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Climate Change and Ecological Projects Jointly Promote Vegetation Restoration in Three-River Source Region of China

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Abstract: As the source of the Yellow River, Yangtze River, and Lancang River, the Three-River Source Region (TRSR) in China is very important to China's ecological security. In recent decades, TRSR's ecosystem has degraded because of climate change and human disturbances. Therefore, a range of ecological projects were initiated by Chinese government around 2000 to curb further degradation. Current research shows that the vegetation of the TRSR has been initially restored over the past two decades, but the respective contribution of ecological projects and climate change in vegetation restoration has not been clarified. Here, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) to assess the spatial-temporal variations in vegetation and explore the impact of climate and human actions on vegetation in TRSR during 2001–2018. The results showed that about 26.02% of the TRSR had a significant increase in EVI over the 18 yr, with an increasing rate of 0.010/10 yr ($P < 0.05$), and EVI significantly decreased in only 3.23% of the TRSR. Residual trend analysis indicated vegetation restoration was jointly promoted by climate and human actions, and the promotion of human actions was greater compared with that of climate, with relative contributions of 59.07% and 40.93%, respectively. However, the degradation of vegetation was mainly caused by human actions, with a relative contribution of 71.19%. Partial correlation analysis showed that vegetation was greatly affected by temperature ($r = 0.62$, $P < 0.05$) due to the relatively sufficient moisture but lower temperature in TRSR. Furthermore, the establishment of nature reserves and the implementation of the Ecological Protection and Restoration Program (EPRP) improved vegetation, and the first stage EPRP had a better effect on vegetation restoration than the second stage. Our findings identify the driving factors of vegetation change and lay the foundation for subsequent effective management.

Keywords: Three-River Source Region of China; climate change; Enhanced Vegetation Index (EVI); vegetation change; human actions

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1 Introduction

Vegetation is the main component of terrestrial ecosystems (Song et al., 2018; Naeem et al., 2020). As the link between soil, atmosphere, and water, vegetation is of great significance to earth's energy balance, the global carbon cycle, and human welfare (Law et al., 2002; Qu et al., 2018; Zhang et al., 2020). Vegetation changes are determined by a variety of factors, of which climate and human actions have the greatest impact (Wen et al.,

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2017; Qu et al., 2018; Shi et al., 2021). On the one hand, the establishment, growth, reproduction, and survival of vegetation are directly related to the environment (Sykes, 2009). Climate change, especially changes in precipitation and temperature, greatly affect vegetation. On the other hand, the rapid development of China's economy has led to extensive and even over-exploitation of natural resources, which in turn has led to serious ecological degradation (Fu et al., 2007). Therefore, a range of projects, such as the Grain to Green Project, Wildlife Conservation and Nature Reserve Development Program, and Natural Forest Conservation Project, have been carried out by Chinese government to curb further environmental problems (Lü et al., 2011; Jiang and Zhang, 2016). Natural and human factors have direct or indirect effects on vegetation changes (Wen et al., 2017; Yang et al., 2021). Thus, it is essential to understand the vegetation dynamics and the effect of climate change and human actions on these dynamics.

Various methods have been developed to evaluate the effects of climate and human actions on vegetation, including regression models (Liu et al., 2014), threshold segmentation (Jiang et al., 2020), residual trends (John et al., 2016), and partial derivative-based methods (Qu et al., 2020). Among these, the residual trend method proposed by Evans and Geerken (2004) has been regarded as an efficient and simple method to distinguish the effects of human actions from the effects of long-term climate change (Jiang et al., 2017; Kundu et al., 2017; Zhou et al., 2018; Dagnachew et al., 2020). However, the traditional residual trend method has limitations in determining the respective contribution of climate change and human actions to changes in vegetation (Qu et al., 2020). For this reason, Sun et al. (2015) improved the residual trend method based on Xu et al. 's (2009) idea of calculating the relative effect. This method has been successfully used to quantitatively attribute the drivers of vegetation changes (Jin et al., 2020; Shi et al., 2021).

Known as the 'Chinese Water Tower', the Three-River Source Region (TRSR) is the source of the Yellow River, Yangtze River, and Lancang River and is in the hinterland of the Tibetan Plateau. It affects water supply in China and Southeast Asia (Fan et al., 2010; Zhang et al., 2017a), but the ecosystem of the TRSR is very fragile due to high altitude and harsh environment. Over the past few decades, climate warming and human disturbances, such as overgrazing, deforestation, and gold mining, have caused continuous vegetation degradation (Li et al., 2012; Zhang et al., 2017a) and have attracted widespread concern from scientists (Liu et al., 2006; 2008; Yang et al., 2006). Therefore, multiple ecological projects were implemented to protect the ecosystem, including the Hoh Xil National Nature Reserve (established in 1997), TRSR National Nature Reserve (established in 2003), and the Ecological Protection and Restoration Program (EPRP) (implemented in 2005) (Zhu et al., 2015).

As one of the most important areas, the TRSR has been a focus of recent research (Liu et al., 2014; Zhang et al., 2016; Huang et al., 2018). Although some studies have found that vegetation has recovered after the implementation of the first stage of the EPRP (2005–2012), the vegetation in some areas remains significantly degraded (Shen et al., 2018; Xu et al., 2018). Therefore, continuous monitoring of vegetation is invaluable for assessing environmental changes in this area. Also, the increasingly wet and warming climate was once thought to be the main driver of ecological restoration in the first stage of the EPRP (Shao et al., 2016; Huang et al., 2019), so additional study is needed to investigate to what extent the ecological projects have driven restoration during the implementation of the second stage of EPRP (after 2012). Here, we analyzed the vegetation dynamics of TRSR from 2001 to 2018 and evaluated the effect of climate and human actions on vegetation. Firstly, we estimated the spatial-temporal variations in vegetation and climate factors using linear regression analysis. Then, we calculated the respective contribution of climate and human actions in vegetation restoration/degradation areas by residual trend analysis. Finally, we explained the relationship between vegetation, temperature and precipitation based on partial correlation analysis and further analyzed the effect of ecological projects on vegetation. In this study, we try to answer the following questions: 1) Have the main factors driving vegetation growth changed with changes in climate and the implementation of ecological projects in recent years? 2) What are the respective contributions of climate change and human actions in vegetation restoration and degradation areas? Our results provide suggestions for subsequent vegetation management and restoration.

