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The 30m-NDVI-based Alpine Grassland Changes and Climate Impacts in the Three-River Headwaters Region on the Qinghai-Tibet Plateau from 1990 to 2018

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Abstract: The response of long-term vegetation changes and climate change has been a hot topic in recent research. Previously, a Landsat-based fusion model was developed and used to produce a dataset of normalized vegetation index (NDVI) for the Three-River Headwater region on the Qinghai-Tibet Plateau with a spatial resolution of 30 m and the time spanning the nearly 30 years from 1990 to 2018. In this study, the NDVI was applied to an analysis of the spatial and temporal changes in the alpine grassland and the impacts from climate change using the Theil-Sen Median method and linear regression. The results showed that: (1) The regional mean NDVI was 0.39 and showed a spatial pattern of decreasing from the southeast to the northwest in the recent three decades. Among the three parks, the Lancang River Park had the highest NDVI (0.43), followed by the Yellow River Park (0.38) and Yangtze River Park (0.23). (2) An upward trending was found in the NDVI time series at a rate of 0.0031 yr^{-1} (R^2 =0.62, P < 0.01) over the whole period of 1990–2018. The increasing rate (0.00649 yr^{-1}, R^2=0.71, P < 0.01) in the latter period of 2005–2018 was nearly 2.3 times of that (0.00284 yr^{-1}, R^2 =0.31, P < 0.01) in the previous period of 1990–2005. In the latest periods, the three parks experienced rates that were 2.3 to 63 times the corresponding values in the early period. (3) The NDVI is correlated more positively with temperature than precipitation. The impacts of climate change decreased along with the coverage fraction from the higher, median and then lower levels. The climate change can explain 34% of the variability in the NDVI time series of the areas with a higher fraction of grassland coverage, while it was 31% for the median fraction and 20% for the lower fraction. This study is the first to use the 30 m NDVI dataset spanning nearly 30 years to analyze the spatial and temporal variability and climate impacts in the alpine grasslands of the Three-River Headwater region of the Qinghai-Tibet Plateau. The results provide a basis for assessments on the ecological management effects and ecological quality based on long-term baseline data with a higher spatial resolution.

Key words: Normalized Difference Vegetation Index (NDVI); the Three-River Headwater region; alpine grassland; climate change

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface air temperature in 2018 was 1.5–2 ℃ higher than that in the pre-industrial

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era (Zhai et al., 2017; Richardson et al., 2018). Global climate warming has caused significant influences on human society and the ecological environment, which has attracted considerable attention from governments and researchers (Xu et al., 2016; Zhao et al., 2020). Normalized differential vegetation index (NDVI) is an important parameter which has been widely applied to quantify grassland vegetation changes. NDVI was found to be better than other indicators in reflecting the dynamic changes of vegetation in a long time series (Zhang et al., 2020). For data availability, the most widely used data has come from MODIS, with a spatial resolution of 250 m and time period spanning 2000 to the present, which would cause difficulties in assessments requiring greater spatial detail or covering the period before 2000. Landsat-based NDVI provides a better option with its longer time span, retrospective to 1970s, and its higher spatial resolution of 30 m (Geng et al., 2014; He et al., 2015). However, the great challenges it poses are its data quality and the need to rebuild the time series, and data fusion has been developed to resolve these problems (Liao et al., 2016).

Remote sensing technology provides long time-series observation datasets for the monitoring of vegetation changes on a regional spatial scale. Remote sensing has been widely used in studies on vegetation coverage, net primary productivity and growth dynamics (Li and Shi, 2000; Xie et al., 2002; Fang et al., 2003; Chu et al., 2021; Rao et al., 2021). Many remote sensing products have been applied to explore the changes of vegetation and the impact of climate change (Li et al., 2000). However, those products are characterized as representing a long time series since 1981 but a lower spatial resolution, for example, from 250 m– 1 km for MODIS and the Global Land Surface Satellite (GLASS) Production to about 8 km for GIMMS NDVI3g (Tu et al., 1998; Yang, 2005; Zhou, 2008). Until now, no study has reported on the NDVI product with a time span of nearly 30 years and a spatial resolution of 30 m.

