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Spatiotemporal changes in vegetation coverage and its driving factors in the Three-River Headwaters Region during 2000–2011

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Abstract: The Three-River Headwaters Region (TRHR), which is the source area of the Yangtze River, Yellow River, and Lancang River, is of key importance to the ecological security of China. Because of climate changes and human activities, ecological degradation occurred in this region. Therefore, "The nature reserve of Three-River Source Regions" was established, and "The project of ecological protection and construction for the Three-River Headwaters Nature Reserve" was implemented by the Chinese government. This study, based on MODIS-NDVI and climate data, aims to analyze the spatiotemporal changes in vegetation coverage and its driving factors in the TRHR between 2000 and 2011, from three dimensions. Linear regression, Hurst index analysis, and partial correlation analysis were employed. The results showed the following: (1) In the past 12 years (2000–2011), the NDVI of the study area increased, with a linear tendency being 1.2%/10a, of which the Yangtze and Yellow River source regions presented an increasing trend, while the Lancang River source region showed a decreasing trend. (2) Vegetation coverage presented an obvious spatial difference in the TRHR, and the NDVI frequency was featured by a bimodal structure. (3) The area with improved vegetation coverage was larger than the degraded area, being 64.06% and 35.94%, respectively during the study period, and presented an increasing trend in the north and a decreasing trend in the south. (4) The reverse characteristics of vegetation coverage change are significant. In the future, degradation trends will be mainly found in the Yangtze River Basin and to the north of the Yellow River, while areas with improving trends are mainly distributed in the Lancang River Basin. (5) The response of vegetation coverage to precipitation and potential evapotranspiration has a time lag, while there is no such lag in the case of temperature. (6) The increased vegetation coverage is mainly attributed to the warm-wet climate change and the implementation of the ecological protection project.

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1 Introduction

The Three-River Headwaters Region (TRHR), which is located in the south of Qinghai Province, is the source area of the Yangtze River, Yellow River, and Lancang River, known as "Chinese water tower" (Liu *et al*., 2008). This region is not only an important ecological barrier of China but also one of the regions with a sensitive and fragile ecological environment (Shao *et al*., 2010). The fourth IPCC report has stated that the global mean land surface temperature (LST) increased by 0.74℃ over the past 100 years (1906–2005), while the LST increased by 0.65℃ over the past 50 years; the increase rate of the latter was twice that the former (IPCC, 2007). In China, the LST has increased by 0.5–0.8℃ over the past 100 years, with significant variation in precipitation (Yin *et al*., 2010). Global climate change has a significant impact on terrestrial ecosystems (IPCC, 2007; Zhao *et al*., 2011). As the main body of the terrestrial ecosystem, vegetation is not only the bear of climate change, but also generates a feedback effect on the climate change, and it plays the role of an "indicator" in the study of global change (Liu *et al*., 2012; Cui *et al*., 2009). Research shows that vegetation activities enhanced significantly in the northern hemisphere against the background of climate warming (Myneni *et al*., 1997), and the same trend was detected in China (Fang *et al*., 2003).

In recent years, the Qinghai-Tibet Plateau has been identified to be sensitive to climate changes; the TRHR, located in the hinterland of the Qinghai-Tibet Plateau, is also very sensitive to climate changes. Under the influence of climate change and human activities, significant changes in the ecological environment have occurred in the TRHR, mainly reflecting as serious grassland degradation, wetland destruction, glacier retreat, and soil erosion etc. (Liu *et al*., 2008; Yi *et al*., 2011). Vegetation is a comprehensive indicator of ecological environment change, and hence, spatiotemporal changes in vegetation and its response to climate change have become the key topics in global change research (Zhang *et al*., 2011; Xin *et al*., 2007). So far, extensive research has been carried out by domestic and foreign scholars (Liu *et al*., 2008; Li *et al*., 2011; Piao *et al*., 2006; Zhang *et al*., 2007; Qian *et al*., 2010; Zhang *et al*., 2013), of which, Liu Jiyuan has analyzed the temporal and spatial characteristics of grass degradation in the TRHR and concluded that grass degradation in the TRHR is a continuously changing progress that has a long-term influence over a large area, and is obviously different in different regions (Liu *et al*., 2008). The response of different types of vegetation to climate change in the TRHR was discussed, and the effectiveness of ecological conservation was assessed quantitatively by separating the contribution of human activity from climate factors to vegetation growth. The contribution of climate change and human activity to vegetation growth was calculated to be 79.32% and 20.68%, respectively (Li *et al*., 2011). The tendency of the NDVI and its spatial differentiation characteristics during the period 1981–2001 were discussed (Zhang *et al*., 2007). During 1982–2006, especially after 2004, climate changes resulted in an increase in plant productivity of the grassland in the TRHR, as revealed by the research on the trends in climate change in the growing season and the response of the grassland to climate changes (Qian *et al*., 2010).

To sum up, previous studies focused on the temporal and spatial characteristics of vegetation change and explored the correlation between vegetation and climate factors on the whole. However, the future trend of vegetation in the TRHR is still unclear, and climate factors are limited to temperature and precipitation. Therefore, in this study, we analyzed the spatiotemporal changes in vegetation coverage and focused on the interactions between climate change and human activities in the process of vegetation growth using the satellite-sensed NDVI data recorded during 2000–2011, with linear regression analysis, Hurst exponent analysis, and other methods. We also adopted temperature, precipitation, and potential evapotranspiration as climate factors to explore the correlation between climate and vegetation. Periodic evaluation of vegetation coverage changes in the TRHR, which is the largest nature preservation zone in China, is of great significance for the construction of a regional ecological environment, protection of ecological security in source areas and downstream areas, and promotion of sustainable social and economic development.

