

## Spatiotemporal Variation of Vegetation Cover on the Qinghai-Tibet Plateau and Its Response to Climatic Factors: Postprint

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### Abstract

Investigating the spatiotemporal distribution characteristics of vegetation cover on the Tibetan Plateau holds significant ecological value and practical implications for advancing understanding of climate change and ecological conservation. Utilizing MODIS NDVI data at 1 km/month resolution from 2000–2016 along with meteorological observation data, and employing the maximum value compositing method, trend analysis, and correlation analysis, this study examines the distribution characteristics of NDVI across the Tibetan Plateau at various temporal scales and its relationship with precipitation and temperature. The results demonstrate: (1) Vegetation conditions in the southeastern Tibetan Plateau are substantially better than those in the northwestern region, with the distribution pattern of vegetation cover exhibiting strong consistency with the spatiotemporal distribution of regional hydrothermal conditions. Over the past 17 years, the area of vegetation improvement on the Tibetan Plateau has exceeded that of degradation, with severely degraded regions primarily located in the southwestern plateau. NDVI values exhibited a modest increasing trend from 2000 to 2016. (2) Except for summer precipitation, precipitation in all other seasons displayed an increasing trend during the study period, while temperatures showed an increasing trend across all seasons, most notably in spring, indicating an overall “warm-humidification” trend in the Tibetan Plateau climate. Overall, annual precipitation demonstrated a strong positive correlation with annual maximum NDVI, whereas annual mean temperature showed a positive correlation with annual maximum NDVI in the southeastern plateau but a negative correlation in the southwestern plateau. Both precipitation and thermal conditions constitute influencing factors for plateau vegetation growth, with precipitation exerting a more pronounced influence on vegetation cover than temperature.

## Full Text

### Preamble

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**Spatio-temporal Variation of Vegetation Coverage over the Tibetan Plateau and Its Responses to Climatic Factors\***

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### Abstract

Investigating the spatio-temporal distribution characteristics of vegetation cover over the Tibetan Plateau holds significant ecological value and practical importance for enhancing our understanding of climate change and ecological environmental protection. Using monthly Normalized Difference Vegetation Index (NDVI) data at 1 km resolution from the Moderate-resolution Imaging Spectroradiometer (MODIS) spanning 2000–2016, along with meteorological observation data, this study analyzed the distribution patterns of NDVI across different temporal scales and its relationship with precipitation and temperature over the Tibetan Plateau based on Maximum Value Composites (MVC), linear trend analysis, and correlation analysis methods. The results showed that: (1) Vegetation conditions in the southeastern plateau were significantly better than in the northwestern region. The spatial distribution pattern of vegetation coverage maintained good consistency with the spatio-temporal distribution of regional hydrothermal conditions. Over the past 17 years, the area of improved vegetation coverage was larger than that of degraded vegetation, with severely degraded areas mainly located in the southwestern plateau. NDVI exhibited an increasing trend with small amplitude across the Tibetan Plateau from 2000 to 2016. (2) Except for summer precipitation, which showed a decreasing trend, seasonal precipitation in other seasons increased during the study period, while seasonal temperature presented an increasing trend, with spring temperature increasing at the highest rate. Overall, climate change exhibited a “warm and humid” variation trend over the plateau. Annual precipitation was positively correlated with annual maximum composite NDVI. Mean annual temperature

was positively correlated with NDVI in the southeastern plateau and showed an inverse relationship with NDVI in the southwestern region. Both precipitation and heat conditions affected vegetation growth, with precipitation having a more significant effect on vegetation than temperature.

**Keywords:** normalized difference vegetation index; Tibetan Plateau; spatio-temporal distribution; climate change

## Introduction

Against the backdrop of global climate change, human activities, and increasing greenhouse gases, the Tibetan Plateau—as a climate-sensitive zone and ecologically fragile region—has exhibited a warming trend, causing glacier retreat, wetland area shrinkage, and permafrost active layer thinning, leading to regional grassland degradation and desertification in agricultural and pastoral areas. Alpine grasslands and meadows serve as the primary forage source for local herders, and issues such as grassland freeze-thaw cycles have become increasingly prominent. Changes in biomass production, allocation, and community structure directly impact the economic livelihoods of farmers and herders, while environmental changes on the Tibetan Plateau have profound effects on global ecosystems. Studying the distribution characteristics and variation patterns of alpine vegetation and its response to climate can deepen our understanding of climate and ecological change mechanisms on the Tibetan Plateau, holding vital ecological value and practical significance.

