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Original Research

Analysis of Spatial and Temporal Variations of NDVI and its Influencing Factors During the Vegetation Growing Season from 1999 to 2019 in Inner Mongolia

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Abstract

Global climate change exerts a profound influence on regional vegetation dynamics. Investigating the spatial and temporal variations of the normalized difference vegetation index (NDVI) within watersheds and its responses to climate change is essential for supporting the development and management of regional ecological environments. This study analyzed spatial and temporal variations of NDVI during the vegetation growing season in Inner Mongolia, along with its responses to climate change, using slope analysis and correlation analysis. The study utilized monthly NDVI composite products from MODIS and meteorological data spanning 1999 to 2019. The key findings are: Inner Mongolia's spatial distribution of average NDVI values exhibited a distinct pattern, with values decreasing progressively from northeast to southwest. During the study period, the mean NDVI values in Inner Mongolia during the growing season demonstrated a significant upward trend, with an average annual increase of 0.0016. Over the 21-year period, temperature trends in Inner Mongolia remained relatively stable, whereas precipitation showed a significant increasing trend. The correlation between vegetation NDVI and climatic factors during the growing season varied significantly across regions. Precipitation was found to have a stronger and more consistent influence on vegetation growth compared to temperature, underscoring its pivotal role in the region. The interannual shift in the center of gravity of average NDVI values was minimal, predominantly confined to northeastern Inner Mongolia. These findings offer a valuable scientific basis for Inner Mongolia's ecological environment protection and restoration efforts.

Keywords: inner Mongolia, normalized difference vegetation index, precipitation, temperature

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Introduction

In terrestrial ecosystems, vegetation represents a critical component, functioning as an essential barometer for environmental changes [1-4]. Both climate change and anthropogenic activities significantly influence vegetation. Under the pervasive influence of climate change, key environmental factors such as temperature and precipitation – vital for the phenology, growth, development, and reproduction of vegetation – affect vegetation by altering the environmental conditions to which it is exposed [5-7]. The unpredictability introduced by human activities further complicates the growth and development of vegetation [8]. Consequently, the dynamics of vegetation change have become a central focus of global change research, emphasizing the need for a comprehensive understanding of the interactions between vegetation cover, environmental factors, and their responses to climate change and human interventions [9-11].

Vegetation indices provide valuable indirect measures of surface vegetation growth and cover, biomass magnitude, and vegetation types [12]. Among these indices, the Normalized Difference Vegetation Index (NDVI), which quantifies vegetation growth by measuring the difference between near-infrared (NIR) and red (RIR) light, is extensively employed for quantitative analyses of vegetation cover [13-15]. The NDVI serves as a critical indicator of ecosystem health, reflecting parameters such as vegetation cover, biomass, and biodiversity. Its applications extend significantly to land management and ecological restoration. By analyzing NDVI variations, practitioners can assess the efficacy of restoration efforts, identify priority intervention areas, and optimize management strategies. Furthermore, the NDVI is a pivotal tool for monitoring ecosystem health, supporting the achievement of Sustainable Development Goals (SDGs). Integrating NDVI data into policy development can promote climate action, terrestrial ecological conservation, sustainable urban development, and international cooperation, thereby contributing to global sustainable development [16].

Extensive research on vegetation dynamics and their influencing factors has been conducted at varying scales using remote sensing technology, yielding significant insights [17, 18]. For instance, Novillo et al. analyzed NDVI trends and reported that vegetation growth outpaced its decline in the studied area [19]. Sharma et al. explored the relationship between NDVI and variables such as surface temperature, soil moisture, and precipitation in Nagar, India, revealing pronounced seasonal and interannual variability in vegetation growth [20]. Obuchowicz et al. utilized 35 years of annual and quarterly NDVI time-series data to evaluate vegetation cover dynamics in Switzerland, finding a 0.6% annual growth rate in average NDVI across 61% of the country [21]. Similarly, Liu et al. conducted a comprehensive spatial and temporal analysis of NDVI in China, integrating NDVI with the Standardized Precipitation Evapotranspiration Index (SPEI). Their findings indicated that 71.02% of the national land area exhibited improved vegetation, while 22.97% showed degradation, with an overall non-significant trend of aridity [22].

Research in the Mount Everest Nature Reserve revealed a general upward trend in grassland NDVI, with precipitation exerting a more pronounced effect than air temperature and grazing [23]. Pei et al. conducted a detailed analysis of NDVI's relationship with climatic factors across different monthly scales, focusing on Inner Mongolia grasslands. They observed that NDVI was significantly influenced by temperature and precipitation variations, with stronger correlations during the growing season [24]. Yang et al. examined NDVI temporal variations in Inner Mongolia from 1982 to 2011 and identified significant increases in annual NDVI values for typical and desert grasslands. However, no significant NDVI fluctuations were noted in desert grasslands during summer, autumn, or the entire growing season. Their findings highlighted a stronger correlation between NDVI and precipitation than air temperature [25].

Inner Mongolia, located on China's northern frontier, forms a significant part of the Mongolian Plateau, with grasslands serving as the dominant vegetation cover. This region, characterized by temperate arid and semi-arid ecosystems, is highly vulnerable to global climate change and functions as a critical ecological barrier in northern China [26, 27]. Spanning approximately 2,400 kilometers from east to west, Inner Mongolia exhibits diverse vegetation types – ranging from forests to grasslands and deserts – reflecting the gradients in precipitation and temperature [28, 29]. A detailed analysis of NDVI patterns and their responses to climatic factors in this region can elucidate the complex interactions between terrestrial ecosystems and climate variability, providing valuable insights for ecological restoration and sustainable development.

Although numerous studies have explored the spatial and temporal dynamics of NDVI in Inner Mongolia, most focus on interannual scales, often neglecting seasonal variations during non-growing periods. Additionally, a unified framework linking environmental factors to NDVI variability remains lacking. This study adopts the vegetation growing season (April to October) as the temporal framework to investigate the spatial and temporal patterns of NDVI and its responses to climatic variables across seasons. Using remotely sensed data and regional meteorological datasets from China, the research examines NDVI variations in Inner Mongolia from 1999 to 2019, offering scientific references for vegetation restoration and ecological conservation in the region.

Materials and Methods

Study Area

The Inner Mongolia Autonomous Region, located along the northern frontier of China within the Eurasian continent, spans a geographical range of 97º12′ to 126º04′E in longitude and 37º24′ to 53º23′N in latitude. This region is predominantly characterized by a plateau landscape, encompassing an area of approximately 118.3 Km^2, constituting 12.3% of China's total land area. The majority of the terrain lies at an elevation exceeding 1,000 m above sea level and experiences a temperate continental monsoon climate. The climatic conditions facilitate an extensive east-west orientation, with the region stretching roughly 2,400 km.

The soil types in Inner Mongolia are diverse, exhibiting distinct spatial distribution patterns shaped by variations in climate, topography, and vegetation. The eastern part of the region is significantly influenced by monsoonal activity, receiving relatively abundant annual precipitation of approximately 400-500 mm, primarily concentrated during the summer months. The prevailing climate in this area is temperate monsoon. Winters are characterized by consistently low temperatures across the region, with minimum temperatures dropping below -30ºC in high-latitude areas such as Hulunbuir and Xing'anmeng, where the winter season is prolonged. In contrast, summer temperatures vary, with moderate averages of around 20ºC in the eastern areas and peak temperatures exceeding 30ºC in the arid western desert zones [30].

As illustrated in Fig. 1, the gradients in precipitation and temperature drive a distinct transition in vegetation types from northeast to southwest. The predominant vegetation shifts from forests in the northeast to grasslands and eventually to desert landscapes towards the southwest [31].

