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Marked observed interannual differences in the vegetation response to the trend towards a warmer and wetter climate in northwest China

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Abstract

Located in the interior of Eurasia, the Northwest China undergoes severe drought as oceanic moisture is hard to travel a long distance and cross lots of mountain barriers. These special geo-climatic conditions result in Northwest China being highly sensitive to climate change. In this study, the response of the normalized difference vegetation index (NDVI) to the trend towards a warmer and wetter climate in Northwest China from 1982 to 2019 were investigated. The results show that there were significant differences between the periods 1982–2000 and 2000–2019, with overall precipitation decreasing before 2000 but increasing afterwards. After 2000, the temperature increasing rate slowed down, whereas the NDVI increased at an obviously faster rate. Compared with the period 1982–2000, the NDVI during the period 2000–2019 was more affected by precipitation than by the temperature. The results of a normalized linear regression also show that, for most vegetation types, the temperature played a more dominant role during the period 1982–2000, whereas precipitation had a more significant effect on the NDVI during the period 2000–2019. Throughout the study period, the temperature had a greater impact on forest NDVI and the precipitation had a greater impact on the NDVI in areas of bare land. In addition, the results show that the strength of the relationship between the NDVI and climate in Northwest China changed over time, with the relationship between NDVI and precipitation tending to become stronger and the relationship between NDVI and temperature tending to become weaker. The results will provide a new understanding of the relationship between vegetation and climate in Northwest China and help to better cope with the risks brought by climate change.

Key words: Northwest China; vegetation; warmer and wetter climate; NDVI;

1. Introduction

In arid areas, vegetation is affected by the limited precipitation and strong evapotranspiration and is highly sensitive to climate change (Fensholt et al., 2009;

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McGwire et al., 2000). There have been a large number of studies related to climate change in Northwest China, and these show a clear trend towards warmer and wetter conditions in the region in recent decades (Liu et al., 2013; Shi et al., 2002; Shi et al., 2007; Wang et al., 2020; Wang et al., 2007; Zhang et al., 2021; Zheng et al., 2021).

The relationship between vegetation and climate is very complex. On the one hand, vegetation is affected by the climate, and the spatial heterogeneity of vegetation growth is closely related to the climate conditions. For example, the spatial patterns in vegetation productivity in grassland areas where water is scarce are consistent with the spatial patterns in annual precipitation (Piao et al., 2006). However, vegetation can continuously adapt to changes in climate conditions: for example, it was found that the precipitation threshold for vegetation growth in Australia decreased from 1982 to 2010 (Ukkola et al., 2016). In addition, some studies have found that the relationship between temperature and vegetation productivity may change over time given other environmental limitations (Angert et al., 2005; Beck and Goetz, 2012). Thus, the impact of climate on vegetation is a dynamic process and may change over time.

There have been many studies on the relationship between vegetation and climate in Northwest China, but most of which have been carried out over different time scales and usually focused on a fixed short period of time, which resulted in different results. (Cao et al., 2011; Guo et al., 2008; Xiu-hua et al., 2009; Zhang et al., 2016; Zhao et al., 2011). As climate varies with time, its impact on vegetation growth varies in different time periods. In addition, most these studies analyzed all vegetation as a whole, while few have distinguished between different vegetation cover types. This study aimed to address these problems in earlier studies. The discrepancy in the NDVI response to climate change for different periods within the overall study period were analyzed for different vegetation types.

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2. Methodology

2.1 Study area

This study focuses on northwest China (Figure 1). Located in the interior of Eurasia, the altitude of this region ranges from –152 m to 8058 m, with most areas lying at an altitude of over 1000 m. The complex terrain means that the oceanic moisture is hard to travel a long distance and cross the mountain barriers, resulting in a dry climate.