Previous research on Tibetan Plateau vegetation coverage has primarily focused on spatio-temporal distribution characteristics of vegetation cover, climatic factors affecting vegetation growth, and phenological information of alpine meadows. Studies on the plateau's vegetation spatio-temporal distribution have mainly employed satellite remote sensing monitoring analyses from different sources. For instance, Long et al. [9] analyzed vegetation cover dynamic changes in China since the 1980s, identifying the Tibetan Plateau as one of the main regions experiencing vegetation cover decline. Regarding local vegetation changes on the plateau, Zhuoga et al. [10-11] analyzed vegetation distribution and variation trends in Tibet, discussing how climate change and human activities affected vegetation variation characteristics in different regions. Other studies [12-14] suggested that vegetation in Ali region showed improvement, while grassland degradation in Nagqu exhibited a pattern of initially rapid then slowing decline, with vegetation in Lhasa showing a closer relationship with precipitation than temperature. Lü Yang et al. [15] employed trend analysis and Hurst exponent methods, while Liao Qingfei et al. [16] analyzed spatio-temporal variation trends and abrupt change characteristics of vegetation cover in the eastern agricultural region of Qinghai Province, concluding that precipitation variation and grain-for-green measures were important influencing factors for vegetation cover changes.

In studies examining overall plateau vegetation characteristics, Peng et al. [17]

used Hurst exponent to indicate vegetation growth trends on the Tibetan Plateau, while other research [18] utilized ecological models to reveal overall vegetation increase with local degradation phenomena. Studies at different temporal scales [19] showed that Tibetan Plateau vegetation overall exhibited a fluctuating upward trend. Li Bin et al. [20] used semi-variogram analysis to explore spatio-temporal variation characteristics of plateau vegetation, and Li Huixia et al. [21] quantitatively assessed the implementation effects of ecological protection and construction projects in the Three-River Headwaters region by separating contributions of climatic elements and human activities to vegetation indices. Increased precipitation on the Tibetan Plateau can promote vegetation growth, with both showing good positive correlation [22-23], though Peng et al. [24] found that areas with good precipitation-vegetation cover correlation were mainly located in the northeastern plateau. While temperature increases benefit alpine plant growth [25], excessively high temperatures are detrimental to alpine grassland development [24,26]. Xu Manhou et al. [27] conducted warming simulation experiments on alpine meadow vegetation, concluding that appropriate warming and precipitation could significantly promote alpine meadow vegetation growth. Regarding phenological research, Ma Xiaofang et al. [28-31] extracted phenological information of alpine grasslands on the Tibetan Plateau, analyzing variation trends in annual average conditions, green-up period, senescence period, and growing season length, as well as their response patterns to climate change.

Most previous studies on Tibetan Plateau vegetation cover have used NOAA (National Oceanic and Atmospheric Administration) AVHRR-NDVI data, focusing on vegetation distribution characteristics in different plateau regions or phenological information of alpine meadows, with few addressing overall plateau vegetation cover characteristics under recent global warming [32-33]. Particularly unclear are questions regarding whether precipitation and temperature on the Tibetan Plateau show positive or negative correlations with vegetation cover at different temporal scales. This study utilizes relatively high spatio-temporal resolution MODIS (Moderate-resolution Imaging Spectroradiometer) NDVI satellite products and meteorological data from 98 stations across the Tibetan Plateau, employing Maximum Value Composites (MVC), trend analysis, and correlation analysis methods to analyze vegetation cover spatio-temporal distribution and variation patterns across different temporal scales over the past 17 years under global warming, and to explore the impacts of precipitation and temperature changes on vegetation cover, providing theoretical support for environmental protection and ecological security barrier construction in plateau regions.

