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Impact of Extreme Climate on the NDVI of Different Steppe Areas in Inner Mongolia, China

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Abstract: The frequency of extreme climate events has increased resulting in major changes to vegetation in arid and semi-arid areas. We selected 12 extreme climate indices and used trend analysis and multiple linear regression models to analyze extreme climate trends in steppe areas of Inner Mongolia and their impact on the normalized difference vegetation index (NDVI). From 1998 to 2017, the NDVI of the Inner Mongolia steppe increased overall; however, there was a small area of decrease. Extreme climate indices related to warming exhibited increasing trends, particularly in the desert steppe. Although the extreme precipitation index did not change significantly overall, it increased in the northeastern and southwestern regions of the study area and decreased in the central region. The established model showed that the extreme climate explained the highest NDVI variation in desert steppe (R^2 = 0.413), followed by typical steppe (R^2 = 0.229), and meadow steppe (R^2 = 0.109). In desert steppe, TX90P (warm days index) had the greatest impact; in typical steppe, R10 (number of heavy precipitation days index) had the greatest impact; in meadow steppe, R95P (very wet days index) had the greatest impact. This study offered new insights into dynamic vegetation changes in steppe areas of Inner Mongolia and provided a scientific basis for implementing environmental protection strategies.

Keywords: extreme climate; NDVI; desert steppe; typical steppe; meadow steppe; Inner Mongolia

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1. Introduction

The increasing frequency and scale of extreme climate events are one of the most obvious manifestations of climate change [1–4], and this trend is projected to continue in the future [5,6]. Extreme climate exerts a huge impact on plant physiology and growth by affecting soil moisture, nutrients, microbial activities, and atmospheric conditions [7,8], thereby affecting the material and energy cycles of terrestrial ecosystems. Therefore, the most immediate and substantial economic and environmental impacts of climate change are caused by the changes in vegetation due to extreme climate change [7].

The responses of diverse vegetation types to climate extremes vary because of their different ecological amplitudes. On a larger scale, the formation of each vegetation type (e.g., meadow steppe, typical steppe, and desert steppe) is quite different [9]. Many scholars have studied the impact of extreme climate on different vegetation types in various bioclimatic regions [10–13]. John et al. (2013) studied the impact of extreme climate events on the Mongolian Plateau and found that desert and grassland vegetation have significantly different responses to extreme climates, such as summer drought and heavy rain [14]. Cheng et al. (2021) studied the potential relationship between extreme climate events and vegetation in the Heihe River Basin, China, and found that the degree of correlation between the normalized difference vegetation index (NDVI) and extreme climate varied among different vegetation types [15]. The variations in the responses of different vegetation types to extreme climates may be more evident in distinct steppe types in arid and semi-arid steppe regions, which are extremely sensitive to climate change.

Although many studies on the differences in the responses of different steppes to climate change have been published, they primarily focus on the impact of average climate (average temperature and precipitation) [16–19]. For example, Bao et al. (2015) studied the growth season and monthly NDVI responses of different biomes in Mongolia and found that on a long-term scale, the effects of climate change on vegetation growth differed in different biomes, months, and climate conditions [20]. Guo et al. (2020) studied the relationship between the NDVI and climate in different biomes of Inner Mongolia and found that the interannual variability of temperature and precipitation was significantly related to changes in the NDVI, and had obvious spatial heterogeneity in different biomes [21]. The NDVI responses of different steppe types to average climate change were also diverse. However, compared with average climate, extreme climate is more sudden, short-term, and destructive, and will have a strong impact on the NDVI of the steppe. Several studies have been conducted on the relationship between extreme climate and different vegetation types in Inner Mongolia; on the interannual scale, NDVI was consistent with the trend of extreme precipitation and extremely low temperatures but was opposite to the trend of extremely high temperatures [11,13,22]. While previous studies have performed correlation analysis between extreme climate and the NDVI, a causal analysis has never been performed. Correlation analysis can only reveal the degree of correlation between independent and dependent variables, but not the degree of influence of the independent variable on the dependent variable. Moreover, to the best of our knowledge, no other research has been conducted on the impact of extreme climate on the NDVI of different steppes in Inner Mongolia. In this study, we aim to fill this gap in the literature.

Inner Mongolia is a typical arid and semi-arid area, an important ecological barrier in northern China, and a major livestock production base. The natural steppe is the mainland cover type, covering an area of 8.67 million square kilometers, which supports more than 20 million people [23]. In the context of climate warming, the steppe of Inner Mongolia has experienced unprecedented impacts, including more frequent and serious extreme weather events [24]. Moreover, owing to the relatively large spatial span between the above three steppes, the impacts of extreme climate are also different. Among them, meadow steppe (forest steppe) is located in the transition zone between forest and steppe, and has the highest biodiversity [25] and ecosystem functions [26] among the steppe types. Moreover, it is the second largest steppe type in Inner Mongolia. Desert steppe is the transition zone between desert and steppe, and it is the steppe type most at risk of desertification [27]. Therefore, studying the impacts of extreme climate on different steppes in Inner Mongolia will help provide strong evidence for local biodiversity conservation, maintain ecosystem stability, and prevent desertification; furthermore, it is needed to provide a necessary reference for local policymakers.

The main purpose of our research was to reveal (1) NDVI changes in different steppes during the study period, (2) extreme climate change, and (3) the degree of influence of extreme climate on the NDVI of different steppes.

2. Study Area

Inner Mongolia is located in northern China, on the southern part of the Mongolian Plateau (37°24′ N–53°23′ N, 97°12′ E–126°04′ E). It has a total land area of approximately 1.183 million km^2 (Figure 1) and is the main gathering place for China's ethnic minorities (primarily Mongolians). The high-elevation terrain is dominated by the Mongolian Plateau, which includes complex and diverse landforms [28]. The climate is arid and semi-arid, making it one of the most sensitive regions to global climate change. From east to west, the vegetation types are coniferous forest, coniferous broad-leaved mixed forest, broad-leaved forest, meadow steppe, typical steppe, desert steppe, and desert [29]. The main landscape type is natural steppe.