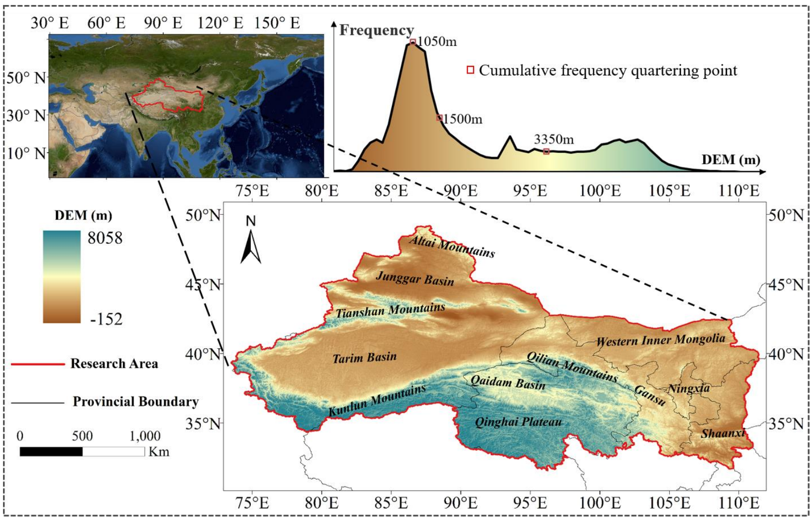

Figure 1. Study area and elevation

2.2 Data and methods

2.2.1 NDVI time series

In this study, combined GIMMS NDVI and MODIS NDVI data acquired during the period 1982–2019 were used. The GIMMS NDVI data were acquired at 15-day intervals during the period 1982–2015 and had a spatial resolution of 8 × 8 km; these data were provided by the National Natural Science Foundation of China's Environmental and Ecological Science Data Center for West China

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(http://data.tpdc.ac.cn/zh-hans/data/1cad1a63-ca8d-431a-b2b2-45d9916d860d/?q=GIMMS). MODIS NDVI data for 2000–2019 that had a spatial resolution of 250 × 250 m and that were also acquired at 15-day intervals were provided by NASA (https://reverb.echo.nasa.gov). Both datasets were composited into monthly values using the maximum value composite (MVC) technique. The NDVI during the growing season was calculated by averaging the values for the period April to October. A complete NDVI time series for 1982 to 2019 that had a spatial resolution of 8 × 8 km was constructed using pixel-wise linear regression. The new 2016-2019 was called the expanded NDVI. To check the accuracy of the constructed long-term time series, statistical analysis was performed on the GIMMS NDVI and the extended NDVI. The results are shown in Fig 2.

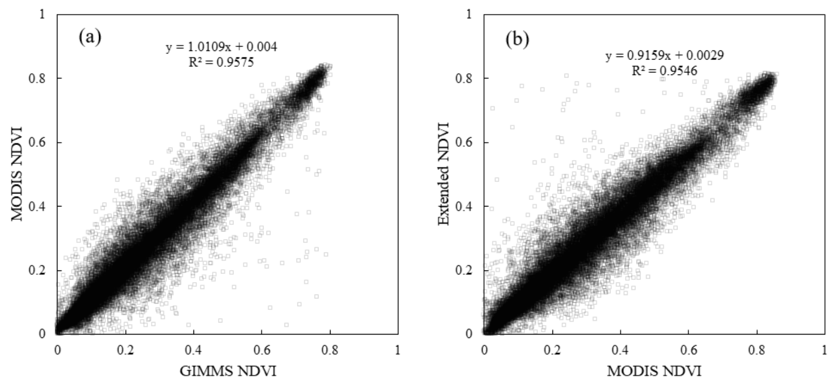

Figure 2. Results of the consistency checks for the different datasets: (a) MODIS NDVI pixel values plotted against GIMMS NDVI pixel values; (b) MODIS NDVI pixel values plotted against extended NDVI pixel values

2.2.2 Climate variable time series

The time series of gridded climate variable data (precipitation and temperature) used in this study were obtained by applying multiple regression and residual interpolation at a spatial resolution of 1 × 1 km to meteorological station observations (Zheng et al., 2021). The data has been verified to have a high accuracy by comparing with the meteorological station data (Zheng et al., 2021).

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2.2.3 Other data

The land cover data originated from Tsinghua University. See (https://www.resdc.cn/Datalist1.aspx?FieldTyepID=1,3) for more information. The afforestation data for Northwest China were obtained from the National Bureau of Statistics (http://www.stats.gov.cn) and the population and GDP data were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn).

2.2.5 Partial correlation analysis

Partial correlation coefficients can be defined by equations (6) and (7) (Kenett et al., 2015; Liu et al., 2015; Song and Ma, 2011):

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{6}$$

and

$$r_{xy,z} = \frac{r_{xy}-r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}}, \tag{7}$$

where r_{xy}, r_{xz}, r_{yz} are the correlation coefficients between variables x and y, x and z, and y and z, respectively; $\bar{x}$ and $\bar{y}$ are the average of x and y, respectively; and $r_{xy,z}$ is the partial correlation coefficient between x and y, excluding the influence of z on x and y.

In this study, the statistical significance of the partial correlations was calculated using the t-test (equation (8)) (Song and Ma, 2011) with the significance level set to 0.05:

$$t_{xy,z} = \frac{r_{xy,z}}{\sqrt{1-r_{xy,z}^2}}\sqrt{n-m-1}. \tag{8}$$

Here, m is the number of independent variables (m = 2 in the study) and n is the number of samples.