2 Data and methods

2.1 Data source and preparation

The MOD13Q1 datasets obtained from NASA's Earth Observing System during 2000 to 2011 were used in this study (http://e4ftl01.cr.usgs.gov). The spatial and temporal resolutions of NDVI are 250 m × 250 m and 16 day, respectively. The NDVI is widely used in the research of regional vegetation coverage changes because of its high spatial resolution and good data quality through dealing with water, clouds, and heavy aerosol. We acquire annual and monthly NDVI datasets of our study area during the period 2000–2011 by the Maximum Value Composite method in order to eliminate extreme values after format and projection transformation by MODIS Re-projection Tools.

The meteorological datasets, with 16 meteorological stations in the TRHR during 1980–2011, consisting of daily mean temperature, daily maximum temperature, daily minimum temperature, relative humidity, sunshine hours, wind speed, and precipitation, were collected from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn).

2.2 Methods

2.2.1 Linear regression analysis

The method of linear regression can simulate the trend for each pixel. The slope of the linear regression was the index fitting the trend in vegetation dynamics for every pixel by using the least-squares method in the study period, which can comprehensively reflect the spatiotemporal variation characteristics of vegetation coverage (Song *et al.*, 2008). The slope is calculated as follows:

$$Slope=\frac{n\times\sum_{i=1}^{n}i\times NDVI_i-\sum_{i=1}^{n}i\sum_{i=1}^{n}NDVI_i}{n\times\sum_{i=1}^{n}i^2-\left(\sum_{i=1}^{n}i\right)^2} \tag{1}$$

where $Slope$ is the trend in vegetation coverage change, n is equal to 12, i is the order of year from 1 to 12 in the study period, and $NDVI_i$ is the mean $NDVI$ in the ith year. When $Slope>0$, the NDVI shows an increasing trend, and when *Slope*<0, the NDVI shows a decreasing trend.

2.2.2 Hurst exponent analysis

The Hurst exponent, estimated by R/S analysis, is used as a measure of the long-term memory of the time series. It was first proposed by the British hydrologist Hurst, and its main principles are as follows (Zhang *et al.*, 2011; Li *et al.*, 2012; Jiang *et al.*, 2004).

1. Given a time series $\{\xi(t)\}$ t=1, 2, … , n, divide the time series into τ subseries $\xi(t)$.
2. Define the mean sequence of the time series.

$$\langle\xi\rangle_\tau = \frac{1}{\tau}\sum_{t=1}^{\tau}\xi(t) \qquad \tau=1, 2, \cdots \tag{2}$$

3. Calculate the cumulative deviation.

$$X(t,\ \tau) = \sum_{u=1}^{t}\left(\xi(u) - \langle\xi\rangle_\tau\right) \qquad 1 \leqslant t \leqslant \tau \tag{3}$$

4. Calculate the range sequence.

$$R(\tau) = \max_{1\leqslant t\leqslant\tau} X(t,\tau) - \min_{1\leqslant t\leqslant\tau}(t,\tau) \qquad \tau=1, 2, \cdots \tag{4}$$

5. Calculate the standard deviation sequence.

$$S(\tau) = \left[\frac{1}{\tau}\sum_{t=1}^{\tau}\left(\xi(t) - \langle\xi\rangle_\tau\right)^2\right]^{\frac{1}{2}} \qquad \tau=1, 2, \ldots \tag{5}$$

If $R/S \propto \tau^H$, the time series shows the Hurst phenomenon and the H value is called the Hurst exponent, which can be obtained by least-squares fitting in the double logarithmic coordinate system. According to Hurst (1951), the value of Hurst exponent expanded from 0 to 1, and it can be divided into three groups: (1) $H > 0.5$ referred to the persistence of the series, which indicated the same trend in the time series in the future, with a greater value for more persistence; (2) $H = 0.5$ implied that the time series was random without persistence, which indicated that changes in the time series in the future would be unrelated to those in the study period; (3) $H < 5$ referred to anti-persistence of the time series, which indicated an anti-trend of the time in the future, with smaller values for more anti-persistence sustainability.

2.2.3 Calculation of potential evaportranspiration

In this study, we adopted the Penman-Monteith model, recommended by the Food and Agriculture Organization, to calculate the potential evapotranspiration. The model integrates mass transfer and energy balance and considers vegetation physiological characters, and it is valid in both arid and humid climates. Hence, this model has been applied widely around the world (Allen *et al.*, 1998). The model as follows:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\dfrac{900}{T+273}U_2\left(e_s - e_a\right)}{\Delta + \gamma(1 + 0.34U_2)} \tag{6}$$

where △ is the slope of the saturation vapor pressure curve (kPa/℃), R_n is the net radiation (MJ/(m^2·d)), G is the soil heat flux (MJ/(m^2·d)), γ is the psychrometric constant (kPa/℃), T is the mean temperature (℃), U_2 is the wind speed at a height of 2 m (m/s), e_s is the mean saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

2.2.4 Partial correlation analysis

The geographic system is a complex multifactor system, and one change will inevitably affect the other change. In partial correlation analysis, when two variables simultaneously associate with the third variable, the impact of the third one is excluded, and only the correlation of the other two variables is estimated (Xu *et al.*, 2002). The formula is as follows:

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

where $r_{xy\cdot z}$ is the partial correlation coefficient between variables x and y after fixing variable z; r_{xy}, r_{xz}, r_{yz} are the correlation coefficients between variables x and y, x and z, and y and z, respectively.

