frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 09 February 2023
DOI 10.3389/fevo.2023.1067209

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SPECIALTY SECTION
This article was submitted to Environmental Informatics and Remote Sensing,
a section of the journal
Frontiers in Ecology and Evolution

RECEIVED 11 October 2022
ACCEPTED 17 January 2023
PUBLISHED 09 February 2023

CITATION
Li G, Yu L, Liu T, Bao Y, Yu J, Xin B, Bao L, Li X, Chang X and Zhang S (2023) Spatial and temporal variations of grassland vegetation on the Mongolian Plateau and its response to climate change.
Front. Ecol. Evol. 11:1067209.
doi: 10.3389/fevo.2023.1067209

Spatial and temporal variations of grassland vegetation on the Mongolian Plateau and its response to climate change

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The Mongolian Plateau is an arid and semi-arid region with grassland as its main vegetation. It has a fragile ecosystem and is a sensitive area for global warming. The study is based on MODIS NDVI data and growth season meteorological data from 2000 to 2018, this study examined the spatial and temporal variation characteristics of grassland vegetation on the Mongolian Plateau during the growing season using trend analysis, partial correlation analysis, and residual analysis, and it explores the dual response of NDVI changes to climate and human activities. The study's findings demonstrated that the growing season average NDVI of grassland vegetation on the plateau gradually increased from southwest to northeast during the growing season; the growing season average NDVI demonstrated a significant overall increase of 0.023/10a ($p < 0.05$) from 2000 to 2018, with an increase rate of 0.030/10a in Inner Mongolia and 0.019/10a in Mongolia; the area showing a significant increase in NDVI during the growing season accounted for 91.36% of the entire study area. In Mongolian Plateau grasslands during the growing season of 2000–2018, precipitation and downward surface shortwave radiation grew significantly at rates of 34.83mm/10a and 0.57 W/m2/10a, respectively, while average air temperature decreased slightly at a rate of −0.018°C/10a. Changes in meteorological factors of grassland vegetation varied by region as well, with Inner Mongolia seeing higher rates of precipitation, lower rates of average air temperature, and lower rates of downward surface shortwave radiation than Mongolia. On the Mongolian Plateau, the NDVI of grassland vegetation in the growing season showed a significant positive correlation with precipitation (0.31) and a significant negative correlation with average air temperature (−0.09) and downward surface shortwave radiation (−0.19), indicating that increased in NDVI was driven by an increase in precipitation paired with a decrease in air temperature and a decrease in surface shortwave radiation. The overall increase in NDVI caused by human activity in the grasslands of the Mongolian Plateau was primarily positive, with around 18.37% of the region being beneficial. Climate change and human activity both affect NDVI variations in Mongolian Plateau grasslands, which are spatially heterogeneous. Moderate ecological engineering and agricultural production activities are crucial for vegetation recovery. This work is crucial to further understanding surface–atmosphere interactions in arid and semi-arid regions in the context of global climate change.

KEYWORDS

Mongolian Plateau, grassland vegetation, climate change, NDVI, vegetation changes

1. Introduction

One of the key scientific topics in global change research has been how terrestrial ecosystems respond to and give feedback on global climate change (Fu, 2018; Yu G. et al., 2020). The report of working group I of the sixth assessment of IPCC (Ar6) stated that the average global surface temperature rose by around 1°C during 1850–1900 and the average temperature change over the next 20 years will be 1.5°C, with average precipitation also predicted to rise (Zhou et al., 2021). Extreme weather events have become more frequent as a result of global warming, which has a negative influence on vegetation changes and the balance of the entire ecosystem (Fu et al., 2014). One of the largest and most extensively dispersed terrestrial ecosystems, grasslands contain one-third of the world's terrestrial carbon pool and served as the foundation for the development of animal husbandry (Scurlock and Hall, 1998; Du et al., 2004). However, the grassland ecosystem habitats are delicate, prone to outside perturbation, and extremely sensitive to changes in global temperature and the environment, particularly in arid and semi-arid regions where water resources are short (Scurlock and Hall, 1998). For a complete understanding of the interaction between ecosystems and climate change in the context of climate warming, it is crucial to clarify how vegetation changes in grassland ecosystems respond to climate change (Gao et al., 2017).

The arid and semi-arid Mongolian Plateau is a typical ecologically fragile area that has experienced significant desertification in the past (Kang et al., 2007). Guo (2021) examined that the characteristics of desertification evolution on the plateau from 2000 to 2019 using MODIS/MCD43A4 data in conjunction with GEE and Markov models. He came to the conclusion that the desertification area on the Mongolian Plateau region has shown a weakening decreasing trend in recent decades (Guo, 2021). However, recent studies using remote sensing observations have revealed that there are significant regional differences in the vegetation changes on the plateau: the vegetation in the larger areas of Inner Mongolia has tended to become greener as a result of ecological conservation efforts, whereas the vegetation in some areas of Mongolia still shows general overall degradation (Li et al., 2022). Numerous studies have investigated how the various vegetation varieties react to climate change. For instance, Xie et al. (2022) used the maximum synthesis method, trend analysis, and correlation analysis to analyze the spatial and temporal variation characteristics of vegetation and the mechanisms influenced by climatic factors based on MODIS normalized vegetation index, enhanced vegetation index, and meteorological data in the Yellow River basin from 2000 to 2018. They discovered that throughout the growing season, temperature and precipitation—which were both very important for grassland—were mainly positively connected with the vegetation indices, with a lag time of 1 month for temperature and 3 months for precipitation (Xie et al., 2022). In 2015, Shen et al. investigated how vegetation in the grassland region of China responded to climate change. They discovered that the region's overall vegetation cover had increased over the previous 25 years, and there was a clear spatial variation in seasonal changes (Shen et al., 2015). According to Peng et al. (2013), the NDVI of vegetation during the growing season on the Qinghai–Tibet Plateau exhibited a positive association with both the average maximum temperature and lowest temperature of the growing season (Peng et al., 2013). According to Shen et al. (2016), the NDVI of grassland vegetation on the Tibetan Plateau was strongly negatively associated with the mean maximum temperature and positively correlated with the mean minimum summer temperature (Shen et al., 2016). Currently, the long-term changes of grassland vegetation on the Mongolian plateau during the growing season and their attribution are still relatively rare, and it is still unclear how human activities affect these changes and regional differences. And basically, the relationship between NDVI and meteorological factors is revealed in a holistic manner, ignoring how different vegetation types are responding to climate change. Therefore, it is crucial to research recent trends in vegetation change and the factors that have contributed to them on the Mongolian Plateau.

In light of this, this paper uses one-dimensional linear trend analysis, partial correlation analysis, and multiple regression residual analysis based on MODIS NDVI data and meteorological data (precipitation, average air temperature and downward surface shortwave radiation) from 2000 to 2018 to characterize the spatial and temporal variation of NDVI in the growing season (May–September) of grassland vegetation on the Mongolian plateau. In order to better understand the interrelationship between vegetation, climate, and human activity, it also looked at the factors that influence NDVI changes caused by both the climate and human activity. Clarification of the characteristics of the spatial and temporal variation of grassland vegetation on the Mongolian Plateau and its response to climate change can provide a scientific basis for revealing the mechanism of the relationship between grassland vegetation and climate change. It can also aid in scientific understanding of the response and feedback relationship between vegetation change and global change in various physical and human environments.