2.2.6 Normalized linear regression

For a further comparison of the impact of the temperature and precipitation on the NDVI, a multivariate linear regression was conducted. The NDVI was then given as

$$NDVI = b_0 + b_1 \times Temperature + b_2 \times Precipitation + \varepsilon. \quad (9)$$

Here, $NDVI$ represents the value of the NDVI during the growing season, b_0 is the intercept of the regression model, and b_1 and b_2 are the regression coefficients for the temperature and precipitation, respectively. ε is the regression residual.

In addition, due to the dimensional difference between the temperature and precipitation, a normalization was carried out so that the importance of the influence of these two climate factors on the NDVI could be compared. After the normalization, the larger the absolute value of the regression slope, the more significant the impact of the corresponding independent variable on the NDVI. The normalization can be represented by

$$var_{nor} = \frac{var - var_{min}}{var_{max} - var_{min}}, \quad (10)$$

where var is the variable to be normalized – in this study, the NDVI, temperature, or precipitation; var_{min} and var_{max} are the minimum and maximum value, respectively, of the variable in the time series; and var_{nor} is the normalized value of var.

3. Results and Discussion

3.1 Impact of climate variables on the NDVI

Significant differences were also found in the spatial characteristics of the trends in the precipitation, temperature, and NDVI before and after 2000 (Figure 3). Before 2000, in most parts of the study region, including southern Qinghai, southern Gansu, and the whole of Shaanxi, the precipitation shows a downward trend, whereas, after 2000, it increases in most of these areas. Although the temperature increases during

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both periods, the rate of increase before 2000 is significantly greater than that after 2000, with more regions passing the significant test. Compared with before 2000, in the areas where there is an increasing NDVI trend, the trend after 2000 is more significant. The same is true where the NDVI trend is downwards, particularly in the Junggar basin, Tianshan and southern Qinghai.

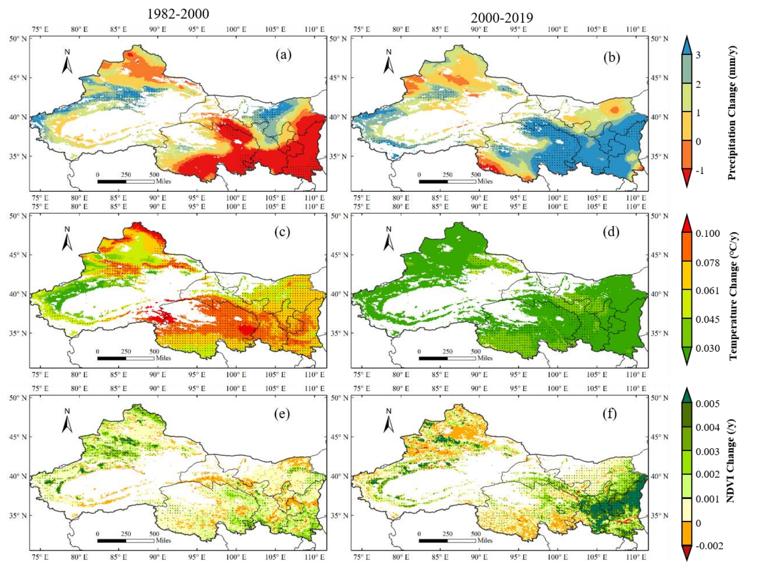

Figure 3. Spatial characteristics of the trends in (a) precipitation, (c) temperature, and (e) NDVI for 1982–2000; spatial characteristics of the trends in (b) precipitation, (d) temperature, and (f) NDVI for 2000–2019 for northwest China during the growing season. The areas marked with dots pass the significance test (S < 0.05)

To study effects of climate change on the NDVI, we calculated the partial correlation coefficients between the NDVI and precipitation and NDVI and temperature for each pixel in the study area for the periods 1982–2000 and 2000–2019. The results are shown in Figure 4. For 1982–2000, the areas with a positive correlation between the NDVI and precipitation are mainly located in the Tianshan Mountains, the western part of Xinjiang, the southern parts of Gansu and Ningxia, and the western part of Inner Mongolia; the areas where the correlation is negative are mainly located in Qinghai and the southern part of Shaanxi. The main areas where there is a positive correlation

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between the NDVI and temperature are found in the Altai Mountains, the western part of Xinjiang, the northern and southern parts of Qinghai and northern Shaanxi; the main areas where there is a negative correlation are located in the Qilian Mountains, western Inner Mongolia and southern Ningxia. For the period 2000–2019, there is a significant increase in the extent of the areas where there is a significant positive correlation between the NDVI and precipitation: these areas are mainly in the east of the study region; in contrast, there is a decrease in the extent of the areas where there is a positive correlation between the NDVI and temperature. In addition, the correlation between the NDVI and precipitation and the NDVI and temperature exhibit opposite characteristics in many regions: the NDVI is negatively correlated with precipitation but positively correlated with temperature in southern Qinghai and southern Shaanxi, which are areas that either are at a high altitude or have a high annual precipitation. However, in the Junggar Basin and the areas surrounding the Tarim Basin, which have a dry climate, the NDVI is positively correlated with precipitation but negatively correlated with temperature.