The correlation coefficient model is as follows:

$$r_{xy}=\frac{\sum_{i=1}^{n}\sum_{\mathrm{j}=1}^{12}\left(x_{\mathrm{ij}}-\bar{x}\right)\left(y_{i\mathrm{j}}-\bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\sum_{\mathrm{j}=1}^{12}\left(x_i-\bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\sum_{\mathrm{j}=1}^{12}\left(y_i-\bar{y}\right)^2}} \tag{8}$$

where r_{xy} is the correlation coefficient between variables x and y, whose value is between −1 and 1; x_{ij} is the NDVI in the ith year jth month; y_{ij} is the mean monthly temperature, precipitation, or potential evapotranspiration in ith year, jth month or $(j-1)$th month; $\bar{x}$ and $\bar{y}$ are the NDVI in the mean month, mean temperature, mean precipitation, or mean potential evapotranspiration in a month.

3 Characteristics of vegetation coverage change in the TRHR

In this section, we examine the temporal vegetation dynamic changes, spatial differential characteristics of NDVI and trend analysis of NDVI.

3.1 Temporal vegetation dynamic changes in the TRHR

3.1.1 Entire regional scale

In the past 12 years (2000–2011), the NDVI of the study area increased, with a linear tendency of 1.2%/10a, and the NDVI value ranged from 0.4214–0.4638 (Figure 1a). The NDVI change during the study period was divided into 8 stages, and wave peaks occurred in 2001, 2005, 2007, and 2010, whereas wave valleys were observed in 2002, 2006, and 2008.

3.1.2 Source regional scale

The trend in the NDVI increase in the Yangtze River source region (YZRSR), which has the lowest NDVI value (0.3282–0.3666), is slightly faster than that for the entire study area, with a linear tendency of 1.7%/10a (Figure 1b). The NDVI values in the Yellow River source region (YRSR), which possesses the highest NDVI (0.5557–0.6173), show an increasing trend with a linear tendency of 1.1%/10a. Apart from more obvious decreases in 2002 and 2011, the NDVI values are relatively stable during the other years (Figure 1c). In contrast, the NDVI values in the Lancang River source region (LRSR) show a decreasing trend with a linear tendency of –0.7%/10a; obvious decreases were observed in 2005 and 2006, and the highest and lowest NDVI values were observed in 2001 and 2006, respectively (Figure 1d).

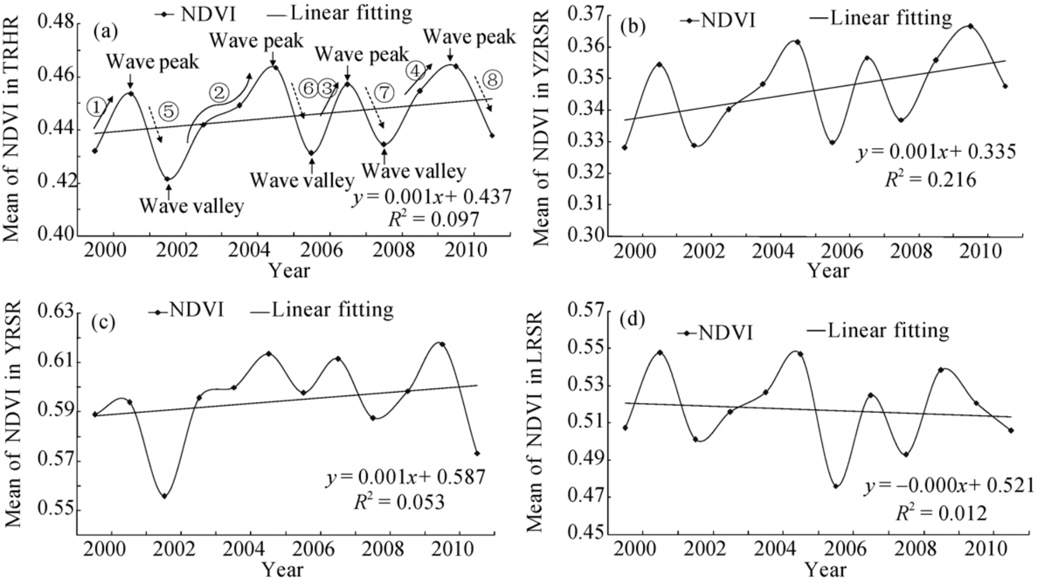

Figure 1 Annual mean NDVI curve and its variation trend with year in the TRHR during 2000-2011

3.1.3 County scale

According to the change in NDVI values in every county in the TRHR during 2000–2011, we can draw two conclusions: (1) The NDVI values in the eastern counties were considerably higher than in the western counties. (2) The trend of the change in NDVI values was divided by 34°N parallel. The counties in the north showed an increasing trend, of which Xinghai, Tongde, and Zeku had the top three rates of increase, at 3.90%/10a, 3.40%/10a, and 3.05%/10a, respectively. Further, the counties in the south primarily exhibited decreasing trends, of which the largest rate of decrease was observed in Nangqian county, at –1.67%/10a, followed by Yushu county, at –0.94%/10a (Figure 2).