Therefore, this study applied a 30m NDVI product to investigate the vegetation dynamics across the Three-River Headwater region from 1990 to 2018. The data of higher spatial-temporal resolution NDVI was previously developed from a spatio-temporal data fusion model by taking advantage of the different satellite sensors of Landsat, MODIS and AVHRR, for the Three-River Headwater region from 1990 to 2018. By using these data, this study aimed to analyze the spatial-temporal changes of alpine grassland and the impacts from climate change over the past 30 years in the Three-River Headwater region on the Qinghai-Tibet Plateau. This analysis provides a data and knowledge basis for the decision-making on ecosystem restoration and protection in the future. As the first to use the 30m NDVI data product of the longer time span of nearly 30 years, this study would be fully implemented in this region.

2 Materials and methods

2.1 Study area

The Three-River Headwaters region (89°45′–102°23′E and 31°39′–36°12′N) is the source of the Yangtze, Yellow and Lancang rivers, located in the hinterland of the Qinghai-Tibet Plateau (Fig. 1). The region is considered as the water tower of China, and even of Asia, but its fragile ecosystem and rich biodiversity are very sensitive to global climate change (Ma et al., 2020). Qinghai-Tibet Plateau is currently one of the four major pastoral areas in China and one of the best natural pastoral areas in Asia. The region includes 16 counties and 1 township with the total land area of about 3.025×10^5 km^2, accounting for about 43% of Qinghai

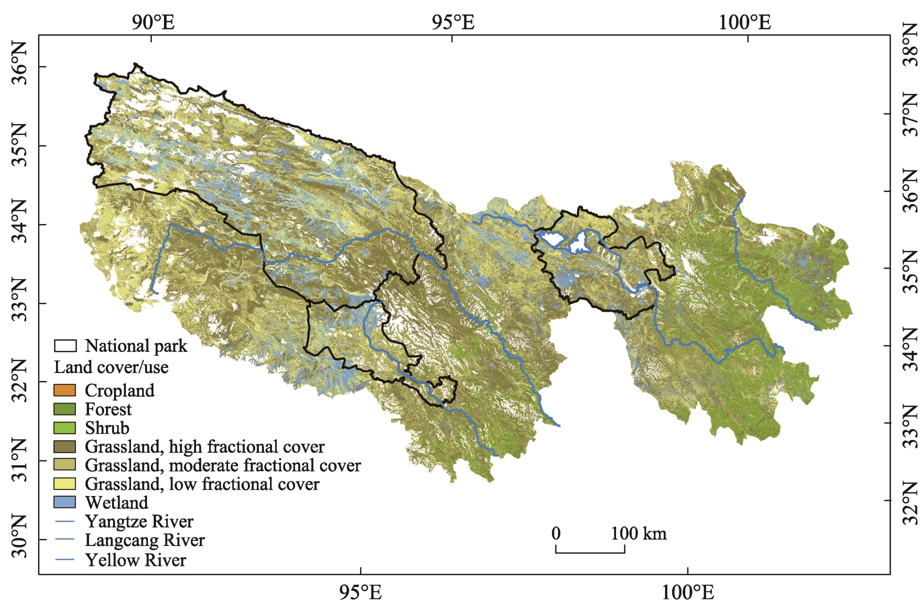

Fig. 1 Land-use and land-cover changes of the Three-River Headwaters region

Province's territorial area. Its grassland is the main ecosystem type, covering 65.4% to 69.53% of the total area (Wang et al., 2017). It has an alpine continental climate with annual mean air temperature of below 0 ℃ and annual total precipitation of 400 mm, according to the 30-year averages of the observations from 18 meteorological stations in the region (Wu et al., 2019). The temperature in the Three-River Headwater region area is relatively high from June to September, with an average maximum temperature of 10.6 ℃ (Han et al., 2020).