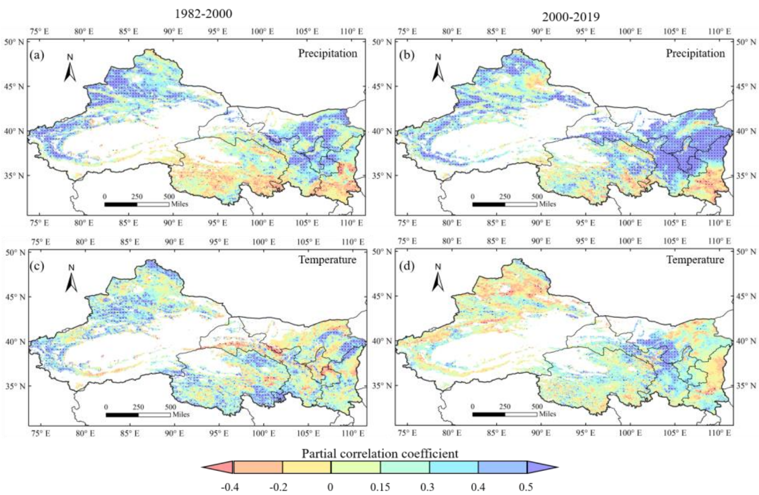

Figure 4. Spatial characteristics of the partial correlation coefficients between the NDVI and (a) precipitation and (c) temperature for 1982–2000 and between the NDVI and (b) precipitation and (d) temperature for 2000–2019 in northwest China. The area marked with dots pass the significance test (S < 0.05)

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Frequency statistics were calculated for the partial correlation coefficients between the gridded NDVI values for different vegetation types and temperature and between these values and precipitation. The results are shown in Figure 5. It can be seen that the response of the NDVI to temperature and precipitation in northwest China varies greatly between the two parts of the study period as well as by vegetation type. For cropland and grassland, during the period 1982–2000, the temperature and precipitation had a similar effect on the NDVI, whereas during the period 2000–2019, the NDVI was affected more by the precipitation than the temperature. For the forest land-cover type, the influence of the temperature on the NDVI was more significant than that of the precipitation during both periods. For shrubland, the NDVI was more affected by temperature during the period 1982–2000 but more affected by the precipitation during the period 2000–2019. For the sparse vegetation in areas of bare land, the impact of precipitation on the NDVI were greater than that of temperature during both periods. On the whole, compared with 1982–2000, for all vegetation types, the NDVI was more affected by precipitation during the period 2000–2019 and less affected by the temperature.

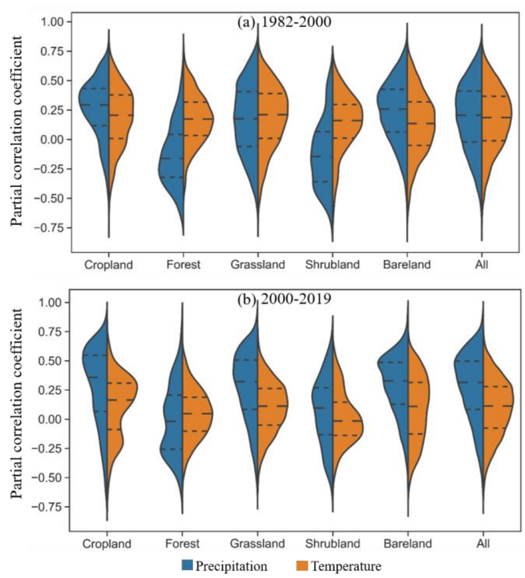

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Figure 5. Statistics relating to the frequency distribution of the partial correlation coefficients between NDVI and precipitation and NDVI and temperature for different vegetation cover types during the periods (a) 1982–2000 and (b) 2000–2019 in northwest China

In order to more comprehensively analyze the impact of the climate on the NDVI in northwest China, a normalized linear regression analysis was carried out on the relationships between the annual regional average NDVI and the temperature and the annual average NDVI and the precipitation. The results are shown in Figures 6 and 7. From 1982 to 2000, with the exception of the bare land class, the temperature regression coefficient is greater than that of the precipitation coefficient, which indicates that the temperature had a more dominant influence on vegetation in northwest China during this period, whereas during the period 2000–2019, the influence of the precipitation was more dominant. During this latter period, with the exception of forest areas, the precipitation regression coefficient is greater than the temperature regression coefficient. However, during both periods, the temperature had a greater impact on the forest areas than the precipitation did, whereas in areas of bare land less it had a smaller impact. These results are consistent with the results of the partial correlation analysis described above.

