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Influence of Key Climate Factors on Desertification in Inner Mongolia

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Abstract: Desertification is a major environmental problem facing the world today, and climate change is an important factor influencing desertification. This study investigates the impact of changes in key climate factors on desertification based on normalized difference vegetation index data, precipitation data and evaporation data from Inner Mongolia between 1982 and 2020 using correlation analysis, regression modelling, and residual analysis. The results show that precipitation and evaporation are significantly correlated with mild desertification and severe desertification, respectively, with correlation coefficients reaching 0.98 and −0.96, respectively. In severely desertified areas in central-eastern Inner Mongolia, there is a high correlation between desertification and temperature, the characteristics of the correlation of average maximum and minimum temperatures with desertification are similar to those of the correlation of average temperature with desertification, and the average maximum and minimum temperatures are well correlated with mild desertification, with correlation coefficients as high as 0.98 and 0.978, respectively. Climate contribution accounts for 97% of desertification in severely desertified areas, indicating that climate change has increased desertification in these areas. In regions with improved desertification, approximately 75% are primarily influenced by climate change (with a relative contribution greater than 50%), with climate factors exhibiting a relative contribution greater than 75% to desertification in 30% of these regions.

Keywords: desertification; climate change; human activities; response relationship; quantitative analysis

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1. Introduction

The United Nations Convention to Combat Desertification defines desertification as the degradation of land in arid, semi-arid and dry sub-humid areas, indicating that desertification is essentially a manifestation of land degradation under certain conditions [1,2]. Climate change has a very complex impact on desertification, as it alters vegetation cover and vegetation indices in desertified areas [3–5]. At present, the influences of various climate factors on desertification remain unclear. Therefore, carrying out research to fill this knowledge gap has a reference value for improving the ecological environment [6].

Desertification processes are influenced by human factors [7] and natural factors [8] Numerous studies have been conducted on the impact of climate change on desertification. Schmidt [9] studied the response of vegetation to precipitation in different vegetation zones using NOAA/AVHRR normalized difference vegetation index (NDVI) data, and the results showed that vegetation is sensitive to precipitation. Paruelo and Lauenroth [10] carried out research using climate factors and found that precipitation and temperature are the main climate factors that control the regional variations in the difference between the maximum and minimum NDVI throughout the year. Ackerly et al. [11]. conducted modelling experiments in the San Francisco Bay area using various climate factors and found through comparison that vegetation is highly sensitive to climate change. Based on EOS-MODIS remote sensing data, it was found that the average precipitation has a greater impact on the dynamic changes in desertification than the average temperature in the Hunshandake

Sandy Land [12]. Significant increases in temperature, precipitation and evaporation in Northwest China have led to an increase in drought hazard in the Taklimakan Desert, Hexi Corridor Desert and Qaidam Desert, accelerating desertification [13]. Wind speed is the main external factor in the formation of desertification in northern China [14,15], affecting topography [16] and sand transport and deposition [17,18]. To date, research on the impact of climate on desertification has shifted from qualitative research to quantitative analysis [19]. However, most previous studies have relied on sparse meteorological stations and have focused on the qualitative examination of the influence of individual climate factors on desertification [12,20]. This approach hinders a comprehensive and profound understanding of the impact of climate change on desertification.

In summary, this study uses temperature, precipitation, evaporation and NDVI data between 1982 and 2020 from a total of 156 meteorological stations in and around the study area and employs methods such as residual analysis to reveal the response relationships between desertification and key climate factors both qualitatively and quantitatively. It not only enriches the research on desertification but also provides a reference for ecological environment construction.

2. Materials and Methods

2.1. Overview of the Study Area

The Inner Mongolia Autonomous Region is located between 37°24′–53°23′ N and 97°12′–126°04′ E, with a total area of 1.183 million km^2. It is adjacent to eight provinces/regions (Figure 1) and shares borders with Mongolia and Russia in the north. The study area has an average elevation of approximately 1000 m and is the second largest among the four major plateaus in China. It spans the humid, semi-humid, semi-arid, and arid regions of eastern and central Asia. Precipitation is low and irregular, and there are sudden changes in temperature. In spring, the temperature increases quickly and it is often windy; the summer is relatively short with heavy rainfall; in autumn, temperatures drop and frost occurs frequently; and the winter is long and extremely cold with unpredictable weather.