2.2 Data

2.2.1 NDVI data

The NDVI dataset was obtained by the data fusion model Res-CNN developed by the authors of this paper. The inputs of the model include the higher spatial resolution data of Landsat5, Landsat7 and Landsat8-OLI, and the higher temporal resolution data of AVHRR and MODIS. All of the data were collected from GEE (https://code.earthengine.google.com/). The final dataset has a temporal resolution of 8 days and a spatial resolution of 30 m, spanning the period from January 1990 to December 2018. The original data were processed on its file formation, its map projection, cropping and band calculation to obtain the NDVI dataset for the Three-River Headwaters region. The annual NDVI was derived by the method of maximum value synthesis, which can further reduce or eliminate the influences of clouds, atmospheric and solar altitude angles on the remote sensing images, and is widely used (Bao et al., 2015).

2.2.2 Land cover data

The land use raster data set with a 1 km resolution in 2010 was used, which was extracted from Landsat TM/ETM+/OLI and HJ-1 satellite remote sensing images. The land uses include Cropland, Forest, Shrub, high fractional cover grassland, medium fractional cover grassland, low fractional cover grassland, and Wetland (Liu et al., 2003; Xu et al., 2016). The data source was the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn).

2.2.3 Climate data

Meteorological data obtained from the China Meteorological Science Data Sharing Network (http://cdc.cma.gov.cn/) included precipitation and temperature from 1990 to 2018. The spatial raster data of the meteorological elements of the Three-Rivers Headwater region, with a spatial resolution of 250 m and a temporal resolution of 8 days, were obtained by spatial interpolation. The annual scale precipitation and temperature data were obtained by the 8-day meteorological data summation synthesis.

2.3 Methods

2.3.1 Theil-Sen Median method

The Theil-Sen Median method, also known as the Sen slope estimation method, is a robust non-parametric statistical trend analysis method which is often used in the trend analysis of long-term vegetation series. Two advantages of this method are that it does not require samples to follow a specific distribution and it is not disturbed by outliers. It also has a strong ability to avoid measurement errors or outlier data (Nengzouzam et al., 2019). The calculation formula is:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j-i}, \forall j > i\right) \quad (1)$$

where β is the trend of vegetation change, i and j are the time serial numbers, and x_i and x_j respectively represent the NDVI values at times i and j. If $\beta > 0$, then the vegetation coverage shows an upward trending; if $\beta < 0$, then the vegetation coverage shows a downward trending.

Considering that the ecosystem protection and restoration program in the region began in 2005 (Shao et al., 2016), we further analyzed the inter-annual trends of NDVI in the two stages of the periods covering 1990 to 2004 and 2005 to 2018, as the stages before and after the project began.

2.3.2 Linear regression method

Linear regression was used to detect the impacts of climate change on the NDVI time series in the period from 1990 to 2018. This approach was assumed to eliminate the influence of occasional abnormal factors on the vegetation growth during the research period, and to more closely reflect the evolutionary trend of vegetation cover in the long-term sequence (Li et al., 2011). The calculation formula is:

$$Y = AX + B \quad (2)$$

where A is the regression coefficient after normalization; X is the independent variable, which includes year, precipitation and temperature in our study; Y is dependent variable, which is NDVI in our study; and B is the intercept. If the significance level $P < 0.05$ then there is correlation; otherwise, there is no correlation between the independent variable and the dependent variable.

3 Results

3.1 The spatial distribution of NDVI

The spatial distribution of the NDVI is presented through its mean during the nearly 30 years from 1990 to 2018 in the Three-River Headwater region (Fig. 2). The regional mean NDVI was 0.39 in the nearly three decades period. The means in each decade were 0.36, 0.39 and 0.41 in the 1990s, 2000s and 2010s, that is, the latter two decades were higher, by 5.56% (2000s) and 13.89% (2010s), than the earlier decade (1990s). The NDVI showed a spatial pattern from higher values above 0.6 in the southeastern part of the study region to lower values below 0.1 in the northwestern part. The NDVI was mostly in the range between 0.1 and 0.4, with the area percent of 46.3% for the term of grassland; the area with high NDVI values (from above 0.4 to 0.5) accounted for 23.5%; the area with NDVI values from 0.5 to

0.6 accounted for 9.5%; and the area with NDVI values above 0.6 accounted for 5%. Among the three parks, the Lancang River Park had the highest NDVI (0.43), followed by the Yellow River Park (0.38) and Yangtze River Park (0.23). From 1990 to 2018, the NDVI of the Three-River Headwaters Region showed a fluctuating upward trend (Fig. 3). The maximum value occurred in 2018 and the minimum occurred in 2012.