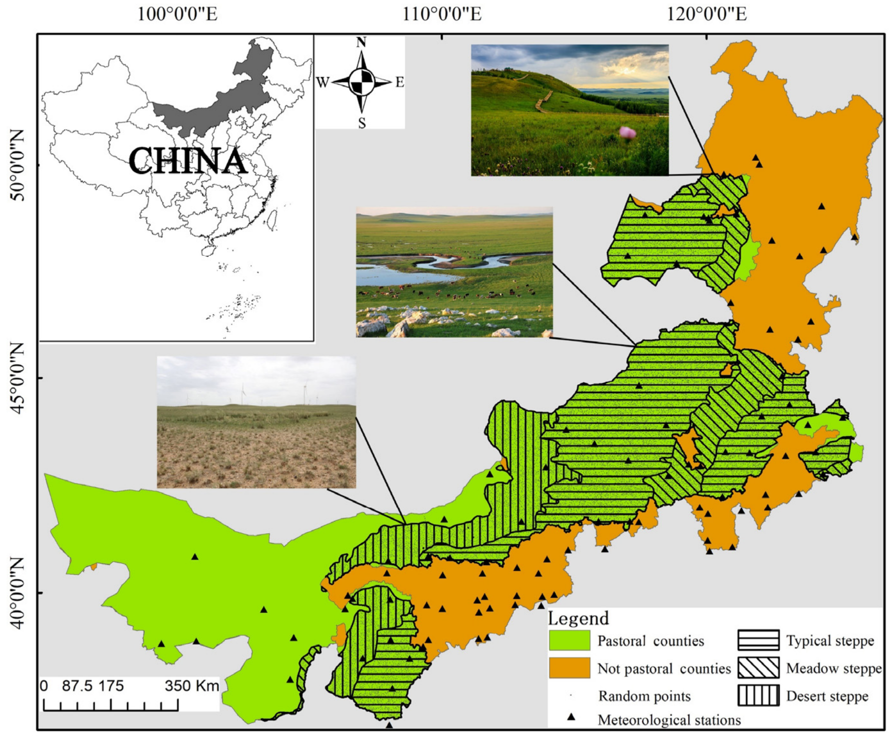

Figure 1. Inner Mongolian pastoral areas of different steppe types and the locations of meteorological stations.

To extract the natural steppe, this study selected a research area based on the vegetation type map [30] and husbandry counties of the Inner Mongolian administration division [31]. The aim was to reduce the influence of other landscape types on the results. There were three types of steppe in the study area: meadow steppe, typical steppe, and desert steppe (Figure 1).

3. Materials and Methods

3.1. Data and Data Processing

3.1.1. NDVI Dataset

The NDVI can effectively represent the growth of vegetation, and it is widely used to measure the response of vegetation to climate. We chose it to represent the vegetation growth status and change trends of the different steppes. NDVI data were obtained from the Resources and Environmental Science Data of the Chinese Academy of Sciences (http://www.resdc.cn; accessed on 7 June 2021). The annual NDVI was determined from continuous-time series monthly SPOT/VEGETATION NDVI satellite remote sensing data from 1998 to 2017, using the maximum value composite (MVC) method [30,32]. These data effectively reflect the distribution and change of regional vegetation coverage and have been widely used in vegetation monitoring, vegetation resource utilization, and other research related to the environment.

3.1.2. Extreme Climate Data

The extreme climate data were based on daily data of 96 ground meteorological stations in Inner Mongolia and the extreme climate index calculated by RClimDex (http://cccma.seos.uvic.ca/ETCCDI/software.shtml; accessed on 7 March 2022). This software was developed and maintained by Zhang and Yang [33] of the Climate Research Branch of the Meteorological Service of Canada. According to the climate characteristics of the study area, 12 extreme climate indices were selected from 27 categories recognized by the World Meteorological Organization (WMO; Table 1). Among them, seven were extreme climate indices related to precipitation, and the remaining five were extreme climate indices related to temperature. The ground meteorological data were obtained from the Resources and Environmental Science Data of the Chinese Academy of Sciences (www.resdc.cn/; accessed on 7 June 2021).

Table 1. Extreme climate indices.

	ID	Indicator Name	Definition	Unit
Precipitation	CDD	Consecutive dry days.	Maximum length of dry spell, maximum number of consecutive days with RR < 1 mm: let RR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where $RR_{ij} < 1$ mm.	Days
	CWD	Consecutive wet days.	Maximum length of wet spell, maximum number of consecutive days with RR $\geq$ 1 mm: let RR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where $RR_{ij} \geq 1$ mm.	Days
	R10	Number of heavy precipitation days.	Annual count of days when PRCP $\geq$ 10 mm: let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where $RR_{ij} \geq 10$ mm.	Days
	R20	Number of very heavy precipitation days.	Annual count of days when PRCP $\geq$ 20 mm: let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where $RR_{ij} \geq 20$ mm.	Days
	R95P	Very wet days.	Annual total PRCP when RR > 95th percentile.	mm
	RX5	Max 5-day precipitation amount.	Monthly maximum consecutive 5-day precipitation.	mm
	SDII	Simple daily intensity index.	Annual total precipitation divided by the number of wet days (defined as PRCP $\geq$ 1.0 mm) in the year.	mm/day
Tempe-rature	GSL	Growing season length.	The number of days between the beginning of the day on which the average daily mean temperature was >5 °C and the day on which the average daily mean temperature was <5 °C for at least 6 days.	Days
	SU25	Summer days.	Annual count when TX (daily maximum) > 25 °C.	Days
	TN10P	Cool nights.	Percentage of days when TN < 10th percentile.	Days
	TX10P	Cool days.	Percentage of days when TX < 10th percentile.	Days
	TX90P	Warm days.	Percentage of days when TX > 90th percentile.	Days

Note: RR refers to daily precipitation and PRCP refers to precipitation.