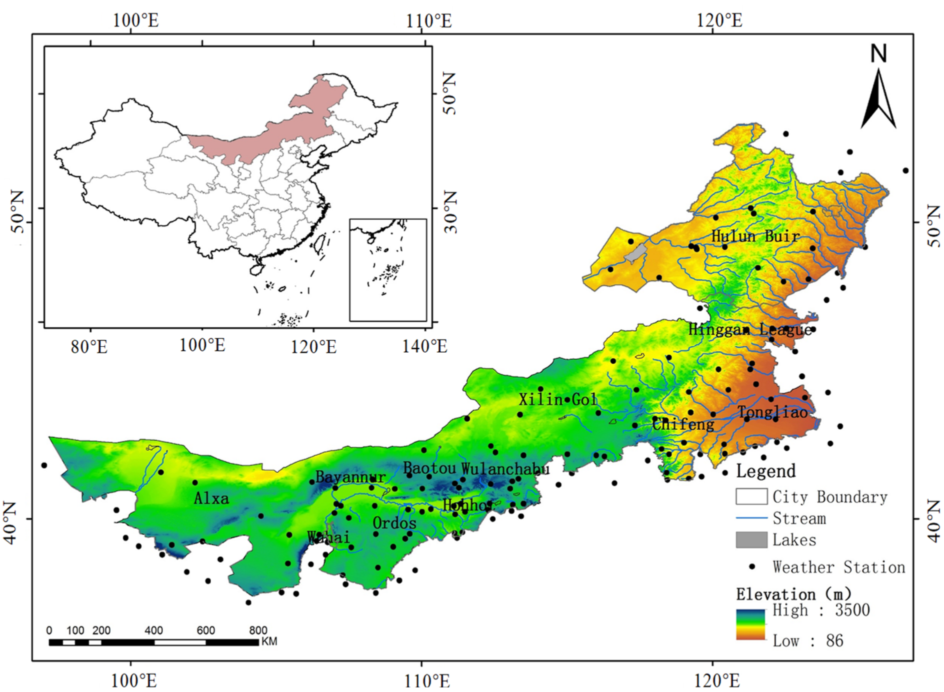

Figure 1. Geographical location of the study area.

2.2. Materials

2.2.1. Remote Sensing Material

NASA AVHRR CDR NDVI V5 NDVI data with a spatial resolution of 5 km and a temporal resolution of 4 days were collected for nearly 39 years from 1982 to 2020 in Inner Mongolia and its surrounding areas.

2.2.2. Meteorological Material

The monthly data of average temperature, average maximum temperature, average minimum temperature, precipitation, evaporation, wind speed, and ground temperature collected at 156 meteorological stations in and around the study area between 1982 and 2020 were compiled by weather bureaus. Upon verification, there were no significant discontinuities or random fluctuations in the meteorological data from any station, and changes in data exhibited relative uniformity and consistency, indicating the data are reliable and can represent the regional climate conditions.

2.3. Data Processing Methods

(1) Vegetation coverage

This study estimates the vegetation coverage based on the NDVI using a pixel bipartite model [21], with the following equation:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{1}$$

where FVC is the fractional vegetation coverage, $NDVI_{veg}$ is the maximum NDVI of vegetation in the study area, and $NDVI_{soil}$ is the NDVI of bare soil in the study area.

For pure bare soil pixels, the theoretical value of $NDVI_{soil}$ is close to 0 and does not change with time. However, in reality, influenced by factors such as atmospheric conditions, surface moisture and sunlight conditions, the $NDVI_{soil}$ is not a constant value; rather, it typically varies within the range of -0.1 and 0.2. For pure vegetation pixels, the vegetation types and their composition, the spatial distribution of vegetation and the seasonal changes in vegetation growth all contribute to the spatiotemporal variability of NDVIveg. To reduce the influence of clouds and phenological cycles, according to the grey level distribution of the NDVI, the upper and lower thresholds of the NDVI are intercepted at the 0.95 and 0.05 confidence levels to approximately represent the $NDVI_{veg}$ and $NDVI_{soil}$, respectively.