## 1. Study Area

The Tibetan Plateau is located in southwestern China, extending from the Pamir Plateau in the west to the Hengduan Mountains in the east, and from the Himalayas in the south to the Kunlun and Qilian Mountains in the north. Within

China's borders, it measures approximately 2,945 km from east to west and 1,532 km from north to south, covering  $2.62 \times 10^6$  km<sup>2</sup> and accounting for 26.8% of China's total land area [28,34]. As the world's highest-altitude plateau, the Tibetan Plateau features warm-humid climate in the southeast and dry-cold climate in the northwest under the combined influence of various geographical factors. The plateau's climate is characterized by strong solar radiation, large diurnal temperature variation, and small annual temperature variation. Precipitation decreases from southeast to northwest, with distinct wet and dry seasons.

[Figure 1: see original paper] Altitude and location of meteorological stations over the Tibetan Plateau

## 2. Data Sources

The Normalized Difference Vegetation Index (NDVI) can characterize vegetation cover degree and growth status, enabling monitoring of vegetation growth dynamics. Through the combination of infrared and near-infrared bands, NDVI can express vegetation information status and objectively reflect vegetation cover degree and growth conditions across large spatio-temporal scales, including leaf area index, biomass, and absorbed photosynthetically active radiation [38-40]. Its time-series data have become a fundamental tool for large-scale vegetation studies based on bioclimatic characteristics [41], and NDVI has been widely applied in global and regional large-scale vegetation change and climate interaction studies.

The data were obtained from MODIS NDVI satellite products provided by the MODIS Land Processes Distributed Active Archive Center (LP DAAC, <http://lpdaac.usgs.gov/main.asp>). The data format is HDF-EOS, with Sinusoidal projection. Reprojection processing was performed using the MODIS Reprojection Tool (MRT) to convert the data to standard latitude-longitude grid coordinates. Remote sensing image processing software ENVI (The Environment for Visualizing Images) was used to mosaic downloaded data according to the Tibetan Plateau extent, clip the plateau vector boundary, and save the output as GEOTIFF format for subsequent correlation calculations between vegetation indices and meteorological elements, mapping of vegetation spatial distribution, and plotting of variation trend curves.

Meteorological data were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>), including monthly precipitation and temperature data from 98 meteorological stations across the Tibetan Plateau region from 2000 to 2016. The stations include all sites in Qinghai and Tibet, as well as Tashikuergan in Xinjiang, Wushaoling, Maqu, and Hezuo in Gansu, Deqin and Zhongdian in Yunnan, and Shiqu, Muli, and Jiulong in Sichuan.

### 3. Methods

The study period was divided into interannual, seasonal, and growing season temporal scales. Seasonal division followed meteorological standards: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February of the following year). The growing season was selected as June-September. Maximum Value Composites (MVC) were adopted, which can eliminate cloud effects on vegetation indices to some extent and obtain the maximum NDVI values for different study periods.

For vegetation cover classification, an equal-interval method [32] was used to divide NDVI values into different grades. Vegetation change rates were classified as severely degraded, moderately degraded, lightly degraded, basically unchanged, lightly improved, moderately improved, and significantly improved based on the magnitude of change rate. The variation trend over time was analyzed using trend line analysis [42], performing unary linear regression analysis on NDVI values for each grid cell. The regression equation's change rate (slope) indicates the vegetation cover change trend during 2000-2016: slope  $> 0$  indicates increasing vegetation cover with more obvious trends as values increase; slope  $< 0$  indicates decreasing vegetation cover; slope  $= 0$  indicates no change.

The linear regression of vegetation index and climate element  $x$  with time  $t$  was fitted using least squares method to obtain the change rate of vegetation index and climate elements over time. When analyzing relationships between vegetation index and climate elements, NDVI values were first interpolated to each observation station to calculate correlation coefficients between NDVI and precipitation/temperature. In trend or correlation coefficient analysis, if the correlation coefficient exceeds the critical value corresponding to degrees of freedom  $n-2$  in the significance test table, the change rate or correlation coefficient passes the specified significance level  $P$  value test.

## 2. Results Analysis

### 2.1 Spatial Distribution Characteristics of Vegetation Cover

The spatial distribution maps of multi-year average vegetation index for different seasons, growing season, and annual composites in 2016 show that vegetation conditions in the southeastern Tibetan Plateau were significantly better than in the northwestern region. Due to the influence of the East Asian summer monsoon, the southern plateau receives favorable hydrothermal conditions, supporting evergreen broadleaf forests and coniferous forests, while the northwestern plateau is basically arid with poor hydrothermal conditions, supporting grasslands and deserts. This indicates that the vegetation cover distribution pattern maintains good consistency with the spatio-temporal distribution of regional hydrothermal conditions.