3.2. Methodology

3.2.1. Interpolation of Meteorological Data

In this study, we used a clear workflow for data interpolation and analysis (Figure 2). First, using altitude as a covariable, we interpolated the 12 types of extreme climate data from 1998 to 2017 using the ANUSPLIN (The Australian National University, Canberra, ACT, Australia) software and obtained 12 sets of raster extreme climate data with a resolution of 1 $\times$ 1 km [34].

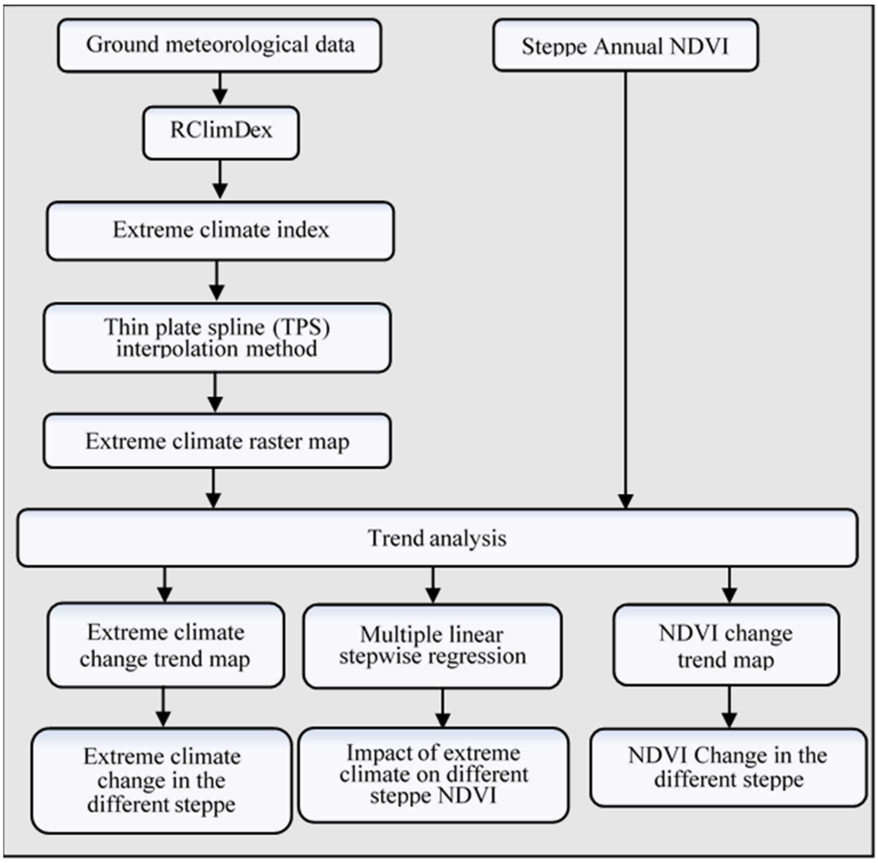

Figure 2. Algorithm flowchart for determining the influence of extreme climate on different steppe areas. NDVI, normalized difference vegetation index.

3.2.2. Dynamic Variation of NDVI

In this study, the trend analysis method was used to analyze the changing trend of the NDVI during the research period; that is, time t was taken as the independent variable to conduct a unary linear regression analysis of the NDVI [35]. The calculation formula was as follows:

$$Slope = \frac{n\sum_{i=1}^{n} iNDVI_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{n\sum_{i=1}^{n} i^2 - \left[\sum_{i=1}^{n} i\right]^2} \tag{1}$$

where n is the number of monitoring years (equal to 20 in this study), and i denotes the year (=1, 2, 3, . . . , 20), $NDVI_i$ is the annual mean NDVI value in the ith year. When slope < 0, there was a decreasing trend in NDVI and vice versa.

The correlation coefficient R between the NDVI series and time was used to judge the magnitude and nature of vegetation cover change and the significance of the correlation coefficient was determined [35]. The critical values were 0.444 and 0.561 at significance levels of 0.05 and 0.01, respectively, as verified from the corresponding tables. According to the NDVI trend slope and significance critical value, vegetation change types were divided into extremely significant degradation (SLOPE < 0, $p < 0.01$), significant degradation (SLOPE < 0, $0.01 < p < 0.05$), no significant change ($p > 0.05$), significant increase (SLOPE > 0, $0.01 < p < 0.05$), and extremely significant increase (SLOPE > 0, $p < 0.01$).

3.2.3. Sample Selection

Random points created in ArcGIS 10.3 were used to generate random points with an interval of 2 km, for a total of 21,435 random points (3392 points in meadow steppe, 13,269 points in typical steppe, and 4774 points in desert steppe). Both the geographical detector model and the multiple linear stepwise regression (MLSR) model were calculated based on the random points generated above.

3.2.4. The Multiple Linear Stepwise Regression (MLSR)

We applied MLSR to reveal the impact of extreme climate on different steppes in Inner Mongolia. The 12 types of extreme climate were used as independent variables, and the NDVI was the dependent variable [36]. Three models were established (in meadow, typical, and desert steppe). The standardized coefficient of MLSR can represent the degree of influence of a single independent variable on the dependent variable when other independent variables are fixed, and it can also avoid multicollinearity problems.

4. Results

4.1. Dynamic Variation of Different Steppe NDVI

From 1998 to 2017, the spatiotemporal variation in steppe NDVIs both increased and decreased by area; however, the overall trend was of an increase. In particular, the NDVI increased significantly in the east, northeast, and southwest of the study area (i.e., the northeast meadow steppe and typical steppe in the southwest), while it decreased significantly in central and eastern areas. The NDVI area of meadow steppe increased the most, accounting for 33.10% of the whole meadow steppe area, with an extremely significant increase of 22.28% and a significant increase of 10.88%; only 2.54% of the area saw a decrease. The NDVI area of typical steppe increased by 12.28% overall, with an extremely significant increase accounting for 11.83% and a significant increase of 4.05%; only 3.22% of the area saw a decrease. Compared with the other two steppe types, the increase in desert steppe NDVI accounted for a smaller proportion (7.62% in total), and 2.06% of the area saw a decrease (Figure 3).