(2) Selection and classification of desertification indicators

Referring to the desertification classification standards of the Food and Agriculture Organization of the United Nations and the United Nations Environment Programme as well as other relevant literature on desertification classification [22,23], the degree of desertification is classified into four levels: severe desertification, moderate desertification, mild desertification and non-desertification. Details can be found in Table 1.

Table 1. Classification of vegetation coverage in the study area.

Type Name	Vegetation Cover (f, %)	Surface Features
Severe desertification	<10	It is mainly a desert, bare land, Gobi and alpine sparse vegetation area
Moderate desertification	10–20	Desert and oasis transition zone areas, salinization areas with little vegetation and sandy vegetation areas
Mild desertification	20–50	It is mainly a grassland or other natural vegetation area, grassland, cultivated land mixtures and cultivated land
Non-desertification	>50	It is mainly a woodland, arable land and high-cover grassland

(3) Correlation analysis

For the relationships between FVC and various climate factors, the simple correlation between FVC and each climate factor is analysed by pixel-based spatial analysis [24] using the following calculation equation:

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

where R_{xy} is the correlation coefficient between variables x and y, x_i is the FVC for the ith year, y_i is the climate factor value for the ith year, $\overline{x}$ is the multiyear average of FVC, $\overline{y}$ is the multiyear average of climate factor, and n is the sample size.

R_{xy} is the correlation coefficient between two elements, and it is used to judge the degree of relationship between them. Its value falls within the interval $(-1, 1)$. $R_{xy} > 0$ indicates a positive correlation, suggesting that the two elements develop in the same direction; in contrast, $R_{xy} < 0$ indicates a negative correlation, meaning that the two elements develop in opposite directions. The closer the absolute value of R_{xy} is to 1, the closer the relationship between the two; in contrast, an absolute value closer to 0 indicates the two elements are less related.

(4) Residual analysis

To differentiate the impacts of climate change and human activities on desertification changes in the study area, this study employs residual analysis [25] to distinguish the contributions of these two influencing factors. This method uses climate factors as independent variables and vegetation coverage as the dependent variable for linear regression analysis. Based on the vegetation and climate data of the same period, the following regression model is established to reflect the response of vegetation to climate under natural conditions in the study area:

$$\mathrm{FVC_{pre}} = \alpha \times X_1 + \beta \times X_2 + \ldots + \gamma \times X_3 + \delta \tag{3}$$

where $\mathrm{FVC_{pre}}$ is the FVC of vegetation under the influence of climate change, X_1 is the average temperature (°C), X_2 is the precipitation (mm), X_3 is the ground temperature (°C), and α, β, γ, and δ are regression coefficients, with δ being a constant.

Based on the above equation, regression models are separately established for precipitation, evaporation, temperature and ground temperature in relation to vegetation coverage, and the regression equation of each climate factor passes the significance test at the 0.05 level.

$$\mathrm{FVC_{res}} = \mathrm{FVC_{obs}} - \mathrm{FVC_{pre}} \tag{4}$$

where $\mathrm{FVC_{res}}$ is the residual, which represents the FVC of vegetation under the influence of human activities; $\mathrm{FVC_{obs}}$ is the original FVC; and $\mathrm{FVC_{pre}}$ is the FVC of vegetation under the influence of climate change.

The $\mathrm{FVC_{res}}$ and $\mathrm{FVC_{pre}}$ are calculated using the above equation. Then, linear regression is performed on the $\mathrm{FVC_{res}}$ and $\mathrm{FVC_{pre}}$ sequences with years, respectively, to obtain the variation trends of FVC solely under the influence of human activities and climate change, i.e., $\mathrm{S(FVC_{res})}$ and $\mathrm{S(FVC_{pre})}$, respectively. A positive trend indicates that human activities or climate change have an inhibiting effect on the development of desertification, and a negative trend suggests that human activities or climate change have a promoting effect on the development of desertification.

(5) Relative contributions of human activities and climate change to desertification

The relative contributions of climate change and human activities to desertification are calculated in this study using the contribution classification method proposed by Sun et al. [26]. The specific calculation methods are shown in Table 2. The relative roles of climate change and human activities in the vegetation change described in this study refer to their own combined effects and do not reflect the relative effects of their individual factors.