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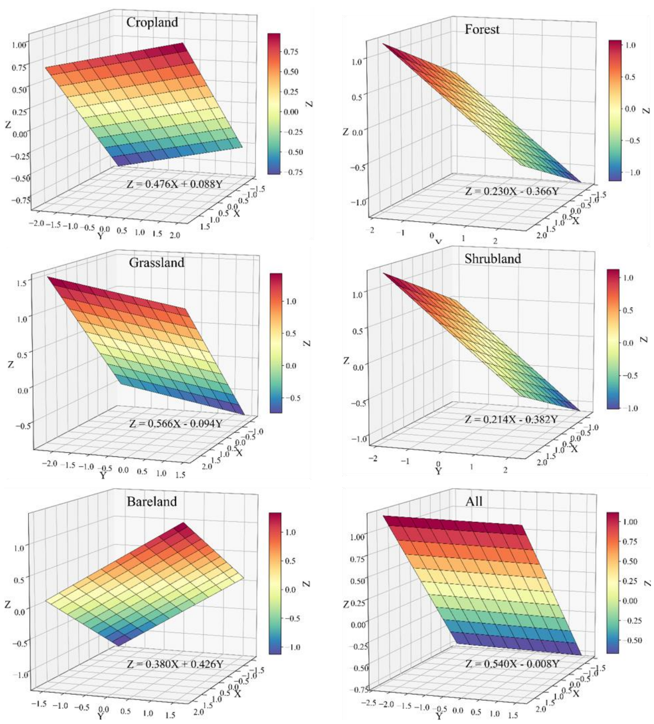

Figure 6. Normalized linear regression results for the relationships between the NDVI and temperature and NDVI and precipitation for different vegetation types in northwest China from 1982 to 2000. X represents the normalized temperature, Y the normalized precipitation, and Z the normalized NDVI.

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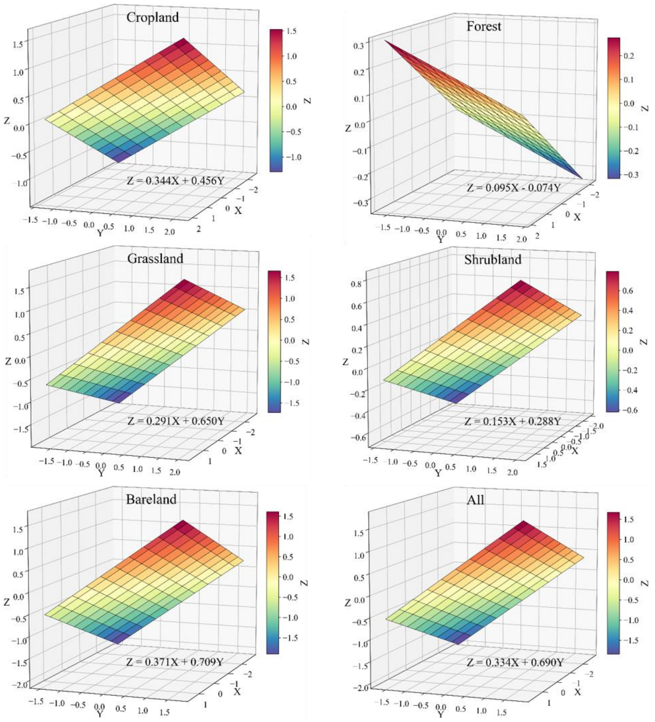

Figure 7. Normalized linear regression results for the relationships between the NDVI and temperature and NDVI and precipitation for different vegetation types in northwest China from 2000 to 2019. X represents the normalized temperature, Y the normalized precipitation, and Z the normalized NDVI.