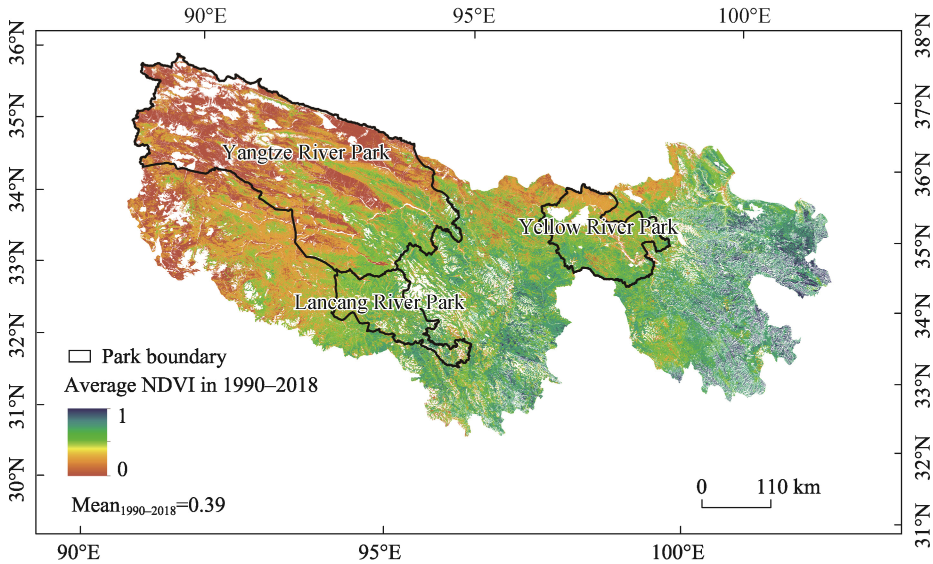

Fig. 2 The spatial distribution of average NDVI for whole period from 1990 to 2018 in the Three-River Headwaters region

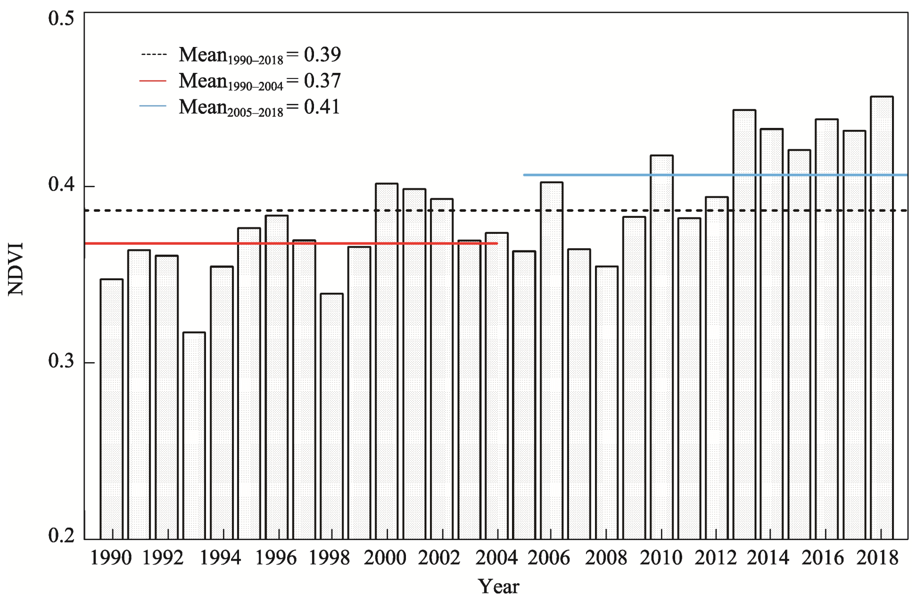

Fig. 3 Interannual trends of NDVI from 1990 to 2018 in the Three-River Headwaters region

