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Characteristics of Spatial and Temporal Vegetation Index Variability and Its Responses to Temperature and Precipitation in Mongolia

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Abstract: The Mongolian Plateau, a vital ecological barrier in northern China, is of great importance for studying vegetation dynamics in Mongolia against the background of climate warming. Such studies can enhance our understanding of regional vegetation responses to global warming and contribute to the establishment of a stronger ecological barrier in northern China. Here, we analyzed the spatial and temporal characteristics of the NDVI (normalized difference vegetation index) in Mongolia using 8 km resolution GIMMS NDVI3g data from 1990 to 2022, along with temperature, precipitation, and elevation data. Trend analysis and correlation methods were used to examine the relationships between the NDVI and temperature, as well as precipitation. The results showed four important aspects of these relationships. (1) The NDVI in Mongolia increased significantly from 1990 to 2022 at a rate of 0.0015 yr^{-1} (P<0.05). (2) Mongolia's NDVI increased from 1990 to 2022 in 60.73% of the country. Of this total, the area with a significant increase accounted for 31.67% and was concentrated on the eastern and western edges. The area experiencing a significant decrease accounted for 15.67% and was mainly located on the southwestern edges. (3) The NDVI analysis revealed significant increasing trends in all regions except for those at elevations of 1500–2000 m. The greatest rate of increase was observed between 500 and 1000 m, and the increasing trend weakened as elevation continued to increase before gradually becoming significant again. Additionally, the NDVI increased significantly across different slopes, and the rate of increase decreased as the slope increased. (4) From 1990 to 2022, Mongolia's NDVI was mostly negatively correlated with temperature. This occurred over 66.75% of the total land area, with 17.21% of the region exhibiting a significant negative correlation, mainly in the southwest. Conversely, the NDVI demonstrated a positive correlation with precipitation, encompassing 86.71% of the total land area. Approximately 40.44% of the region had a significant positive correlation, primarily in the southwest. In conclusion, throughout the experimental period, the vegetation state in Mongolia improved. However, due to the warming and drying climate, more attention should be paid to vegetation degradation in the south-central region.

Key words: normalized difference vegetation index; slope; elevation; trend analysis; correlation analysis; Mongolia

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1 Introduction

Vegetation plays a crucial role in terrestrial ecosystems and is sensitive to global climate change, so it is an important factor in geography and ecology (Piao et al., 2011). Vegetation can be used to maintain ecosystem functions, monitor and evaluate ecosystem health, and track ecological issues such as land cover change, grassland degradation, and desertification (Peng et al., 2011). The Normalized Difference Vegetation Index (NDVI) is an effective tool for monitoring vegetation because it accurately reflects changes in vegetation growth and biomass, as well as ecosystem parameters.

Mongolia is an important ecological barrier in northern China. The study of vegetation dynamics in this country is of great theoretical and practical significance for an in-depth understanding of the characteristics of the regional vegetation response to global warming and the construction of a stronger ecological barrier in the northern part of China.

Mongolia located in the central and northern part of the Mongolian Plateau, and it constitutes an essential component of the plateau. Grasslands occupy about 80% of the country, and animal husbandry is one of the economic pillars on which it relies (Yang et al., 2019). In the 21st century, the rapid development of Mongolia's two pillar industries, livestock husbandry and mining, has led to the overuse of natural resources, such as pasture and groundwater, and the intensification of land desertification (Tao et al., 2015; Anari et al., 2017). Studies have identified climate warming as an important cause of vegetation changes in the mid- to high-latitude regions of the Northern Hemisphere (Peng et al., 2011; Zhang, 2014), with temperature and precipitation influencing ecosystem stability, biodiversity, and energy flow through their effects on vegetation (Miao et al., 2016; Bao et al., 2017; Tong et al., 2018; Jiang, 2020). In addition to its response to climate, the NDVI is also correlated with topographic factors such as elevation and slope (Li et al., 2017; Xiong et al., 2023). The effects of topographic and climatic factors are prone to nonlinear enhancement, and the interaction of environmental factors affects the distribution of the NDVI (Meng et al., 2018).

Since the 1980s, the vegetation conditions in Mongolia have been generally improving (Bao et al., 2015). Increasing global temperatures caused by global warming have led to drier conditions in some areas. Extreme weather events have also affected precipitation patterns and evapotranspiration. These changes have resulted in longer growing seasons, altered vegetation distributions, and an overall imbalance in the ecosystems (Zhao et al., 2018; Lv et al., 2021; Yu et al., 2022). In this paper, we used GIMMS (Global Inventory Modelling and Mapping Studies), the NDVI, air temperature, precipitation, and elevation data to study the spatial and temporal variability of the NDVI in Mongolia and its responses to air temperature and precipitation through trend and correlation analyses. Our results provide a scientific basis for understanding the vegetation changes in Mongolia and guiding future adjustments of the ecological construction policy on the Mongolian Plateau in China.