3.2 Spatial differential characteristics of NDVI in the TRHR

3.2.1 The general characteristics of NDVI

The general NDVI characteristics in the TRHR are shown in Figure 3. The NDVI values showed a decreasing trend from southeast to northwest. Low NDVI values were mainly distributed in the north of Maduo and Qumacai counties, the west of Zhiduo and Zaduo counties, and Tanggula town, because these counties are mainly distributed in the alpine grassland region of the upper Yangtze River, alpine desert steppe region of Hoh Xil, and alpine grassland area of Huashixia-Zhaling Lake. In contrast, high NDVI values were distributed in Banma, Jiuzhi, Gande, Henan, Zeku and Tongde counties, and south of Xinghai county, and east of Maqin county. This is because these counties are mainly distributed in the forest and temperate grassland region of the Huangshui-Yellow River Basin, cold-temperate coniferous forest and alpine shrub region of the southern Qinghai Plateau, as well as alpine shrub and alpine meadow area in Yushu (Figure 3a). The NDVI in the study area showed “bimodal structure”, i.e., the mean NDVI value was 0.4430 and the proportion of NDVI values between 0.1 and 0.8 was 92.81%, of which the proportions of values 0.1–0.3, 0.3–0.6, and 0.6–0.8 were 27.6%, 34.79%, and 30.42%, respectively (Figure 3b).

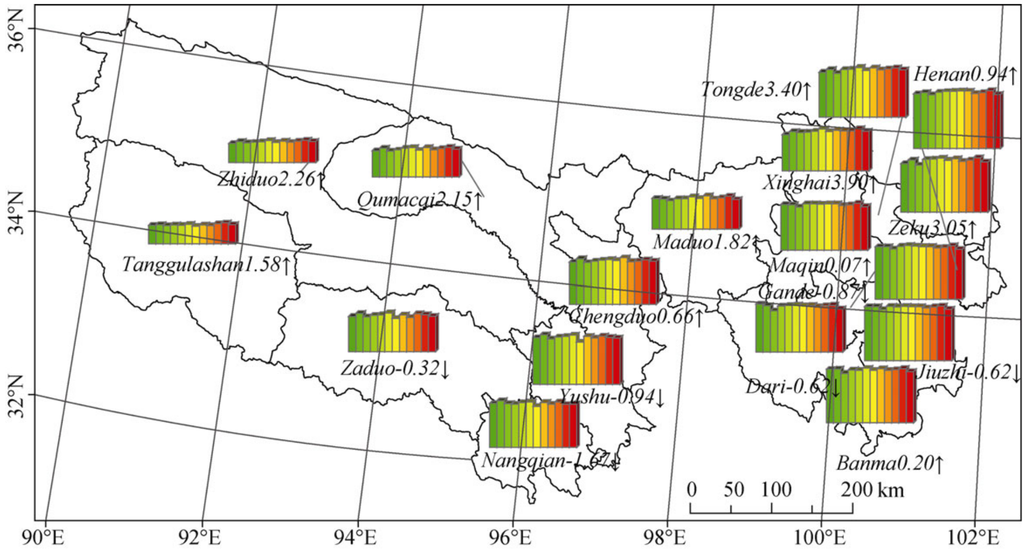

Figure 2 Annual change curve of NDVI in each county of the TRHR during 2000-2011 (%/10a)

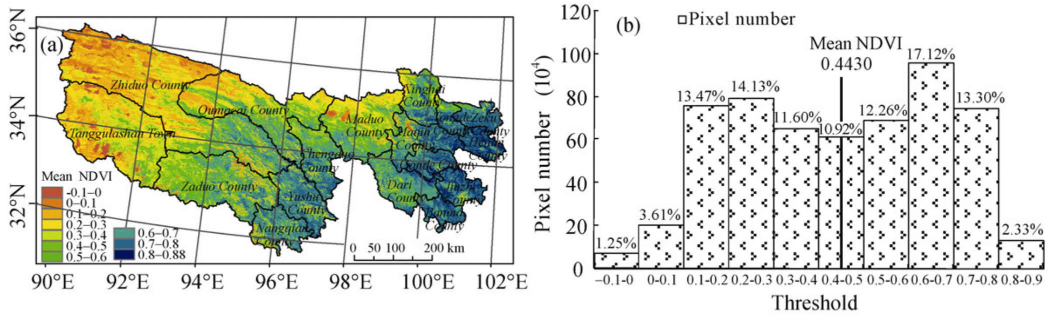

Figure 3 Spatial distribution of NDVI (a) and its frequency distribution (b) in the TRHR

3.2.2 The stability of vegetation coverage change

The standard deviation (SD) in the study area was between 0.001 and 0.42. The spatial distribution of SD showed that the central part of the TRHR experienced the highest fluctuation, followed by the eastern part, and the western has the highest stability. Apart from water bodies, the highest fluctuation in the past 12 years was mainly distributed in Nangqian county, east of Zaduo county, south of Yushu, and the boundaries of Qumacai county, Chengduo county, and Zhiduo county. The regions with relatively stable values were located to the northwest of the study area, such as Zhiduo county, Tanggula town, and Qumacai county, because these regions were are mostly desert areas, with low vegetation coverage and low inter-annual fluctuation (Figure 4).