Table 1 The frequency of the mean NDVI from 1990 to 2018 in the Three-River Headwaters region

NDVI	Area (km^2)	Percentage (%)
< 0.1	1410.9	15.7
0.1–0.4	3155.8	46.3
0.4–0.6	2249.3	33.0
> 0.6	340.8	5.0
Total	6816.07	100

3.2 The inter-annual changes in NDVI

The regional mean annual NDVI showed an increasing trend in the study region for the period from 1990 to 2018, as shown in Fig. 4 and Fig. 5. The increasing trend showed a rate of 0.0031 yr^{-1} (R^2 =0.62, P < 0.01) in the whole period. The ecological protection construction project was implemented in 2005, and the increasing rate (0.00649 yr^{-1}, R^2 = 0.71, P < 0.01) in the latter period of 2005–2018 was nearly 2.3 times that in the previous period of 1990–2005

(0.00284 yr^{-1}, $R^2 = 0.31$, $P < 0.01$). Among the three parks (Fig. 4b), the Lancang River Park had the fastest rate of increase (0.0178 yr^{-1}, $R^2 = 0.63$, $P < 0.01$) in NDVI in the latest period from 2005 to 2018, while it had the slowest rate of increase (0.00017 yr^{-1}, $R^2 = 0.02$, $P < 0.05$) in the early period from 1990 to 2005. However, the latest period showed rates that were 2.3 to 63 times the corresponding rates in the early period in either the three parks or in the whole region.

The degree of NDVI change in the Three-River Headwaters region was examined using the Theil-Sen Median. The results of NDVI changes in the grasslands of the Three-River Headwaters region can be seen in Fig. 6. The overall grassland in the Three-River Headwaters region showed a slight improvement from1990 to 2018, while local degradation of grassland occurred at various places in the Three- River Headwaters region, but the degraded area was small.

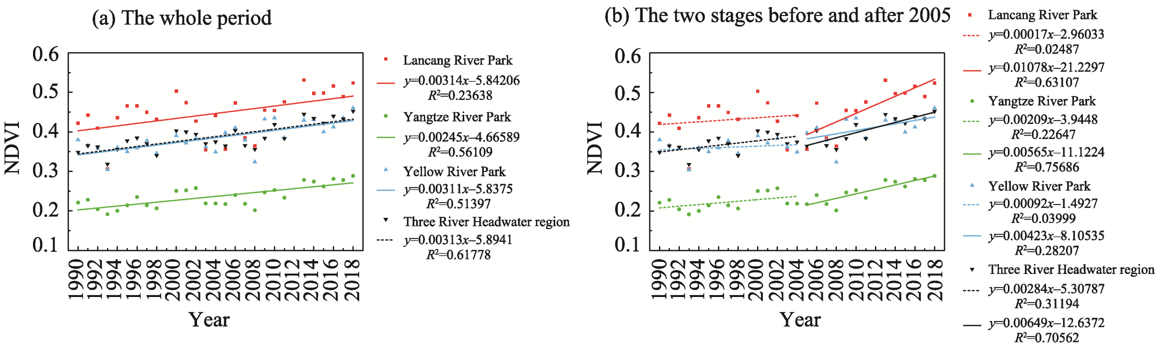

Fig. 4 Interannual changes of NDVI and its linear regression for the whole period (a) and the two stages (b) before and after 2005 in the period from 1990 to 2018 in the Three-River Headwaters region on Qinghai-Tibet Plateau