2 Data and methods

2.1 Study area

Mongolia located in Northeastern Asia (41°36′–51°43′N, 87°54′–119°54′E) and covers an area of 1.564×10^6 km^2. It is nestled between Russia and China, and serves as an important ecological barrier. Mongolia has varied geomorphological features, with highlands and mountains dominating the landscape, and the terrain is high in the west and low in the east. The climate is cold, dry, and windy, which significantly affects vegetation growth, agriculture, and animal husbandry. The country experiences a low and unevenly distributed precipitation that is concentrated in summer, with average annual values ranging from 196.11 to 349.17 mm. The temperature varies seasonally, with cold winters and warm summers. The average annual temperature ranges from 0.47 ℃ to 3.24 ℃.

2.2 Data sources

The data used in this study include four basic types. 1) NDVI data: The GIMMS NDVI Global Vegetation Index dataset from 1990–2022 provided by the National Aeronautics and Space Administration (NASA) was downloaded from https://nex.nasa. gov/nex. The dataset was version 3g.v1 in ncf data format. Data were extracted and the projection was defined using PyCharm to obtain NDVI data with a period of 15 d and a resolution of 8 km. Then the 15 d data were averaged to obtain the monthly data, and the annual data were calculated by the Maximum Value Composition (MVC) method. 2) Temperature and precipitation data: The 1990–2022 climate reanalysis data provided by the European Meteorological Office (ECMWF) were downloaded from https://www.copernicus.eu/en/access-data/dataset/reanalysis-era5-land. The spatial resolution of this dataset was 0.1°, and it was in the ncf data format. Data were extracted, the projection was defined, and the data were resampled using PyCharm to obtain yearly temperature and precipitation data for 1990–2022 with an 8 km resolution. 3) DEM data: The SRTM (Shuttle Radar Topography Mission) DEM data were downloaded from https://earthexplorer.usgs.gov/. The spatial resolution of this dataset was 90 m. Based on the DEM, Mongolia was categorized into five levels according to elevation and slope, namely 500–1000 m, 1000–1500 m, 1500–2000 m, 2000–2500 m, and >2500 m. The slopes ranged from 0–67° and were categorized into 0°–5°, 5°–10°, 10°–15°, 15°–20°, and >20°. 4) Vector boundary data of Mongolia were sourced from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). The GIMMS NDVI3g yearly data at a resolution of 8 km, yearly temperature and precipitation data, and DEM and slope data for 1990–2022 were obtained using Mongolia vector boundary cropping.

2.3 Research methodology

2.3.1 Univariate linear regression model

Using the least squares method to calculate the univariate linear regression model between NDVI and year, the calculation formulas were:

$$y = bx + c \quad (1)$$

$$b = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2} \quad (2)$$

$$c = \overline{y} - b\overline{x} \quad (3)$$

where y represents the NDVI; the independent variable x represents the year; b is the coefficient (rate of change); c is a constant; and $\overline{y}$ and $\overline{x}$ are the mean values of the NDVI and year from 1990 to 2022, respectively. After obtaining the one-dimensional linear model, significance testing was conducted using the F-test, with the following equations:

$$F = \frac{U}{Q'(n-2)} \quad (4)$$

$$U = b^2 \sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \quad (5)$$

$$Q = \sum_{i=1}^{n}\left(y_i - y'\right)^2 \quad (6)$$

where y' represents the fitted values of y which were calculated using the univariate linear regression model. After calculating the F-value, in the F distribution table with α=0.05, the critical value of F was found to be 4.16. If F>4.16, the regression equation is significant.

2.3.2 Mann-Kendall trend analysis

The Mann-Kendall trend test was performed to analyze trends in NDVI, temperature, and precipitation in Mongolia from 1990 to 2022. This approach allows the calculation and validation of trends and their significance, using the following equation (Zhang et al., 2018a; Zhang et al., 2018b):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sgn\left(x_j - x_k\right) \quad (7)$$

where S is the statistics; x_j and x_k are the NDVI, temperature, and precipitation data for the corresponding years 1990–2022; n represents the length of the time series in years, including values of 33 (1990–2022), 15 (1990–2004), and 19 (2004–2022); $Sgn\,(x_j–x_k)$ is the sign function:

$$Sgn\left(x_j - x_k\right) = \begin{cases} 1, & x_j > x_k \\ 0, & x_j = x_k \\ -1, & x_j < x_k \end{cases} \quad (8)$$

When $n \geqslant 10$, the statistic S follows an approximately normal distribution with expectation and variance.

This yields the standard normal distribution statistic:

$$E(S) = 0 \quad (9)$$

$$Var(S) = n(n-1)(2n+5)/18 \quad (10)$$

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{(S+1)}{\sqrt{Var(S)}}, & S < 0 \end{cases} \quad (11)$$

The trend is increasing when the Z value is greater than 0 and decreasing when the Z value is less than 0 (A R et al., 2017). In this study, the significance level α was 0.05, and 1.96 corresponded to the boundary value of the 95% confidence interval in the normal distribution. When the absolute value of Z was $\geqslant$1.96, the observed trend of change was considered to be significant at the 95% significance level. Combining the S and Z values, the results of the analysis were categorized into four classes: significant decrease (S<0, $|Z|$<1.96), non-significant decrease (S<0, $|Z|$>1.96), significant increase (S>0, $|Z|$<1.96) and non-significant increase (S>0, $|Z|$>1.96).