Data Sources

This study utilized monthly NDVI synthetic products from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/). The dataset spans from January 1999 to December 2019, with a temporal resolution of one month and a spatial resolution of 1 km. Monthly and annual NDVI data were derived using the synthesis method and extracted from the vector layer representing the study area boundary in ArcGIS 10.4. This approach effectively captures inter-annual variations and growth patterns of vegetation.

Meteorological datasets, including monthly air temperature, precipitation, and evapotranspiration across China from January 1999 to December 2019, were sourced from the National Earth System Science Data Center (http://www.geodata.cn/). These datasets were constructed using the CRU global 0.5º climate data and WorldClim high-resolution climate data, with regional downscaling in China implemented via the Delta spatial downscaling method. To ensure reliability, the datasets were validated against observational data from 496

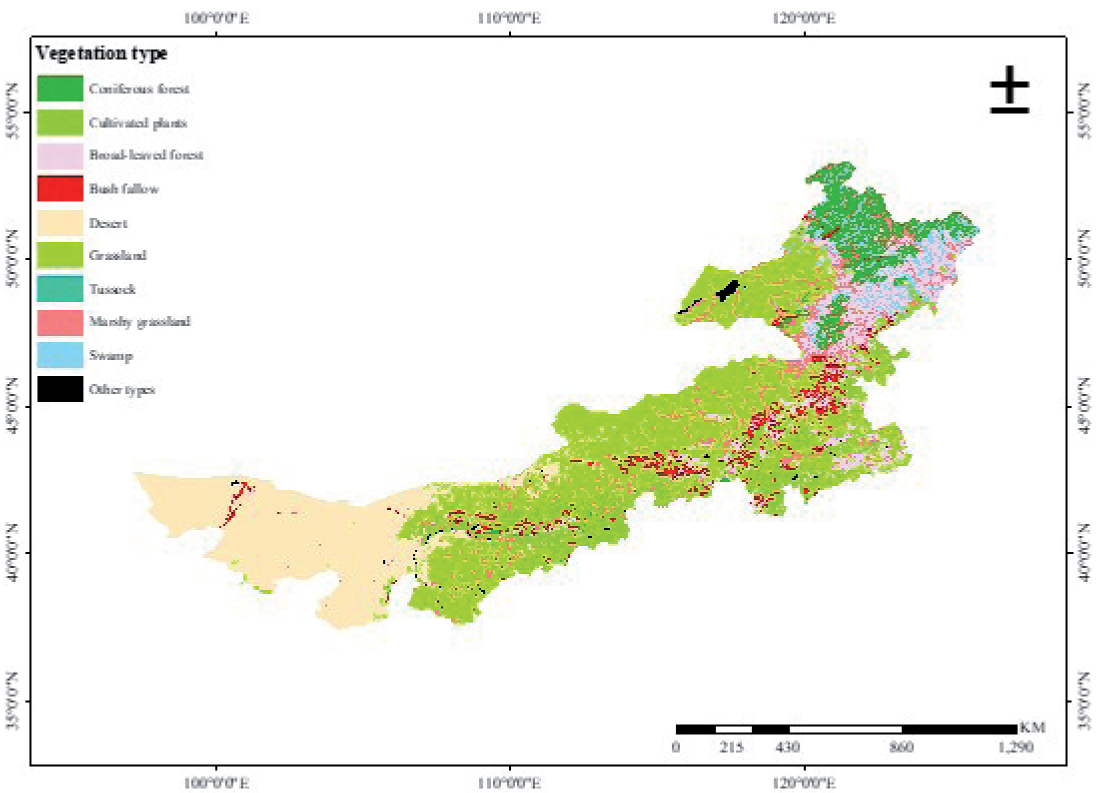

Fig. 1. Vegetation-type map of the study area.

independent meteorological stations. The meteorological raster data were then processed in ArcGIS, where the vector layer of the study area boundary was applied to extract masks consistent with the NDVI data in terms of pixel size and image projection.

Research Methods

Technical Flowchart

The technical flow of this study is shown in Fig. 2.

Analysis of NDVI Trends

For analyzing NDVI time-series data, the trajectory of each raster point was characterized using one-way linear regression analysis, applied to time-series data aggregated annually for each pixel. The slope calculation was conducted as follows [32]:

$$\text{slope} = \frac{n\sum_{i=1}^{n} i\text{NDVI}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \text{NDVI}_i}{n\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{1}$$

In the above formula, the variable i signifies the sequential number of years, ranging from 1 to 21, whereas NDVI_i represents the mean normalized difference vegetation index value for the i-th year, and n indicates the aggregate number of years under consideration, spanning 1999 to 2019 (21 years). The term *slope* delineates the trajectory of alteration observed for a single pixel element, which was segregated into three distinct categories based on the test results as follows: an ascending trend (*slope*>0), a descending trend (*slope* < 0), and a stable trend (*slope* = 0) [33].

The statistical significance of the NDVI time-series trends was evaluated using Pearson's correlation test. The resulting trends were assessed at a 95% confidence interval (P<0.05) to determine their statistical significance.

Calculation of the Correlation between NDVI and Climate Factors

Correlation analysis provides a robust methodology for elucidating the interrelationships between