2 Materials and Methods

2.1 Study area

The TRSR is situated in the south of Qinghai Province (31°39′N–36°12′N, 89°45′E–102°23′E), China, covering an area of approximately 0.36 million km^2. The Yellow River Basin (YRB), Yangtze River Basin (YARB), and Lancang River Basin (LRB) account for 39.0%, 43.2% and 17.8% of the TRSR, respectively (Fig. 1a). There are 16 counties and one township in this region, and about 660 000 people live here (Huang et al., 2019). TRSR is the largest alpine wetland ecosystem in the world, and is rich in rivers, lakes, snow mountains, and glaciers (Jiang et al., 2016). It has an annual precipitation range of 262.2 to 772.8 mm, and an annual average temperature range of −5.6°C to −3.8°C (Zhang et al., 2017a). TRSR is an ecologically sensitive area due to its high altitude (2583–6824 m) (Fig. 1b) (An et al., 2017). Permafrost is distributed widely in this region, covering more than 75% of the area (Jiang and Zhang, 2016). Grassland accounts for 65.37% and is the main ecosystem of the TRSR (Liu et al., 2008). Due to the limitation of climate and topography, the grassland ecosystem is very fragile and can be easily damaged if used improperly (Fan et al., 2010).

2.2 Data

2.2.1 Satellite data

Remote-sensed vegetation indices enable us to monitor and analyze long-term and large-scale changes in vegetation. The Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) has been used widely to estimate vegetation changes (Setiawan et al., 2014; De Beurs et al., 2015; Zhang et al., 2017b). EVI uses MODIS surface reflectance data in the blue, red, and near-infrared spectral bands that have been corrected for molecular scattering, ozone absorption, and aerosol as its input (Huete et al., 2002; Zhou et al., 2014; Didan, 2015b). The blue band removes residual atmospheric contamination caused by smoke and sub-pixel thin clouds, and feedback adjustment is used to minimize changes in the canopy background and maintain sensitivity over dense vegetation conditions (Zhou et al., 2014; Didan, 2015b). Here, we used monthly EVI with a spatial resolution of 1 km from 2001 to 2018 from the MOD13A3 product (https://search.earthdata.nasa.gov/search). MOD13A3 monthly products are obtained by using the weighted time average of MOD13A2 products with low cloud cover, low viewing angle, and the highest EVI value in the month (Didan, 2015a; Didan, 2015b). The TRSR required two scenes to cover its entire area, thus we used a total of 432 images over 18 yr. Then, MODIS Reprojection Tool (MRT) is used to satellite image resample and mosaic, and EVI monthly data is converted into annual data using ArcGIS software for the following analysis.

2.2.2 Climate data

We used mean annual precipitation and temperature data from 50 standard meteorological stations in TRSR and its surroundings during 2001–2018, which were obtained from China Meteorological Data Service Center (CMDC, http://data.cma.cn). Through the spatial inter-

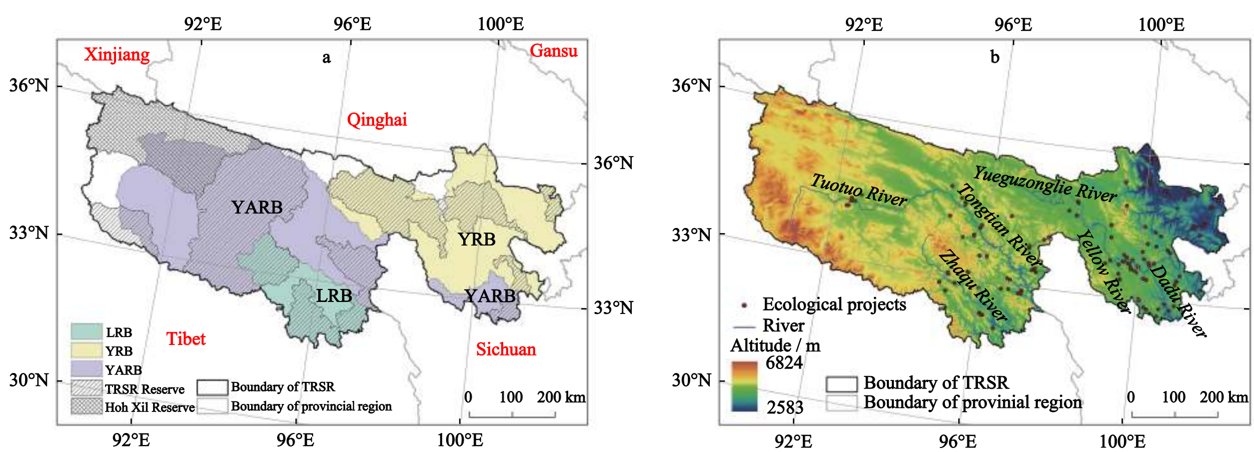

Fig. 1 Three-River Source Region (TRSR) and its nature reserves (a) and the elevation of TRSR and the distribution of ecological restoration projects (such as 'Black Beach' management, rodent control, returning grazing land to grassland) (b). YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

polation program ANUSPLIN (Hutchinson and Xu, 2013), we interpolated the meteorological data into 1 km resolution to match the resolution of the MODIS EVI data.

2.2.3 Elevation data

The Digital Elevation Model (DEM) of 90 m resolution was downloaded from the Chinese Academy of Environmental Science data center (https://www.resdc.cn/).

2.3 Methods

2.3.1 Linear regression analysis

The interannual trends of vegetation parameters and climate factors are evaluated by linear regression analysis (Fensholt and Proud, 2012; Deng et al., 2019; Jahelnabi et al., 2020). The slope of the linear regression is estimated by the least square method and calculated by the following formula:

$$Slope = \frac{n\sum_{i=1}^{n} iX_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} X_i}{n\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (1)$$

where X_i is the value of the variable in the ith year; n is the number of years. When $Slope > 0$, the variable exhibits an increasing trend over time, otherwise it exhibits a decreasing trend.

T test is used to test the significance of the trend:

$$t = \frac{r\sqrt{n-q-1}}{\sqrt{1-r^2}} \quad (2)$$

where t is the t-test value; r is the correlation coefficient; n is the sample size; q is the number of independent variables. The trend is significant when t is larger than the critical value, otherwise it is not significant.

2.3.2 Partial correlation analysis

In a complex geographic system, the change of one element will inevitably lead to the change of other elements. Partial correlation analysis is employed to eliminate the influence of the third variable when analyzing the correlation between two variables (Xu, 2002). Vegetation is largely affected by temperature and precipitation, and the correlation between them is often assessed by partial correlation analysis (Wen et al., 2017; Deng et al., 2019). The partial correlation coefficient is calculated as:

$$r_{xy\cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}} \quad (3)$$

where $r_{xy,z}$ is the partial correlation coefficient between variables x and y by eliminating the influence of variable z. $r_{xy,z} > 0$ means there is a positive correlation between x and y, otherwise it is a negative correlation. r_{xy}, r_{xz}, r_{yz} are the correlation coefficients between variables x and y, x and z, y and z, respectively. r_{xy} can be calculated by:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (4)$$

where x_i and y_i are the values of x and y in the ith year; $\bar{x}$ and $\bar{y}$ are the average values of x and y in n years.