2.3.3 Pearson's correlation analysis

The Pearson correlation coefficient was used to analyze the correlations between NDVI, temperature, and precipitation from 1990 to 2022, and was calculated by the following formula (Jin et al., 2020):

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \quad (12)$$

In this equation, r is the correlation coefficient, and the range of values is [–1, 1]; x is the annual average value of NDVI from 1990 to 2022; and y is the annual average temperature and annual precipitation value from 1990 to 2022. After calculating the correlation coefficients, the critical value was determined to be 0.3439 for α=0.05, so $|r|$>0.3439 indicated that the correlation was significant and the reverse indicated that it was not significant.

3 Results and analysis

3.1 Characteristics of temporal and spatial changes in the NDVI

3.1.1 Characteristics of temporal changes

Vegetated ecosystems in Mongolia were mainly characterized as steppe, desert, and the Gobi. From 1990 to 2022, the mean NDVI values remained low, ranging from 0.3295 to 0.4252. The lowest annual mean was 0.3295 in 1992, whereas the highest was 0.4252 in 2019. From 1990 to 2022, the annual mean NDVI in Mongolia increased significantly at a rate of 0.0015 per year (P<0.05). The breakpoint test revealed a shift in Mongolia's NDVI in 2004, dividing the annual mean NDVI changes into two stages of 1990–2004 and 2004–2022. The multi-year mean NDVI for 1990–2004 was 0.3497, indicating a non-significant decreasing trend with a rate of 0.0013 yr^{-1}. In contrast, the multi-year mean NDVI from 2004–2022 was 0.3712, a significant increasing trend with a rate of 0.0036 yr^{-1} (P<0.05) (Fig. 1).

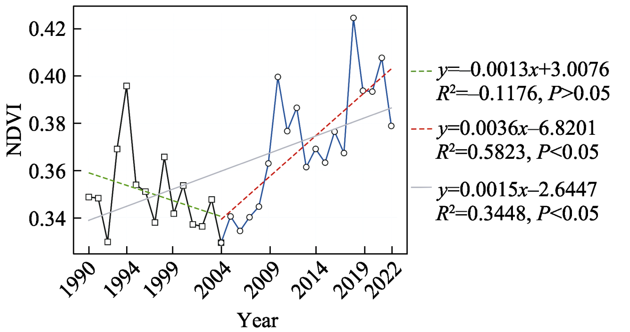

Fig. 1 The annual average NDVI changes from 1990 to 2022 in Mongolia

3.1.2 Characteristics of spatial changes

From 1990 to 2022, the NDVI in Mongolia increased by 60.83%. The areas characterized by significant increases accounted for 31.67% of the country and were concentrated along the eastern and western peripheries. Simultaneously, the areas with non-significant increases accounted for 29.16% of the total area, mainly in the central-northern region. Areas with decreases accounted for 39.17%. Within this category, areas with significant decreases accounted for 15.67%, mainly located in the southwestern edges, whereas areas with non-significant decreasing trends accounted for 23.50% and were mainly distributed in central Mongolia (Fig. 2a). From 1990 to 2004, the annual average NDVI in Mongolia decreased over an area that accounted for 64.95% of the country. Regions with significant decreases accounted for 6.42% and were distributed in the central-northern and southwestern edges. Conversely, the non-significant decreasing areas accounted for 58.53% and were concentrated in the central and eastern regions. Regions with NDVI increases accounted for 35.05%, with significantly increasing areas accounting for 1.20%, mainly distributed in the western, northern, and southern edges. Areas with non-significant increases accounted for 33.85% and were mainly distributed in the western and southeastern regions (Fig. 2b). From 2004 to 2022, Mongolia predominantly experienced NDVI increases in 73.64% of the national territory. Regions with significant increases accounted for 27.69% and were mainly distributed in the northeastern parts of Mongolia. Concurrently, areas with non-significant increases accounted for 45.77% and were concentrated in the central-northern regions. Regions with NDVI decreases accounted for 26.54%, with significantly decreasing areas accounting for 6.32%. These were mainly distributed in the southwestern edges. Areas with non-significant decreases accounted for 20.22% and were mainly distributed in the southern and southwestern regions (Fig. 2c). Overall, from 1990 to 2022, Mongolia experienced a notable expansion in areas with improved vegetation compared to those undergoing degradation, which indicated a positive environmental trajectory.

3.2 Characteristics of NDVI topographic distribution

Based on the statistics for the elevation distribution, from 1990 to 2022, the highest annual mean NDVI was 0.4307 within the range of 2000–2500 m. The other ranges, in descending order, were >2500 m, 500–1000 m, 1500–2000 m, and 1000–1500 m, with multi-year mean NDVI values of 0.4109, 0.4103, 0.3730, and 0.3076, respectively (Fig. 3a). From 1990 to 2022, the highest growth rate of the NDVI was 0.0037 yr^{-1} (P<0.05) at the elevation range of 500–1000 m. The growth rates for the other elevation ranges were as follows: >2500 m, 1000–1500 m, 2000–2500 m, and 1500–2000 m, with values of 0.0015 yr^{-1} (P<0.05), 0.0012 yr^{-1} (P<0.05), 0.0011 yr^{-1} (P<0.05), and 0.0004 yr^{-1}, respectively (Fig. 3b–f).