2. Materials and methods

2.1. Study area

The Mongolian Plateau is located in the central hinterland of East Asia, between 39°41′1.40″ to 50°53′40.24″ N and 87°44′58.76″ to 120°34′27.19″ E (Figure 1A). It extends from the Great Khingan Mountains in the east to the Altai Mountains in the west, and from the Kent-Yabunov Mountains in the north to the Yinshan Mountains in the south, mainly including all of Mongolia and the whole territory of Inner Mongolia Autonomous Region, China (Liu, 1993). The Mongolian Plateau is a massive, gently sloping plateau with an average elevation of 1,580 meters. With mountains in the north and west, sizable hills in the center and east, and the huge Gobi Desert in the southwest, the landscape is high in the west and low in the east, falling gradually from the surrounding mountains to the high plains in the middle (Zhang et al., 2018). The Mongolian Plateau experiences four distinct seasons: cold and lengthy winter, dry and windy spring, hot and brief summer, and cool autumn. The climate is temperate continental with an uneven temperature distribution, with relatively low temperatures in the humid north and east caused by the influence of moisture from the Arctic Ocean to the north, and relatively high temperatures in the arid southwest. The semi-humid zone in the north and east gradually gives way to semi-arid, arid, and highly arid zones in the southwest, with an average annual precipitation on the plateau of around 200 mm and an irregular spatial and temporal distribution of precipitation (Zhang et al., 2009; Miao et al., 2014). While Inner Mongolia and Mongolia share many natural characteristics, and their populations used to lead mostly nomadic and herding lifestyles, significant socioeconomic contrasts have emerged between the two regions as a result of social and economic development. Since 1978, China has attached great attention to ecological restoration projects in the northern China to reverse the depredated environment, and as a

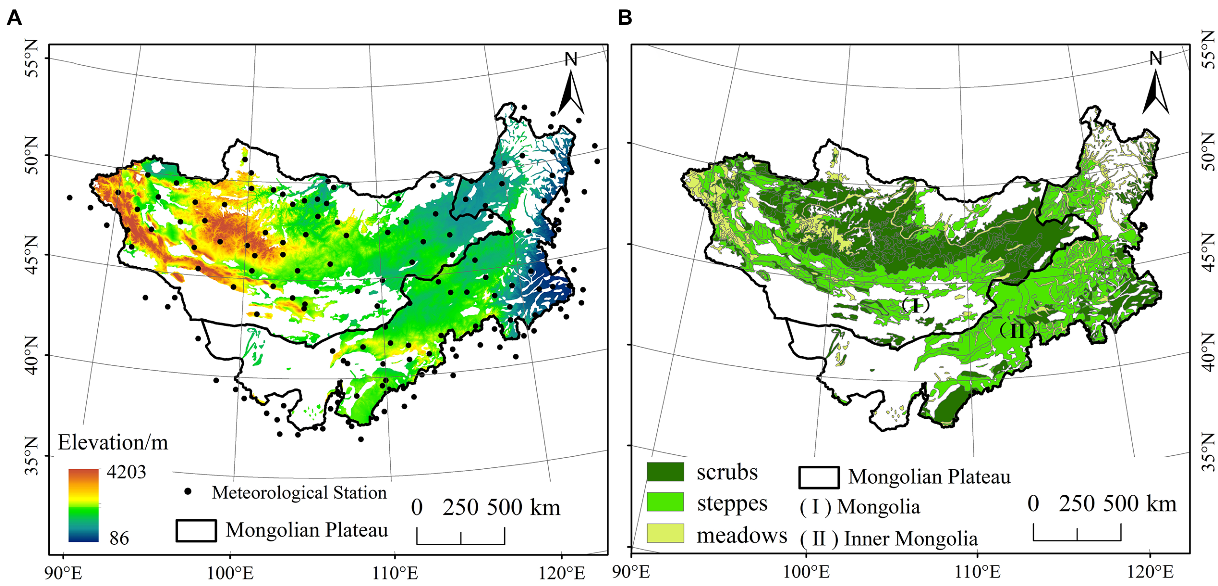

FIGURE 1
(A) Geographical location and meteorological stations of Mongolian Plateau and **(B)** distribution of grassland vegetation types.

result, many ecological restoration projects have been implemented in Inner Mongolia, which was in contrast for Mongolia, where human disturbances were rare. Steppes in the study area are mainly distributed in the southeast, with scrubs in the northeast and north, while meadows are mostly distributed at high altitudes on the western edge of the study area (Figure 1B).

2.2. Data processing and analysis

Meteorological data including precipitation, average air temperature and downward surface shortwave radiation. The meteorological data on the China side were obtained from the National Weather Science Data Center's dataset of monthly values of surface climate information[1], and the Mongolian data were taken from the National Oceanic and Atmospheric Administration's weather data.[2] A total of 86 meteorological observation sites containing valid precipitation data and 98 valid air temperature data in the Mongolian Plateau from 2000 to 2018, in addition to 58 nearby meteorological stations collected as supplementary data (Figure 1A), were interpolated and cropped using professional ANUSPLIN software to obtain 1 km resolution air temperature and precipitation raster data for the study area from 2000 to 2018. The downward surface shortwave radiation data are derived from the monthly value dataset TerraClimate provided by the Google Earth Engine[3] platform with a spatial resolution of 1/24° and resampled to 1 km.

The MOD13A2.006 product data of 2000–2018 from the Google Earth Engine platform (see footnote 3) with a spatial resolution of 1 km and a temporal resolution of 16 days, were used in this investigation to extract NDVI. In this study, the average NDVI values from May to September were used to characterize the NDVI values during the growth season, and the NDVI values of all pixels in the study region pertaining to each type of grassland were used to represent the NDVI values of this type of grassland vegetation.

The 1:4,000,000 vegetation map published by the Chinese Academy of Sciences in 1996, was used to determine the vegetation types in Inner Mongolia, and a 1:3,000,000 vegetation map provided by the Mongolian Academy of Sciences was used to determine the vegetation types in Mongolia. The accuracy of these datasets was verified utilizing a combination of ground verification, remote sensing techniques, and discriminative interactive human–computer interpretation of the data.

2.3. Methods

2.3.1. Slope trend analysis

In this study, we used the regCoef function in NCL to compute NDVI trends and examine the NDVI trends of grassland vegetation on the Mongolian Plateau in the growing seasons from 2000 to 2018. The regCoef [x, y (lat|:, lon|:, time|:)] function is mostly used to process multidimensional x- and y-arrays. To determine the multiyear trend of NDVI, linear regression coefficients (using least squares) were produced. The calculating equation is as follows:

$$NDVI_{Slope} = \frac{n\sum_{i=1}^{n}(iQ_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} Q_i}{n\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)} \quad (1)$$

where $NDVI_{Slope}$ is the slope of NDVI change during the research time period, i is the study year, n is the time series length (19 years), and Q_i is the NDVI value for the growing season in year i. Positive $NDVI_{Slope}$ indicating the NDVI is increasing, while negative values means the NDVI is decreasing.