2.3.3 Residual trend analysis

Vegetation changes caused by climate and human actions are often distinguished by residual trend analysis (Evans and Geerken, 2004; Geerken and Ilaiwi, 2004; Herrmann et al., 2005; Chu et al., 2019). This method assumes that the growth of vegetation depends on the climate. After removing the climate influence, the vegetation change is considered to be caused by human actions (Wessels et al., 2007). Using EVI as the dependent variable and climate factors as independent variables to acquire a multiple linear regression equation, then the predicted EVI (EVI_{pre}) can be calculated from the equation to represent the impact of climate factors on EVI.

$$EVI_{pre} = a \times Tem + b \times Pre + c \quad (5)$$

where Tem represents temperature, Pre represents precipitation; a and b are the regression coefficients between EVI and temperature, and between EVI and precipitation; c is a constant.

The impact of human actions on EVI is represented by residual, which is the difference between the observed EVI and the predicted EVI. The formula is as follows:

$$EVI_{res} = EVI_{obs} - EVI_{pre} \quad (6)$$

where EVI_{obs}, EVI_{pre} and EVI_{res} refer to observed EVI, predicted EVI and residual EVI, respectively.

The slopes of EVI_{obs}, EVI_{pre} and EVI_{res} are calculated according to Formula 1. Then, using Sun et al.'s (2015) approach (Table 1), the respective contribution of climate change and human actions to vegetation change is estimated.

Table 1 A method to assess the respective contribution of climate change and human actions to vegetation change (Sun et al., 2015)

Vegetation trend	Predicted and residual		Relative contribution/%		Explanation
	$Slope_{pre}$	$Slope_{res}$	Climate change	Human actions	
Increase ($Slope_{obs} > 0$)	> 0	> 0	$\frac{Slope_{pre}}{Slope_{obs}} \times 100$	$\frac{Slope_{res}}{Slope_{obs}} \times 100$	Vegetation restoration is induced by climate and human actions
	> 0	< 0	100	0	Vegetation restoration is only induced by climate
	< 0	> 0	0	100	Vegetation restoration is only induced by human actions
Decrease ($Slope_{obs} < 0$)	< 0	< 0	$\frac{Slope_{pre}}{Slope_{obs}} \times 100$	$\frac{Slope_{res}}{Slope_{obs}} \times 100$	Vegetation degradation is induced by climate and human actions
	< 0	> 0	100	0	Vegetation degradation is only induced by climate
	> 0	< 0	0	100	Vegetation degradation is only induced by human actions

Notes: $Slope_{obs}$, $Slope_{pre}$, and $Slope_{res}$ are the slopes of EVI_{obs}, EVI_{pre}, and EVI_{res}, respectively

3 Results

3.1 Spatio-temporal changes in vegetation dynamics during 2001–2018

The spatial distribution of EVI is shown in Fig. 2a. The average EVI in TRSR from 2001 to 2018 was 0.14, and exhibited an increasing distribution from northwest to southeast. EVI was highest in YRB with an average value of 0.19, followed by LRB and YARB with a value of 0.18 and 0.14, respectively. Using linear regression, we determined that 74.74% of the TRSR showed an increasing trend in EVI (Fig. 2b), of which the significantly increased area accounted for 26.02% of TRSR, with an increasing rate of 0.010/10 yr ($P < 0.05$) (Fig. 2c), mainly concentrated in west YARB and north YRB. A significant decreasing trend in EVI covered only 3.23% of TRSR, mainly in east YARB, south YRB and northwest LRB. In addition, the EVI variations in the three source regions were calculated (Fig. 2d). The regions with a significant increase in EVI were larger in YARB (26.80%) and YRB (21.21%), but smaller in LRB (4.63%). The proportion of areas with significant decrease was small in all three source regions. Thus, the vegetation has begun to recover in TRSR, but degradation still exists.

3.2 Climate change trends during 2001–2018

The temporal variations in temperature and precipitation are shown in Fig. 3. During the 18 yr, the temperature and precipitation in TRSR increased by 0.43°C/10 yr ($P < 0.05$) and 37.43 mm/10 yr, respectively. The spatial distribution of temperature and precipitation (Fig. 4) in TRSR gradually increased from northwest to southeast. During 2001–2018, the temperature of 92.70% of the TRSR had an increasing trend, of which 55.04% of TRSR showed a significant increase, mainly in most areas of YARB and YRB. The area where the temperature decreased significantly only accounted for 0.75% of TRSR. The precipitation in 94.57% of the study area showed an upward trend, and only 5.43% of the area showed a downward trend. The precipitation trend in the regions that passed the significance test all increased, accounting for 10.09% of the TRSR, mostly concentrated in the west YRB.

3.3 Relative contributions of climate change and human actions to vegetation change

Based on the methods in Table 1, we found that in areas where EVI significantly increased, the average relative contributions of climate change and human actions were 40.93% and 59.07%, respectively (Fig. 5). In areas where EVI significantly decreased, the average relative contribution of climate change was 28.81%, while that of human actions was 71.19%. The restoration of vegetation was jointly promoted by climate and human actions, and human actions made greater contribution, while the degradation was mainly induced by human actions.

The impacts of climate and human actions on vegetation vary from region to region. Increased EVI primarily caused by climate change (relative contribution > 50%) was distributed in central YARB and west YRB, covering 34.23% of the total restored areas. Human-induced (relative contribution > 50%) increased EVI ac-