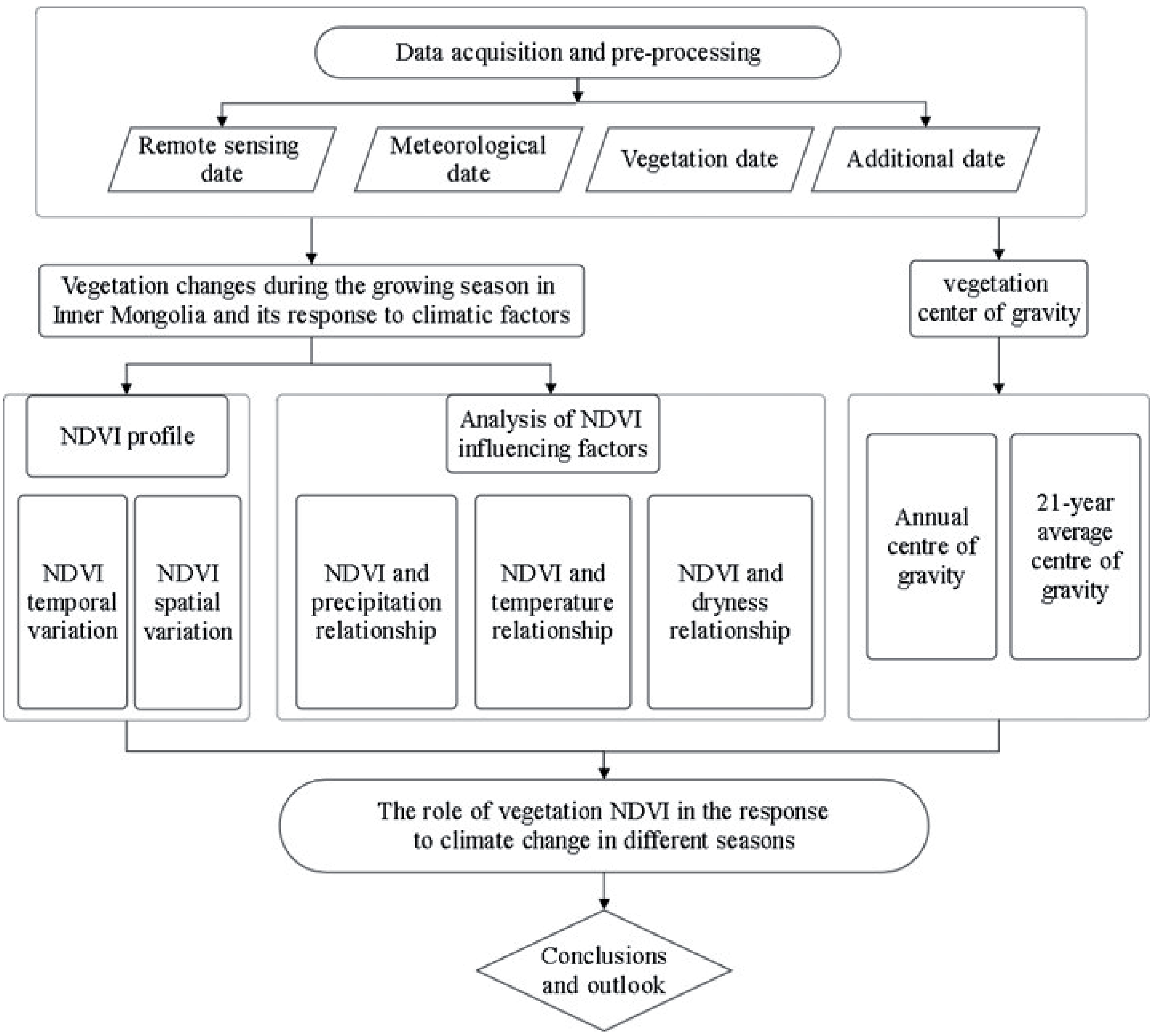

Fig. 2. Technical flowchart.

quantitative variables, such as geographical factors. The correlation coefficient quantifies the degree of correlation between two elements. When two variables share a relationship with a third variable, partial correlation analysis can be used to control for the influence of the third variable, thereby improving the accuracy of the correlation assessment between the primary variables. The formula for calculating the correlation coefficient is as follows [34, 35]:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2(y_i-\overline{y})^2}} \quad (2)$$

In the formula, R_{xy} denotes the coefficient of correlation between variable x and variable y; x_i and y_i denote the values of these two variables in the i year, with $\overline{x}$ and $\overline{y}$ as the average values of the two variables, respectively; and n is the total number of years (21 years in total, from 1999 to 2019).

Calculation of Drying Index

The drying index is a critical metric for quantifying regional wetness and dryness, with applications in climate science, hydrology, and vegetation studies. It has recently become a widely used indicator in global climate change research [36, 37]. Various experimental methods exist for calculating the drying index, with the most common approach using the ratio of annual potential evapotranspiration to annual precipitation, expressed as follows [38]:

$$AI = \sum ET_0 / \sum P \quad (3)$$

In the formula, AI is the aridity index, $\sum ET_0$ is the annual potential evapotranspiration (mm), and $\sum P$ is the annual precipitation (mm). In China, the area with an aridity index (AI)<1.0 is humid, whereas AI between 1.0 and 1.5 indicates a semi-humid area; AI between 1.5 and 4.0 denotes a semi-arid area, while AI>4.0 signifies an arid area.

The Vegetation Center of the Gravity Migration Model

The center of gravity migration model is a widely used analytical approach for identifying the temporal mean center of elements in a time series within a specific geographical area. This model enables detailed analysis of the targeted elements' spatial distribution and evolutionary dynamics using key indicators, including the centroid, movement vector, and displacement vector magnitude [39, 40]. Unlike traditional static analysis methods, the center of gravity migration model emphasizes the dynamic spatio-temporal variation of elements, providing direct insights into directional shifts. The formula for calculating the center of gravity is as follows [41]:

$$(\overline{x}, \overline{y}) = \left(\frac{\sum_{i=1}^{n} N_i x_i}{\sum_{i=1}^{n} N_i}, \frac{\sum_{i=1}^{n} N_i y_i}{\sum_{i=1}^{n} N_i}\right) \quad (4)$$

In the formula, x and y are the center of gravity coordinates of vegetation NDVI; N_i is the average NDVI value of the ith raster; x_i and y_i are the coordinate values of the ith planar-to-spatial unit; and n is the time period.

Results and Discussion

Spatial and Temporal Characteristics of NDVI in Inner Mongolia

Spatial Distribution Characteristics of NDVI during the Growing Season

The spatial distribution of the mean NDVI during the growing season from 1999 to 2019 in Inner Mongolia, as illustrated in Fig. 3, exhibited a distinct decreasing gradient from the northeast to the southwest, accompanied by significant geographical variations. This distribution pattern aligns closely with the observed NDVI variations across different vegetation types, transitioning sequentially from forests to grasslands and eventually to deserts. The mean NDVI value over the 21-year period in Inner Mongolia was recorded at 0.32. The highest NDVI value (0.76) was observed in the Daxing'anling forest region, located in northeastern Inner Mongolia, a region predominantly characterized by the extensive presence of cold-temperate coniferous forests. Towards the west, the temperate grassland biome forms the core vegetation type. Due to the combined influences of geographical location and climatic conditions, grassland ecosystems in Inner Mongolia display distinct zonal patterns, which include, in order from southeast to northwest, temperate meadow grassland, temperate typical grassland, temperate desert grassland, temperate desert steppe, and temperate desert [42, 43]. Regions with NDVI values below 0.2, representing 35% of the total land area, are primarily distributed in the arid desert regions of southwestern Inner Mongolia, characterized by minimal annual precipitation and sparse vegetation cover. Regions with NDVI values between 0.2 and 0.4, accounting for 32% of the total area, are mainly located in the northern sectors, including Ordos, Bayannur, Baotou, Ulanqab, and the western districts of the Xilingol League. Areas with NDVI values ranging from 0.4 to 0.6, constituting 21% of the total land area, include the eastern regions of Xilingol League, southern parts of Hohhot and Ulanqab, the central area of Chifeng City, and the western grasslands of Hulunbuir City. Regions with NDVI values exceeding 0.6, representing the highest NDVI values observed, account for 12% of the total land area. These areas are predominantly located in Hulunbeier

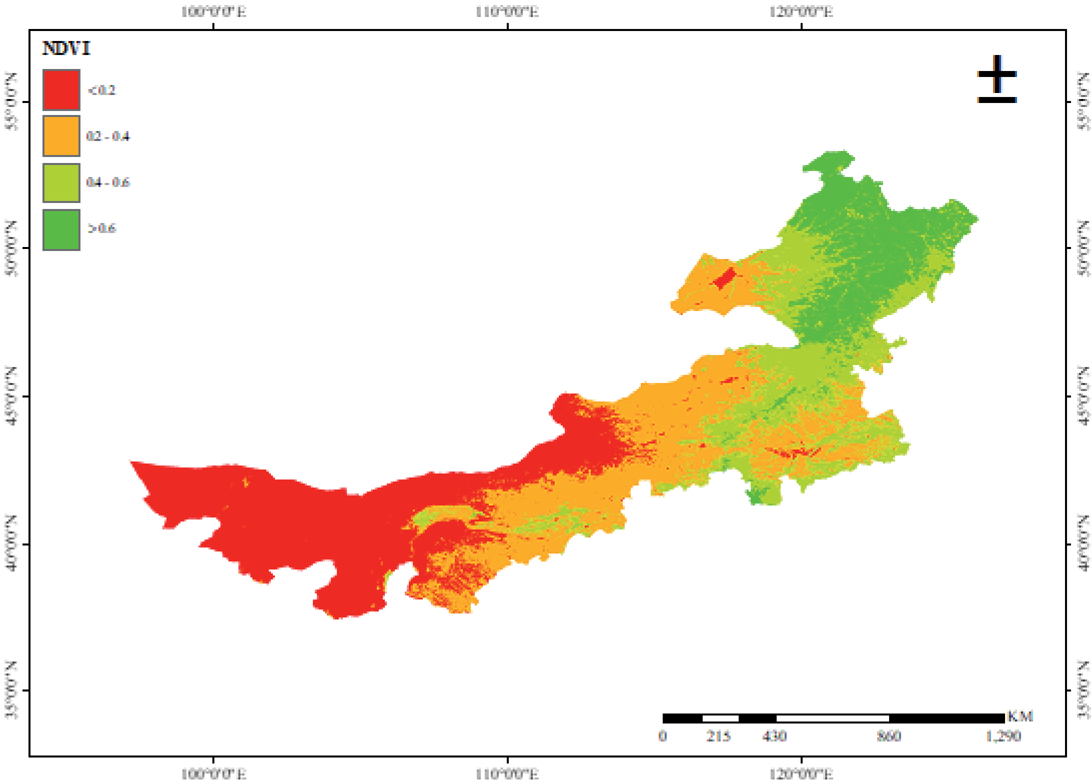

Fig. 3. Spatial distribution of average NDVI values during the growing season in Inner Mongolia.

and Xing'anmeng, where woodland vegetation is most prevalent.