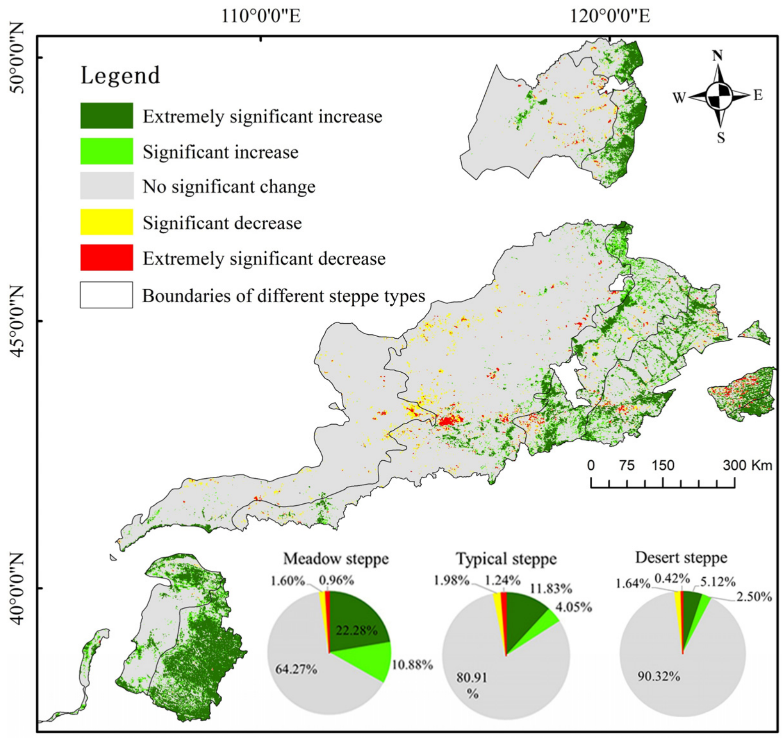

Figure 3. Normalized difference vegetation index (NDVI) changes for different steppe types of Inner Mongolia from 1998 to 2017, based on the interannual variation trend of the NDVI and its significance.

4.2. Extreme Temperature Variation of Different Steppe Types

Figure 4 shows the spatial distribution of extreme temperature trends for different steppe types. In the desert steppe, the GSL index (growing season length) had the most obvious increasing trend (>0), accounting for 85.29% of the entire desert steppe area, in which the trend 0.45–0.78 days/year area reached 28.28%; the SU25 index (summer days) exhibited an increasing trend for 81.97% of the desert steppe, of which the trend 0.20–0.46 days/year area accounted for 35.88%; for the TX90P index (warm days exhibited an increasing trend for 51.67% of the entire desert steppe area, in which the trend (0.04–0.27 days/year) area accounted for 38.49%. However, in the desert steppe, the TN10P (cool nights) and TX10P (cool days) indices decreased significantly (Trend < 0), with areas reaching 100% and 96.26%, respectively. In summary, in the desert steppe, there was a clear trend of increasing frequency of extreme temperature events related to warming and a decreasing frequency of extreme temperature events related to cooling.

In the typical steppe, the increasing trend areas of the GSL, SU25, and TX90P indices reached 54.86%, 59.96%, and 15.83%, respectively. Among them, the trend 0.45–0.78 days/year, 0.20–0.46 days/year, and 0.04–0.27 days/year areas accounted for 14.87%, 17.23%, and 5.46%, respectively. The increasing trends of TN10P and TX10P only appeared in 13.91% and 17.43% of the area, respectively; the remaining areas exhibited a decreasing trend.

In the meadow steppe, the increasing GSL trend accounted for 66.5% of the area, but the trend (0.45–0.78 days/year) area only accounted for 6.03%. The increasing trend area of the SU25 and TX90P indices accounted for 29.74% and 16.33%, respectively, in which the areas with the largest increasing trends (0.20–0.46 days/year and 0.04–0.27 days/year) accounted for only 3.20% and 5.95%, respectively; the increasing trends of the TN10P and TX10P indices only appeared in 10.05% and 20.84% of the areas, respectively; the remaining areas exhibited a decreasing trend.

In summary, there were differences in the increasing and decreasing trends of extreme temperature in the three different steppe types. In general, the frequency of extreme temperature events related to warming increased (desert steppe > typical steppe > meadow steppe), while the frequency of cold extreme temperature events decreased (desert steppe > typical steppe > meadow steppe).