Table 2. Calculation methods for the contributions of change and human activities to FVC changes.

FVC_{obs} Trend	FVC_{pre} Trend	FVC_{res} Trend	Climatic Change Contribution Rate (%)	Human Activities Contribution Rate (%)	Meaning
$S(FVC_{obs})$ Rise	>0	>0	$\frac{S(FVC_{pre})}{S(FVC_{obs})}$	$\frac{S(FVC_{res})}{S(FVC_{obs})}$	Climate change and human activities cause desertification mitigation
	>0	<0	100	0	Climate change is causing desertification mitigation
	<0	>0	0	100	Desertification mitigation caused by human activities
$S(FVC_{obs})$ Decline	<0	<0	$\frac{S(FVC_{pre})}{S(FVC_{obs})}$	$\frac{S(FVC_{res})}{S(FVC_{obs})}$	Climate change and human activities are causing desertification to accelerate
	<0	>0	100	0	Climate change is causing desertification to accelerate
	>0	<0	0	100	Desertification is accelerated by human activities

3. Results

3.1. Identification of Desertification

The process of desertification is a continuous and time-evolving phenomenon of land degradation, and by studying the trends of desertification, it is possible to simulate the results of degradation and judge the extent of desertification. As shown in Figure 2, through the analysis of remote sensing data in the past 39 years, the desertification areas in Inner Mongolia are mainly concentrated in the central and western parts of the study area. Among them, the proportion of mild desertification areas is the largest, mainly distributed in the central area of the study area, the proportion of severe desertification areas is the smallest, mainly distributed in the northwest area of the study area, and the moderate desertification area is mainly distributed in the western area of the study area. With the passage of time, the scope of desertification in Inner Mongolia has tended to decrease.

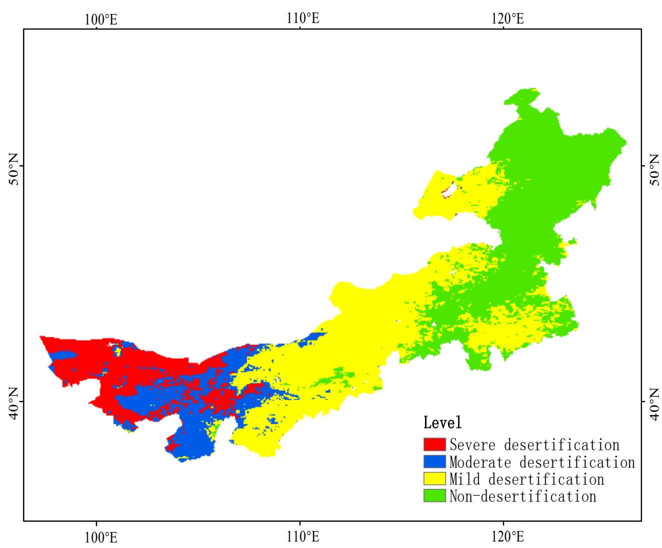

Figure 2. Spatial distribution of desertification levels in Inner Mongolia from 1982 to 2020.

3.2. Qualitative Response Relationship between Annual Desertification and Key Climate Factors

Figure 3 shows there is a significant spatial variation the relationship between vegetation coverage and precipitation. Regions with mild desertification and weak vegetation growth show a stronger relationship with precipitation, and these areas are mainly concentrated in the central part of Inner Mongolia, with a correlation coefficient as high as 0.98. As precipitation increases, the degree of desertification in these regions improves significantly. In regions with severe desertification, vegetation coverage is low and weakly correlated with precipitation, as reflected by a correlation coefficient of only 0.25.