Based on the slope distribution statistics from 1990 to 2022, the highest multi-year mean NDVI in Mongolia was 0.5490 at a slope range of 10°–15°. The other ranges, in descending order, were 15°–20°, 5°–10°, >20°, and 0°–5°, with multi-year NDVI mean values of 0.5228, 0.5019, 0.4711, and 0.3044, respectively (Fig. 4a). The highest NDVI growth rate was 0.0016 yr^{-1} at 0°–5°. The growth rates for 5°–10°, 10°–15°, 15°–20°, and >20° were 0.0012 yr^{-1} (P<0.05), 0.0010 yr^{-1} (P<0.05), 0.0009 yr^{-1} (P<0.05), and 0.0009 yr^{-1} (P<0.05), respectively (Fig. 4b–f).

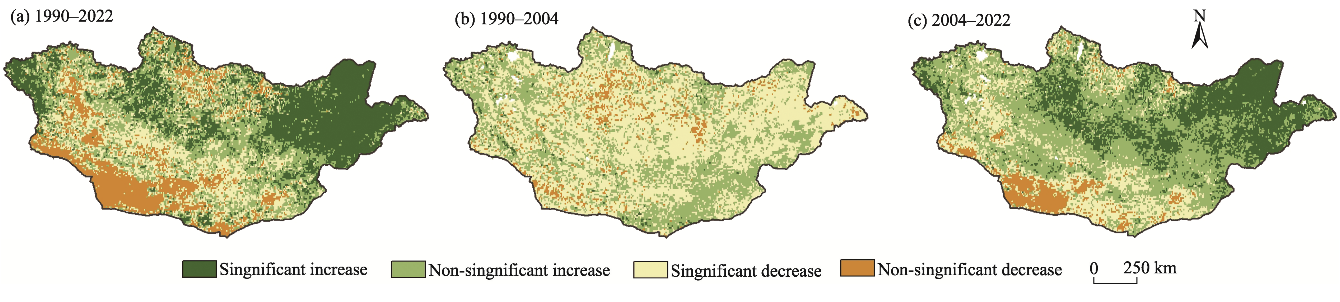

Fig. 2 Spatial trends of NDVI (a) from 1990 to 2022, (b) from 1990 to 2004 and (c) from 2004 to 2022 in Mongolia

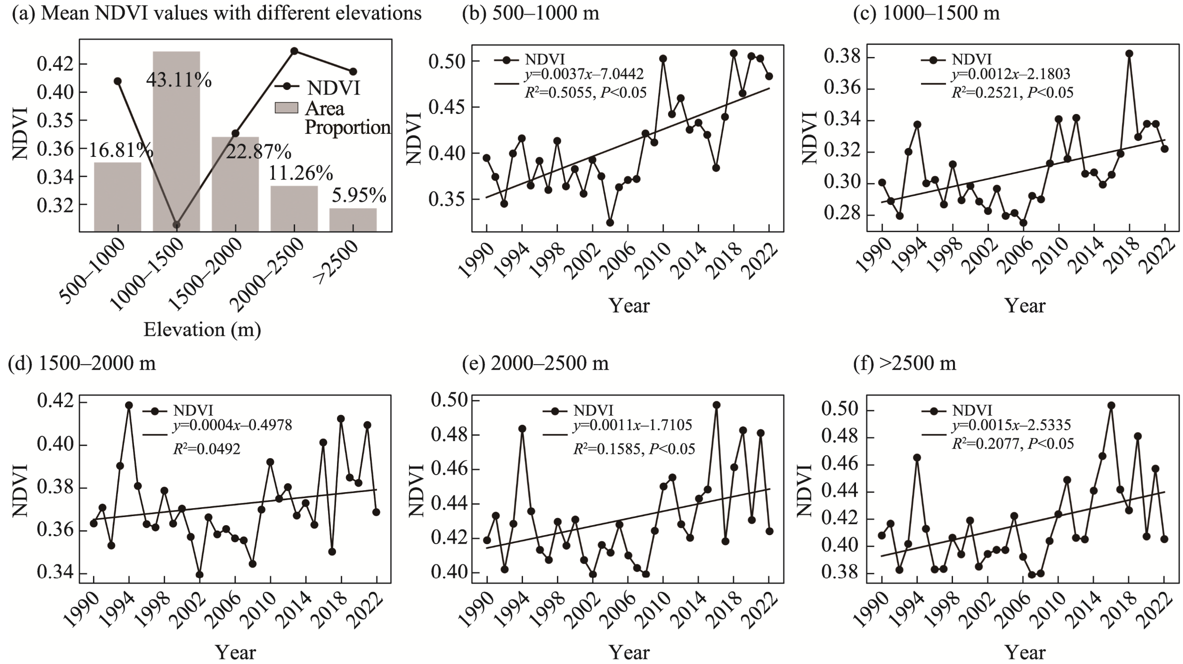

Fig. 3 NDVI changes in (a) mean values at different elevations, (b) 500–1000 m range, (c) 1000–1500 m range, (d) 1500–2000 m range, (e) 2000–2500 m range, and (f) >2500 m range in Mongolia, 1990–2022