1 http://data.cma.cn/
2 https://www.ncei.noaa.gov/maps-and-geospatial-products/
3 https://code.earthengine.google.com/

2.3.2. ANUSPLIN meteorological data interpolation

The meteorological stations on the Mongolian Plateau were interpolated using the ANUSPLIN multivariate data interpolation and analysis software package for meteorological data created by the Australian National University (Hijmans et al., 2005). It is made up of eight submodule programs that offer a comprehensive set of functions for statistical analysis, data diagnosis, and the computation of spatial distribution standard errors (Hijmans et al., 2005; Liu et al., 2008a). The SPLINA and LAPGRD modules, whose built-in thin-disk smooth spline function enables the inclusion of covariates (elevation, coastline, etc.), are the principal applications for interpolating temperature and precipitation (Liu et al., 2008b). The local thin-disk smooth spline function's theoretical statistical model is written as:

$$Z_i = f(x_i) + b^T y_i + e_i \left(i = 1,2,\ldots\ldots,N\right) \quad (2)$$

where z_i is the dependent variable, located at point i in the interpolation space; x_i is a d-dimensional vector with respect to the sample independent variables; f is an unknown smooth function with respect to x_i; y_i is a p-dimensional independent covariate; b^T is a p-dimensional coefficient with respect to the y_i coefficients; e_i is a random error term in the independent variable, with expectation 0; and N is the number of interpolated sample points.

In this study, the optimal spatial interpolation model was used for spatial interpolation of precipitation and air temperature, that was, a three variable local thin disk smooth spline function with longitude and latitude as independent variables of precipitation and elevation as covariate of air temperature, and the number of splines was set to 2.

2.3.3. Partial correlation analysis

When two variables are simultaneous correlated with a third variable, partial correlation analysis is the process of removing the impact of the third variable and examining only the level of correlation between the other two variables. The calculating equation is as follows:

$$R_{xy,z} = \frac{R_{xy} - R_{xz} - R_{yz}}{\sqrt{\left(1 - R_{xz}^2\right)\left(1 - R_{yz}^2\right)}} \; R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (3)$$

where $R_{xy\ z}$ is the partial correlation coefficient; R_{xy}, R_{xz}, R_{yz} are the simple correlation coefficients between x, y, z. If $R_{xy\ z}$ is greater than 0, then the two variables are positively correlated, otherwise if $R_{xy\ z}$ is less than 0, then the two variables are negatively correlated.

2.3.4. Residual analysis

By eliminating the effects of precipitation and air temperature on the NDVI long time series change, natural and anthropogenic factors in vegetation cover change were distinguished. The predicted value of NDVI is fitted by meteorological factors, that is, the impact of climate change. According to the residual trend method, the difference between the calculated NDVI prediction and the actual value is regarded as anthropogenic influences (Evans and Geerken, 2004).

$$NDVI_{pre} = aT + bP + c \quad (4)$$

$$\varepsilon = NDVI_{real} - NDVI_{pre} \quad (5)$$

Where $NDVI_{pre}$ is the NDVI prediction value obtained by establishing a binary linear regression model based on NDVI, precipitation, and air temperature time series data, with NDVI as the dependent variable and air temperature and precipitation as the independent variables, under the assumption that anthropogenic influences have no impact. T and P are growing season air temperature and precipitation; a, b, and c are model parameters.

Where ε is the residual of NDVI; $NDVI_{real}$ is the NDVI value in the remote sensing image. Calculate with formula (1) ε if it is positive, it means that anthropogenic influences promote NDVI, otherwise, it indicates an inhibitory effect.

3. Results

3.1. Spatial and temporal variation of NDVI in growing seasons of grassland vegetation on Mongolian Plateau

The spatial distribution of growing season average NDVI of grassland vegetation on the Mongolian Plateau from 2000 to 2018 showed that it gradually increased from southwest to northeast (Figure 2A). On the plateau, low NDVI values are primarily found in the southwest and center, and high values are primarily concentrated in the northeast Great Khingan Mountains. The multi-year growing season average of NDVI for the three different grassland vegetation in order of magnitude were: meadows (0.36) > scrubs (0.31) > steppes (0.27). The average NDVI for the growing season of grassland vegetation on the Mongolian Plateau was around 0.30, and the average NDVI for Inner Mongolia and Mongolia were 0.36 and 0.26, respectively. The average NDVI and trends of various grassland vegetation types varied greatly between Inner Mongolia and Mongolia. As can be seen from Table 1, in terms of both the multiyear average NDVI and multiyear NDVI trends, the vegetation was significantly greener in Inner Mongolia than in Mongolia. The average NDVI of various types of grassland vegetation in both regions for the growing seasons in 2000–2018 was compared. The results showed that higher values for Inner Mongolian meadows (0.49) than Mongolian meadows (0.28), inner Mongolian scrubs (0.38) than Mongolian scrubs (0.29), and inner Mongolian steppes (0.33) than Mongolian steppes (0.19).

In terms of time variation, the average NDVI of the growing seasons on the Mongolian Plateau showed a considerable increase overall from 2000 to 2018, while the NDVI values of scrubs, steppes, and meadows exhibited strong increasing trends (Figure 3). Grassland vegetation demonstrated a considerable overall rising trend (Figure 2B), with an increase of 0.023/10a, as can be seen in Figure 3. During the growing season, NDVI increased significantly for meadows, steppes, and scrubs, with the change trend varying among the vegetation types; the largest NVDI increase was found for scrubs (0.028/10a), followed by steppes (0.021/10a), and meadows (0.020/10a). On the Mongolian Plateau, the area of growing season grassland vegetation showing an increasing NVDI trend (91.36%) is significantly larger than the area showing a decreasing trend (8.64%). Additionally, when looking at the entire Mongolian Plateau spatially, the rising trend for Inner Mongolia is 0.030/10a while that for Mongolia is only 0.019/10a. The comparison of NDVI trends for various types of grassland vegetation in Inner and Outer Mongolia during

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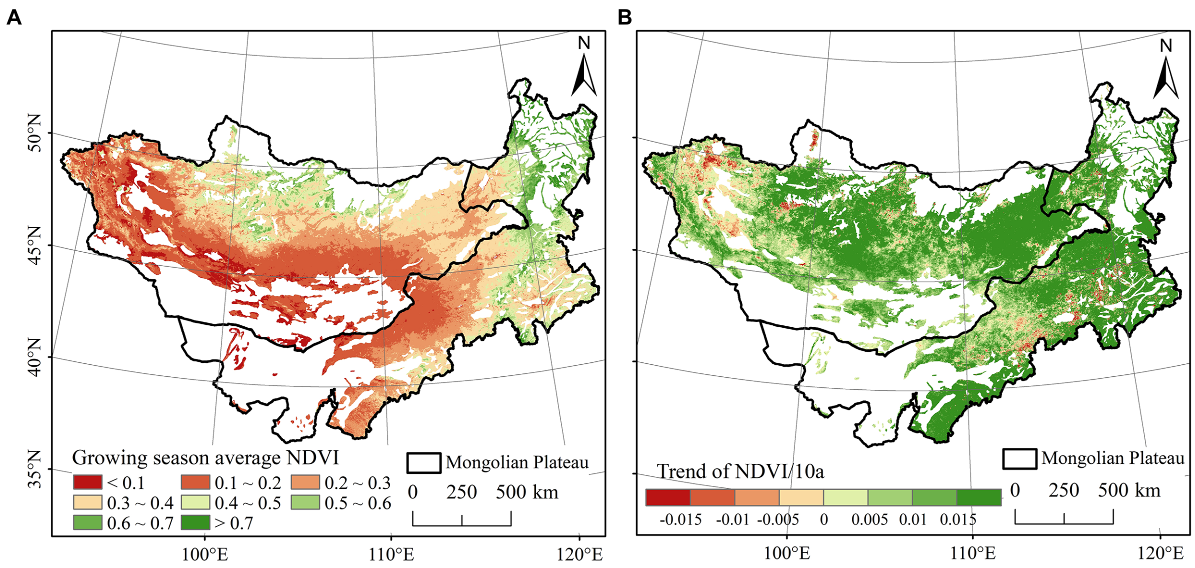

FIGURE 2
(A) Spatial distribution map of average NDVI **(A)** and NDVI change trend **(B)** for grassland vegetation during growing season from 2000 to 2018 across Mongolian Plateau.