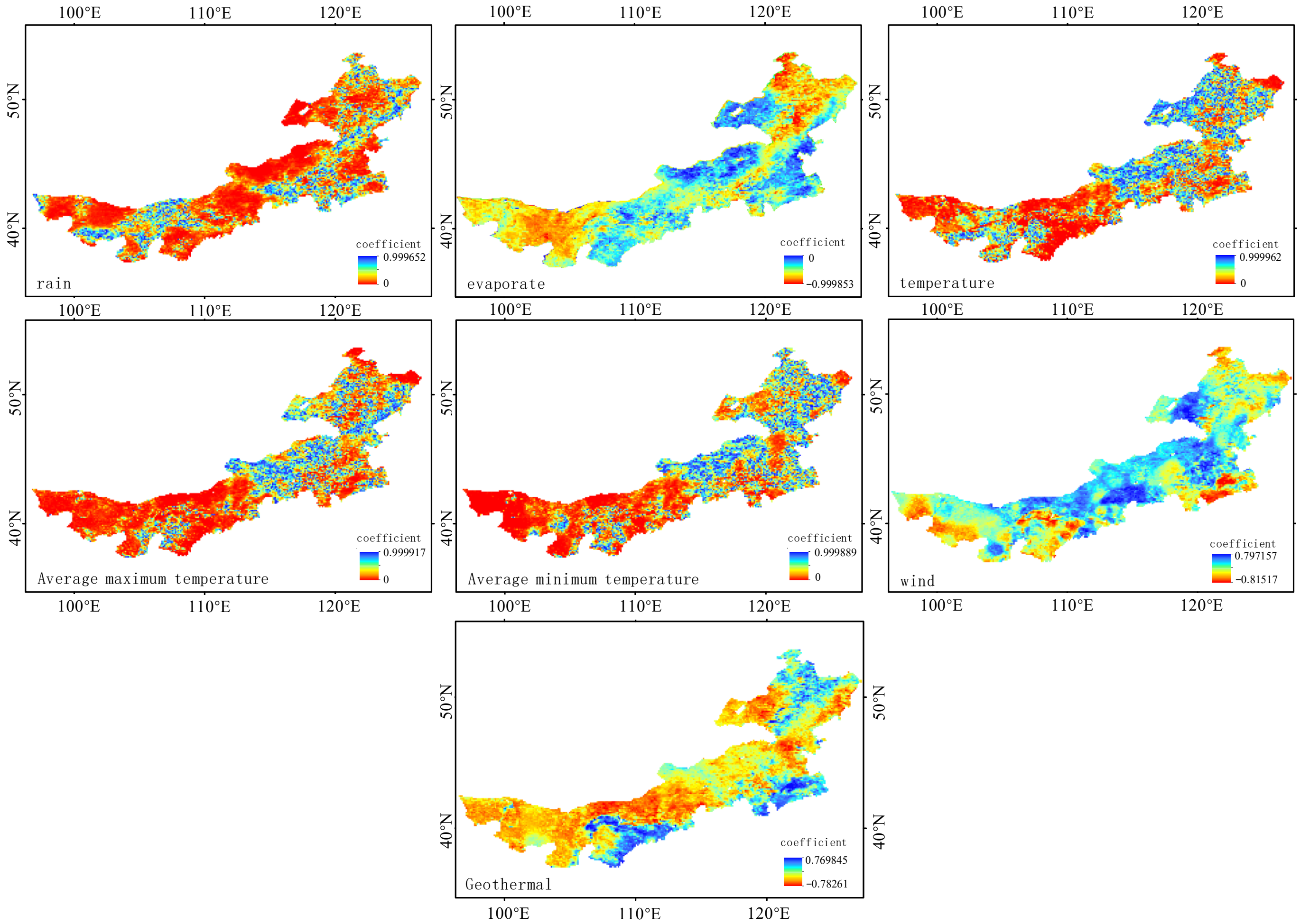

Figure 3. Spatial distribution of correlation coefficients between annual vegetation coverage and key climate factors.

The correlation between vegetation coverage and evaporation is generally high: the higher the evaporation is, the more severe the desertification in the local area is. Regions with severe desertification and weak vegetation growth have a stronger relationship with evaporation and are mainly concentrated in severely desertified regions in the western part of the study area, with a correlation coefficient as high as −0.96.

There is significant spatial variability in the relationship between vegetation coverage and average temperature, with a high correlation between vegetation coverage and temperature in the central-eastern region of Inner Mongolia. The relationship between desertification and temperature also varies spatially, with a weak relationship between the two in regions with a high degree of desertification. The characteristics of the correlation of the average maximum and minimum temperatures with desertification are similar to those of the average temperature with desertification. There is a strong positive correlation of the average maximum and minimum temperatures with mild desertification, with correlation coefficients as high as 0.98 and 0.978, respectively. These results indicate that desertification improves with the increase in the average maximum temperature.