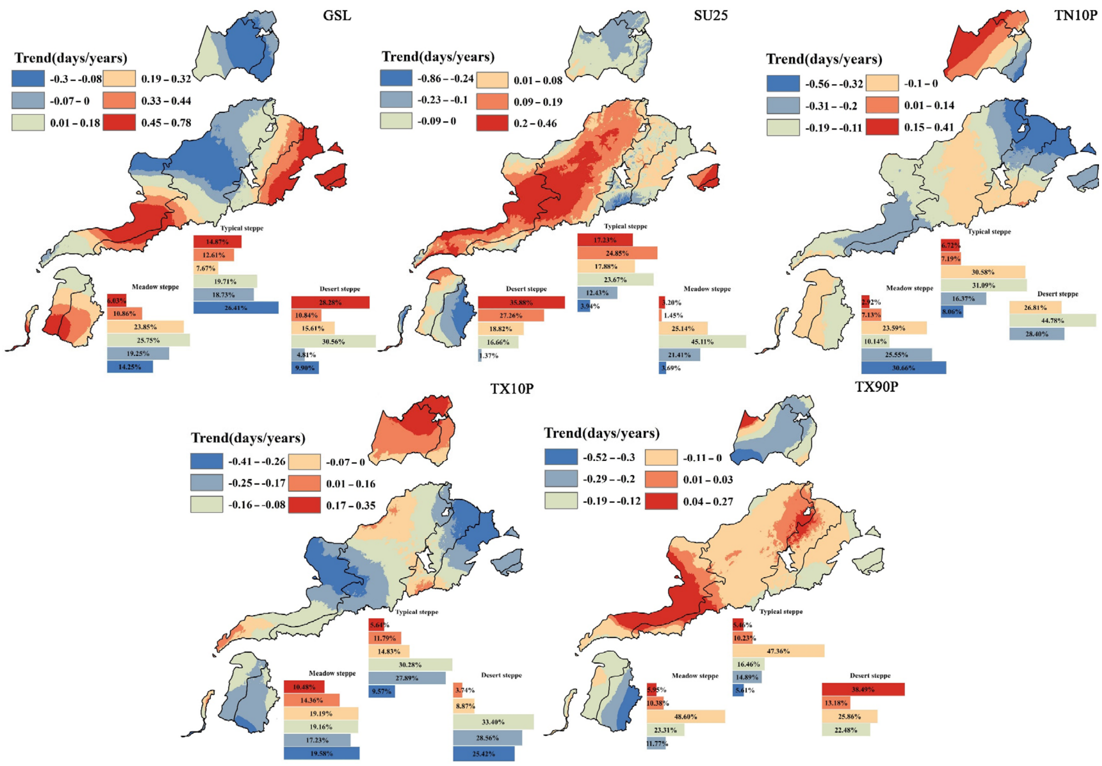

Figure 4. Spatial distribution of extreme temperature change in different steppe areas of Inner Mongolia from 1998 to 2017. Indices: GSL, growing season length; SU25, summer days; TN10P, cool nights; TX10P, cool days; TX90P, warm days.

4.3. Extreme Precipitation Variation of Different Steppe Types

There was little change in extreme precipitation in the steppe of Inner Mongolia, and the differences in the three types of steppe were relatively small (Figure 5). The consecutive wet day (CWD) index exhibited an increasing trend over a large area; however, the increase was not significant (0.06 days/year). The consecutive dry day (CDD) index exhibited a decreasing trend in the typical steppe (accounting for 95.88% of the total area); however, from the perspective of the entire study area, the index had obvious spatial heterogeneity, increasing in the northeast and southwest regions, and decreasing in the remaining area. The R10 (number of heavy precipitation days) and R20 (number of very heavy precipitation days) exhibited conspicuous increasing trends, primarily in the Mu Us Sandy Land in the southwest, with trends reaching 0.17–0.34 days/year and 0.09–0.16 days/year. This may also be the reason for the extremely significant increase in the NDVI during the study period. The trend range of the R95P index (very wet days) was between −4.15 and 3.91 days/year. The meadow steppe and typical steppe areas decreased by 62.4% and 69.99%, respectively, but the area of desert steppe increased by 62.42%. The RX5 index (max 5-day precipitation amount) exhibited a decreasing trend in most of the study area, including meadow steppe (63.57%), typical steppe (68.99%), and desert steppe (66.34%); spatially increasing areas were primarily in the north, east, and southwest of the study area. The SDII index (simple daily intensity index) also increased spatially in the north, east, and southwest, with relatively small differences in all three steppe types.

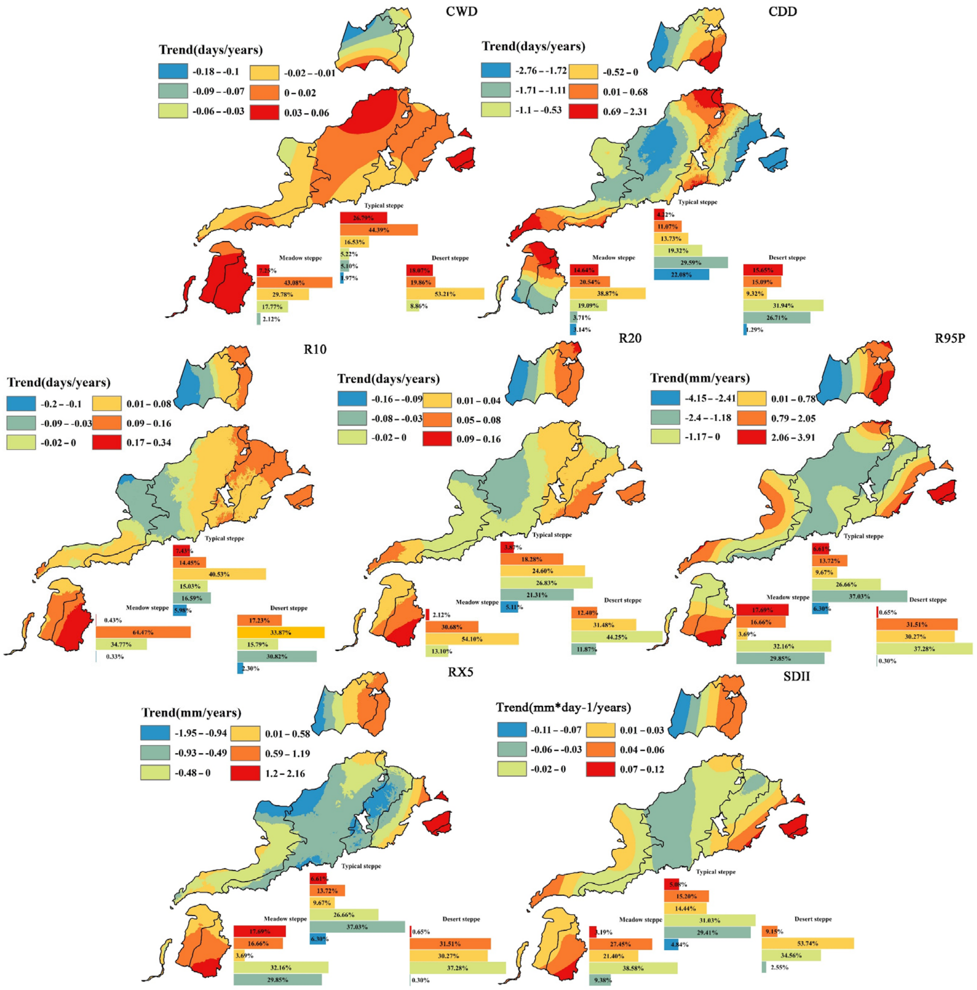

Figure 5. Spatial distribution of extreme precipitation trends in the different steppe areas of Inner Mongolia from 1998 to 2017. Indices: CDD, consecutive dry days; CWD, consecutive wet days; R10, number of heavy precipitation days; R20, number of very heavy precipitation days; R95P, very wet days; RX5, max 5-day precipitation amount; SDII, simple daily intensity index.