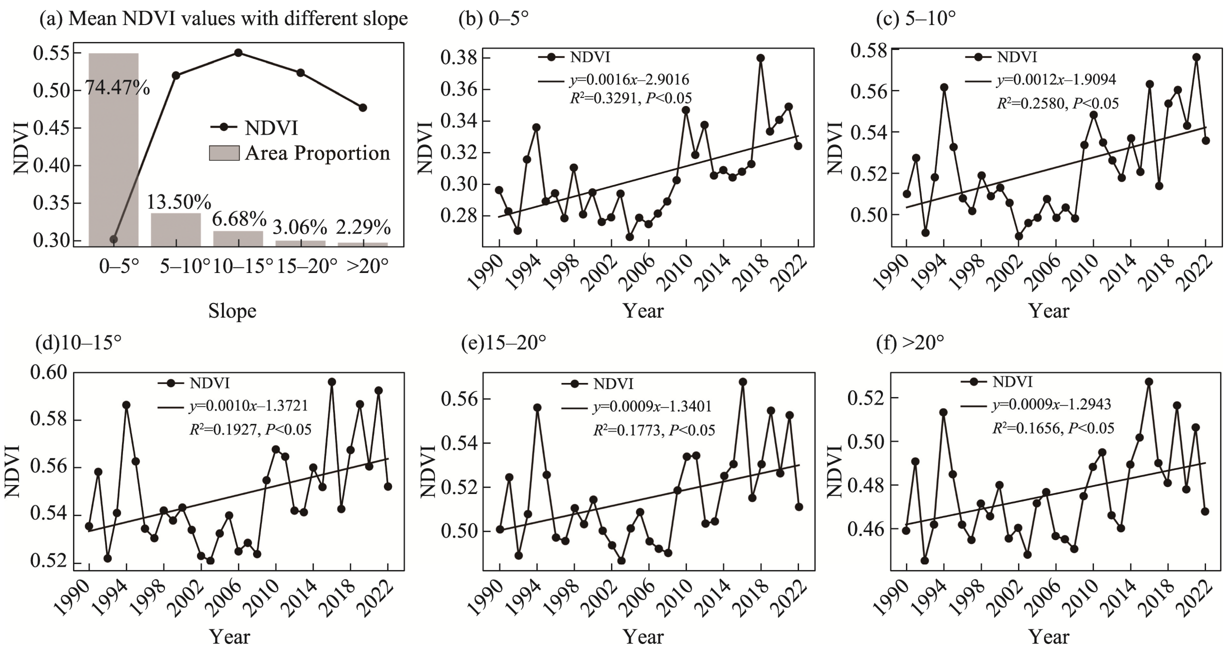

Fig. 4 NDVI changes in (a) mean values for different slope ranges, (b) 0°–5° range, (c) 5°–10° range, (d) 10°–15° range, (e) 15°–20° range, and (f) >20° range in Mongolia, 1990–2022

In summary, the NDVI increased at various elevation and slope levels. Specifically, there was a decline followed by an increase in the NDVI as elevation increased, while NDVI increased and then remained stable with increasing slope. The distributions of the NDVI by elevation and slope revealed that the NDVI was higher at lower elevations and slopes. The increase in the NDVI above 2500 m may be closely related to global warming.

3.3 Characterization of NDVI responses to temperature and precipitation

3.3.1 Characteristics of interannual changes in temperature and precipitation

From 1990 to 2022, the annual average temperatures increased across 99.37% of Mongolia. The regions with significant increases accounted for 67.73%, mainly distributed in the central and southern parts of Mongolia. The non-significantly increasing areas accounted for 31.12%, primarily distributed in the northern regions. Regions with non-significant decreases comprised only 1.14%, mainly distributed sporadically throughout the central-northern parts (Fig. 5a). The study period was divided into two stages, with 2004 as the boundary. From 1990 to 2004, the annual average temperatures increased in 85.58% of the national territory. Regions with significant increases accounted for 5.84%, mainly distributed in the central regions, while the non-significantly increasing areas accounted for 79.75% and were also concentrated in the central regions. Non-significantly decreasing areas comprised only 14.41%, mainly distributed in the southwestern and northeastern parts of Mongolia (Fig. 5c). From 2004 to 2022, annual average temperatures continued to increase across 97.74% of the country. The significant increases accounted for only 0.97%, mainly distributed in the northeastern parts, while the non-significantly increasing areas accounted for 96.77% and encompassed most parts of Mongolia. The non-significantly decreasing areas comprised only 2.26%, mainly distributed sporadically along the central-northern edge (Fig. 5e).