TABLE 1 Comparison of growing season average NDVI and associated trend of grassland vegetation types in Inner Mongolia and Mongolia from 2000 to 2018.

Growing season average NDVI of grassland vegetation in Inner Mongolia and Mongolia during 2000–2018			NDVI change trend of grassland vegetation in Inner Mongolia and Mongolia during growing season 2000–2018 /10a		
Vegetation type	Inner Mongolia	Mongolia	Vegetation type	Inner Mongolia	Mongolia
Scrubs	0.38	0.30	scrubs	0.040	0.024
Steppes	0.33	0.19	steppes	0.027	0.013
Meadows	0.49	0.28	meadows	0.026	0.016

the growing seasons in 2000–2018 (Table 1) shows the following: Inner Mongolia scrubs (0.040) > Mongolia scrubs (0.024); Inner Mongolia steppes (0.027) > Mongolia steppes (0.013); Inner Mongolia meadows (0.026) > Mongolian meadows (0.016). Among them, NDVI increased most significantly for grasslands in eastern and southern Inner Mongolia during the growing seasons. Areas showing a decrease in NDVI for grassland vegetation were mainly found in the central and western parts of Chifeng City and the southern part of Xilin Gol League in Inner Mongolia, the northern part of Tuv Province, the border area between Tuv Province and Govisumber Province, the eastern part of Zavkhan Province, and the northern part of Khuvsgul Province (Figure 2B).

3.2. Climate change traits on the Mongolian Plateau

This paper uses the ANUSPLIN meteorological interpolation model to interpolate the growing season precipitation and average air temperature across the Mongolian Plateau based on the measured data from meteorological stations. Additionally chosen was the TerraClimate monthly value dataset's downward surface shortwave radiation. It also calculates the growing season average air temperature, precipitation and downward surface shortwave radiation trends in the grassland vegetation to further explain the spatial and temporal variation of NDVI in the growing season on the Mongolian Plateau. From 2000 to 2018, the growing season precipitation increased significantly by 34.83 mm/10a the downward surface shortwave radiation increased by 0.57 W/m^2/10a and average air temperature decreased slightly by −0.018°C/10a throughout the grassland (Table 2 and Figure 4). The growing season precipitation for each grasslands vegetation types showed a significant increasing trend for scrubs (37.55 mm/10a), steppes (31.11 mm/10a), and meadows (40.45 mm/10a), and the average air temperature trend indicated a downward trend for scrubs (−0.273°C/10a), steppes (−0.121°C/10a), and meadows (−0.089°C/10a). In the grassland vegetation, the downward surface shortwave radiation during the growing season increased for scrubs and steppes at rates of 0.27 W/m^2/10a and 1.09 W/m^2/10a, respectively, while it decreased for meadows at a rate of −0.47 W/m^2/10a. The trends of precipitation, average air temperature and downward surface shortwave radiation for each kind of grassland vegetation in the growing season varied by location. Each grassland vegetation in Inner Mongolia has a higher precipitation trend than the corresponding grassland vegetation in Mongolia. Similarly, Inner Mongolia has a higher average air temperature trend than Mongolia, while Inner Mongolia has a lower downward surface shortwave radiation trend than Mongolia. Following is a comparison of the change trend of meteorological factors during the growing season of grassland vegetation in Inner Mongolia and Mongolia (Table 3) specifically shows the following, the growing season precipitation trend

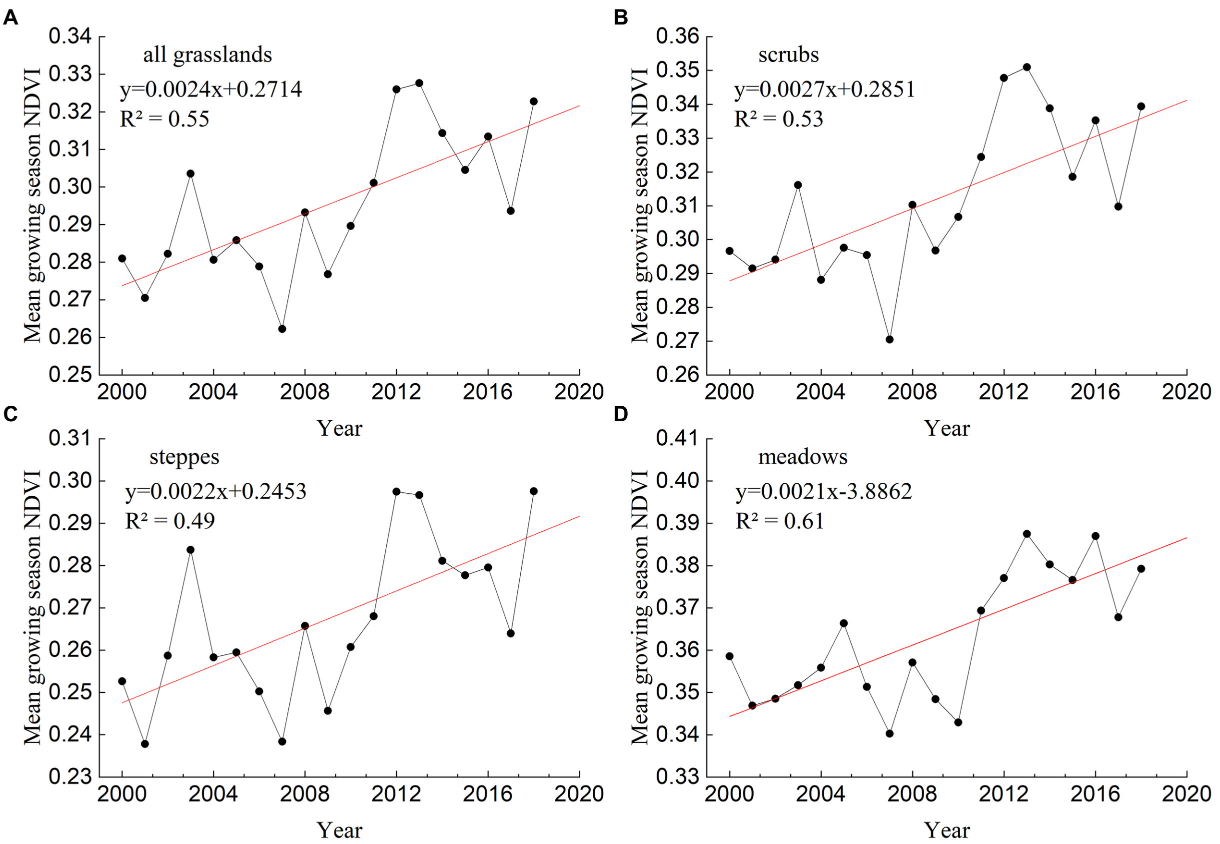

FIGURE 3
NDVI changes for different types of grassland vegetation on Mongolian Plateau during growing seasons from 2000 to 2018. **(A)** All grasslands, **(B)** scrubs, **(C)** steppes, **(D)** meadows.