In general, the difference in the trend of extreme precipitation among the three steppe types was smaller than that of extreme temperatures. However, spatially, the trend of extreme precipitation increased in the northern, eastern, and southwestern parts of the entire study area were more obvious than those of other regions.

4.4. Impact of Extreme Climate Change Trends on NDVI in Different Steppe Types

We took the trend of extreme climate change as the independent variable, the trend of steppe NDVI as the dependent variable, and used the MLSR model to explain the impact of extreme climate on the NDVI for the different steppe types.

For the meadow steppe, only 5 of the 12 extreme climate indices had a significant impact on the changing trend of the NDVI (Table 2); the adjusted R^2 of the resulting model was only 0.109, indicating that the contribution rate of the five selected variables to the changing trend of the NDVI in the meadow steppe was 10.9% during the research period. Four of these were extreme climate indices related to precipitation, and one was related to temperature. The standard partial regression coefficients of these five indices were all positive, indicating a positive correlation with the NDVI. The maximum regression coefficient was for R95P, up to 0.203, indicating that it had the greatest influence on the extreme climate of the meadow steppe. GSL, CDD, and R10 were 0.193, 0.178, and 0.176, respectively. The CWD had the smallest regression coefficient (0.083).

Table 2. Model of the impact of extreme climate on the normalized difference vegetation index (NDVI) of meadow steppe.

Model	Unstandardized Coefficients		Standardized Coefficiens	t	Sig.	Collinearity Statistics	
	B	Std. Error				Tolerance	VIF
Adjusted R^2:0.109							
(Constant)	-2.331×10^{-5}	0.000		−0.114	0.909		
Slope R10	0.022	0.002	0.176	10.203	0.000 ***	0.877	1.140
Slope R95P	0.000	0.000	0.203	10.839	0.000 ***	0.742	1.348
Slope CWD	0.011	0.003	0.083	3.476	0.001 ***	0.458	2.182
Slope CDD	0.001	0.000	0.178	7.752	0.000 ***	0.494	2.025
Slope GSL_	0.004	0.001	0.193	6.169	0.000 ***	0.265	3.771

Note: *** stands for $p < 0.01$.

For the modeling of typical steppe, 10 of the 12 extreme climate indices had significant impacts on the NDVI (Table 3). Among them, five were extreme climate indices for precipitation and five for temperature. The contribution rate of extreme climate to the NDVI trend of the typical steppe was 22.9%, and its influence on the typical steppe was greater than that on the meadow steppe (R^2 = 0.109), with an adjusted R^2 of 0.229. Of the 10 independent variables, 5 were positively correlated with the NDVI trend, and 5 were negatively correlated with the direction of the model-fitting coefficient. Among them, R10 had the highest standardized coefficient of 0.337; that is, in typical steppe, R10 was the most important influencing factor in extreme climates and had a significant positive effect. TX10P had a significant negative effect on the changing trend of typical steppe NDVI because its standardized coefficient was −0.225. The standardized coefficients of TN10P and GSL were 0.245 and 0.150, respectively, indicating that they were also significant influencing factors of typical steppe NDVI in extreme climates. The absolute value of the standardization coefficients of the other factors was less than 0.1.

Table 3. Model of the impact of extreme climate on the normalized difference vegetation index (NDVI) of typical steppe.

Model	Unstandardized Coefficients		Standardized Coefficiens	t	Sig.	Collinearity Statistics	
	B	Std. Error				Tolerance	VIF
Adjusted R^2: 0.229							
(Constant)	0.000	0.000		2.293	0.022		
Slope CDD	0.000	0.000	0.085	7.965	0.000 ***	0.512	1.954
Slope CWD	−0.006	0.002	−0.053	−3.571	0.000 ***	0.259	3.856
Slope GSL	0.003	0.000	0.150	11.809	0.000 ***	0.359	2.785
Slope R10	0.017	0.001	0.337	16.515	0.000 ***	0.139	7.189
Slope R95P	0.000	0.000	−0.067	−3.820	0.000 ***	0.186	5.366
Slope RX5	0.000	0.000	0.053	2.737	0.006 **	0.152	6.577
Slope SU25	−0.003	0.001	−0.090	−4.727	0.000 ***	0.161	6.220
Slope TN10P	0.007	0.000	0.245	15.129	0.000 ***	0.221	4.525
Slope TX10P	−0.007	0.001	−0.225	−12.599	0.000 ***	0.183	5.478
Slope TX90P	−0.001	0.001	−0.030	−1.702	0.089 *	0.189	5.278

Note: * stands for $p < 0.1$; ** stands for $p < 0.05$; *** stands for $p < 0.01$.

The adjusted R^2 of the model established in the desert steppe was 0.413, indicating that the contribution rate of extreme climate to the NDVI trend was 41.3%. This contribution rate was much higher than those of meadow steppe and typical steppe. However, compared with typical steppe, there were fewer factors that have significant extreme climate effects on the desert steppe. Among six significant factors, three were positively correlated with the NDVI trend, and three were negatively correlated (Table 4). Slope TX90P had the greatest influence, with a standardized coefficient of −0.236, indicating that this factor was the most important factor affecting the changing trend of desert steppe NDVI in extreme climates. The standardized coefficients of R95P and SU25 also reached −0.183 and −0.167, respectively, exhibiting a negative correlation with the changing trend of desert steppe NDVI. SDII and RX5 had positive effects on the NDVI trend; their standardization coefficients were 0.189 and 0.167, respectively. These two independent variables were both related to precipitation, and so they had a positive impact on the changing trend of NDVI in the desert steppe. R20 had the smallest absolute value of the standardized coefficient, indicating that it had the least influence among the six factors, but it had a positive effect on the changing trend of desert steppe NDVI.