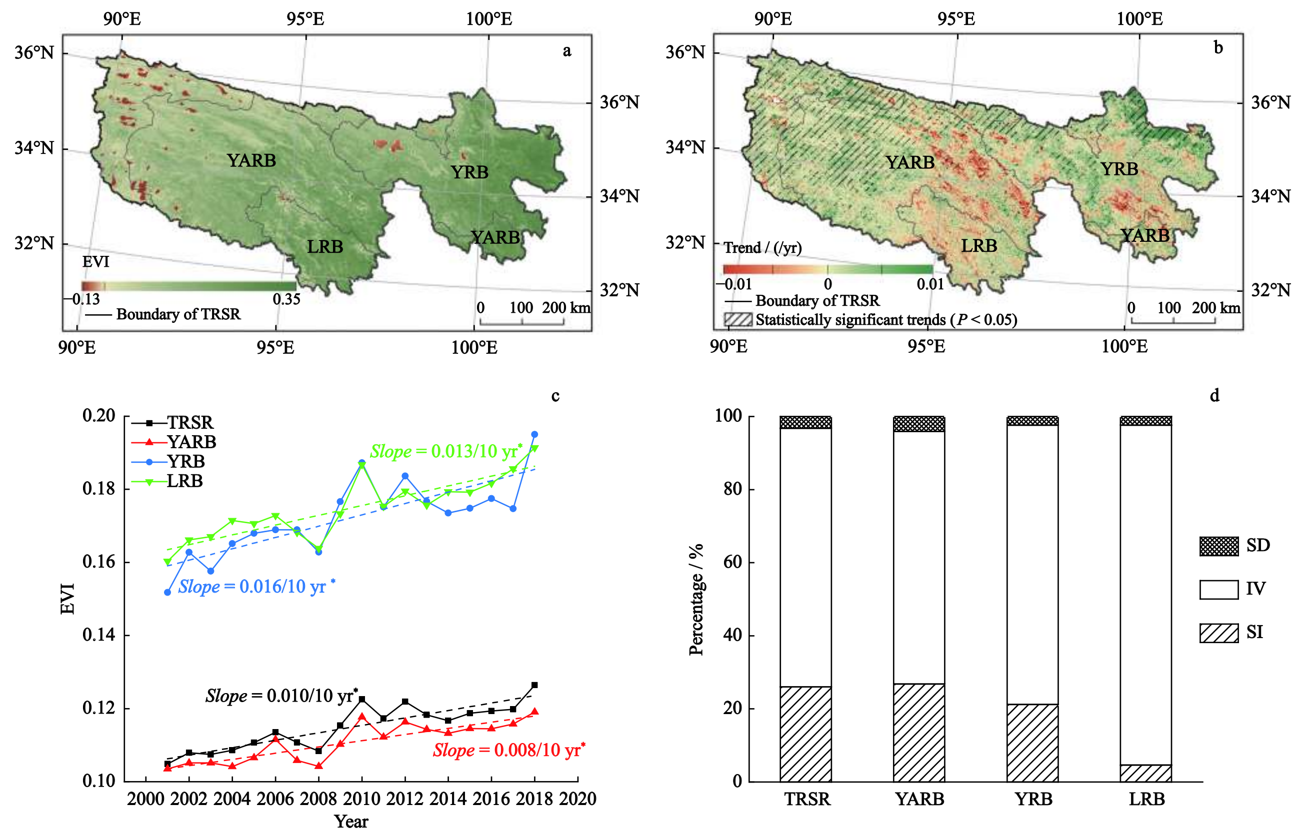

Fig. 2 Trends in Enhanced Vegetation Index (EVI) in Three-River Source Region of China from 2001 to 2018. (a) spatial distribution of annual mean EVI; (b) spatial distribution of trends of EVI ; (c) interannual change trend in EVI in areas where EVI has significantly increased (* $P < 0.05$); (d) area percentages of changes in EVI in each river source. SI, significant increase; IV, insignificant variation; SD, significant decrease; YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

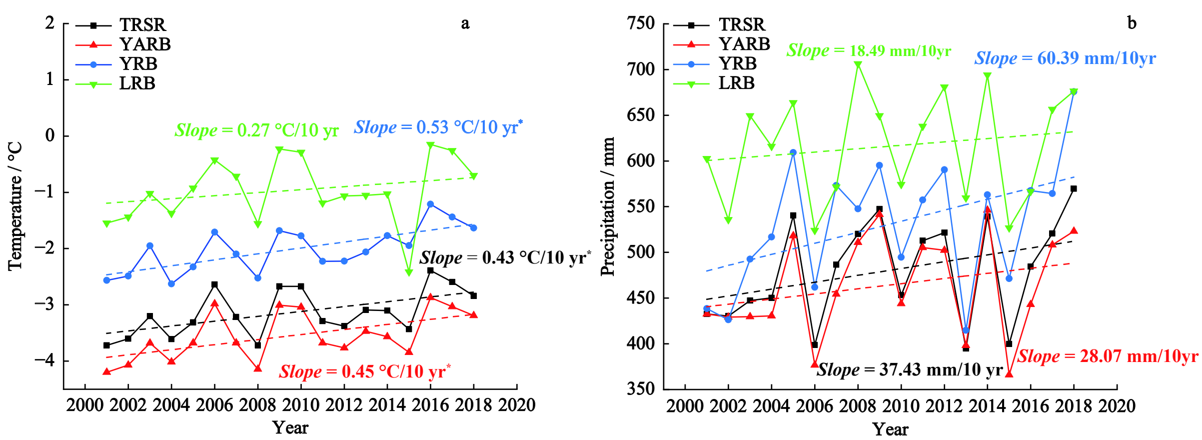

Fig. 3 Interannual change trend in annual mean temperature (a) and mean annual precipitation (b) in Three-River Source Region of China during 2001–2018 (* $P < 0.05$). YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

counted for 65.84% of the total restored areas, mainly in west YARB, northeast YRB, and southeast LRB. Areas where climate change dominated decreased EVI (relative contribution > 50%) accounted for 17.23% of the total degraded regions, which were mainly scattered in east YARB, while those mainly induced by human actions (relative contribution > 50%) accounted for 82.79% and were mainly distributed in east YARB, south YRB, and northwest LRB. Therefore, the improvement of vegetation in central YARB and west