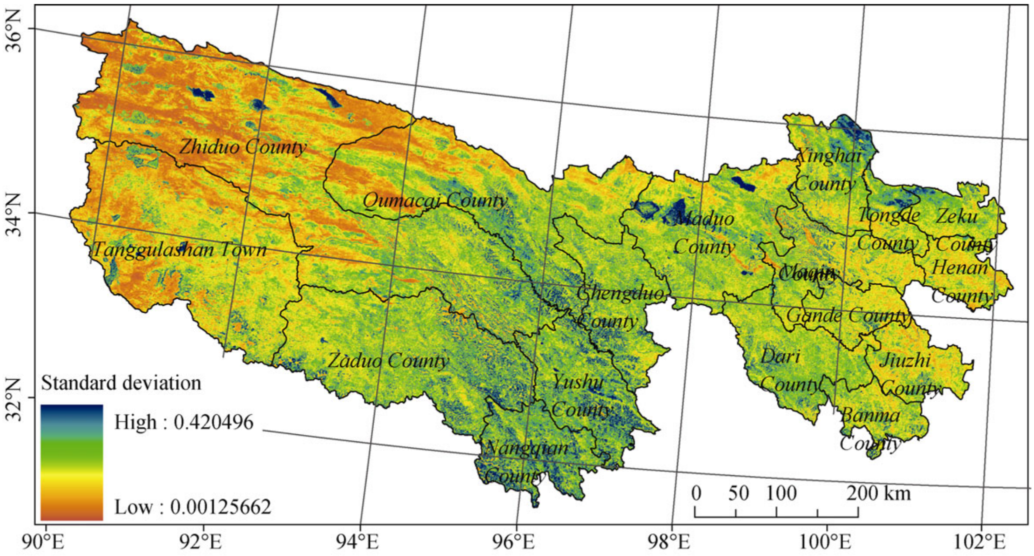

Figure 4 Stability of vegetation change in the TRHR during 2000–2011

3.3 Trend analysis of NDVI

3.3.1 Trend of NDVI change in the TRHR

Linear regression analysis was employed in this study to detect the trend in NDVI change, and the results were divided into categories of extremely significant (0.01), significant (0.05), weakly significant (0.1) and insignificant level (Figure 5). The average rate of NDVI change was 1.2%/10a. The areas where the NDVI showed an increasing trend accounted for 64.06%, and the areas with extremely significantly increasing trends accounted for 9.27%; these areas were mainly distributed to the north of Zhiduo county, northwest of Qumacai county, and north of Maduo county and Xinghai county. In contrast, the regions showing a decreasing trend accounted for 35.94%; these regions included Nangqian county, Zaduo county, Yushu county, Maqin county, Gande county, Dari county and Jiuzhi county, which exhibit obvious vegetation degradation phenomenon (Table 1). Generally speaking, the vegetation

Table 1 Areas and proportion of vegetation NDVI change in the TRHR during 2000-2011

Type	Pixel number	Area (km^2)	Percentage (%)	Cumulative percentage (%)
Extremely significantly increase	162756	10172.25	2.90	2.90
Significantly increase	357380	22336.25	6.37	9.27
Weakly significantly increase	308727	19295.44	5.50	14.77
Increase	2765663	172853.94	49.29	64.06
Extremely significantly decrease	24119	1507.44	0.43	64.49
Significantly decrease	72664	4541.50	1.29	65.78
Weakly significantly decrease	87708	5481.75	1.56	67.35
Decrease	1832409	114525.56	32.65	100

changing trend revealed a pattern: the vegetation coverage of the northern and western parts was better than that of the southern and eastern.

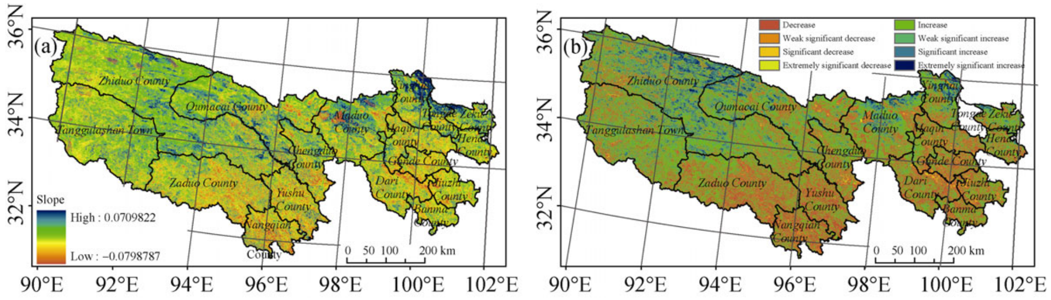

Figure 5 Trend (a) and significant (b) of vegetation change in the TRHR during 2000-2011

3.3.2 Future trend of NDVI in the TRHR

The average Hurst exponent of NDVI was 0.5545 (with a range of 0.1524 to 0.8222), 81.29% of which were less than 0.5, indicating that the reverse characteristics of vegetation coverage change is significant. Conversely, only 18.71% of the values were greater than 0.5. The regions with high values were distributed in the northwest of Zhiduo county, Maqu county, and the boundary of Zeku county and Henan county, indicating that the trend of vegetation coverage change in these areas has remained the same. In contrast, regions with low values were mainly distributed in the east of Zhiduo county, Zaduo county, Yushu county, the north of Nangqian county, and the center of Qumacai county, indicating that the future trend of vegetation coverage change will be completely different from that in the past (Figure 6a).