Table 4. Model of the impact of extreme climate on the normalized difference vegetation index (NDVI) of desert steppe.

Model	Unstandardized Coefficients		Standardized Coefficiens	t	Sig.	Collinearity Statistics	
	B	Std. Error				Tolerance	VIF
Adjusted R^2:0.413							
(Constant)	0.000	0.000		4.564	0.000 ***		
Slope R20	0.009	0.003	0.089	3.222	0.001 ***	0.160	6.244
Slope R95P	0.000	0.000	−0.183	−10.884	0.000 ***	0.433	2.311
Slope RX5	0.001	0.000	0.167	9.163	0.000 ***	0.370	2.705
Slope SDII	0.032	0.005	0.189	6.710	0.000 ***	0.155	6.435
Slope SU25	−0.004	0.000	−0.167	−11.247	0.000 ***	0.558	1.793
Slope TX90P	−0.008	0.001	−0.236	−13.946	0.000 ***	0.428	2.336

Note: *** stands for $p < 0.01$.

5. Discussion

5.1. NDVI Dynamics

The NDVI of the Inner Mongolian steppe increased significantly from 1998 to 2017, and there were obvious spatial differences. The increase areas were primarily concentrated in the north, east, and southwest, which was consistent with results of research on the

NDVI change in China [37]. The main increase in the northern part of the study area was for the meadow steppe in the western foothills of the Greater Khingan Mountains. Studies have revealed that the main driving forces for the increase in the NDVI in this area were precipitation and temperature [38]. Moreover, our research results also show that the increasing trend of extreme precipitation events and the decreasing trend of extreme temperature events in this area were evident and may also be a reason for the increase in the NDVI of the steppe in this region. The areas where the NDVI increased in the eastern and southwestern parts of the study area were primarily the typical steppe areas of Horqin Sandy Land and Mu Us Sandy Land. China has implemented a series of ecological restoration projects (such as the Grain for Green Program, the Natural Forest Conservation Program, and the Sand Control Programs for areas near Beijing and Tianjin) in the above areas since 2000, and has achieved positive results [39,40]. Moreover, our research results showed that the increasing trend of extreme precipitation in this region was more obvious than that in other regions. Therefore, the implementation of ecological restoration projects and climate change [41] was the reason for the significant increase in the NDVI in the above regions.

Typical areas where the steppe NDVI was significantly degraded are shown in Figure 6. The reduced areas were primarily sandy land (a, b, c, d, e, and g in Figure 6) and the periphery of urban areas (f and h). Therefore, the desertification and expansion of construction land were the main reasons for the significant degradation of steppe NDVI. The degradation of the NDVI in the Hunshandake Sandy Land (a, b, and g) was relatively serious, which was consistent with the results of Wang et al. [42]. Changes in precipitation were the main reasons for the serious desertification and vegetation degradation [43]. The Horqin Sandy Land also had relatively small areas of significant NDVI degradation (c, d, and e), and desertification was the main cause. Desertification in this area was primarily affected by topography [44], climate fluctuations, reclamation, and livestock pressure [45]. In addition, the expansion of construction land has led to significant degradation of steppe NDVI (f, h).

5.2. Extreme Climate Change in Different Steppe Types

Overall, the steppe of Inner Mongolia showed an increase in extreme climate events related to warming, and a decreasing trend in extreme climate events related to cooling, which was consistent with the results of Tong et al. [24]. Among the three types of steppe, this characteristic was most obvious for desert steppe because it experienced stronger effects of climate warming; this was consistent with the results of Yang et al. [46]. The extreme climate change trend in the meadow steppe area was the smallest. The meadow steppe in Inner Mongolia is mostly forest meadows; therefore, climate in this region is regulated by the forest ecosystem. Studies have found that the low intensity of extreme climate in the meadow steppe of Inner Mongolia may be due to climate change resistance caused by the carbon storage function of forests [24,47]. The extreme climate in the typical steppe area also showed a rising trend of warm extreme climates and a decreasing trend of cold extreme climates; this trend was lower than that of desert steppe and higher than that of meadow steppe. This may be because typical steppe was more affected by climate warming than meadow steppe but less affected than desert steppe [48].

The changing trend of extreme precipitation in the steppe of Inner Mongolia was not obvious, and the differences between the three steppe types were not large. However, most of the indices exhibited an increasing trend in the northeast and southwest, but a decreasing trend in the central region, which was consistent with previous observations [24,49].