Trends in Growing Season NDVI

The vegetation NDVI change trends in Inner Mongolia over the past two decades (1999-2019) were analyzed by calculating the average NDVI values during the growing season for each year. As illustrated in Fig. 4, the vegetation NDVI values remained relatively stable and showed incremental growth from 2002 to 2008, followed by more pronounced fluctuations between 2009 and 2015. In Inner Mongolia, the NDVI exhibited a statistically significant upward trend ($P<0.05$), with annual average NDVI values ranging from 0.28 to 0.35. The lowest value of (0.28) was recorded in 2001, while the highest value of (0.35) was observed in 2013, indicating an average annual increment of 0.0016.

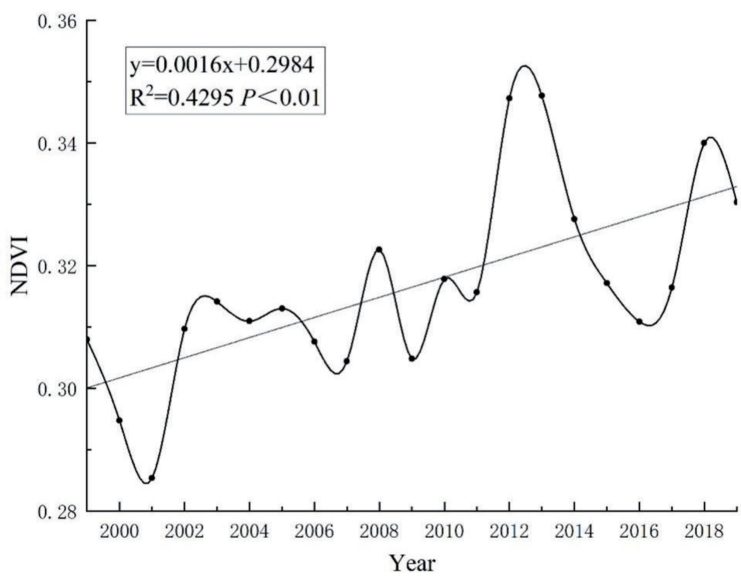

Fig. 4. Interannual variation trends of average NDVI in Inner Mongolia during 1999-2019.

Spatial Trends of NDVI during the Growing Season

To investigate the dynamics of vegetation NDVI in the study area, this research quantified its interannual variability across spatial dimensions and the corresponding distribution of image elements. As illustrated in Fig. 5a) and 5b), the majority (66.73%) of landscapes demonstrated a positive trend in NDVI metrics. This upward trend was predominantly concentrated in the northeastern regions of Inner

a)

b)

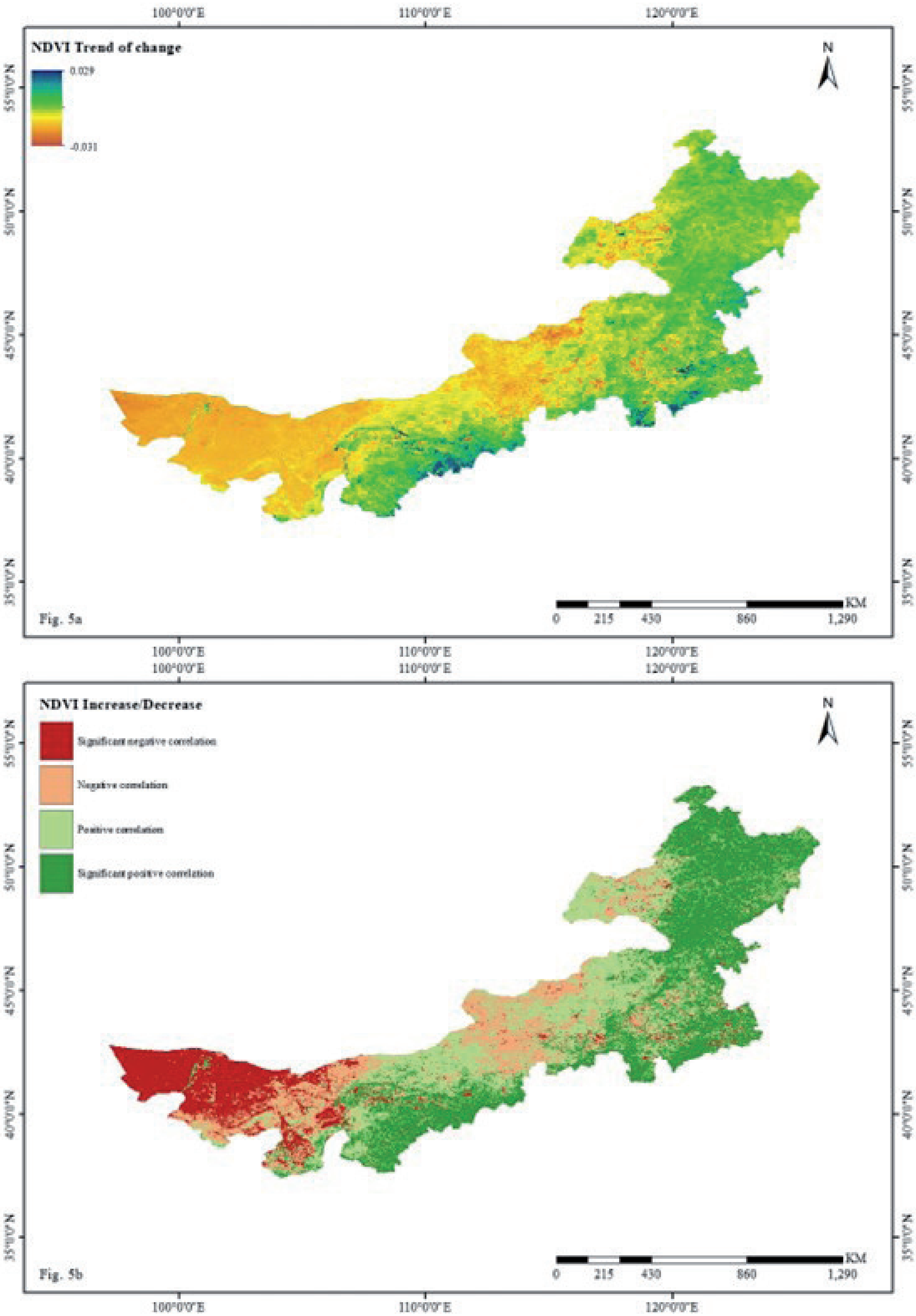

Fig. 5. Change trends a) and statistical significance b) of interannual average NDVI values in the vegetation growing season in Inner Mongolia during 1999-2019.

Table 1. The proportion of image elements (pixel ratio) of interannual NDVI, with significance for each, in Inner Mongolia during 1999-2019.