TABLE 2 Change trend of growing season meteorological factors for grassland vegetation on Mongolian Plateau from 2000 to 2018.

Grassland type	Growing season precipitation/(mm/10a)	Growing season mean air temperature/(°C/10a)	Growing season downward surface shortwave radiation/ (W/m²/10a)
The whole grassland	34.83	−0.180	0.57
Scrubs	37.55	−0.273	0.27
Steppes	31.11	−0.121	1.09
Meadows	40.45	−0.089	−0.47

of Inner Mongolia scrubs (60.37 mm/10a) > Mongolia scrubs (31.63 mm/10a), Inner Mongolia steppes (41.16 mm/10a) > Mongolia steppes (18.42 mm/10a), Inner Mongolia meadows (68.31 mm/10a) > Mongolia meadows (24.21 mm/10a). The growing season average air temperature trend of Inner Mongolia scrubs (−0.057°C/10a) > Mongolia scrubs (−0.330°C/10a), Inner Mongolia steppes (−0.085°C/10a) > Mongolia steppes (−0.166°C/10a), Inner Mongolia meadows (−0.042°C/10a) > Mongolia meadows (−0.117°C/10a).

3.3. Correlation between NDVI and meteorological factors of the grassland vegetation on Mongolian Plateau

The Mongolian Plateau is located in an arid and semi-arid region, and the amount of precipitation directly affects the change of NDVI. The average air temperature and downward surface shortwave radiation are also one of the direct causes of NDVI change in the Mongolian Plateau to explore the response of grassland vegetation to climate change, we conducted a partial correlation analysis and significance test of the NDVI of grassland vegetation with precipitation, average air temperature, and downward surface shortwave radiation during the growing season of 2000–2018. The results indicate that (Tables 4, 5 and Figure 5A), the NDVI of grassland vegetation during the growing season on the Mongolian Plateau generally showed a highly significant positive correlation with precipitation ($p < 0.05$), with a partial correlation coefficient of 0.31. In the Inner Mongolia region, the partial correlation coefficient between NDVI and precipitation was 0.37, with 0.26 for scrubs, 0.44 for steppes, and 0.20 for meadows. In Mongolia, it was 0.28, with 0.33 for the scrubs, 0.25 for steppes, and 0.14 for meadows. This suggests that the key element influencing the development of grassland vegetation on the plateau is precipitation throughout the growing season, i.e., increasing precipitation encourages increased NDVI in grassland

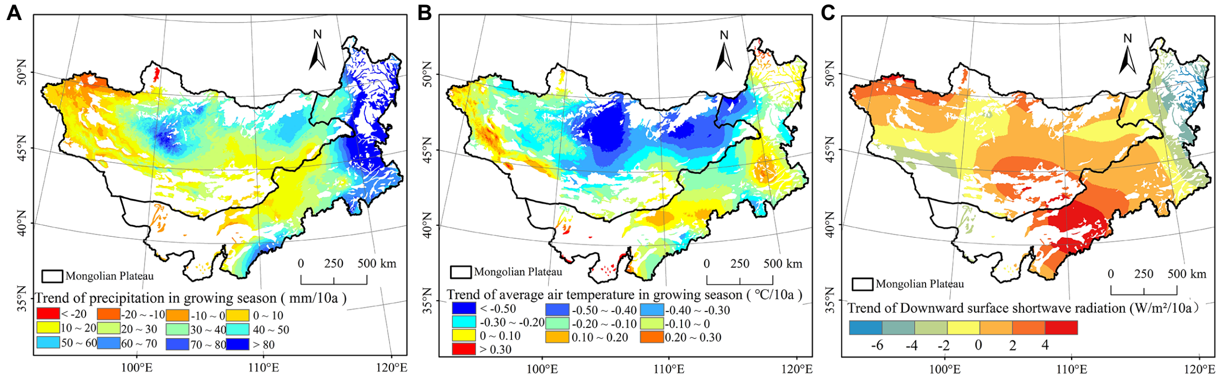

FIGURE 4
Temporal and spatial variation trend of growing season meteorological factors for grassland vegetation on Mongolian Plateau from 2000 to 2018. **(A)** Trend of precipitation in growing season (mm/10a), **(B)** Trend of air temperature in growing season (°C/10a), **(C)** Trend of downward surface shortwave in growing season (W/m^2/10a).

TABLE 3 Comparison of meteorological factors change trends of grassland vegetation types in Inner Mongolia and Outer Mongolia during growing seasons from 2000 to 2018.

Precipitation trend of grassland vegetation growing seasons in Inner Mongolia and Mongolia from 2000 to 2018 (mm/10a)			Trend of average air temperature of grassland vegetation growing seasons in Inner Mongolia and Mongolia from 2000 to 2018 (°C/10a)		Trend of downward surface shortwave radiation of grassland vegetation growing seasons in Inner Mongolia and Mongolia from 2000 to 2018 (W/m^2/10a)	
Vegetation type	Inner Mongolia	Mongolia	Inner Mongolia	Mongolia	Inner Mongolia	Mongolia
The whole grassland	48.35	26.09	−0.074	−0.246	0.54	0.60
Scrubs	60.37	31.63	−0.057	−0.329	−0.46	0.46
Steppes	41.16	18.42	−0.085	−0.167	1.33	0.80
Meadows	68.31	24.21	−0.042	−0.117	−2.28	0.58

vegetation. The areas with a positive correlation between NDVI and precipitation in the growing season accounted for 86.87% of the entire grassland distribution area, and only about 13.13% of the distribution area showed a negative correlation, these areas were mainly concentrated in the eastern meadows range of Zavkhan Province, the central meadows range of Khuvsgul Province and the western scrubs range in Mongolia, and some scattered areas showed negative correlations mostly in the meadows ranges of Bayan-Ulgii, Uvs and Khovd Provinces; negative correlations existed in the northern steppes of Alxa League and some steppes ranges of Great Khingan in Inner Mongolia.

It is obvious from Tables 4, 5 and Figure 5B that the average growing season air temperature showed a highly significant negative correlation ($p<0.05$) with the NDVI of grassland vegetation, with a partial correlation coefficient of −0.09, and the partial correlation coefficients between NDVI and air average temperature in Inner Mongolia and Mongolia were − 0.04 and − 0.12, respectively, with −0.02 for scrubs, −0.08 for steppes, and 0.12 for meadows in Inner Mongolia, and − 0.16 for scrubs, −0.09 for steppes, and − 0.08 for meadows in Mongolia. Areas showing a negative correlation between NDVI and average air temperature in the growing season accounted for 63.92% of the entire grassland vegetation distribution area, and about 36.08% of the area showed a positive correlation. Positive correlation areas are primarily found in Inner Mongolia's Great Khingan Mountains meadows area, the scrubs area east of Tongliao City, the Xilin Gol League's southern scrubs area, and the Alxa League's northern scrubs and southern meadows areas. It has also been discovered in the steppes of northern Dornogovi Province and eastern Dundgovi Province, the steppes of central Govi-Altai Province, the scrubs in the north, the meadows in the south and west of Arkhangai Province, the meadows of northern Khuvsgul Province, and the meadows of northern western Bayan-Ulgii Province and western Uvs Province in Mongolia.