3.2 Characteristics of the response of vegetation to climate change over time

According to the above analysis, it is clear that the impact of the temperature and precipitation on vegetation in northwest China differed between the two periods 1982–2000 and 2000–2019. To explore whether there were interannual variations in the relationships between the temperature and vegetation greenness and precipitation and vegetation greenness, the partial correlation coefficients for the relationships between the regional average NDVI and temperature and the regional average NDVI and precipitation were calculated for the different vegetation types for the period 1982–2019 using a nine-year sliding window. The results of this are presented in Figure 8. For forest, grassland, and shrubland, the correlation between the NDVI and temperature

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shows an obvious downward trend, indicating that the positive impact of the temperature on these types of vegetation was weakening over time. In contrast, for the grassland and shrubland classes, the correlation between the NDVI and precipitation increases over the study period, indicating that the precipitation was having an increasing influence on the vegetation. For areas of bare land, there is an obvious turning point in the correlation between the NDVI and temperature and between the NDVI and precipitation: before 1999, there is a significant decrease in the correlation between the NDVI and precipitation, whereas there is a significant increase in the correlation between the NDVI and temperature; after 1999, both these trends change direction. Overall, the strength of the relationship between the NDVI and precipitation in northwest China became stronger over the years 1982–2019, whereas the relationship between the NDVI and temperature weakened.

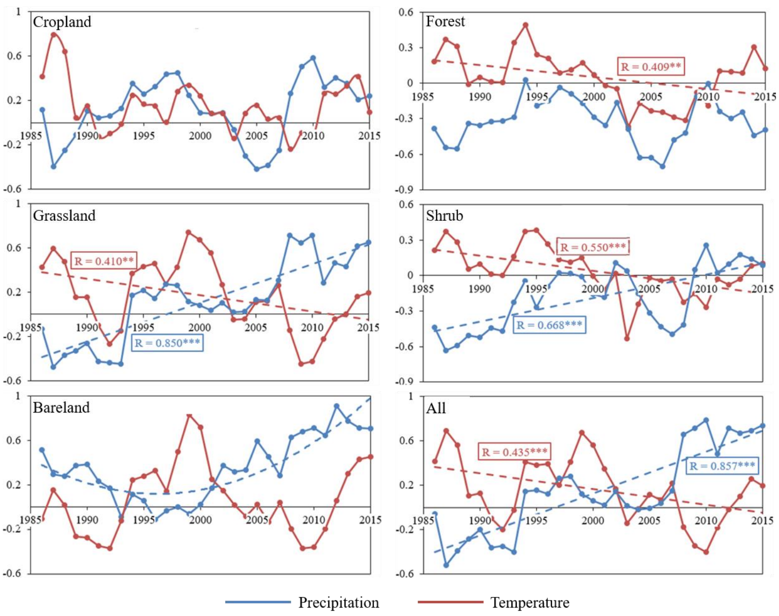

Figure 8. Partial correlation coefficients for the relationships between the regional nine-year average NDVI and temperature and the nine-year average NDVI and precipitation for different vegetation types in northwest China for the period 1982–2019. R represents the partial correlation coefficient: values are given for relationships exhibiting significant changes only.

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By calculating the partial correlation coefficients between the NDVI and temperature and NDVI and precipitation for each pixel using a nine-year sliding window, the spatial characteristics of the trends in these partial correlation coefficients were obtained. The results are shown in Figure 9. It can be seen that in most parts of northwest China, there is a downward trend in the correlation between the NDVI and temperature, with this trend being significant for 30% of pixels; there is an upward trend in the correlation between the NDVI and precipitation, with this trend being significant for 32% of pixels. It is generally agreed that vegetation will continue to adapt to climate change in order to grow better (Ukkola et al., 2016). As the climate of northwest China has become warmer and wetter in recent years, the response of the vegetation in this region to temperature and precipitation has changed, which means that the potential risks brought by future climate change cannot be ignored.

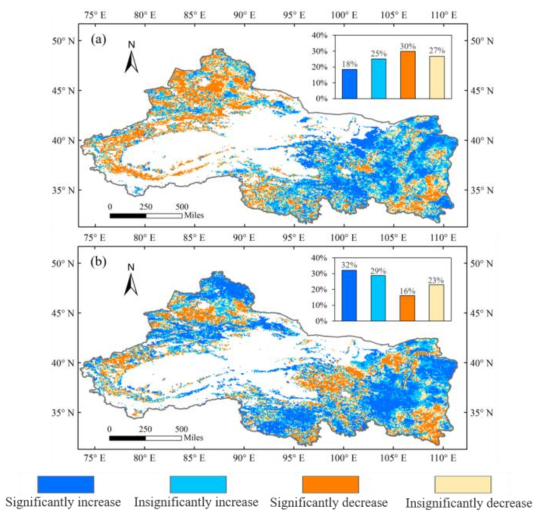

Figure 9. Spatial distribution of significant changes in partial correlation coefficients between the NDVI and (a) temperature and (b) precipitation in northwest China, calculated using a nine-year sliding window for the period 1982–2019

3.3. Disturbances due to human activity and uncertainties affecting the analysis

In addition to the influence of climate change, human activities (urbanization, industrialization, afforestation, etc.) also have an important impact on vegetation (Guan