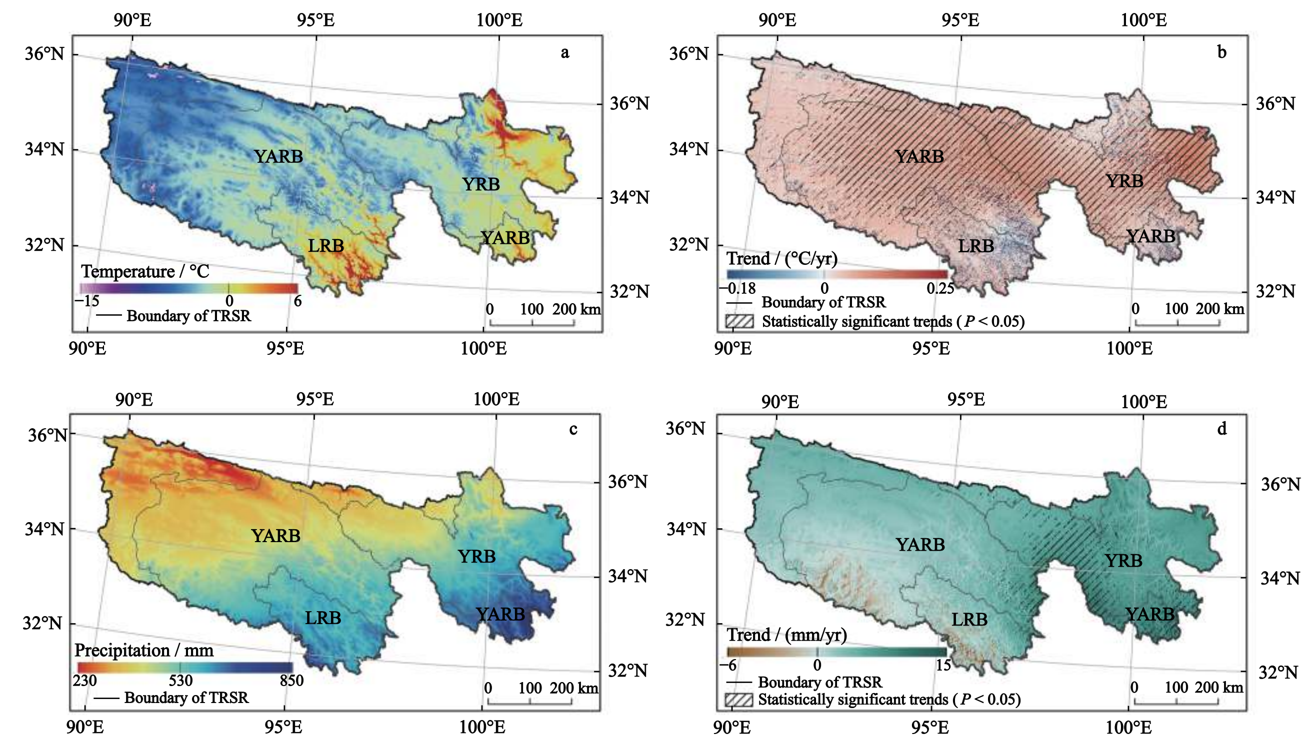

Fig. 4 Annual mean temperature (a), mean annual precipitation (c) and their trends (b, d) in Three-River Source Region of China during 2001–2018. YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

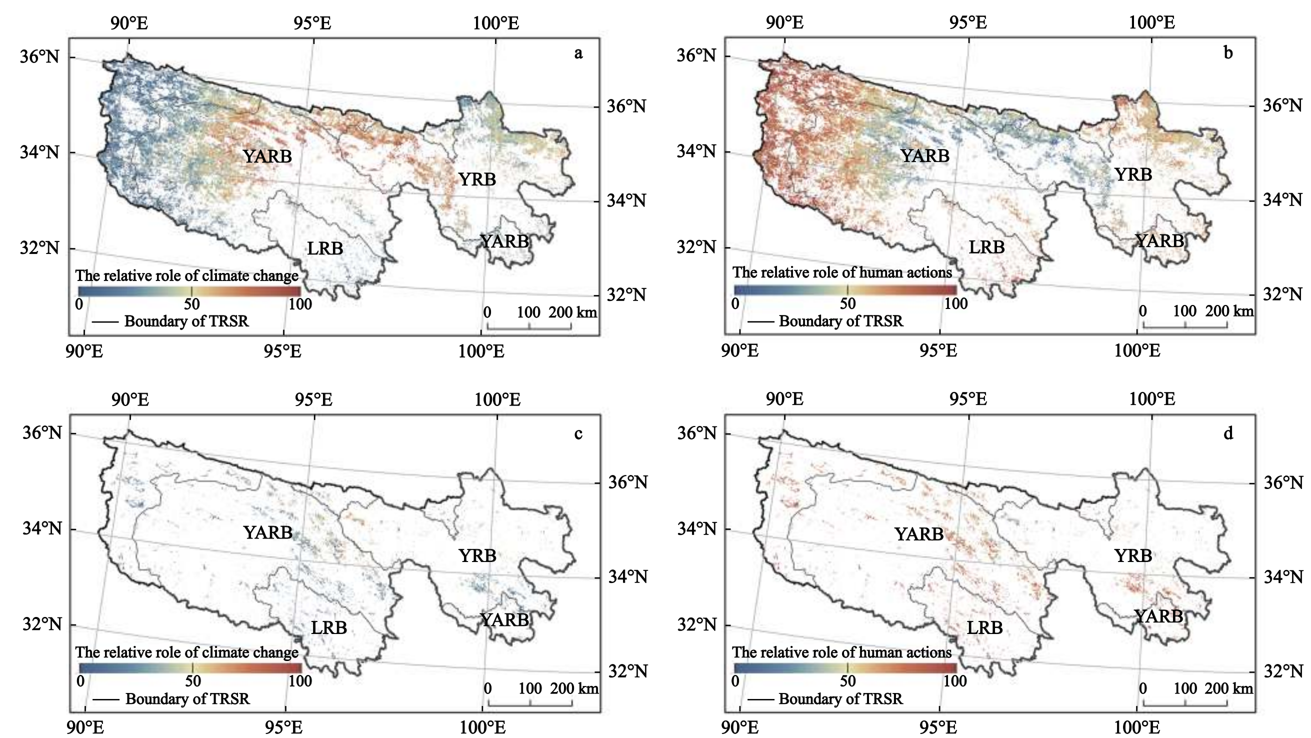

Fig. 5 Respective contribution of climate change and human actions in areas with significant increases in Enhanced Vegetation Index (EVI) (a, b) ($P < 0.05$) and areas with significant decreases in EVI (c,d) ($P < 0.05$) in Three-River Source Region of China from 2001 to 2018. YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

YRB was mainly caused by climate, while in west YARB, northeast YRB, and southeast LRB, vegetation improvement was mainly caused by human actions. Vegetation degradation in most areas of the TRSR was mainly caused by human actions.

3.4 The relationship between vegetation variation and climatic factors

We determined the effects of temperature and precipitation on vegetation growth through partial correlation analysis. In TRSR, there was a significant positive correlation between EVI and temperature (r = 0.62, P < 0.05), but no significant negative correlation with precipitation during 2001–2018 (Table 2). This correlation can also be observed in YARB and LRB. In YRB, EVI was not significantly related to temperature and precipitation. Thus, we concluded that vegetation in TRSR was greatly affected by temperature.