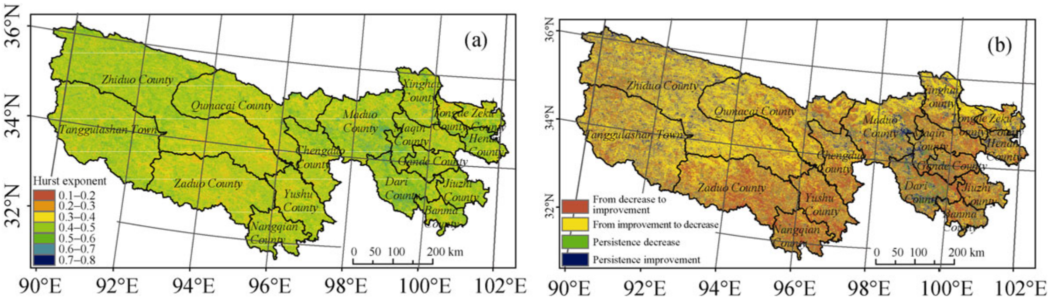

Figure 6 Hurst exponent (a) and future trend (b) of vegetation in the TRHR during 2000-2011

The future trend of vegetation coverage change was plotted by overlaying the results of the slope and Hurst exponent analysis (Figure 6b). We can conclude that the future trend of vegetation coverage in the Yangtze River source region will go from improvement to degradation, while that in the Lancang River source region will go from degradation to improvement. The north of the Yellow River source region will go from improvement to degradation and the middle will go from degradation to improvement. Regions with continued improving and degrading trends were mainly located in counties of Maduo, Dari and Henan.

4 Influencing factors analysis

4.1 The correlation between NDVI and climate factors

In order to ensure the accuracy of the data and enhance the reliability of the research results, this study adopted site-by-site partial correlation analysis to explore the response of vegetation change to climate factors. Details of this approach are as follows: (1) based on the meteorological sites, we extract annual and monthly NDVI values within a boundary of 3×3 km^2; (2) using the NDVI values from this area, we can calculate the partial correlation coefficients between NDVI and the annual and monthly mean temperature, precipitation, and potential evapotranspiration.

On an annual scale, the results show that the partial correlation coefficient of NDVI and temperature fluctuates between positive and negative values, with a decreasing trend. The Partial correlation coefficient of NDVI and precipitation is positive, with an increasing trend. Conversely, the partial correlation coefficient of NDVI and potential evapotranspiration is mostly negative (Figure 7a).

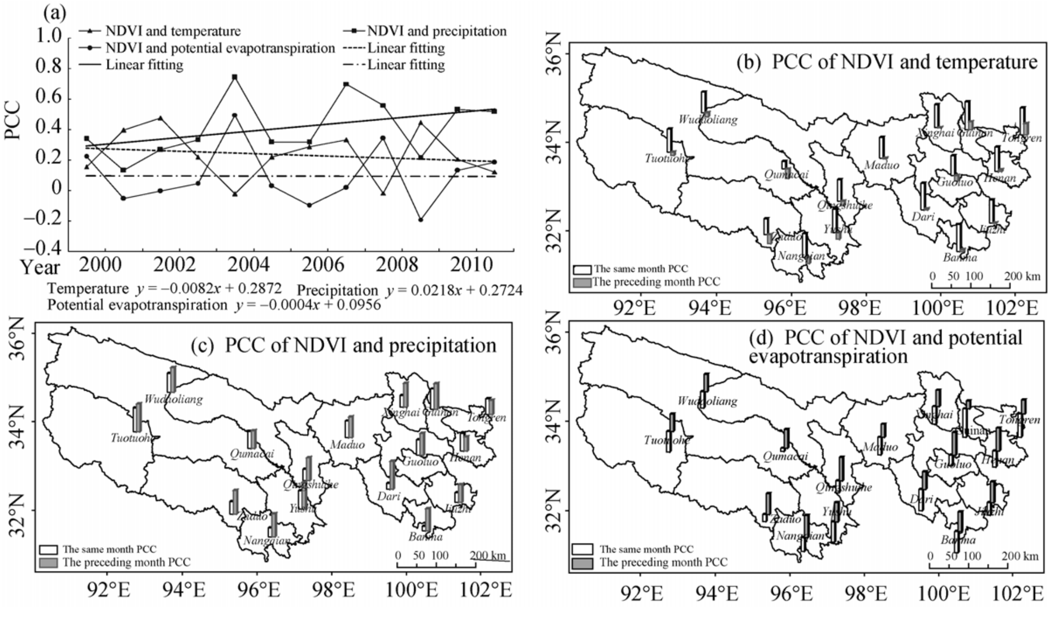

Figure 7 Partial correlation coefficients of NDVI and climate factors in the TRHR during 2000-2011

The regions with high partial correlation coefficients between NDVI and temperature are mainly located in the southeast of Zhiduo county, Chengduo county, Nangqian county, and Tongde county, whereas the regions with negative values are mainly distributed along the boundary of Zhiduo county and Qumacai county, and Xinghai county. The regions with high coefficients between NDVI and precipitation are mainly distributed in Tongde and Zeku counties, and the areas with negative values are all located within the Yellow River source region. Apart from the Wudaoliang and Henan stations, the coefficient between NDVI and potential evapotranspiration exhibits negative correlation in the rest of the study area, and areas with high negative values are mainly distributed in Tanggula town, Maduo county, Nangqian county, and Banma county. This indicates that vegetation growth would be inhibited with the increase in potential evapotranspiration.

On a monthly scale, the results show that the partial correlation coefficient between NDVI and the same month temperature is obviously greater than the preceding month (Figure 7b). Apart from the Tongren and Henan stations, the partial correlation coefficient between NDVI and the same month precipitation is lower than the preceding month (Figure 7c). Thus, the response of NDVI to precipitation exhibits time lag, but this is not the case with temperature. Our conclusion is consistent with Song's research conclusion (Song *et al.*, 2011). NDVI was negatively correlated with the same month potential evapotranspiration but was positively correlated with the preceding month potential evapotranspiration (Figure 7d). In order to explore the mechanism that drives this phenomenon, we further analyzed the partial correlation coefficient between NDVI and the total solar radiation and found that the response of NDVI to the total solar radiation also exhibits time lag. Therefore, the time lag between NDVI and potential evapotranspiration is essentially the delay response to the total solar radiation.