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et al., 2018; Lin et al., 2020; Wang et al., 2012; Xu et al., 2010). The Chinese government has implemented a series of afforestation programs and measures to reduce desertification in northwest China, including the Three-North Shelter Forest Program (1991), the Natural Forest Protection Program (1998), the Cropland to Forest and Grassland Conversion Program (1999), the Law on Desert Prevention and Transformation (2001), the Beijing–Tianjin–Hebei Sandstorm Source Control Project (2002), as well as a project forbidding grazing established in 2003. As a result, the area affected by both desertification and sandy desertification in China has continued to decline since 1999 (Figure 10). An analysis of artificial forests in five provinces in northwest China (Figure 11) showed that the total area covered by these forests is around 260000 km^2; 60000 km^2 of this is in Gansu and Shaanxi provinces. The correlation between the NDVI and the total area of artificial forest was found to be weakest in Qinghai, which has the smallest total area of artificial forest among the provinces analyzed. In Gansu and Shaanxi, the NDVI is greatly influenced by the artificial forests, and the correlation there is greater than 0.80. It appears that the amount of vegetation greenness in Ningxia is also strongly influenced by these artificial forests, and the correlation between the changes in the NDVI and the total area of artificial forest is particularly strong here both before and after 2000.

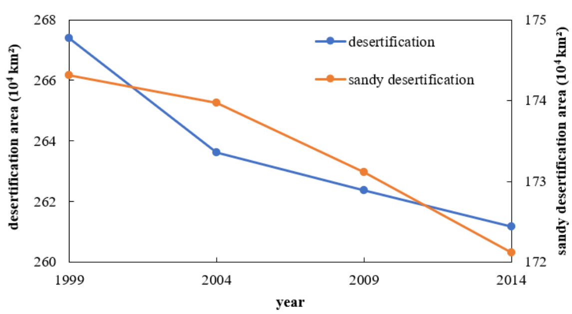

Figure 10. Area affected by desertification (left-hand y-axis) and sandy desertification (right-and y-axis) in China over the period 1999–2014. These data were derived from four national desertification and sandy desertification monitoring bulletins.

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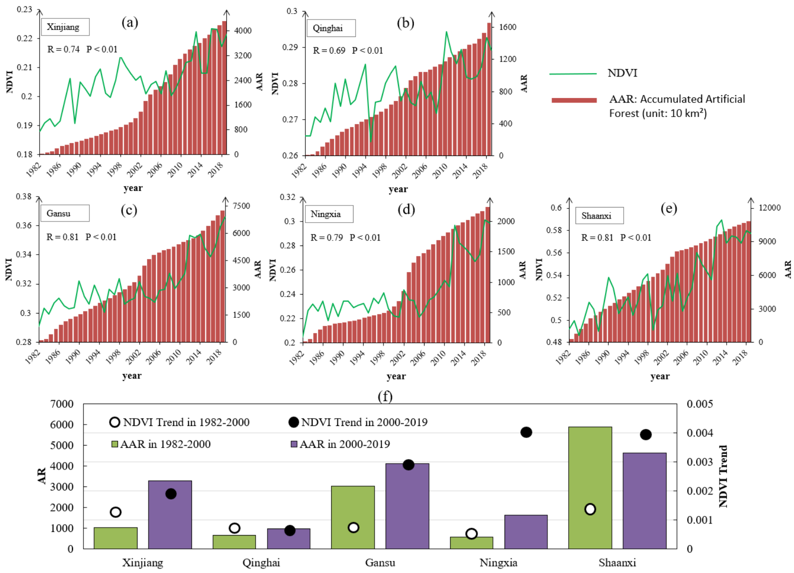

Figure 11. Regional average NDVI and total area of artificial forest in five different provinces in northwest China for the period 1982–2019 (R is the correlation coefficient; P is the significance of the linear relationship between the NDVI and AAR (Accumulated Artificial Forest)); (a)–(e) show data for Xinjiang, Qinghai, Gansu, Ningxia, and Shaanxi, respectively. (f) shows the AAR and the trend in the average NDVI for the same five provinces in northwest China during the periods 1982–2000 and 2000–2019.

From 1995 to 2015, although the total population of northwest China increased, there was a decrease in the rural population as a result of migration to urban centres (Figure 12a); this has tended to lessen the pressure on natural vegetated land and may have contributed to an increase in the NDVI over a large part of the region (Yuan et al., 2019). In addition, a larger population means that agricultural oases are expanding – this is considered to be an important factor promoting the greening of vegetation in northwest China (Jiapaer et al., 2015; Xie et al., 2018). However, the GDP of most areas in the study region increased over the study period (Figure 12b), possibly leading to overgrazing and land degradation (Yuan et al., 2019). Moreover, rapid urbanization can also lead to a reduction in ecosystem services (Guan et al., 2018), which adversely affects vegetation.