The maps of the partial correlation coefficients (Fig. 6) showed that the relationship between temperature and EVI was mainly positive in 82.20% of the study area, and this positive correlation was significant in west YARB and YRB and north LRB and covered 19.36% of the TRSR. Approximately 17.80% of the study area had a negative relationship between temperature and EVI, but this relationship was significant for only 0.67% of the TRSR, which was scattered in east YARB and YRB. Positive partial correlations between EVI and precipitation were observed in 53.86% of the TRSR, of which the significant positive correlation area accounted for about 6.94% of the TRSR, which was mainly concentrated in east YARB, north YRB, and south LRB. Negative partial correlations between precipitation and EVI

Table 2 Partial correlation coefficients between Enhanced Vegetation Index (EVI) and temperature and precipitation in Three-River Source Region of China from 2001 to 2018 (* P < 0.05)

Region	Partial correlation coefficient	
	EVI and temperature	EVI and precipitation
TRSR	0.62*	−0.12
YARB	0.66*	−0.21
YRB	0.35	0.12
LRB	0.57*	−0.31

Notes: YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

covered 46.14% of the TRSR, with a significant negative correlation covering 3.32% of the study area. As a result, vegetation growth in western YARB and YRB and northern LRB was positively correlated with temperature, while in eastern YARB, northern YRB, and southern LRB was positively correlated with precipitation.

3.5 The relationship between vegetation variation and ecological projects

The protection of vegetation is mainly carried out by establishing nature reserves and implementing ecological restoration projects. The TRSR consists of the Hoh Xil National Nature Reserve (established in 1997) and the TRSR National Nature Reserve (established in 2003) (Fig. 1a). The areas with significant changes in EVI within and outside nature reserves are compared in Table 3. From 2001 to 2018, more area had increased EVI in nature reserves than outside of the reserves, 61.92% and 38.08%, respectively, which indicated that the establishment of nature reserves promoted vegetation restoration.

The first stage of the EPRP was implemented from

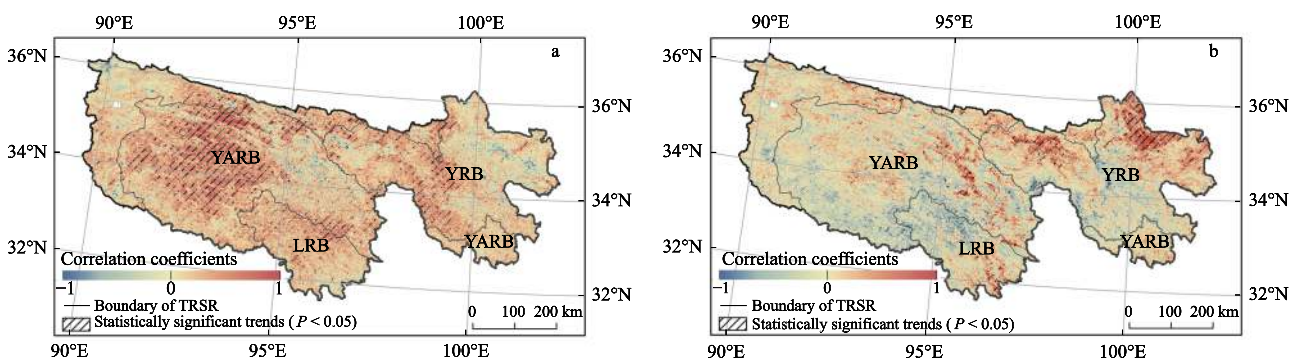

Fig. 6 Partial correlation coefficients between annual mean temperature and annual mean Enhanced Vegetation Index (EVI) (a), and between mean annual precipitation and annual mean EVI (b) in Three-River Source Region of China during 2001–2018. YARB, Yangtze River Basin; YRB, Yellow River Basin; LRB, Lancang River Basin

Table 3 The area where Enhanced Vegetation Index (EVI) was significantly increased/decreased within and outside the nature reserves in Three-River Source Region of China from 2001 to 2018

Region	EVI increased significantly		EVI decreased significantly	
	Area /km^2	Proportion /%	Area /km^2	Proportion /%
Nature reserves	57450	61.92	5571	48.36
Outside nature reserves	35328	38.08	5949	51.64

2005 to 2012, and the second stage started in 2013. We compared the areas where EVI increased significantly during 2001–2012 and 2001–2018 to determine the impact of the first and second stages of the EPRP on vegetation restoration (Fig. 7). The regions with significant increases in EVI from 2001 to 2012 accounted for 24.06% of the TRSR, and the regions with significant increases from 2001 to 2018 accounted for 26.02%. The overlap of these two regions accounted for 15.03% of TRSR, which showed that these areas continued to increase after 2012. In addition, approximately 10.99% of the TRSR had a significant increase in EVI after 2012, which indicated that the vegetation in these areas began to improve after the implementation of the second stage of the EPRP. However, about 9.03% of the TRSR did not show a significant increase after 2012. Thus, the first and second stages of the EPRP promoted vegetation restoration, and the effect of the first stage was greater than the second stage.

4 Discussion

4.1 Vegetation changes in 2001–2018

In our study, we used MODIS EVI data in TRSR from 2001 to 2018 to analyze long-term changes in vegetation. We found that 26.02% of the TRSR showed a significant increase in EVI, with an average rate of increase of 0.010/10 yr. Previous studies have shown similar changes in greenness in vegetation. Liu et al. (2014) found that during 2000–2011, NDVI in 14.77% of the TRSR increased significantly with a linear trend of 0.012/10 yr. This report indicated that more land in TRSR experienced vegetation restoration after 2011. However, there is still a risk of further degradation of TRSR, as a reduction in vegetation has also been observed in eastern YARB, southern YRB, and northwestern LRB. According to Xu et al.'s (2018) research, NDVI deteriorated in the eastern, southern, and western parts of TRSR during 2003–2014. Zhang et al. (2019) also discovered that the areas where NPP decreased were mainly located in southern YARB and LRB between 2001 and 2016. Therefore, the vegetation of TRSR has improved, but the degradation has not been fundamentally resolved and will continue for a long time.