In spring, overall vegetation cover across the plateau was relatively poor, with the best vegetation conditions (NDVI  $> 0.8$ ) located in Nyingchi in southeastern

Tibet, where dense forests are distributed. Areas with better vegetation cover (NDVI > 0.4) were located in the eastern and southeastern plateau, particularly in eastern Qinghai, western Sichuan plateau, and southeastern Tibet. Most plateau areas had NDVI values corresponding to vast deserts in western Qinghai and northern Tibet, with NDVI < 0.2.

As summer and the rainy season arrived, plateau vegetation conditions improved, with areas of NDVI > 0.4 gradually increasing from southeast to northwest. With the end of the rainy season and gradually decreasing temperatures, vegetation began to wither. In winter, plateau vegetation cover showed significant heterogeneity, with NDVI > 0.8 areas mainly located in eastern and southern Qinghai, western Sichuan plateau, and central-eastern Tibet, though these areas decreased compared to summer. The NDVI > 0.4 region shrank sharply southward, mainly located in eastern and southern western Sichuan plateau and southeastern Tibet, while NDVI > 0.6 and NDVI > 0.8 areas decreased significantly.

The spatial distribution of vegetation cover during the growing season and annually was similar to summer characteristics, as the plateau's vegetation growth period is shorter than in plain areas, with the fastest growth period concentrated in summer. However, there were differences in individual regions, with NDVI > 0.8 areas being larger in growing season and annual composites than in summer.

## 2.2 Temporal Variation Characteristics of Vegetation Cover

Vegetation cover change showed obvious seasonal and regional differences. Figure 3 illustrates vegetation change trends across different study periods from 2000-2016. Plateau vegetation experienced both growth and degradation. In spring, most plateau areas showed increasing vegetation trends, distributed in eastern and southern Qinghai, northern western Sichuan plateau, and southeastern Tibet, while central-eastern Nagqu in Tibet and southern western Sichuan plateau experienced severe degradation. In summer, vegetation increase areas were located in northern plateau and most of Qinghai, while vegetation cover decrease areas were in central-western Tibet, particularly evident in northern Tibet. In autumn, vegetation decrease was most obvious, concentrated in southeastern plateau and southern Qinghai. In winter, most plateau vegetation cover showed increasing trends, located in northeastern and southern Qinghai.

The spatial distribution of vegetation cover change during growing season and annually was similar to summer characteristics. Overall, improved vegetation cover area on the Tibetan Plateau was larger than degraded area, with improvement reaching 72%-75% of plateau area and degradation accounting for 25%-28%. Based on annual average NDVI change slope data and distribution patterns, severely degraded areas were mainly located in southwestern Tibetan Plateau (0.0003% of total area), moderately degraded areas were distributed in central-western Tibet and southern Qinghai (0.0045% of total area), and lightly

degraded areas were relatively widespread across most regions except southeastern Tibet (0.1130% of total area). Basically unchanged areas covered 89.4894% of total area, lightly improved areas covered 10.5453%, moderately improved areas covered 0.0739%, and significantly improved areas covered 0.0046%.

The implementation of ecological protection measures such as grain-for-green and grassland ecological compensation mechanisms in recent years has increased moderately and lightly improved vegetation areas in plateau regions, leading to obvious improvement in most plateau vegetation conditions, though different degrees of degradation still exist.

The annual NDVI variation over the Tibetan Plateau from 2000-2016

Based on monthly NDVI statistics from 2000-2016, monthly averages changed with seasons. Due to the long winter half-year with less precipitation and clear weather, NDVI basically remained around 0.1572. After March, with increasing temperature and precipitation, vegetation began to green up, particularly evident in southeastern plateau, and NDVI values increased rapidly. In August, when vegetation was most vigorous, NDVI reached its maximum value (0.3393). After September, with crop maturity, most vegetation began to shed leaves, and NDVI decreased sharply to the annual minimum in December (0.0021). The standard error of monthly NDVI variation was very small, effectively reflecting the annual variation pattern.