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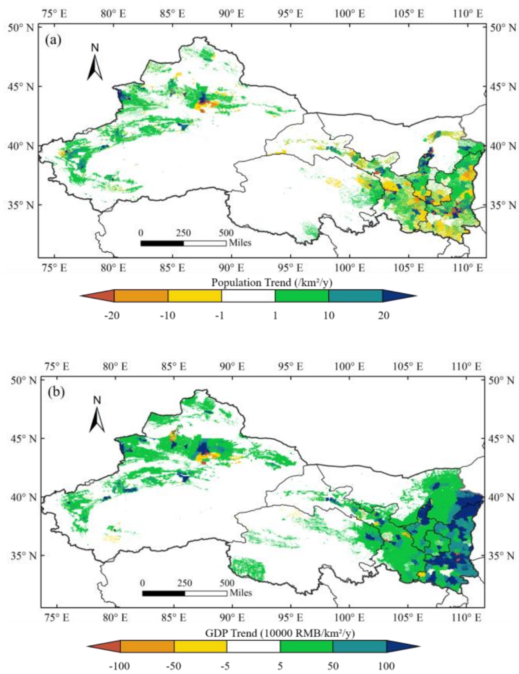

Figure 12 Spatial characteristics of the trends in (a) population and (b) GDP from 1995 to 2019

In this study, both a partial correlation analysis and normalized linear regression were carried out based on the linear correlation between the NDVI and temperature and the NDVI and precipitation. However, the response of vegetation to climate change may be non-linear. Also, the impact of climate on vegetation may not be immediate and could have a time lag ranging from one to several months. These questions have not yet been investigated in great depth and deserve further exploration.

4. Conclusions

In this study, the spatiotemporal trends in the NDVI, precipitation, and temperature were analyzed for different vegetation types in northwest China for the period 1982 to 2019. A linear regression analysis indicated that the details of these trends for 1982–2000 were significantly different from those for 2000–2019, with precipitation

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decreasing before 2000 but increasing afterwards, the temperature growth slowing after 2000, and the NDVI increasing significantly faster. These overall trends were also reflected in the trends for most of the individual vegetation types.

Before 2000, the impact of the precipitation on cropland and grassland was similar to that of the temperature; the temperature had a greater impact on forest and shrubland than the precipitation, while the precipitation had a greater impact on areas of bare land. After 2000, except for the forest class, the positive correlation between the precipitation and vegetation greenness was stronger than that between the temperature and vegetation greenness. In addition, compared with 1982–2000, during the period 2000–2019, the NDVI of all vegetation types was clearly more affected by the precipitation and less affected by the temperature. To gain a more comprehensive understanding of the impact of climate on the NDVI in northwest China, we carried out a normalized linear regression analysis and found that the temperature played a more dominant role during the period 1982–2000 whereas the precipitation played a more dominant role during the period 2000–2019, which was consistent with the partial correlation results.

To explore the characteristics of the vegetation response to climate change over time, we conducted a partial correlation analysis between the NDVI and the climate variables using a nine-year sliding window and found that the relationship between the NDVI and precipitation became stronger, whereas the relationship between the NDVI and temperature became weaker during the period 1982 to 2019 in northwest China.

In addition to the effects of climate change, we also studied the disturbance to vegetation caused by human activities. We found a strong correlation between the total area of artificial forest and the NDVI, indicating the great positive impact of afforestation programs on vegetation in northwest China.

Data and code availability

GIMMS NDVI and MODIS NDVI data are available in http://data.tpdc.ac.cn/zh-hans/data/1cad1a63-ca8d-431a-b2b2-45d9916d860d/?q=GIMMS and

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https://reverb.echo.nasa.gov/, respectively. The land cover data originated from Tsinghua University. See（https://www.resdc.cn/Datalist1.aspx?FieldTyepID=1,3） for more information. The afforestation data for Northwest China were obtained from the National Bureau of Statistics (http://www.stats.gov.cn) and the population and GDP data were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn). All the analyses are made using Python, and the code are available from the corresponding author on reasonable request.

Author contributions

Shijun Zheng, Dailiang Peng and Bing Zhang designed the research ideas. Shijun Zheng and Yan Wang completed the code for analysis. Yuhao Pan prepared the NDVI and climate data. Le Yu helped with the preparation of the land cover datasets. Xuxiang Feng prepared the afforestation data. Changyong Dou prepared the population and GDP data. All authors commented on the paper and provided feedback throughout the data analysis.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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