It is obvious from Tables 4, 5 and Figure 5C that the downward surface shortwave radiation showed a highly significant negative correlation ($p<0.05$) with the NDVI of grassland vegetation, with a partial correlation coefficient of −0.19, and the partial correlation coefficients between NDVI and downward surface shortwave radiation in Inner Mongolia and Mongolia were − 0.15 and − 0.21, respectively, with −0.20 for scrubs, −0.15 for steppes, and 0.12 for meadows in Inner Mongolia, and − 0.16 for scrubs, −0.29 for steppes, and − 0.15 for meadows in Mongolia. Areas showing a negative correlation between NDVI and downward surface shortwave radiation in the growing season accounted for 75.06% of the entire grassland vegetation distribution area, and about 24.94% of the area showed a positive correlation. The locations with positive correlations were mostly found in the steppes distribution regions of Xilin Gol League and Ulanqab City in the center of Inner Mongolia, the scrubs regions of Sukhbaatar and Oriental Province in the east, and the scrubs region of Zavkhan Province in the west.

As shown in Table 5, the partiality correlation coefficients of average air temperature and downward surface shortwave radiation are both

TABLE 4 Partial correlation of NDVI and meteorological factors in the growing season of Mongolian Plateau.

Partial correlation coefficient	Growing season precipitation	Growing season average air temperature	Growing season downward surface shortwave radiation
The whole grassland	0.31**	−0.09**	−0.19**
NDVI of scrub steppe	0.31**	−0.13**	−0.17**
NDVI of grassland	0.36**	−0.09**	−0.21**
NDVI of meadow	0.17**	−0.01**	−0.14**

** Indicates highly significant correlation ($p < 0.05$).

TABLE 5 Partial correlation comparison between NDVI and meteorological factors in growing seasons of Inner Mongolia and Mongolia from 2000 to 2018.

Growing season precipitation			Growing season average air temperature			Growing season downward surface shortwave radiation	
Vegetation type	Inner Mongolia	Mongolia		Inner Mongolia	Mongolia	Inner Mongolia	Mongolia
The whole grassland	0.37**	0.28**		−0.2998**	−0.3642**	−0.15**	−0.21**
Scrubs	0.26**	0.33**		−0.2057**	−0.4289**	−0.20**	−0.16**
Steppes	0.44**	0.25**		−0.3716**	−0.3234**	−0.15**	−0.29**
Meadows	0.20**	0.14**		−0.0556**	−0.2101**	−0.12**	−0.15**

**Indicates extremely significant correlation ($p < 0.05$).

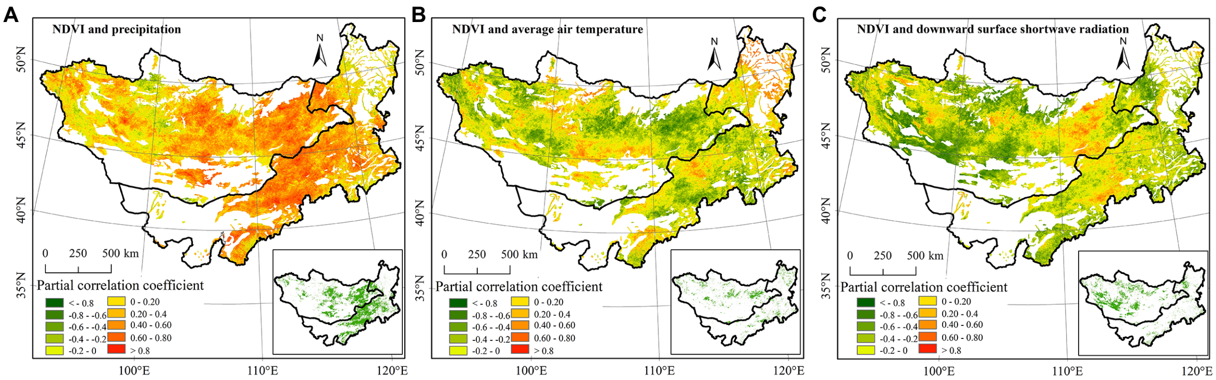

FIGURE 5
Spatial distribution of partial correlation coefficient of growing season NDVI and **(A)** precipitation, **(B)** average air temperature, and downward surface shortwave radiation **(C)** on Mongolian Plateau.

negatively correlated, and all of these correlation coefficients are significant at the 0.05 level. The growing season NDVI of each vegetation in the Mongolian plateau grassland is positively correlated with the growing season precipitation partiality correlation coefficient. This shows that precipitation, a significant factor affecting the interannual dynamics of grassland vegetation in arid and semi-arid regions, primarily controls the growing season NDVI of these three types of vegetation in Mongolian plateau grasslands.

3.4. Effects of human activity on the NDVI in the Mongolian Plateau

Multiple linear regression was developed to simulate the anticipated values of NDVI (NDVIpre) through model parameters and precipitation and air temperature data in order to reveal the effects of climate change on NDVI. This was done using precipitation and air temperature of the long time series as independent variables. The comparison reveals that the multi-year trends of the measured and predicted values are similar (Figure 6), but that the predicted NDVI before 2010 is marginally higher and the predicted value after 2010 is lower than the actual value. The measured NDVI is 0.0023 greater than the predicted NDVI of 0.0014, as determined by the slope of change.

In addition to natural factors like climate change, human activities also play a significant role in the change in NDVI of grassland vegetation. Positivity in the slope of the residual change trend indicates positive disturbance, and human activities support rising NDVI and vegetation recovery. Negative disturbance, caused by human activities, will result in a decrease in NDVI and have a suppressive effect on the vegetation recovery if the slope of the residual change trend is negative.

The residual trend was statistically analyzed to better understand how human activities affect the growth status of vegetation (Figure 7). We discovered that human activity had considerably impacted 18.37% of the grasslands on the Mongolian Plateau, with Inner Mongolia

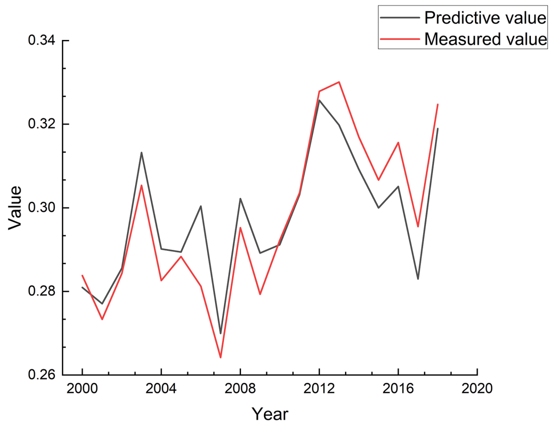

FIGURE 6
Comparison of predicted and measured NDVI values for grasslands on the Mongolian Plateau from 2000 to 2018.