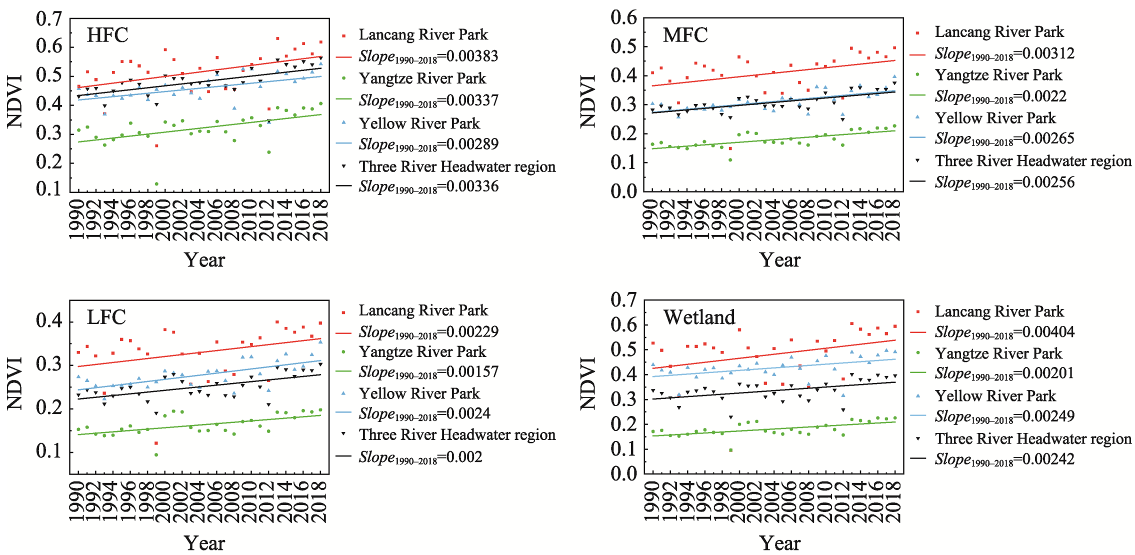

Fig. 5 Interannual changes of NDVI for the grassland with higher, median and lower coverage fractions of the wetland in the period from 1990 to 2018 in the Three-River Headwaters region

Note: The abbreviations HFC, MFC and LFC are for higher, median and lower fractions of grassland coverage, respectively.

3.3 Climate change and their impacts on NDVI

3.3.1 Climate change

The climate change were analyzed firstly based on the inter-annual changes and trends in annual total precipitation and annual mean air temperature. A warming wetting climatic change was found for the whole region (Fig. 7) and for the areas with the different fractions of grassland coverage (Fig. 8) in the study region based on the data for the period from 1990 to 2018. The annual total precipitation varied from a minimum value of 402.547 mm in 2015 to a maximum value of 590.19 mm in 2009, with an average of 482.72 mm. Among the three parks, the Lancang River Park has the largest annual precipitation but the smallest increasing trend of 18.5 mm per ten years ($R^2 = 0.053$, P=0.067), while the Yangtze River Park has the smallest annual precipitation but the largest increasing trend of 30.0 mm per ten years ($R^2 = 0.27$, P <0.01). In the comparison among different grassland coverage fractions, the increasing rates of precipitation were almost the same, all within the range from 26.4 mm (the lower fraction of grassland coverage) to 27.2 mm per ten years (Fig. 8).

