) observed that vegetation growth in drier areas is controlled by precipitation and solar radiation more than other climatic factors. Furthermore, as reported by [He et al. \(2020\)](#), the sensitivity of vegetation toward climatic variables shows significant seasonal variation.

We found a positive correlation between MODIS vegetation indices and climate variables in this study. Weak correlation was observed between the NDVI and VCI for rainfall at an annual basis and during the drier seasons. On the contrary, a significant strong positive correlation exists between these indices and the rainy seasons. Therefore, in this study, both the NDVI and VCI are strongly influenced by *Belg* and *Meher* rainfall, and the influence is significant. [Tadesse et al. \(2020\)](#) observed precipitation as a significant factor for woodland vegetation and as having a positive correlation with the NDVI. In addition, a strong positive correlation has been found between the NDVI and seasonal rainfall in most years from 2000 to 2008 ([Getahun & Shefine, 2015](#)). Similar observations have been made by several authors in their respective studies ([Jiang et al., 2019](#); [Kalisa et al., 2019](#); [Wedajo et al., 2019](#); [Zhang et al., 2020](#)).

The mean annual temperature is moderately associated with the NDVI but weakly associated with the VCI (not statistically significant). Both the *Belg* and *Meher* temperatures are moderately correlated with the NDVI and VCI. In this case, the degree of influence of the temperature during *Belg* and *Meher* over the mean NDVI and VCI is moderate. In this study, the *Kiremt* temperature was found to significantly influence the vegetation condition in the study area more than rainfall. [Muir et al. \(2021\)](#) noted the larger effects of temperature on the NDVI, which is consistent with the present study, particularly during *Belg* and *Meher*. In contrast to this paper, a negative correlation was found between temperature and NDVI in Gojjam ([Getahun & Shefine, 2015](#)), in Nigeria ([Igbawua et al., 2016](#)), and in the Dhidhessa River Basin of Ethiopia ([Wedajo et al., 2019](#)). On the other hand, [Zewdie et al. \(2017\)](#) and [Melku et al. \(2020\)](#) associated the declining patterns of vegetation dynamics in northwestern Ethiopia and the Gojeb River catchment of the Omo-Gibe Basin, Ethiopia, respectively, with increasing pressure from human activities, apart from the effects of natural factors.

5 Conclusion

This research was conducted to analyze vegetation dynamics at spatiotemporal scales and its nexus with climate variables in the

Borana rangelands of southern Ethiopia. Both the NDVI and VCI showed the Borana rangelands are dominated by sparse vegetation, especially shrubs and grasslands, during the entire study period. The vegetation condition (greenness or dryness) varies from one region to another across the study area, and it is highly influenced by climate variability and change. Climate variables are strongly associated with the NDVI and VCI, particularly during the growing seasons, namely, *Belg* and *Meher*. During the growing seasons, both rainfall and temperature are strongly associated with the NDVI and VCI (statistically significant), whereas during *Bega* and *Kiremt*, the correlation coefficient exhibited weak to moderate association (not significant). Therefore, the vegetation dynamics in the Borana rangelands are strongly influenced by climate variability. The findings of this study provide a clear picture of the influence of climate variability on the vegetation condition under an annual and seasonal timescale. Hence, the results are beneficial for the development of proper intervention policies and provide information relevant to sustainable rangeland management in the study area.

Data availability statement

The data analyzed in this study are subject to the following licenses/restrictions: The meteorology data used to support the findings of this study are available from the corresponding author upon request. Requests to access these datasets should be directed to adismite2011@gmail.com.

Author contributions

MW conceptualized the paper and was also involved in the literature review, data collection, analysis, and paper writing. GF and KB were involved in the literature review, data analysis, and paper writing. EG was involved in the literature review and paper writing. All authors read and approved the final manuscript for publication.

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Conflict of interest

Author EG was employed by Climpect Data Science.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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