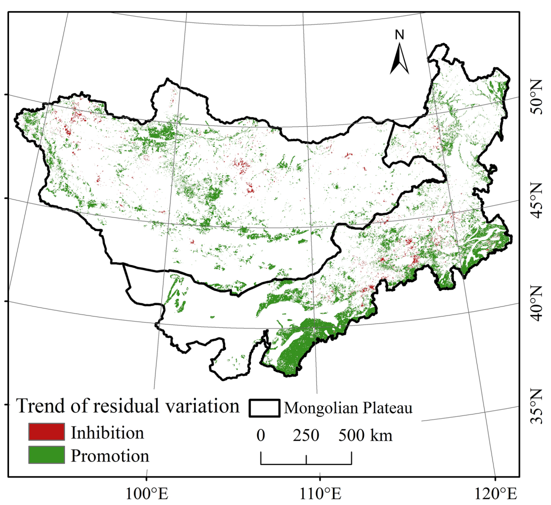

FIGURE 7
Trend distribution of NDVI residuals on the Mongolian Plateau from 2000-2018.

accounting for 11.67% of these impacts and Mongolia for 6.68%. On the Mongolian Plateau, there were 17.24% of grassland regions with positive NDVI residual trends, including 11.07% in Inner Mongolia and 6.16% in Mongolia. The overall effect of human activities on NDVI growth was primarily facilitative. These areas are primarily found in Inner Mongolia's Great Khingan Mountains, the Xilin Gol League grassland region, Tongliao City, the Erdos City region, Dundgovi Province, Ovorhangay Province, and Khuvsgul Province of Mongolia, among other places. Due to ecological engineering construction, agricultural development, grazing bans and rest periods, etc., these areas are impacted by human activities that promote vegetation. About 1.13% of the areas inhibited by human activities, including 0.60% in Inner Mongolia and 0.52% in Mongolia, are concentrated in various urban clusters, such as Ulaanbaatar, Tuv Province, Hohhot and Baotou City, etc. These areas have high population density, developed economic development, urban expansion, and a large amount of land turned into construction land. There are also inhibiting effects of human activity in the Hulunbuir steppe area, the Xilin Gol League steppe area, and the steppe area in eastern Mongolia. These effects are primarily brought on by excessive grazing and other actions that stunt the growth of vegetation.

4. Discussion

4.1. Growing season NDVI variations and its correlation with climatic factors

This study used MODIS NDVI data and meteorological data from 2000 to 2018 to analyze the spatial and temporal variation characteristics of NDVI and correlation with its meteorological factors during the growing season of grassland vegetation on the Mongolian Plateau. It was discovered that on the Mongolian Plateau, the average NDVI of grassland vegetation growing seasons showed a substantial upward trend from 2000 to 2018, with the largest increase in the Great Khingan Mountains of Inner Mongolia, followed by a larger increase in the area around Arkhangai Province in northern Mongolia, and the average growing season NDVI gradually climbed from the southwest to the northeast. Numerous studies on the spatial and temporal characteristics of NDVI changes in grasslands on the Mongolian Plateau have been conducted recently. Bai and Alatengtuya (2022) used decision tree classification to analyze the spatial and temporal changes of grassland cover in the grassland area of the Mongolian Plateau from 2001 to 2020. They discovered that the grassland area had gradually increased over the previous 20 years, while the vegetation cover had gradually decreased from the northeast to the southwest. (Bai and Alatengtuya, 2022). The Mongolian Plateau's vegetation cover reached 14.60 and 18.43% from 1986 to 1999 and 2000 to 2013, respectively, according to Zhang et al.'s analysis of NDVI data on the vegetation cover from 1982 to 2013 (Zhang et al., 2018). Dai et al. (2014) used a one-dimensional linear regression method to assess the NDVI trend on the Mongolian Plateau from 1982 to 2006, which showed that the NDVI of vegetation has improved during the preceding 25 years (Dai et al., 2014). The findings mentioned above generally agree with this study's conclusions. In this paper, in addition to the spatial and temporal variation of NDVI of grassland vegetation across the Mongolian Plateau, we also compared grassland vegetation in two regions with different land use management practices, Mongolia and Inner Mongolia, and found that both the multiyear average NDVI and NDVI variation trends in Inner Mongolia during the growing season resulted in greener vegetation than that in Mongolia. Li et al. (2021) noted that numerous ecological protection and restoration initiatives have been launched in China since 1978, with the Three Northern Protective Forests, the Key Construction Project for Soil and Water Conservation, the Beijing-Tianjin Wind and Sand Source Control Project, among 13 others, being the main ecological initiatives covering the dry zone. These initiatives have improved land degradation and increased ecosystem functions in dry regions, and they have had significant effects on vegetation, the water cycle, desertification, and ecosystem services (Ouyang et al., 2016; Bryan et al., 2018; Li et al., 2021). They have also helped to make the vegetation greener. In contrast, rather than being driven by human activity, changes in the vegetation cover in the Mongolian region are mostly caused by climatic change (John et al., 2013).

By analyzing the meteorological data for the Mongolian Plateau, we discovered that the average air temperature has been weakly dropping since 2000, while there has been a large increase in precipitation and downward surface shortwave radiation during the growing season of the entire Mongolian Plateau grassland vegetation distribution area. Among them, Inner Mongolia had more precipitation than Mongolia, whereas the trend of average air temperature and downward surface shortwave radiation fluctuates more in Mongolia than in Inner Mongolia. This discovery is consistent with earlier research by Cao et al. (2019) and Yu et al. (2021), who used satellite observations and numerical simulations to identify a general cooling trend brought on by revegetation in semi-arid regions of northern China. However, some studies, such as those by Huang and Peng, reported that the greening of vegetation may lead to atmospheric warming effects in arid and semi-arid regions due to the effect of enhanced net radiation (Peng et al., 2014; Huang et al., 2018). Due to its significant role in changing surface characteristics, surface energy, and water balance, vegetation degradation or improvement has an impact on local and regional climate through interactions between the land surface and the atmosphere (D'Odorico et al., 2013). The effect of plant restoration on the regional water cycle is more significant and debatable in arid and semi-arid regions than temperature. According to several research reports, a coupled land–atmosphere global climate model demonstrated that the greening of vegetation in northern China boosts precipitation and reduces increased evapotranspiration (Li et al., 2018). Zhu et al. (2021) found that revegetation in a semi-arid basin led to a significant decrease in the aridity index and more precipitation was involved in the soil water–groundwater cycle (Zhu et al., 2021). However, there are also other findings; for example, Jackson et al. (2005) and Ge et al. (2020) found that extensive revegetation led to increased evapotranspiration, which in turn could lead to severe water shortage (Jackson et al., 2005; Ge et al., 2020).

4.2. Spatial heterogeneity of correlations between NDVI and climatic factors

The effects of average air temperature, precipitation and downward surface shortwave radiation on grassland vegetation vary widely across space. This region's grassland vegetation's NDVI shows a positive correlation with precipitation and a negative correlation with average air temperature and downward surface shortwave radiation, indicating that more precipitation and less average air temperature and downward surface shortwave radiation are favorable for vegetation growth. For instance, Lin et al. (2020) used GIMMS-MODIS data to study the spatial and temporal variation characteristics of NDVI in northern China from 1982 to 2018, and explored the primary drivers of NDVI changes using regression analysis. The findings revealed that precipitation has a positive dominant effect on NDVI in Inner Mongolia (Lin et al., 2020). According to the findings of studies by Dai and others, high temperatures cause more evaporation in arid and semi-arid regions, while a decrease in surface moisture inhibits the growth of vegetation (Dai et al., 2014). On the other hand, an increase in precipitation promotes the growth of vegetation. In their investigation on the detection of trends and attribution of vegetation greening in China over the previous 30 years, Piao et al. (2015) determined that precipitation was the primary factor driving vegetation greening in arid regions. The amount of precipitation during the growing seasons is higher in Inner Mongolia than in Mongolia, and the region has less of a decrease in average air temperature and downward surface shortwave radiation, which is consistent with a better recovery of vegetation in Inner Mongolia than in Mongolia.