Regions with a positive correlation between vegetation coverage and average wind speed according to correlation analysis account for 63% of the study area, and these areas are mainly located in the central part of Inner Mongolia. The positive correlation coefficient between the average wind speed and mild desertification is as high as 0.77, indicating that mild desertification improves with the increase in the average wind speed. The negative correlation coefficient between the average wind speed and severe desertification is as high as −0.79; in such regions, the vegetation is sparse, and phenomena such as sandstorms and dust storms contribute to vegetation destruction, exacerbating desertification. Regions with a positive correlation between vegetation coverage and average ground temperature according to correlation analysis account for 31% of the study area, and these areas are primarily located in the northeastern and central parts of Inner Mongolia.

The negative correlation coefficient between the average ground temperature and severe and moderate desertification is as high as −0.78, and the increase in average ground temperature will increase the degree of desertification in such regions. The correlation coefficient between the average ground temperature and mild desertification is only 0.24, indicating a low sensitivity of mild desertification to changes in average ground temperature.

3.3. Quantitative Analysis of the Impacts of Key Climate Factors and Human Activities on Desertification

As shown in Figure 4, regions with positive residual values account for 30% of the study area, and these areas are mainly concentrated in mildly desertified areas, indicating that in such areas, human activities have played a positive role in improving desertification and have slowed the desertification process to a certain extent. Regions with negative residual values account for 70% of the study area, and these areas are mainly concentrated in the central part of Inner Mongolia; these areas include severely and moderately desertified areas, as well as some non-desertified areas, indicating that in such areas, human activities have played a negative role in improving desertification and have intensified the degree of desertification to some extent. The FVC gradually increases from west to east under the influence of climate factors, with the lowest simulated values obtained for severely desertified areas, followed by those for moderately desertified areas, and the largest simulated values were obtained for mildly desertified areas. These results indicate that climate change has played a positive role in improving desertification, and slowed the process of desertification to some extent; moreover, climate change has contributed to the improvement of desertified areas in Inner Mongolia, with the greatest positive impact on mildly desertified areas.

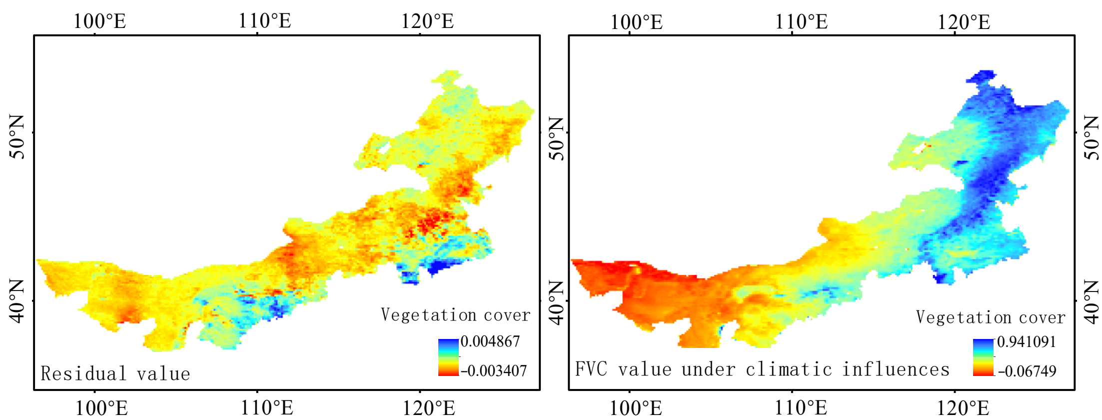

Figure 4. Spatial distribution of residual analysis results.

As shown in Figure 5, the human contribution exhibits a pattern of being high in the west and low in the east, and the contribution in severely desertified areas is higher than that in moderately and mildly desertified areas. In severely desertified areas, the human contribution is negative and mostly −95%, indicating that human activities have aggravated the degree of desertification in these areas. In mildly desertified areas, the human contribution is slightly higher and positive, at around 93%, suggesting that human activities have played a positive role in improving desertification in these areas, with a significant impact on mildly desertified areas. In regions with improved desertification, changes in desertification are primarily influenced by human activities in approximately 25% of these regions, and these areas are mainly concentrated in the northwestern part of Inner Mongolia. In regions with aggravated desertification, changes in desertification are primarily affected by human activities in approximately 70% of these regions, and they are mainly concentrated in Ordos and Hohhot.