Significance	Pixel ratio
Significant reduction	14.72%
Decrease (insignificant)	18.55%
Increase (insignificant)	28.88%
significant increase	37.85%

Mongolia, particularly in Hulunbeier, Xing'anmeng, Tongliao, and Chifeng, as well as in the south-central areas of Ordos and Hohhot. In contrast, approximately 33.27% of the region exhibited a declining NDVI trend, primarily located in Xilingol City, central Inner Mongolia, and the desert regions of western Inner Mongolia. This decline can be attributed to low annual precipitation and high evapotranspiration rates, resulting in reduced vegetation cover. By evaluating the statistical significance of NDVI values and pixel ratios of image elements (Fig. 5b) and Table 1), it was found that 37.85% of the study area exhibited a statistically significant increase in vegetation NDVI ($P<0.05$), whereas 14.72% of the area experienced a statistically significant decline ($P<0.05$). These findings underscore the heterogeneous nature of NDVI dynamics across the region.

Responses of Growing Season NDVI to Climatic Factors

A meta-analysis of correlation coefficients was conducted annually from 1999 to 2019 to examine the relationship between mean NDVI values during the growing season and various climatic factors. This comprehensive analysis involved calculating correlation coefficients and conducting significance tests to evaluate the relationships between mean NDVI and meteorological variables. Detailed results are presented in Figs 6, 7, and 8 and Table 2 and 3.

The findings revealed that, across Inner Mongolia, the correlation coefficients between mean NDVI values and precipitation during the growing season were significantly higher, indicating a strong relationship. Approximately 72.77% of the study area exhibited a positive correlation with precipitation, with 17.70% of these correlations being statistically significant ($P<0.05$). Conversely, the relationships between mean NDVI and temperature or dryness were generally weaker. Positive correlations with temperature and dryness were observed in 36.31% and 31.87% of the total area, respectively, with only 1.17% and 0.97% exhibiting statistically significant correlations ($P<0.05$). These results suggest that precipitation is the primary climatic determinant of NDVI during the growing season, exerting a more substantial influence than temperature or dryness.

Negative correlations between mean growing season NDVI and temperature were identified in 63.69%

a)

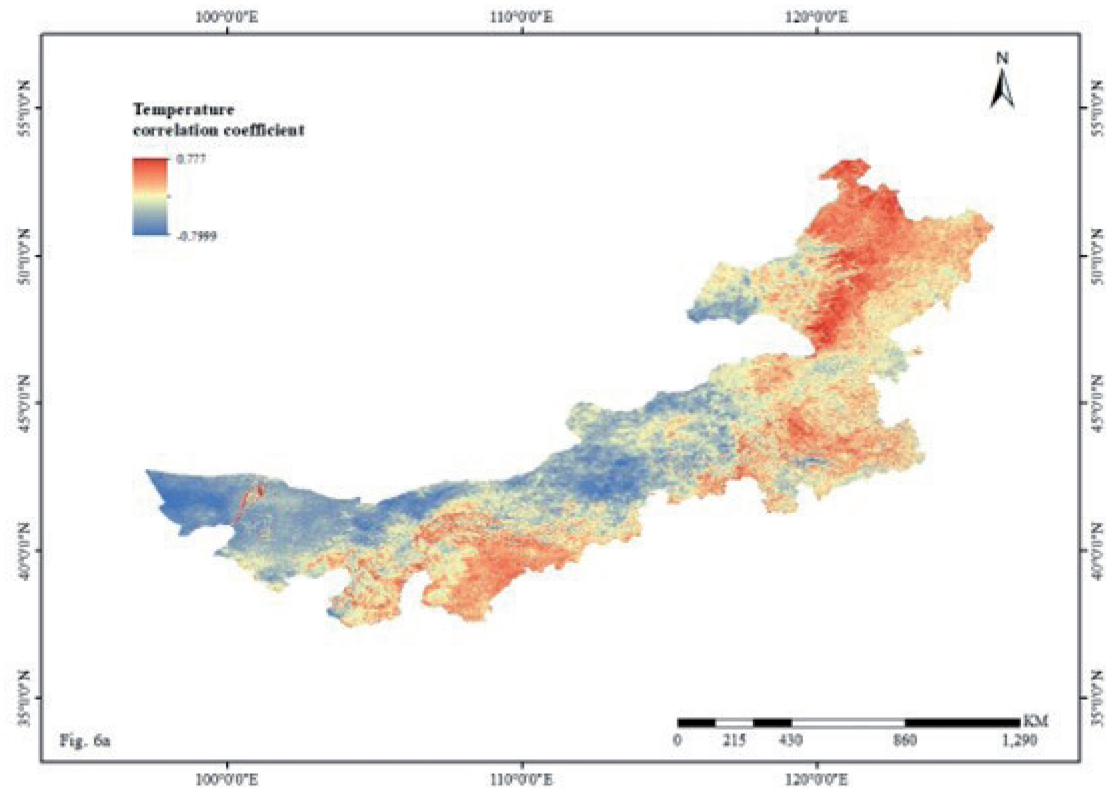

Fig. 6. Correlation coefficients and significance test of the relationship between average growing season NDVI and temperature.

b)

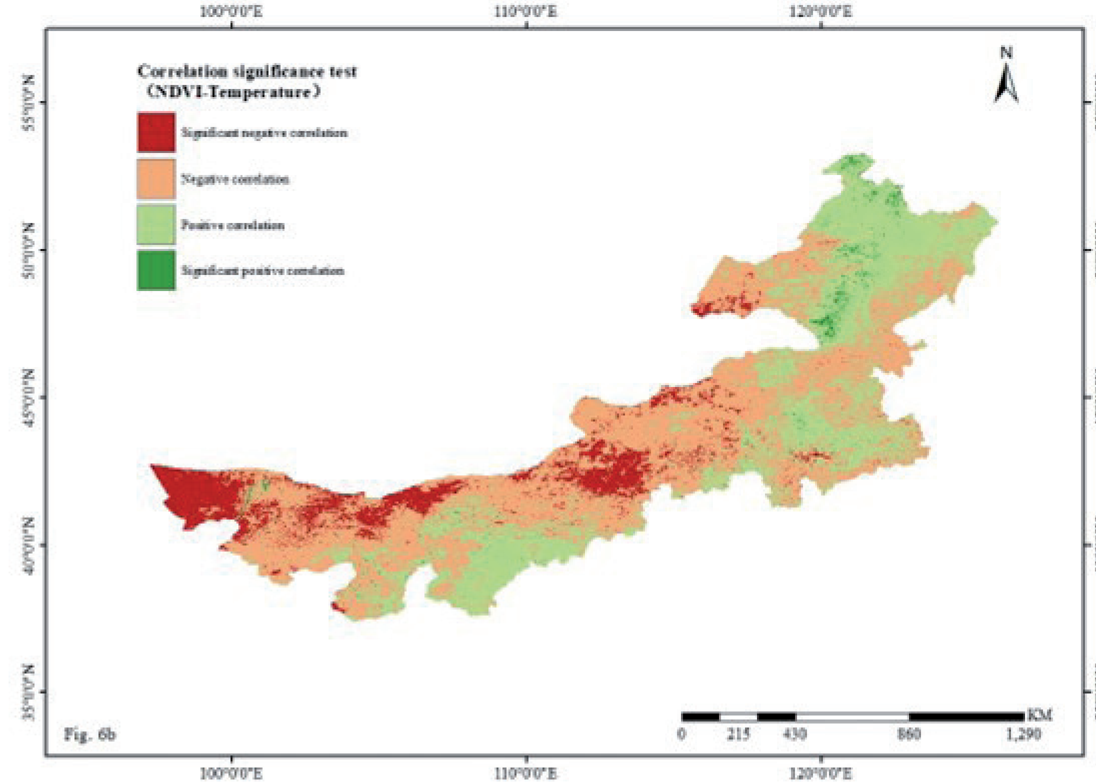

Fig. 6. Correlation coefficients and significance test of the relationship between average growing season NDVI and temperature.

a)