4.3. NDVI and human activities

Overall, the grassland vegetation on the Mongolian Plateau is improving, and human activity is a significant factor in the growth of the vegetation, which can have both positive as well as negative disturbance impacts on NDVI changes. The analysis leads to the conclusion that afforestation and agricultural production have a positive influence on vegetation recovery (Xin et al., 2007). Additionally, it has been discovered that implementing ecological projects like converting farmland back to forestry (grass), conserving soil and water, and enacting policies and regulations on sensible grazing and protecting arable land will all have a positive impact on the development of regional vegetation (Li et al., 2011; Jin et al., 2020). Urbanization and economic growth inevitably have an impact on vegetation, which degrades the local natural environment. This is consistent with the paper's conclusion, which found that human activity interfered negatively in urban areas but positively in agricultural production and grassland reserves.

4.4. Uncertainties and future work

The current study may have some uncertainties. Frist, since Mongolia and Inner Mongolia are included in the research area, there may be differences in the classification systems used for grassland vegetation, which could affect how the vegetation distribution is determined. Furthermore, when discussing the response of vegetation to climate change, this study does not consider the feedback effect of vegetation on climate, and our previous studies show that the feedback effect of vegetation change on regional climate is strong, which may affect the results of this paper, Yu L. X. et al. (2020) determined the response of vegetation change to climate by using a high-resolution land atmosphere coupled regional climate model, and found that the northern part of northern China showed obvious cooling, including the Northeast Plain, the Loess Plateau and the eastern part of the arid and semi-arid areas in the north (Yu L. X. et al., 2020). Li et al. (2022) used a long time series multi-source satellite and a high-resolution land-air coupled regional climate model (WRF) to investigate the climate feedbacks of surface changes observed in the Mongolian Plateau from the 1990s to the 2010s. According to model simulations, vegetation greening produces a local cooling effect, while vegetation degradation produces a warming effect (Li et al., 2022). Liu et al. (2022) used multi-source satellite measurements records and a high-resolution land atmosphere coupled regional climate model (WRF) to investigate the land surface changes and their associated thermal and wet effects in three major ecosystems in the Heilong-Amur River basin from 1982 to 2018, highlighting the different surface responses and feedbacks of different ecosystems to climate change, depending on the specific vegetation variation and background climate, which may lead to warming/cooling and wetting/drying effects (Liu et al., 2022). To better understand the relationship between vegetation and climate in arid zones, future research should consider the feedback effects of vegetation on climate.

5. Conclusions

During the growing season from 2000 to 2018 on the Mongolian Plateau, we examined the temporal and spatial variation of grassland vegetation, as well as how it responded to climate change. We also looked at the partiality connection between precipitation, temperature, downward shortwave radiation, and NDVI. The findings indicate that the grassland vegetation index improved greatly across the plateau from 2000 to 2018, with NDVI increasing at a rate of 0.023/10a during the growing season. Only 8.64% of grassland NDVI degraded, compared to 91.36% that significantly improved. The scrubs NDVI increased at the fastest pace (0.028/10a), followed by steppes (0.021/10a), and meadows (0.020/10a). While Mongolia's NDVI climbed at a slower rate of 0.019/10y, it increased at a faster rate of 0.030/10y in Inner Mongolia. Three species of grassland vegetation saw faster NDVI growth rates in Inner Mongolia than in Mongolia.

There is an increasing trend of precipitation and upward shortwave radiation across the Mongolian Plateau, with a significant increase at 34.83 mm/10a and 0.57 W/m^2/10a, respectively, variable grassland vegetation types saw different rates of precipitation and downward surface shortwave radiation throughout the growing season, with meadows receiving the greatest precipitation (40.45 mm/10a), scrubs (37.55 mm/10a), and steppes (31.11 mm/10a), and steppes having the most downward surface shortwave radiation (1.09 W/m^2/10a), followed by scrubs (0.27 W/m^2/10a) and meadows mild drop of −0.47 W/m^2/10a. The average air temperature decreased slightly by −0.018°C/10a, with the greatest rate of decline in scrubs (−0.273°C/10a), followed by steppes (−0.121°C/10a) and meadows with (−0.089°C/10a). The rates of meteorological factors that impact flora in Inner Mongolia and Mongolian grasslands are also varied, with Inner Mongolia seeing higher rates of precipitation and lower rates of average air temperature and downward surface shortwave radiation.

On the Mongolian Plateau, there is a correlation between NDVI variations in grassland vegetation and meteorological factors. It had a 0.31 correlation coefficient with precipitation and exhibited a highly significant positive association ($p < 0.05$). There was a negative connection between NDVI and precipitation during the growing season for only roughly 13.13% of the grassland distribution area, whereas there was a positive association for 86.87% of the whole distribution area. The sensitivity of grassland vegetation types to precipitation was in the order of steppes > scrubs > meadows. Additionally, the connection between NDVI variation and precipitation differed by area, with Inner Mongolia (0.37) having a larger correlation with precipitation than Mongolia (0.28). A highly significant negative correlation with average air temperature and downward surface shortwave radiation were shown, with a correlation coefficient of −0.09 and − 0.19 ($p < 0.05$). The growing season NDVI was negatively associated with average air temperature in 63.92% of the grassland vegetation range, positive in about 36.08% of the grassland range, significantly and negatively correlated with downward surface shortwave radiation in 75.06% of the grassland vegetation range, and positive in about 24.94% of the grassland range. The sensitivity of grassland vegetation types to average air temperature and downward surface shortwave radiation were in the order of meadows > steppes > scrubs. Additionally, there were regional differences in the correlations of NDVI changes with average air temperature and downward surface shortwave radiation, with Inner Mongolia having a greater correlation with average air temperature (−0.04) than Mongolia (−0.12) and having a higher correlation with downward surface shortwave radiation (−0.15) than Mongolia (−0.21). The influence of precipitation on NDVI of grassland vegetation in this region is more pronounced than the relationships between the NDVI of grassland vegetation on the Mongolian Plateau and average air temperature and downward surface short-wave radiation, and the NDVI of grassland vegetation on the Mongolian Plateau is primarily controlled by precipitation during the growing season.

On the Mongolian Plateau, human activity has a large, primarily positive effect on NDVI variations in vegetation. Roughly 17.24% of the areas had a positive residual NDVI trend, and human activities generally facilitated NDVI growth overall, while they inhibited growth in about 1.13% of the regions. This suggests that some of the Mongolian Plateau's ecological conservation and development efforts have been successful.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GL: methodology, software, writing – original draft, writing – review and editing, formal analysis, and validation. TL: methodology, software, writing – review and editing, formal analysis, and software. JY, YB, and BX: project administration, resources, and investigation. XL, XC, and LB: data curation, software, and writing – review and editing. LY: conceptualization, methodology, and funding acquisition. SZ: conceptualization and methodology. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the National Key Research and Development Program of China (2022YFF1300601) the National Natural Science Foundation of China (42071025 and 32161143025).

Conflict of interest

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

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