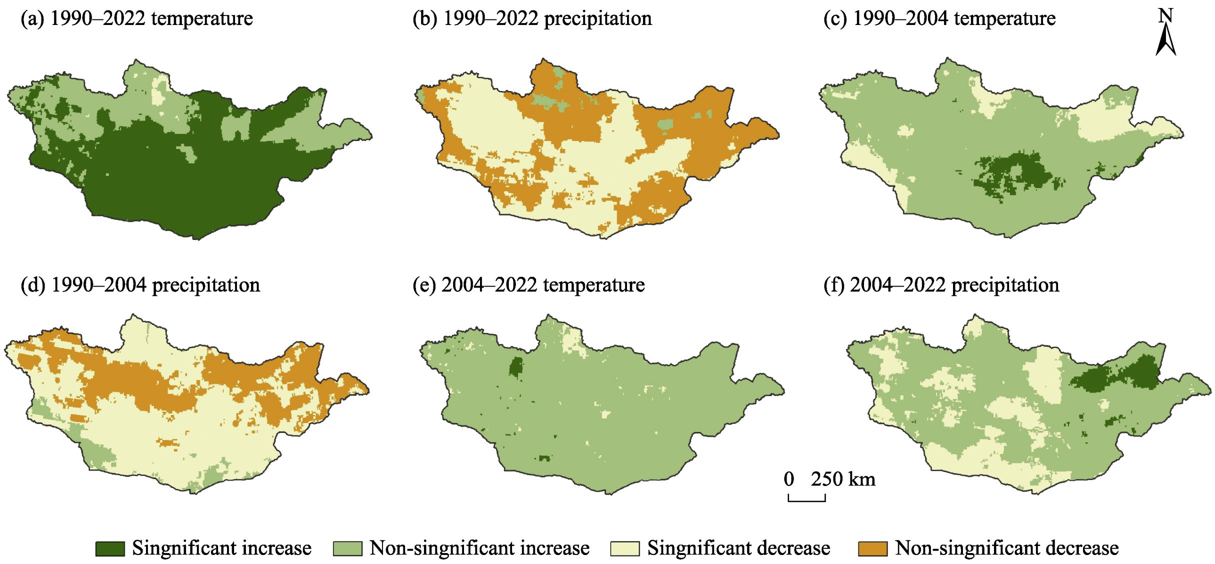

Fig. 5 Spatial distributions of changes of air temperature and precipitation in Mongolia

From 1990 to 2022, the annual precipitation decreased across 97.57% of the country. The regions with significant decreases accounted for 49.90%, predominantly distributed in the western, northern, and eastern regions. Areas with non-significant decreases accounted for 47.14%, mainly distributed in the northwestern and central regions, while the non-significantly increasing areas comprised 2.43% and were primarily distributed in the central-northern and northwestern regions (Fig. 5b). The study period was divided into two stages with 2004 as the boundary. From 1990 to 2004, annual precipitation predominantly decreased over 94.65% of the national territory. The significantly decreasing areas accounted for 34.56%, mainly distributed in the northern regions. Areas with non-significant decreases accounted for 60.09% and were concentrated in the southern regions, while regions with significant increases comprised only 2.43% and were mainly distributed along the southern edge (Fig. 5d). From 2004 to 2022, annual precipitation predominantly increased across 72.99% of the national territory. The significantly increasing areas accounted for 5.34%, primarily distributed in the northeastern parts. Areas with non-significant increases accounted for 67.65% and were mainly distributed in the northwestern and eastern regions, while regions with the non-significant decreases comprised only 27.01% and were primarily distributed in the central and southern parts (Fig. 5f).

In general, from 1990 to 2022, there was a significant increase in temperature and a decrease in precipitation in Mongolia. These changes indicated a clear trend of warming and drying. Interestingly, both periods of 1990–2004 and 2004–2022 showed non-significant increases in temperature, as well as non-significant decreases in precipitation. However, there was a non-significant increase in precipitation in the latter period. From 1990 to 2022, the climate in Mongolia was characterized by warm-drying, with the period of 1990–2004 being warm-dry and the period of 2004–2022 being warm-wet. These trends may explain the changes in the NDVI in Mongolia during this period (Fig. 1).

3.3.2 Responses of NDVI to temperature and precipitation

From 1990 to 2022, there were negative correlations between the NDVI and temperature in 66.75% of the country. The regions with significant negative correlations accounted for 17.21%, mainly located in the southwestern part of Mongolia. Areas with positive correlations accounted for 33.25% of the country, with significantly positively correlated regions making up 1.17%. These were primarily distributed on the eastern and western edges of Mongolia (Fig. 6a). The study period was divided into two stages with 2004 as the boundary. From 1990 to 2004, the NDVI and temperature had negative correlations across 72.05% of the country. Notably, areas with significant negative correlations comprised 22.02%, primarily located in the southern part of Mongolia. Positive correlation areas accounted for 27.95%, with significantly positively correlated regions making up 3.13%. These were mainly distributed in the central-northern regions of Mongolia (Fig. 6c). From 2004 to 2022, Mongolia continued to experience negative correlations between the NDVI and temperature across 67.89% of the national territory. Regions with significant negative correlations accounted for 18.85%, predominantly distributed in the northwestern and southeastern parts of Mongolia. Meanwhile, positive correlation areas accounted for 32.11%, with significantly positively correlated regions making up 0.62%. These were sporadically distributed throughout the northern part of Mongolia (Fig. 6e).