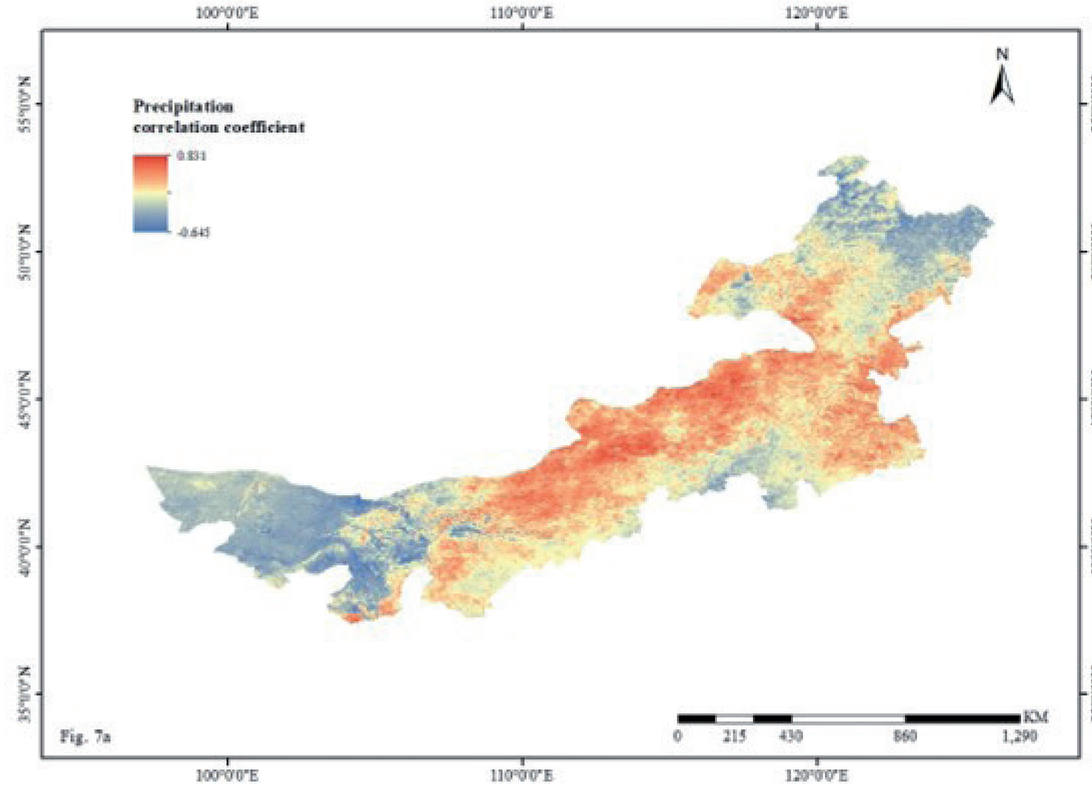

Fig. 7. Correlation coefficients and significance test of the relationship between average growing season NDVI and precipitation.

b)

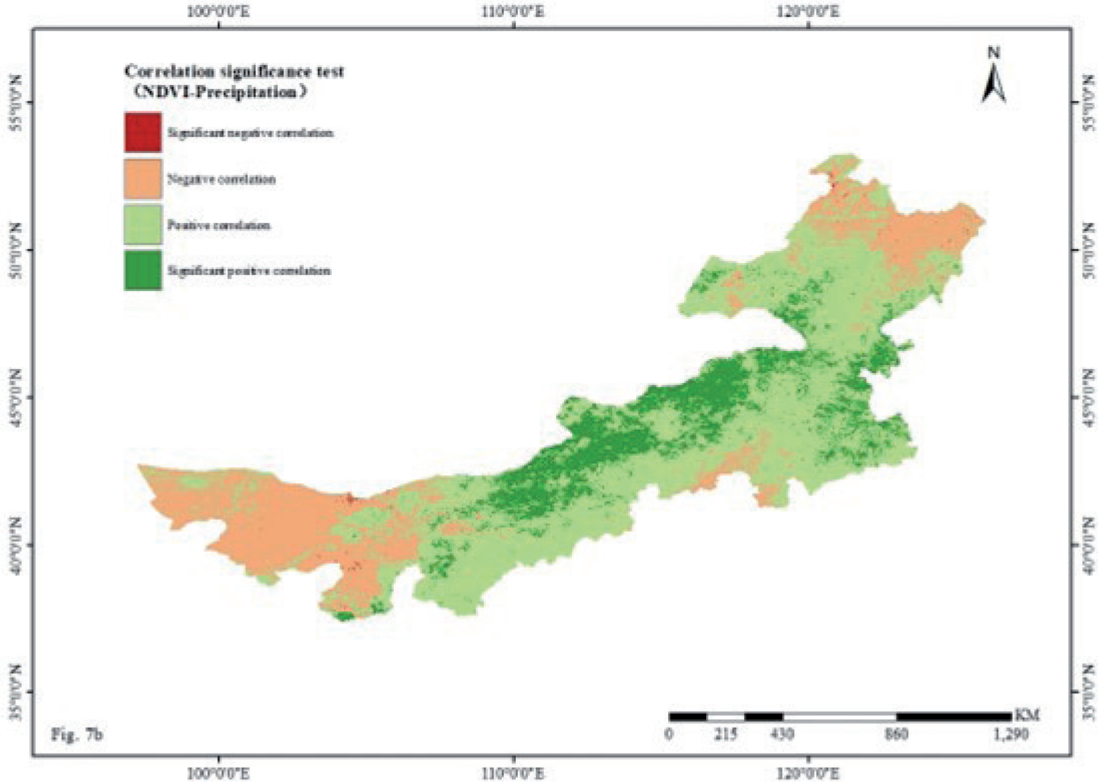

Fig. 7. Correlation coefficients and significance test of the relationship between average growing season NDVI and precipitation.

a)

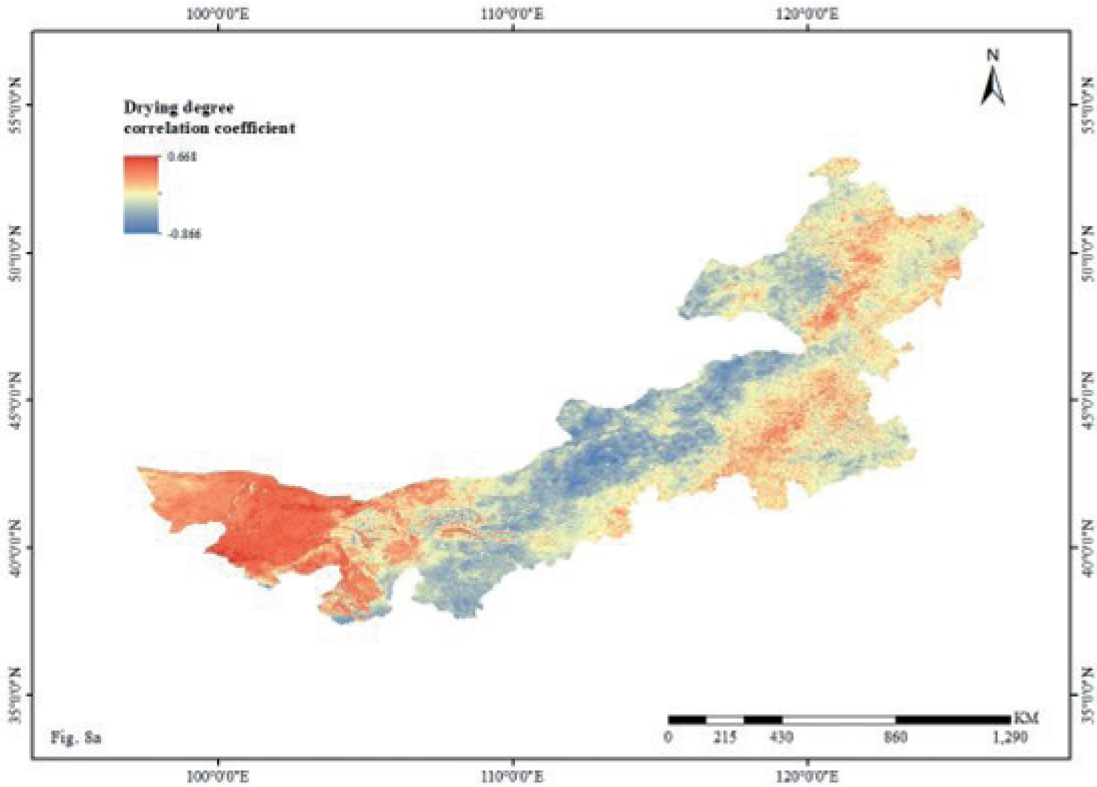

Fig. 8. Correlation coefficients and significance test of the relationship between average growing season NDVI and dryness.