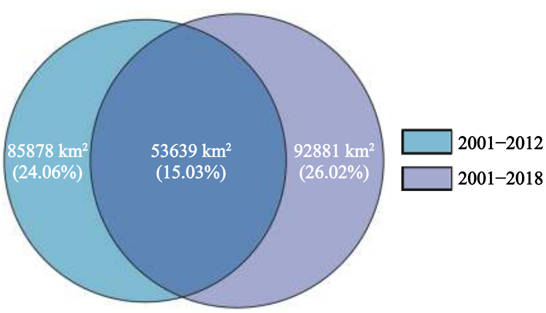

Fig. 7 The area where Enhanced Vegetation Index (EVI) increased significantly during 2001–2012 and 2001–2018 in Three-River Source Region of China

4.2 The role of climate and human actions

As the two main factors affecting vegetation change, the relative contribution of climate change and human actions is the focus of research (Chen et al., 2014; Huang et al., 2018). We found that the improvement of the vegetation in the TRSR was jointly promoted by climate (40.93%) and human actions (59.07%), while degradation was mainly caused by human actions (71.19%) during 2001–2018. Our findings are inconsistent with the results of previous studies which reported that climate was the main driver (Chen et al., 2014; Huang et al., 2018). From 2001 to 2018, the temperature and precipitation of TRSR increased by 0.43°C/10 yr ($P < 0.05$) and 37.43 mm/10 yr, respectively. Therefore, we concluded that TRSR has gradually become warm and humid since 2001, and that these environmental conditions have promoted vegetation growth. At the same time, a range of protection projects, which aim to curb ecological degradation, were carried out by the government, including the establishment of the Hoh Xil Nature Reserve and the TRSR Nature Reserve, and the implementation of the first and second stages of EPRP. Under suitable climate and ecological protection policies, the vegetation of the TRSR is gradually being restored. With the increase and expansion of environmental protection projects, and the enhancement of environmental protection awareness, the impact of human actions on vegetation restoration has become greater and has gradually exceeded the impact of climate. However, in some places, destructive human actions, such as overgrazing, illegal construction of sand quarries and brick burning factories, and over-exploitation of resources, are the main causes of vegetation degradation.

The impact of climate and human actions on vegetation varies in spatial distribution. At high elevations in west TRSR, the cold and dry climate adversely affects the growth of vegetation. However, the establishment of the Hoh Xil National Nature Reserve and the TRSR National Nature Reserve has restored the vegetation in this area. The climatic conditions in central YARB and west YRB are moderate, and the vegetation is positively correlated with temperature and precipitation, so vegetation restoration in this area is mainly caused by climate. Moreover, at low elevations in northeast YRB and southeast LRB, the improvement of vegetation has been mainly promoted by establishing TRSR National Nature Reserve and implementing ecological restoration projects. The degraded vegetation areas were mainly located on both sides of the Tongtian River, the Yellow River, and Zhaqu River. These places have low elevation and sufficient water, so grazing pressure may be more serious, which leads to the decline of vegetation. In addition, due to the implementation of the Ecological Migration Project, many people have moved out of nature reserves, which has further caused the destruction of vegetation outside the nature reserves in east YARB and south YRB. However, although northwest LRB is in the TRSR National Nature Reserve and ecological restoration projects have been carried out here, the vegetation in this area is still degraded. This may be due to the weak effect of ecological projects, and human damage to vegetation is greater than its protection.

4.3 Impact of climate factors on vegetation growth

The vegetation in the TRSR is most affected by temperature and precipitation. Hu et al. (2011) believed that the limiting effect of water on vegetation growth was greater than that of heat during 1982–2000. However, Xu et al. (2011) discovered that during 1982–2006, temperature was the main driver affecting vegetation change, and vegetation coverage will increase as the temperature rises. Zhang et al. (2016) also showed that the positive contribution of temperature to the trend of NPP from 1982 to 2012 was greater than precipitation. These two studies show the importance of temperature for vegetation growth, which was consistent with our study. Due to the low temperature, relatively sufficient rainfall, and numerous rivers, lakes, and swamps, the impact of moisture on vegetation in TRSR is much smaller than that of temperature (Xu et al., 2011; Tong et al., 2014).

The spatial distribution of the partial correlation coefficients indicated that vegetation growth in western YARB and YRB and northern LRB was positively correlated with temperature, while in eastern YARB, northern YRB, and southern LRB was positively correlated with precipitation. The difference between the optimum and actual temperature determines the effect of temperature on photosynthesis (Sun et al., 2016), so the low temperature in western YARB and YRB and northern LRB limits photosynthesis. The cold temperature also slows the mineralization rate of soil organic nitrogen and phosphorus (Sun et al., 2016; Geng et al., 2017). Therefore, the vegetation in these cold regions has improved with the increase in temperature in recent years. In addition, eastern YARB, northern YRB, and southern LRB are located at the edge of the permafrost. Thus, the soil moisture required for vegetation growth mainly depends on the precipitation due to the lack of continuous permafrost, so the increase in precipitation has contributed to the growth of vegetation in these areas. In a small part of central and southern TRSR, vegetation was negatively correlated with precipitation, indicating that precipitation was unfavorable for vegetation growth in this area. This finding was consistent with Zhang et al.'s (2016)study on the correlation between precipitation and NPP. This correlation may be because increased precipitation leads to lower temperature and radiation, thereby inhibiting the photosynthesis of plants. In addition, high precipitation increases soil erosion, which in turn reduces soil organic matter and vegetation productivity (Gao et al., 2013).

4.4 Impact of human actions on vegetation growth

With the increase in population and the development of the economy, the influence of human actions on vegetation growth is increasing. On the one hand, human actions can improve vegetation through the construction of nature reserves and implementation of ecological restoration projects. On the other hand, humans' unreasonable cultivation, overgrazing, and unrestrained exploitation of natural resources will also cause the degradation of vegetation.

Table 3 showed the positive effects of establishing nature reserves on vegetation restoration. The establishment of the nature reserve is to curb the destruction of natural habitats and the reduction of biodiversity caused by human disturbance (Gaston et al., 2008). The northwest part of TRSR is mainly located in the Hoh Xil Nature Reserve. Hoh Xil is a habitat for many rare and endangered animals and plants, with fragile ecosystems and low vegetation productivity. A series of management measures have been taken in this area: regulating herders' grazing behavior by monitoring the range of grazing and the number of livestock and wild animals, controlling traffic flow in wild animal migration areas, and establishing a cross-regional joint law enforcement mechanism with the Qiangtang Nature Reserve and Altun Mountain Nature Reserve to combat ecological violations. The implementation of these management measures has protected biodiversity and has promoted the restoration of the ecosystem of the Hoh Xil Nature Reserve. The TRSR Nature Reserve is an area with concentrated ecological types and important ecological functions. It is a nature reserve network composed of six relatively complete areas (Huang et al., 2018). The TRSR Nature Reserve combines natural restoration with ecological conservation projects to protect grasslands, forests, deserts, wetlands, rivers, and lakes ecosystems. Huang et al. (2019) found that the vegetation coverage and NPP of TRSR Nature Reserves were better than those of non-nature reserves. In addition, the average annual water retention of forest, grassland, and wetland ecosystems in nature reserves was higher than that in non-nature reserves. These positive impacts of the establishment of TRSR Nature Reserve on the restoration of the ecosystem indicate that such reserves are achieving their purpose.