4.2 Trend of climate change in the TRHR

Temperature increased considerably during 1980–2011, with a linear tendency of 0.786℃/10a ($p<0.01$) (Figure 8a). Around 1998, the temperature exhibited a mutation (reliability value is 0.05), which is consistent with Yi's research (Yi *et al.*, 2011). Apart from Guinan station, all stations revealed considerable variation in temperature, and 88% of the stations revealed the mutation, with a period between the end of the 20th century and the early 21st century (Figure 8b).

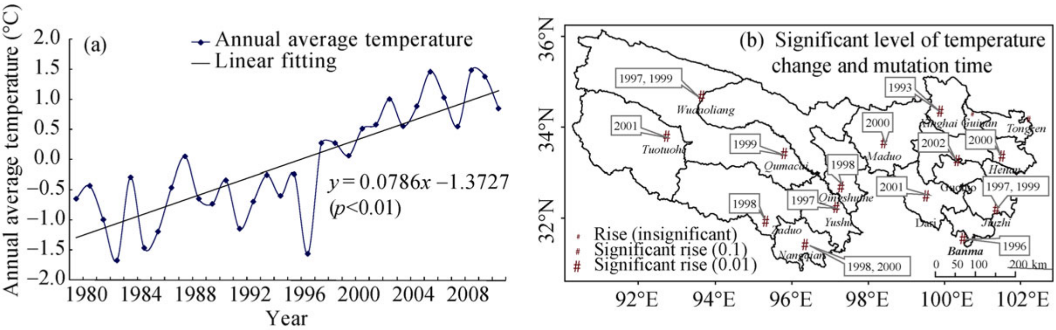

Figure 8 Analysis of temperature changing trend (a) and mutation characteristic (b) in the TRHR during 2000-2011

Precipitation increased slightly during 1980–2011, with a linear tendency of 2.77 mm/10a (Figure 9a), which is consistent with Li's research (Li *et al.*, 2012), but after 2000, precipitation increased considerably, with a linear tendency of 103.9 mm/10a ($p<0.05$). Precipitation was notably high value in 2005 and 2010, which is consistent with the years when the NDVI value was high. The above analysis shows that vegetation growth in the TRHR is strongly influenced by rainfall. Around 2007, the precipitation exhibited mutation (reliability value is 0.05). In addition, the stations to the south of the TRHR revealed a tendency of decrease in rainfall. Apart from the Nangqian, Yushu, Tongren, and Banma stations, all stations reveal the mutation in the precipitation, with a period of the early 1980s and the beginning of the 21st century (Figure 9b).

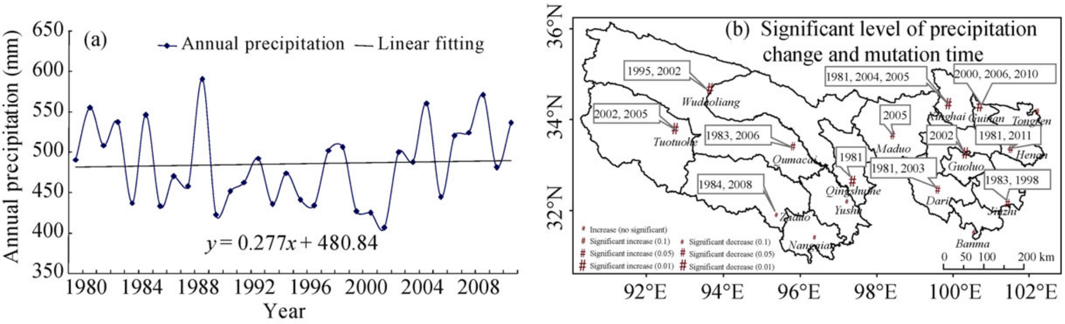

Figure 9 Analysis of precipitation changing trend (a) and mutation characteristic (b) in the TRHR during 2000-2011

Potential evaportranspiration increased slightly (Figure 10a), with a linear tendency of 7.70 mm/10a. Since the mid-1990s, under the background of slight increasing precipitation, a considerable increase in temperature led to an increase in potential evaportranspiration. This will weaken the tendency of warm-wet climate in the TRHR, which is consistent with Xu's research (Xu *et al*., 2012). Apart from the Tuotuohe and Tongren stations, all stations reveal mutation in potential evaportranspiration, with a period consistent with that of precipitation (Figure 10b).