b)

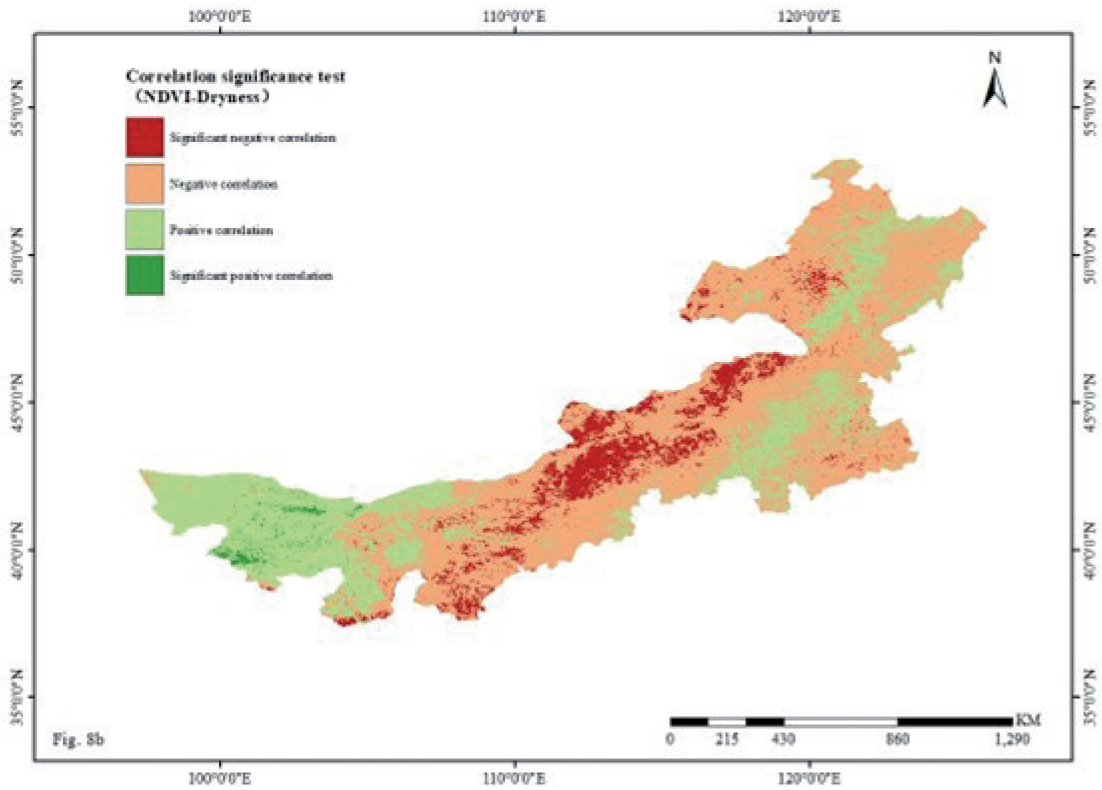

Fig. 8. Correlation coefficients and significance test of the relationship between average growing season NDVI and dryness.

of the region, with 12.47% showing statistically significant correlations (P<0.05). These areas were primarily distributed in the western parts of Hulunbuir City, Xilingol League, Baotou, Bayannur, and Alashan League in central Inner Mongolia. Positive correlations with temperature were observed mainly in the north-central regions of Hulunbuir and Tongliao cities, as well as parts of Chifeng and Ordos City.

The distribution of correlations between NDVI and precipitation exhibited greater regularity. Except for the Alxa League in the west and the northeastern part of Hulunbuir City, most regions positively correlated with precipitation. In terms of dryness, positive correlations were observed primarily in the Alxa League in western Inner Mongolia, a small central area of Hulunbuir City, and the northern part of Chifeng City, while negative correlations predominated in other regions. Notably, significant correlations (P<0.05) with dryness were concentrated in the central and western parts of the Xilingol League.

Displacement of the Center of Gravity

The annual mean NDVI centroids for Inner Mongolia from 1999 to 2019 were meticulously calculated to assess vegetation cover's spatial distribution characteristics

Table 2. Statistical significance of the relationship between average growing season NDVI and climatic factors.

Correlation significance	(Pixel ratio)		
	Temperature	Precipitation	Dryness
Significantly negative correlation	12.47%	0.12%	9.84%
Negative correlation	51.22%	27.11%	58.29%
Positive correlation	35.14%	55.07%	30.90%
Significantly positive correlation	1.17%	17.70%	0.97%

Table 3. The coefficients of correlation between average growing season NDVI and climatic factors.

	Temperature	Precipitation	Dryness
Correlation coefficient	-0.108	0.180	-0.111

and evolutionary trends. As illustrated in Fig. 9, the northeastern region of Inner Mongolia, characterized by extensive forest cover, exhibited the highest annual mean NDVI values. In contrast, the arid southwestern region, dominated by desert landscapes and receiving minimal precipitation, displayed the lowest annual mean NDVI values. This pronounced dichotomy resulted in the annual mean NDVI centroid being predominantly located in the northern part of Dongwuzhumuqin Banner, Xilingol League, Inner Mongolia.

The multi-year average NDVI centroid, representing vegetation dynamics over a 21-year period, was determined by calculating the mean centroid of the annual values. Subsequently, the angular deviation between the centroid of each year and the 21-year mean centroid was systematically computed, using the latter as a reference point (Fig. 10). The analysis revealed a predominant distribution of NDVI centroids within Quadrants I and III, suggesting that over the past 21 years, the increase in vegetation NDVI was more pronounced in the northeastern and southwestern regions of Inner Mongolia than in other areas. Notably, in the northeast, centroids were consistently located farther from the origin and exhibited greater spatial dispersion across all years. Conversely, in the southwest, centroids were more concentrated and generally closer to the origin, with the exception of 2012. This observed pattern indicates that inter-annual variations in vegetation NDVI values were more significant in the northeast than in the southwest, relative to other regions.

Discussion

Situated in the northern frontier of China, the Inner Mongolia Autonomous Region is highly sensitive to global climate variability [44, 45]. This region is characterized by substantial heterogeneity in vegetation distribution, emphasizing the pronounced impact of climatic fluctuations. Inner Mongolia constitutes a quintessential arid and semi-arid landscape, functioning as a critical ecological buffer and a major center for livestock production in northern China. Its natural grasslands cover approximately 8.67 million square kilometers, supporting the livelihoods of over 20 million residents [46-49].