The government carried out the first stage of EPRP in 2005 and implemented 22 ecological restoration projects, such as returning grazing land to grassland, rodent control, artificial rainfall, and 'Black Beach' management (PGQP, 2013; Tong et al., 2014). After the implementation of the project, the deterioration of the ecological environment of the TRSR has been curbed, vegetation coverage has increased, grazing pressure has been reduced, and the functions of soil and water conservation have improved (Jiang et al., 2016; Shao et al., 2016; Zhang et al., 2017a). Moreover, the project has also improved the living conditions of the local residents. However, the restoration of the ecosystem of TRSR is a long-term process, and the effect of the first stage of the EPRP has not yet reached the ideal state (Shen et al., 2018). Therefore, the state launched the second stage in 2013 to consolidate and expand the achievements of the first stage of EPRP. The second stage of EPRP has increased the scope and intensity of protection and was expected to end in 2020. We found that the implementation of the EPRP promoted vegetation restoration, and the promotion effect of the first stage was greater than that of the second stage. This may be because the ecological degradation of TRSR was very serious before the implementation of the first stage of the EPRP. Under the protection of human beings, vegetation recovers quickly. The second stage is implemented based on improved vegetation, so although the vegetation is still recovering, the effect is weaker than the first stage.

In some areas with frequent human actions, the contradictions between population, resources, environment, and economic development are prominent, and human damage to the ecosystem remains serious. In addition, it is worth noting that the area of the reserve is relatively small. The areas of Hoh Xil Nature Reserve and TRSR Nature Reserve are 45 000 km^2 and 152 000 km^2 respectively, accounting for only 54% of TRSR (Zhou et al., 2007; Shen et al., 2018). Further, different protection measures, the ecological environment, and the socioeconomic system will produce different ecological restoration effects (Cai et al., 2015). For areas that do not show positive effects of human actions, it may be because the restoration effects of ecological projects are not yet obvious. Therefore, we should alleviate the contradiction between man and nature and make long-term efforts to protect the ecological environment.

4.5 Challenge and future measures for ecological restoration

Due to the dual impact of climate and human actions, vegetation degradation cannot be completely controlled (Fang, 2013). On the one hand, as temperature continues to rise, potential evapotranspiration will increase rapidly, which may lead to a warm and dry climate in the future and inhibit the growth of vegetation (Liu et al., 2014). Further, rising temperature also leads to the degradation of permafrost (Wang et al., 2020), and the soil loses its ability to prevent water infiltration and thus has strong hydraulic conductivity (Song et al., 2018). The thickening of the active layer and the infiltration of soil moisture make the upper soil drier, thus inhibiting the growth of alpine meadow vegetation with shallow roots (Xue et al., 2009). Similarly, in addition to promoting vegetation growth, increased precipitation will also lower the temperature and increase rainfall erosivity and soil erosion, thereby inhibiting vegetation growth (Huang et al., 2018). On the other hand, human disturbances will continue to destroy the vegetation. For instance, more than 70% of the population of TRSR produces livestock, and although the grazing pressure has been greatly reduced after the implementation of ecological projects, grasslands are still overstocked in some areas (Zhang et al., 2017a). Furthermore, the migration of people from nature reserves will cause damage to non-nature reserves. Meanwhile, ecological migration means that herders may not only change where they live, but also their way of life. They must transform from traditional nomadism to settlement, from animal husbandry to operating in a complex, market-oriented economy (Huang et al., 2018). If eco-immigrants do not have a sustainable livelihood, many of them will return to their old way of life and continue to graze.

In short, ecological projects at this stage have promoted vegetation restoration, but there are still challenges that require sustained and long-term efforts. Policymakers should pay attention to the following points when implementing ecological projects in the future. First, because climate is an important driver of vegetation growth in TRSR, we recommend that climate control measures such as artificial rainfall should be carefully considered in ecological projects. Second, ecological projects can only be carried out effectively with the support of the local residents. In addition to providing migrant subsidies, the government also needs to provide technical training and employment opportunities to increase residents' income (Huang et al., 2018). Third, the ecosystem's response to restoration projects may lag (Tallis et al., 2008), so it is necessary to conduct frequent vegetation monitoring. Finally, vegetation degradation still exists in TRSR and the impact of ecological projects on vegetation has not reached the ideal state, so ecological projects should involve the entire TRSR and should be continuously improved (Huang et al., 2019).

4.6 Uncertainties

There are some uncertainties in residual trend method. First, this paper only used temperature and precipitation for analysis, but research showed that solar radiation or other climatic factors may also affect vegetation growth (Zhang et al., 2016; Shi et al., 2021). Also, the correlation between climate drivers and vegetation may not be a simple linear regression, so nonlinear relationships should also be considered when constructing a climate-based EVI model (Zhang and Ye, 2021). Moreover, this method assumes EVI residuals are mainly caused by human actions. Actually, the residuals not only include the influence of human factors, but also the influence of other environmental factors (Zhang et al., 2016). Nitrogen deposition and CO_2 fertilization, also affect vegetation (Xu et al., 2017; Chen et al., 2019). Therefore, the EVI residual may be partly caused by natural factors, which would cause the impact of human actions to be slightly overestimated. In the future, the residual trend method should be improved and other factors driving vegetation dynamics also need to be further analyzed.

5 Conclusions

Using EVI time series data, linear regression analysis, partial correlation analysis, and residual trend analysis, we identified the trends in vegetation variability, and analyzed the impacts of climate and human actions on vegetation change. We found that 26.02% of the TRSR showed a significant increase in EVI during 2001–2018, with an increasing rate of 0.010/10 yr (P < 0.05), and areas with significant decreases in EVI only accounted for 3.23%. In areas with significantly increased EVI, the relative contributions of climate change and human actions were 40.93% and 59.07%, respectively. In areas with significantly decreased EVI, the relative contribution of climate change was 28.81%, and that of human actions was 71.19%. The restoration of vegetation was jointly promoted by climate and human actions, and human actions made greater contribution. The vegetation degradation was mainly affected by human actions. Because the high plant water availability in TRSR, the correlation between vegetation and precipitation (r = −0.12) was less than temperature (r = 0.62, P < 0.05). By analyzing the area where EVI had changed significantly inside and outside the nature reserve and the changes in EVI after the implementation of the EPRP, we concluded that the establishment of nature reserves and the implementation of the EPRP promoted the restoration of vegetation, and the first stage of EPRP had a larger positive effect on improving vegetation than the second stage. However, due to the coexistence of vegetation restoration and degradation, future protection projects still require continuous and long-term monitoring efforts.

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