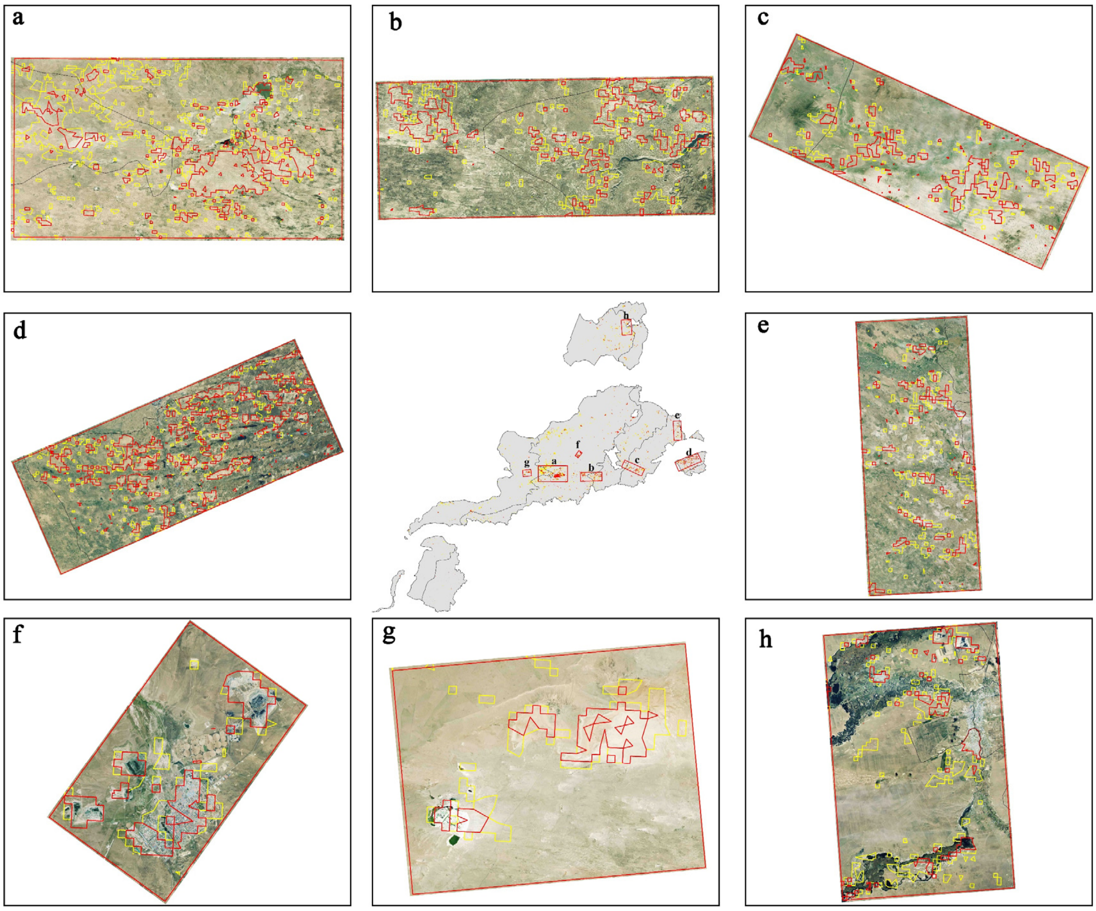

Figure 6. Google Earth images from 2017 showing the normalized difference vegetation index (NDVI) degraded area. (**a**–**h**) show typical areas of significant degradation, where red and yellow lines represent extremely significantly degraded and significantly degraded areas, respectively.

5.3. Degree of Influence of Extreme Climate on Changes in Steppe NDVI

The impact of extreme climate on the three different steppes was in the order of desert steppe (R^2 = 0.413) > typical steppe (R^2 = 0.229) > meadow steppe (R^2 = 0.109). Desert steppe was the most affected by extreme climates. Its land use, land cover changes [50], and human activities [51] are high in intensity, and ecosystems are unstable [52], making it susceptible to the above-mentioned factors and to the greater impact of extreme climate on the NDVI. Most critically, the frequency of extreme climate events was higher than for meadow and typical steppes. Among the models established for the desert steppe, the slope TX90P had the greatest impact on the NDVI. Studies have revealed that among the steppes of Inner Mongolia (including meadow steppe, typical steppe, and desert steppe), the desert steppe experiences the most significant asymmetric warming [46], which reduces soil respiration [53] and plant species abundance [54], adversely affecting the steppe [55]. This was consistent with the results of our study.

For typical steppe, extreme climate explained only 22.9% of the changing trend of the NDVI. However, 10 of the 12 extreme climate indices we selected (five of which were related to precipitation and five to temperature) had a significant impact, indicating that the impact of extreme climate on the NDVI trend was complicated. Studies have revealed that compared with meadow and desert steppe, typical steppe has a greater comprehensive impact on precipitation and temperature [56]. This may also have been the cause of the significant impact of the multi-extreme climate index on the typical steppe. Among the established models, slope R10 had the greatest impact on the changing trend of steppe NDVI, which was different from the desert steppe. For typical steppe, precipitation was the main limiting climatic factor affecting vegetation [57]. Our current view is that in extreme climates, extreme precipitation also has a significant impact on typical steppe, which is consistent with the results of recent studies [58].

Among the steppe types, meadow steppe NDVI was the least impacted by extreme climate. The change in NDVI in the meadow steppe of Inner Mongolia was primarily affected by the average temperature, and the influence of precipitation was not significant [59]. Moreover, extreme climate change in this region was relatively insignificant and the NDVI of the region was less affected.

6. Conclusions

We analyzed the NDVI's change characteristics in different steppe types in Inner Mongolia from 1998 to 2017 and selected 12 extreme climate indices (five extreme temperature indices and seven extreme precipitation indexes) for trend and multiple linear regression analysis. The main conclusions were as follows.

1. From 1998 to 2017, the NDVI of the Inner Mongolian steppe increased significantly overall; however, some localized areas saw a decrease. Among the different steppe types, meadow steppe increased by 33.10% and decreased by 2.54%, typical steppe increased by 12.28% and decreased by 3.22%, and desert steppe increased by 7.62% and decreased by 2.06%.
2. During the study period, the Inner Mongolian steppe exhibited an increase in the extreme temperature index related to warming and a decreasing trend in the extreme temperature index related to cooling. This was most obvious for the desert steppe, followed by typical steppe and then meadow steppe.
3. The extreme precipitation index did not change significantly in the steppe of Inner Mongolia but spatially exhibited an increasing trend in the northeast and southwest and a decreasing trend in the central region. There were no conspicuous differences in changes among the three steppe types.
4. The impacts of extreme climate change on the NDVI trend of different steppe types in Inner Mongolia differed. The explanation rate of NDVI changes in the desert steppe was high ($R^2 = 0.413$), followed by typical steppe ($R^2 = 0.229$), and meadow steppe ($R^2 = 0.109$).
5. Among the three models established, desert steppe was most affected by the TX90P index (standardized coefficient -0.236), typical steppe was most affected by the R10 index (standardized coefficient 0.337), and meadow steppe was most affected by the R95P index (standardized coefficient 0.203).

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