Hua's study demonstrated a clear upward trend in overall NDVI values in Inner Mongolia from 1982-2015, which aligns closely with the findings of this study. However, the observed declining trend in average annual precipitation in Hua's study contrasts with this study's conclusions, a discrepancy that may arise from differences in the review period and meteorological data sources utilized [50]. Similarly, Kang et al. found that Inner Mongolia's maximum and minimum NDVI values occurred in 2019 and 2001, respectively, during 2000-2019. While the minimum values are consistent with those in this study, the discrepancy in the year of the maximum value could be attributed to methodological differences, Kang et al. used 12-month NDVI values as an annual metric, whereas this study focused on NDVI values recorded from April to October. Regarding the spatial patterns of NDVI changes, the areas exhibiting NDVI increases are predominantly located in northeastern Inner Mongolia, which is consistent with this study's findings [51].

Research by Hu et al. provided a comprehensive analysis of vegetation cover dynamics and the influence of precipitation and temperature in Inner Mongolia. Their findings indicate that from 2010-2019, precipitation exerted a stronger influence on NDVI than temperature, which supports the declines observed in this study. Nonetheless, the correlation coefficients between precipitation, temperature, and vegetation NDVI in Hu et al.'s research differ from those in this study, potentially due to the scale of analysis. While Hu et al. conducted interannual correlation analysis, this study examined correlations during the vegetation growing season [52]. Conversely, Zhang et al. found that vegetation growth in Inner Mongolia from 1982 to 2020 was primarily driven by temperature, a conclusion that contradicts this study. This divergence likely arises from differences in spatial scale; Zhang et al. focused on specific vegetation types in the upper regions of Inner Mongolia, whereas this study considered the entire region. These differences in study scope may account for the observed inconsistencies [53].

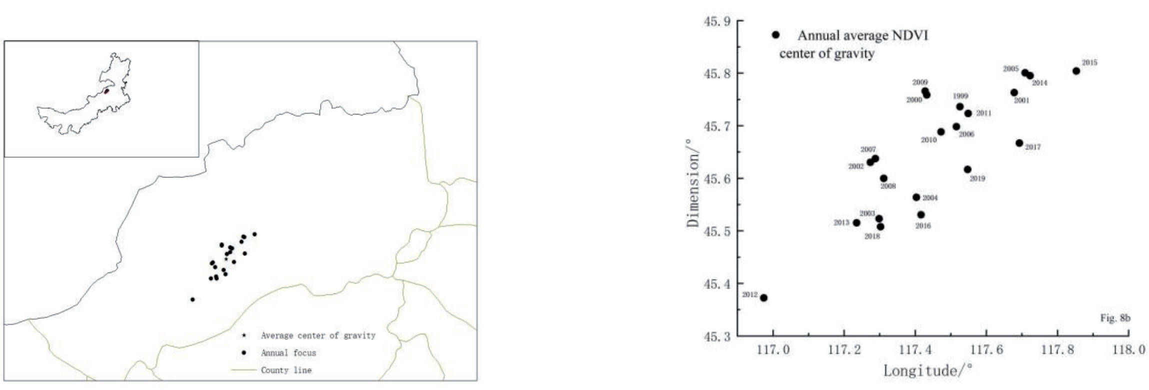

Fig. 9. The variation in the center of gravity of vegetation NDVI in Inner Mongolia.

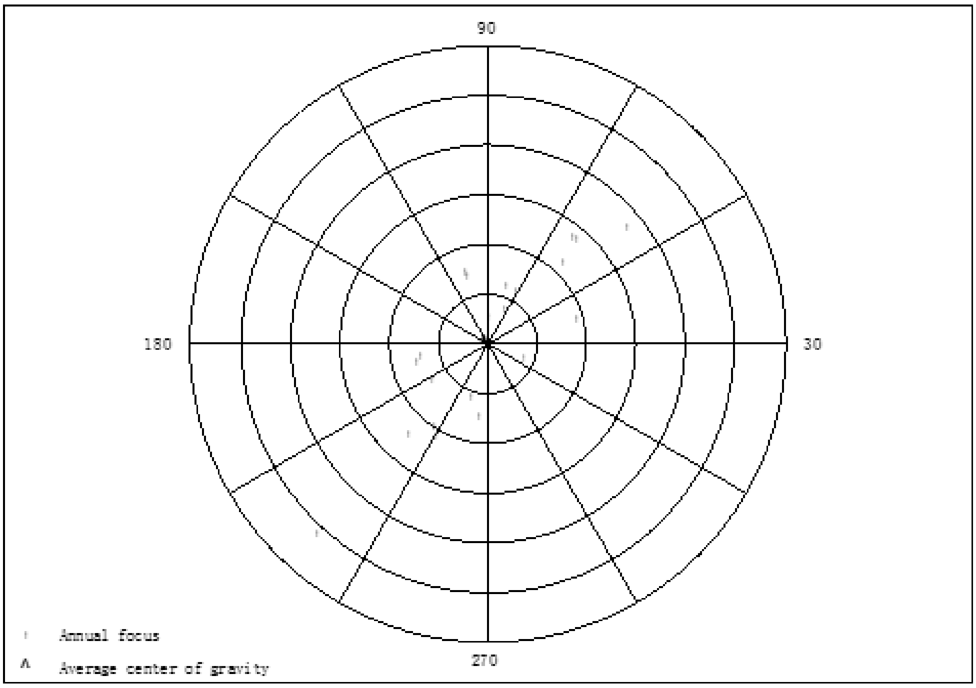

Fig. 10. Radar map showing the NDVI center of gravity distribution in Inner Mongolia.

The Inner Mongolia Autonomous Region has actively participated in national ecosystem restoration initiatives and promoted ecological industries in recent years. Programs such as pasture-to-grassland conversion, rotational grazing systems, and ecological farming practices have significantly enhanced the region's ecological environment, gradually increasing NDVI values [54, 55]. Beyond climatic variables, vegetation growth is influenced by factors such as soil conditions, hydrology, biological interactions, and human activities. These factors interact in complex ways to shape plant growth and ecosystem health. A holistic investigation into these influences is of considerable theoretical and practical importance for ecological conservation, agricultural productivity, and sustainable development [56].

Conclusions

This study systematically examined the temporal and spatial dynamics of the 21-year average growing season NDVI and its determinants in Inner Mongolia using NDVI data (1999-2019) alongside meteorological records from the same period. The key findings are summarized as follows:

(1) The temporal analysis revealed an increasing trend in the 21-year average growing season NDVI, with peaks and troughs of 0.35 (2013) and 0.28 (2001), respectively, and a mean annual increment of 0.0016 ($P<0.05$). Spatially, NDVI displayed a gradient of decline from northeast to southwest, with 12% of the region exceeding an NDVI threshold of 0.6.

(2) During the growing season, NDVI exhibited a positive correlation with precipitation across 72.77% of the region, with 17.70% showing significant positive correlations. In contrast, NDVI was negatively correlated with temperature and aridity across 63.69% and 63.81% of the region, respectively, with significant negative correlations observed in 12.47% and 9.84% of the area. Precipitation emerged as the dominant factor influencing NDVI during the growing season, as increased precipitation facilitated vegetation growth across much of the region.

(3) Using a center-of-gravity migration model, the centroid of average vegetation NDVI in Inner Mongolia showed a gradual southeastward shift, indicating that improvements in vegetation ecological quality were particularly pronounced in southeastern Inner Mongolia, where NDVI increases were significant.

Acknowledgments

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Author Contributions

Weijie Liao substantially contributed to collecting, processing, analyzing, and interpreting data, plus manuscript preparation. Jinting Guo ensured the integrity of the entire study, provided guidance for the ArcGIS software, collected data, gave final approval of the version for publication, and, as corresponding author, reviewed, revised, and finalized manuscripts and contributed to the work equally and should be regarded as co-first authors with Weijie Liao. Qimuge Hasi, Youjie Xu, Jingyuan Wang, and Narisu collected data. Jinting Guo, as the corresponding author, reviewed, revised, and finalized manuscripts.

Conflict of Interest

The authors declare no conflict of interest.

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