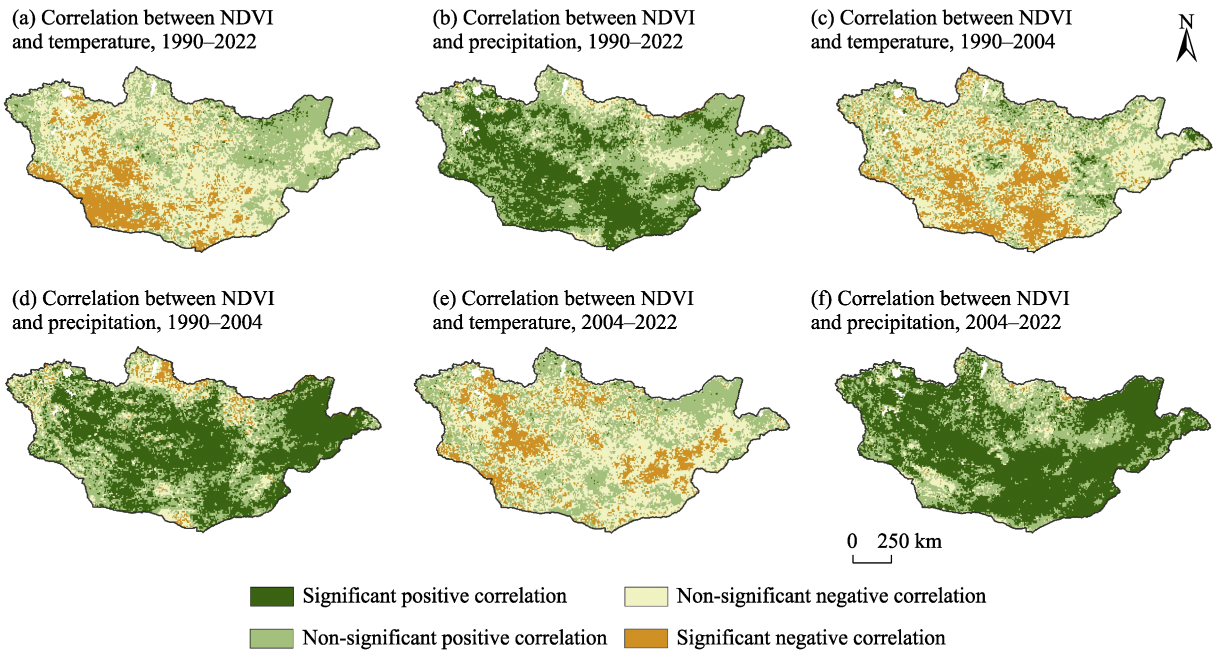

Fig. 6 Spatial distributions of correlations between NDVI and temperature and between NDVI and precipitation

Between 1990 and 2022, 86.71% of the country had positive correlations between NDVI and precipitation. The regions with significant positive correlations accounted for 40.44%, primarily distributed in the southwestern part of the country. On the contrary, 13.29% of the country had negative correlations, with significantly negatively correlated regions making up 0.86%. These were mainly situated on the northern edge of the country (Fig. 6b). The study period was divided into two stages with 2004 as the boundary. From 1990 to 2004, 82.46% of the country had positive correlations between NDVI and precipitation. Notably, the significantly positively correlated regions comprised 51.56%, mainly distributed in the central and eastern regions. Negative correlation areas accounted for 17.54%, with significantly negatively correlated regions making up 3.81%. These were mainly distributed in the western, southern, and northern edge regions (Fig. 6d). From 2004 to 2022, 92.53% of the country had positive correlations between NDVI and precipitation. Regions with significant positive correlations accounted for 63.77% which were primarily distributed in the northwestern and southeastern parts, while negative correlation areas accounted for 7.47%, and significant negative correlation areas made up 0.45%. These were mainly distributed in the northern peripheral regions (Fig. 6f).

In general, there was not a significant correlation (81.62%) between NDVI and air temperature. However, there was clearly a correlation between NDVI and annual precipitation. The decrease in precipitation was determined to be a key factor contributing to the degradation of vegetation in the south-central region of Mongolia.