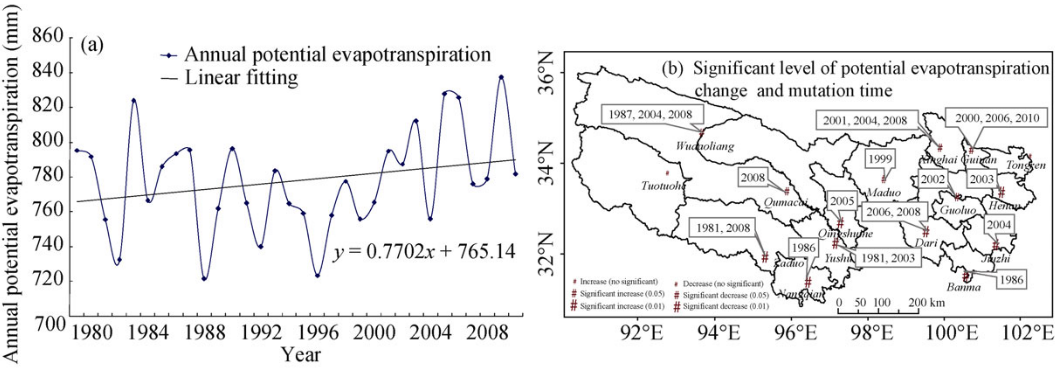

Figure 10 Analysis of potential evaporation changing trend (a) and mutation characteristic (b) in the TRHR during 2000-2011

4.3 Anthropogenic influencing factors analysis

Climate change and anthropogenic factors are two driving forces in the change in vegetation coverage. In particular, with an increase in anthropogenic activity, there has been a considerable effect on vegetation coverage change (Xin *et al*., 2007).

Stockbreeding is the main industry in the TRHR, and an increasing number of livestock is one of the key aspects affecting vegetation coverage change. The correlation between NDVI and livestock was analyzed (Figure 11), and the results show that the number of livestock decreased during 2000–2009 in the TRHR, especially after 2005, ecological protection and construction was implemented in the TRHR. Therefore, the ecological restoration project has shown clear positive effects. In contrast, NDVI increased during 2000–2009, indicating that the overlay of the decreasing number of livestock and warm–wet climate is conducive to vegetation restoration.

It should be noted that although the number of livestock was low during 2006–2009, the annual NDVI still fluctuated strongly, mainly because of climate change.

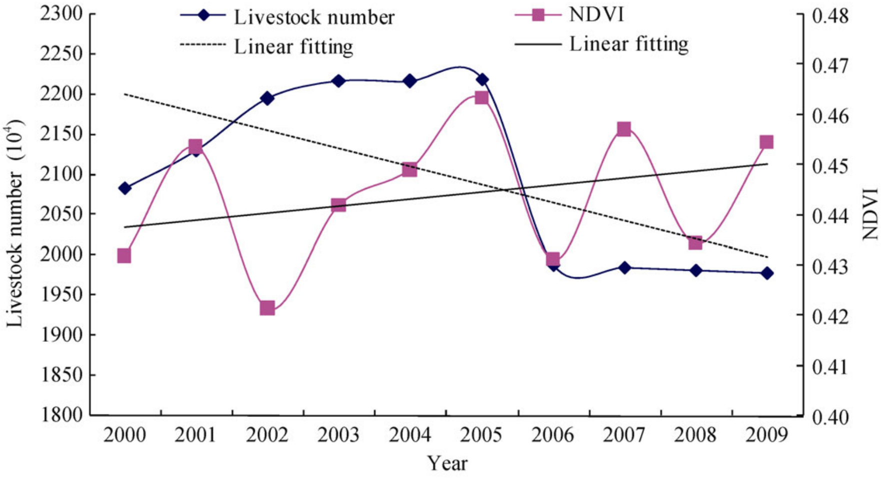

Figure 11 Change of NDVI and livestock number in the Three-River Headwaters Region during 2000–2009

5 Conclusions and discussion

5.1 Conclusions

Based on MODIS-NDVI datasets and by applying linear regression analysis, Hurst exponent analysis, and partial correlation analysis, we analyzed the trend in and driving forces of vegetation coverage changes in the TRHR in the last 12 years. Several conclusions can be drawn as follows:

(1) In the past 12 years (2000–2011), the NDVI of the study area increased, with a linear tendency being 1.2%/10a, of which the Yangtze and Yellow River source regions presented an increasing trend, while the Lancang River source region showed a decreasing trend.

(2) Vegetation coverage presented an obvious spatial difference in the TRHR, and the NDVI frequency was featured by a bimodal structure. Strong fluctuations were mainly distributed in the Nangqian, Zaduo, and Yushu counties. A relatively stable region was located in the northwest of the study area.

(3) The area with improved vegetation coverage was larger than the degraded area, being 64.06% and 35.94%, respectively, in the last 12 years, and presented an increasing trend in the north and a decreasing trend in the south.

(4) The reverse characteristics of vegetation coverage change are significant. In the future, degradation trends will be mainly found in the Yangtze River Basin and to the north of the Yellow River, while the areas with an improving trend are mainly distributed in the Lancang River Basin.

5) The response of vegetation coverage to precipitation and potential evapotranspiration has a certain time lag, while there is no such lag in the case of temperature.

6) The increased vegetation coverage is mainly attributed to the warm-wet climate change and the implementation of the ecological protection project.

5.2 Discussion

The results of the study showed increases in the temperature and precipitation over the past 12 years, which promoted the period of warm-wet climate and was conducive to vegetation restoration, consistent with the conclusions of Shao Quanqin *et al*. (2010). Increase in temperature was considered to be the key factor for the improvement of vegetation coverage (Fan *et al*., 2010). Besides, several ecological restoration projects were implemented in 2005. Therefore, the ecological environment in the TRHR will be further improved. However, the increase in temperature was significantly greater than the increase in precipitation, and hence, we can forecast that with further increase in temperature, potential evapotranspiration will rapidly increase, probably resulting in warm-dry climate in the future and inhibiting vegetation growth. Gaining a deeper understanding of the driving mechanisms and quantitative separation of the contribution rates of climate change and human activities are hot topics of research, which are currently being pursued.

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