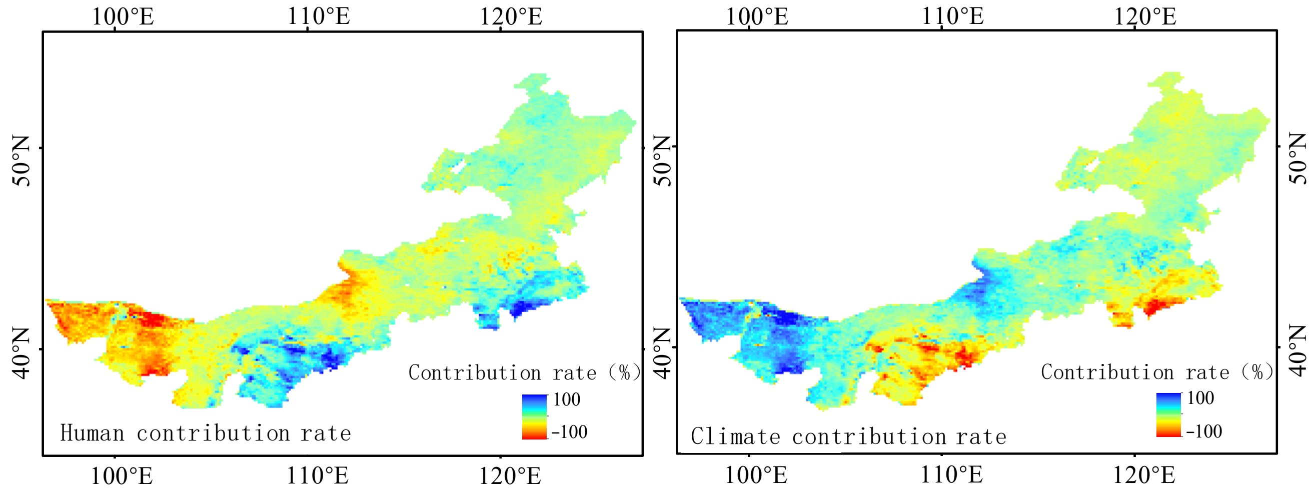

Figure 5. Spatial distribution of relative contribution.

Spatially, the climate contribution in the west is higher than that in the east, and the contribution is high in severely and mildly desertified areas and low in moderately desertified areas. In severely desertified areas, the climate contribution is positive and mostly 97%, indicating that climate change has improved the degree of desertification in these areas and inhibited the development of desertification. The climate contribution in mildly desertified areas is slightly lower than that in severely desertified areas and is negative, at approximately −92%, indicating that climate change has played a role in promoting the development of desertification and has aggravated the degree of desertification in these areas. In regions with improved desertification, changes in desertification are mainly affected by climate change (with a relative contribution > 50%) in approximately 75% of these regions; in particular, the relative contribution of climate change to desertification exceeds 75% in 30% of these regions, which are primarily located in the central and western parts of Alxa and the northern part of Ulanqab. In the regions with aggravated desertification, climate change is the main factor influencing desertification aggravation in approximately 30% of these regions, which are mainly distributed in the southwestern part of Alxa League.