Figure 5 shows the variation trends of NDVI in different seasons, growing season, and annually across the Tibetan Plateau. From the annual mean curve and its linear trend, NDVI showed a significant increasing trend from 2000-2016 with a rate of 0.007/10a and correlation coefficient of 0.613 ( $P < 0.01$ ). After minor fluctuations in 2005, NDVI gradually increased, reaching its lowest value in 2009 (0.3641), then showing a slight decreasing trend before reaching its peak in 2012 (0.3726), followed by a slight decline.

Different seasonal NDVI curves indicated that winter and growing season NDVI showed obvious increasing trends, with increases of 0.01/10a and 0.008/10a respectively, and correlation coefficients of 0.686 and 0.672 (both  $P < 0.01$ ). Other seasons also showed increasing trends: spring (0.008/10a,  $r = 0.621$ ), summer (0.003/10a,  $r = 0.242$ ), and autumn (0.007/10a,  $r = 0.629$ ), with all except summer passing significance tests ( $P < 0.01$ ).

[Figure 2: see original paper] Distribution of maximum NDVI during different seasons over the Tibetan Plateau from 2000-2016

[Figure 3: see original paper] The slope of maximum NDVI during different seasons over the Tibetan Plateau from 2000-2016

[Figure 4: see original paper] The monthly variation of NDVI over the Tibetan Plateau from 2000-2016 (short lines refer to error bars)

[Figure 5: see original paper] The variation trend of NDVI during different seasons over the Tibetan Plateau

### 3. Climate Factor Variation Characteristics

Multi-year monthly average precipitation and temperature showed basically consistent unimodal patterns. Precipitation was lowest in December and January, while minimum temperature occurred in January. Both temperature and precipitation increased significantly after March, reaching annual maximum values in July (precipitation) and August (temperature). The monthly variations showed similar annual patterns to NDVI, though NDVI maximum slightly lagged behind precipitation and temperature peaks.

The monthly precipitation and temperature over the Tibetan Plateau from 2000-2016

Analysis of precipitation and temperature trends in different periods from 2000-2016 showed that winter had the lowest precipitation and temperature, while summer had the highest temperature. Growing season precipitation was highest. Precipitation trends indicated that except for summer precipitation showing a decreasing trend (-4.09mm/10a, not significant), other seasonal precipitation increased, particularly evident in autumn and spring with increases of 2.51mm/10a and 1.99mm/10a respectively. Overall precipitation showed a slow increasing trend, though the change was not significant.

Different study periods all showed increasing temperature trends, particularly significant in spring (0.63°C/10a,  $P < 0.01$ ), followed by summer and growing season (0.43°C/10a). Winter showed the smallest warming amplitude (0.14°C/10a,  $P < 0.10$ ). Except for winter temperature, other seasonal temperature trends passed significance tests ( $P < 0.01$ ). Interannual fluctuations of average temperature in different periods were generally small, particularly for spring and growing season.

Analysis of precipitation and average temperature data from 98 meteorological stations showed large variation in annual average temperature across the Tibetan Plateau from 2000-2016, with multi-year average temperature of 4.56°C. Temperature increased significantly with fluctuations, reaching minimum in 2009 (3.79°C) and secondary low in 2015 (5.15°C), with correlation coefficient of 0.45/10a ( $P < 0.01$ ). Annual precipitation variation was relatively small, with multi-year average of 485.83mm, reaching minimum in 2000 (432.11mm) and maximum in 2016 (537.37mm). Overall, annual precipitation showed a slow increasing trend with amplitude of 2.04mm/10a and correlation coefficient of 0.032, not passing significance tests. Tibetan Plateau climate change presented a “warm-humid” trend.

[Figure 6: see original paper] The variation of annual precipitation and temperature over the Tibetan Plateau from 2000-2016

### 4. Response of Vegetation Cover to Climate Factors

Vegetation index is closely related to climate factors, which can regulate and alter vegetation cover distribution [43-44]. Based on the 17-year average annual

maximum composite NDVI, average temperature, and precipitation, no significant abrupt change occurred in precipitation, while both average temperature and NDVI showed significant increasing abrupt changes, indicating that recent average temperature and vegetation cover have basically consistent increasing trends, though NDVI increase lagged behind temperature increase.