4 Discussion

This study showed that the NDVI in Mongolia increased overall from 1990 to 2022, with significant increases in the eastern part of the country and significant decreases in the southwestern part. This was consistent with the findings of Mu et al. (2012) and Du et al. (2021), but the spatial distribution of the changes in NDVI varied somewhat due to differences in the lengths of the data time series used in these studies. The trend of the annual NDVI changes in Mongolia experienced a significant shift around 2004, potentially linked to the implementation of various environmental policies in the country. These policies include the launch of the "Green Great Wall Project" in 2005, the enforcement of the "National Desertification Control Plan" in 2010, and the establishment of the National Soil Protection and Desertification Control Bureau in 2012. As elevation and slope steepness increase, the NDVI tends to decrease, consistent with the findings of Hu and Xu (2014) on the broader spatial patterns of NDVI and DEM. This suggests that terrain features exert a macro-scale constraint on NDVI distribution, likely influenced by factors such as high elevations and steep slopes, resulting in reduced climate suitability, soil degradation, and reduced water availability. Notably, vegetation at elevations of 500–1000 m, predominantly desert steppe, did not exhibit robust growth. Research indicates that terrain factors are the primarily influences on typical grassland and alpine meadow vegetation in Mongolia, whereas precipitation is the main driver for desert steppe vegetation (Meng et al., 2020). From 1990 to 2022, Mongolia experienced an overall increase in annual average temperature and a decrease in annual precipitation, manifesting as warm-drying characteristics. This period was further divided into two stages: warm-drying from 1990 to 2004 and warm-wetting from 2004 to 2022. In addition, Mongolia witnessed significant increases in NDVI from 2004 to 2022, indicating favorable conditions for vegetation growth due to the warmer and wetter climate. This aligned with the findings of Yang (2019), emphasizing that a warm and humid climate supports the growth of pasture grasses. Previous studies have generally attributed the vegetation NDVI changes in most high-latitude regions of the Northern Hemisphere to climate warming (Peng et al., 2011; Piao et al., 2011). In contrast, the results of this study indicate that the correlation between NDVI and temperature in the study area is not significant. This inconsistency may be due to the cold and arid climate in Mongolia, under which vegetation is less sensitive to temperature changes. Therefore, the impact of temperature on vegetation is small in Mongolia, so precipitation is more critical for vegetation growth. Furthermore, our findings suggest that changes in precipitation play a dominant role in vegetation growth in Mongolia in the context of a warming climate.

This study focused on the effects of temperature, precipitation and topography on the vegetation cover of Mongolia. However, as a large livestock country, there are clear impacts of human activities on the vegetation cover in Mongolia, and human activities, socio-economic and other factors should be included in follow-up studies. This would provide a more comprehensive understanding of the effects and interactions of natural and human factors on the changes in vegetation cover and improve our understanding of the mechanisms underlying vegetation changes.

5 Conclusions

(1) From 1990 to 2022, the NDVI in Mongolia increased significantly (0.0015 yr^{-1}, P<0.05). This included a non-significant decrease from 1990 to 2004 (–0.0013 yr^{-1}), and a significant increase from 2004 to 2022 (0.0036 yr^{-1}, P< 0.05). Spatially, the state of vegetation recovery was better in the eastern part of Mongolia from 1990 to 2022, and vegetation degradation was severe in the southwestern part of the country. The NDVI decreased non-significantly in most areas from 1990 to 2004, but it significantly increased in the eastern part of the country and significantly decreased in the southwestern part of the country from 2004 to 2022.

(2) From 1990 to 2022, the NDVI increased at different elevations and slopes, with higher growth rates at lower elevations (500–1000 m) and slopes (0°–5°) and lower growth rates in regions with elevations from 1500–2000 m and slopes above 15°.

(3) From 1990 to 2022, Mongolia experienced a notable increase in average annual temperature and a decrease in annual precipitation, indicating a clear trend toward warmer and drier conditions. The period from 1990 to 2004 was marked by warm and dry conditions, and from 2004 to 2022, the trend shifted towards warmer and wetter conditions. In Mongolia, the NDVI was primarily correlated with a decrease in annual precipitation and an increase in mean annual temperature. The decrease in precipitation from 1990 to 2022 was a significant factor contributing to the deterioration of vegetation in the southern-central region of Mongolia.

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蒙古国植被指数时空变化特征及其对气温降水的响应

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摘　要：蒙古高原是我国北方重要生态屏障，开展气候变暖背景下蒙古国植被动态变化研究，对于深入了解全球气候变暖的区域植被响应特征及筑牢我国北方生态屏障具有重要的理论与现实意义。本研究以 1990–2022 年 8 km 分辨率逐年 GIMMS NDVI3g 数据、气温和降水及高程数据为基础，采用趋势分析和相关分析方法，分析了蒙古国 NDVI（Normalized Difference Vegetation Index）时空变化特征及其与气温、降水的关系。结果表明：（1）1990–2022 年蒙古国 NDVI 呈显著增长趋势，增长速率为 0.0015 yr^{-1}（P<0.05）。（2）空间上，1990–2022 年蒙古国 NDVI 以增加趋势为主，占国土面积的 60.73%，其中显著增加占 31.67%，集中分布在蒙古国东部及西部边缘地区；显著减少占 15.67%，集中分布在蒙古国西南部边缘地区。（3）从地形上来看，除海拔 1500–2000 m 范围 NDVI 呈不显著增加趋势外，其他区域 NDVI 均呈显著增加趋势，其中 500–1000 m 增加速率最快，并随海拔升高增加趋势先减弱后逐渐显著；不同坡度范围 NDVI 均呈显著增加趋势，并随坡度增加增速降低。（4）1990–2022 年蒙古国 NDVI 与气温以负相关关系为主，占国土面积的 66.75%，其中呈显著负相关的区域占 17.21%，主要分布在蒙古国西南部地区； NDVI 与降水以正相关关系为主，占国土面积的 86.71%，其中呈显著正相关的区域占 40.44%，主要分布在蒙古国西南部地区。研究认为蒙古国植被生态质量总体改善，但气候暖干化引起的中南部区域植被生态恶化应引起重视。

关键词：归一化植被指数；坡度；高程；趋势分析；相关性分析；蒙古国