4. Discussion

As a severely desertified area, Inner Mongolia is mainly covered by grassland vegetation. Precipitation plays a decisive role in the growth of vegetation and has a lagging effect on vegetation, and it is closely related to mild desertification [27]. Vegetation growth is sensitive to temperature changes. During the growing season, both high and low temperatures can affect vegetation growth, thereby exacerbating the degree of desertification. This is consistent with the correlation between vegetation and temperature proposed by Hou et al. [28]. Dong et al. [29] proposed that there is significant spatial variation in the relationship between vegetation coverage and precipitation. Areas with lighter desertification and weaker vegetation growth have a stronger relationship with precipitation. As precipitation increases, the degree of desertification in this area significantly improves, which is consistent with this study to some extent. With the increase in precipitation, the vegetation in the area grows vigorously, the vegetation cover increases, and the degree of desertification improves significantly. In central-eastern Inner Mongolia, there is a high correlation between vegetation coverage and temperature. The relationship between desertification and temperature varies spatially. In severely desertified areas, desertification is weakly correlated with temperature, the characteristics of the correlation of the average maximum and minimum temperatures with desertification are similar to those of average temperature with desertification, and the average maximum and minimum temperatures are well correlated with mild desertification. The patterns obtained in this study are basically consistent with those of previous studies, indicating that precipitation and temperature have significant impacts on desertification [29].

Based on the response relationship between desertification and climate factors, this study quantitatively analyses the impact of annual climate factors on desertification. To date, most studies have considered only precipitation and temperature as the two main factors when calculating the relationship with climate factors using residual analysis [30], and the influence of factors such as evaporation and ground temperature have not been considered; this method may result in discrepancies in the contribution of human activities [31]. Xie et al.'s [32] research has shown that vegetation change is jointly affected by climate and human activities, with climate having an impact of about 77% on vegetation change and human activities having an impact of about 23%. As this study did not consider the lag of vegetation growth on temperature and precipitation, it may exaggerate the contribution rate of human activities, resulting in areas where desertification has improved, with human activities affecting about 30% of the area and climate change affecting about 70% of the area. This study used the classic residual analysis method, stripping off climate and human activity factors; Zhang et al. [33] used the trending residual analysis method to detrend climate and human activities. The results showed that 86% of vegetation growth was affected by human activities, which may further weaken the correlation between climate and vegetation, thereby making a significant contribution from human activities. Desertification has improved in approximately 30% of the regions under the influence of human activities, and Wang et al. [34] showed that this situation may be related to the implementation of a long-term grazing ban policy in Inner Mongolia, which has allowed vegetation to gradually recover under grazing restrictions.

With global warming, the spatiotemporal patterns of precipitation will change significantly, affecting vegetation growth and causing harm to ecosystems. An important cause of this series of phenomena is the imbalance between precipitation and evaporation. In particular, both temperature and precipitation changes can have an impact on land desertification, with temperature mainly affecting the evaporation process and precipitation directly altering the amount of water available on the land [35]. When exploring the response of desertification to climate change, the lag of vegetation growth on climate factors and the uncertainty of remote sensing data, including NDVI data, may have an impact on the research results [36,37]. The climate factors considered are limited. If the common mechanisms of these factors on desertification change can be comprehensively considered, further in-depth research can be conducted on the causes of desertification change, and the analysis will be more thorough.

5. Conclusions

(1) This study comprehensively explores the impact of climate change on desertification through a comprehensive evaluation of multiple climate factors. There is a close relationship between precipitation and mild desertification. As precipitation increases, the degree of desertification in the region significantly improves. The correlation between severe desertification and precipitation is low, with a correlation coefficient of only 0.25. The heavily desertified areas east of central Inner Mongolia have a high correlation with average temperature, and rising temperatures promote vegetation growth. Increasing precipitation, increasing temperature, and decreasing evaporation

are beneficial to alleviate desertification to a certain extent, leading to an increase in ecosystem productivity in the region.

(2) Regions with positive residual values account for 30% of the study area, and they are mainly concentrated in mildly desertified areas, where human activities have played a positive role in improving desertification. The FVC increases from west to east under the influence of climate factors, and climate change has played a positive role in improving desertification and has had the greatest positive impact in mildly desertified areas.

(3) The human contribution accounts for 93% in mildly desertified areas, and climate contribution accounts for 97% in severely desertified areas, indicating that the improvement of desertification in such areas is influenced by both human activities and climate change. Changes in desertification are affected by human activities and climate change in approximately 25% and 75% of regions with improved desertification, respectively.

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Data Availability Statement: The precipitation, temperature, evaporate, wind speed and ground temperature data used were from the national earth system science data centre (http://www.geodata.cn/ accessed on 20 October 2021). The NDVI data used was accessed from the resource and environment science data centre (http://www.resdc.cn/ accessed on 20 October 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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