Interpolating the multi-year average annual maximum composite NDVI of each pixel to meteorological stations revealed that both annual precipitation and annual average temperature were positively correlated with annual maximum composite NDVI, passing significance tests ( $P < 0.10$ ). Precipitation showed better spatial correspondence with vegetation index than temperature. Increased precipitation could extremely significantly promote alpine meadow vegetation growth, while temperature increases could meet heat requirements for normal vegetation growth to some extent, with appropriate warming promoting plateau vegetation growth. However, excessively high temperatures alter plant community microclimate environments, inhibiting vegetation cover [24,26] and directly or indirectly affecting vegetation growth and development.

To understand vegetation index responses to precipitation and average temperature in different plateau regions, correlation coefficients between annual precipitation/average temperature and corresponding vegetation indices were calculated for each plateau observation station. Annual precipitation and vegetation index showed positive correlation in most plateau areas, particularly in northeastern plateau including most of Qinghai, northwestern Tibet, and southern western Sichuan plateau, demonstrating precipitation benefits for grassland vegetation growth [22-23]. Negative correlation areas were mainly located in southeastern Qinghai, most of Tibet, and northern western Sichuan plateau. Positive correlation areas between annual average temperature and vegetation index were mainly located in most of Qinghai, northwestern Tibet, and southern western Sichuan plateau, particularly in central-eastern Tibet, while negative correlation areas were in southwestern plateau, reflecting that temperature has adverse effects on vegetation growth in specific regions.

[Figure 7: see original paper] Correlation coefficients between annual NDVI and annual precipitation or annual mean temperature

For precipitation-scarce and low-temperature areas in western plateau (e.g., Ali region), both precipitation and temperature showed positive correlation with vegetation. For precipitation-rich areas in southeastern plateau, both precipitation and heat conditions affected vegetation, though excessive precipitation might inhibit vegetation growth [24]. For different underlying surfaces, grassland and desert cover areas showed relatively close positive correlation between NDVI and temperature [11], particularly more significant for grassland, while forest areas showed non-significant temperature relationships.

Overall, precipitation had greater impact on vegetation cover than average temperature on the Tibetan Plateau. Both precipitation and temperature showed positive and negative correlations with vegetation index, with precipitation-

vegetation correlations being more significant and passing significance tests ( $P < 0.10$ ).

#### 4. Conclusions

This study analyzed spatio-temporal characteristics and variation trends of vegetation on the Tibetan Plateau from 2000-2016, reaching the following conclusions:

1. Vegetation conditions in southeastern Tibetan Plateau were significantly better than in northwestern plateau. The vegetation cover distribution pattern maintained good consistency with spatio-temporal distribution of regional hydrothermal conditions. In recent years, most plateau vegetation conditions have improved significantly, while severely degraded areas were mainly located in southwestern Tibetan Plateau.
2. NDVI across the Tibetan Plateau from 2000-2016 showed a small amplitude increasing trend. Vegetation changes in all periods passed significance tests ( $P < 0.01$ ). Except for summer precipitation showing a decreasing trend (-4.09mm/10a), precipitation in other seasons increased, and temperatures in all periods showed increasing trends, particularly significant in spring. Overall, Tibetan Plateau climate change presented a “warm-humid” trend.
3. Annual precipitation and average temperature were generally positively correlated with annual maximum composite NDVI, though negative correlation areas existed. Precipitation showed better correlation with vegetation index than temperature. Precipitation had more significant impact on vegetation cover than average temperature on the Tibetan Plateau.

Some studies [45] using Enhanced Vegetation Index (EVI) concluded that Tibetan Plateau vegetation showed non-significant decreasing trends because degradation rates exceeded improvement rates. Differences in study periods and quantitative analysis of vegetation increase/decrease rates, as well as initial climate state effects on vegetation cover changes, may explain discrepancies with our conclusions. This study's conclusions are limited to central-eastern plateau due to sparse observation stations in western plateau. Future research should employ grid data, satellite-estimated precipitation, and relative humidity data to further investigate vegetation type differences and climate response interactions in different plateau regions.

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