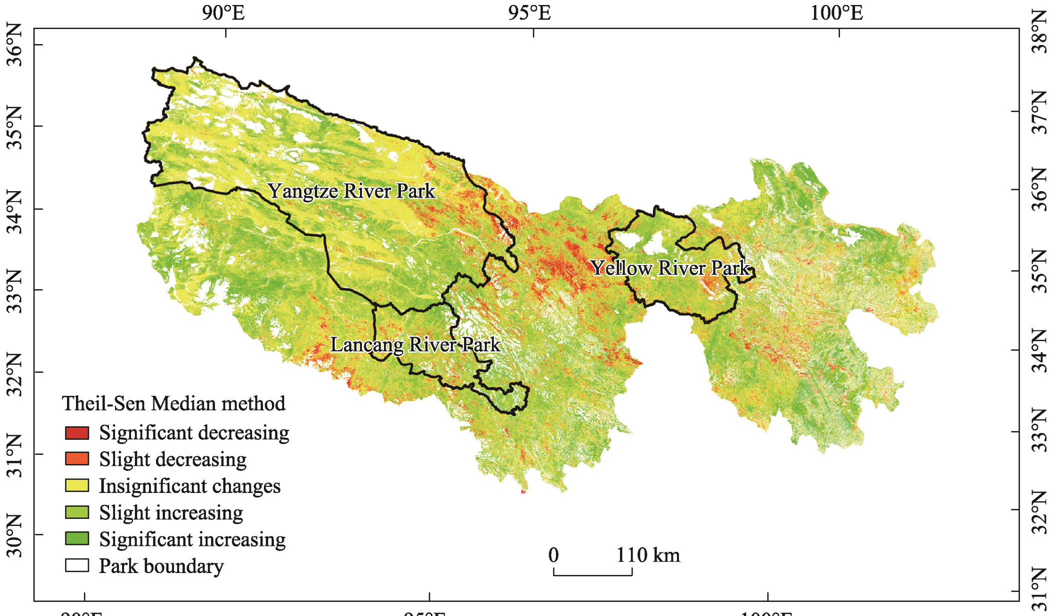

Fig. 6 The spatial pattern of the inter-annual trend of NDVI during the nearly three decade time-span in the Three-River Headwaters region

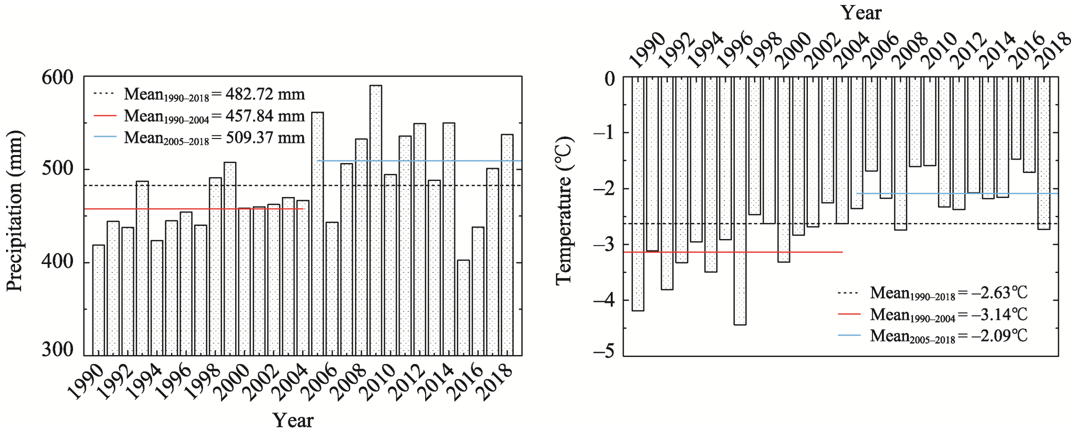

Fig. 7 Inter-annual changes in annual total precipitation and annual mean air temperature in the period from 1990 to 2018 in the Three-River Headwater region

The whole region had experienced a warming climatic change during the study period (Fig. 7 and Fig. 8). The annual mean air temperature varied in the range from the lowest of –4.44 ℃ in 1997 to the highest of –1.48 ℃ in 2016, and increased by a rate of 0.67 ℃ per ten years (R^2 = 0.57, P<0.01) as shown in Fig. 7. Among the three parks (Fig. 8), the Lancang River Park has the highest annual mean air temperature of –0.55 ℃, and the fastest increasing rate (0.07316 yr^{-1}, R^2 = 0.57, P<0.05), while the Yangtze River Park has the lowest annual mean air temperature and the slowest rate of increase (0.0556 yr^{-1}, R^2 = 0.32, P<0.05). The wetland in Lancang River Park showed the fastest warming rate (0.07563 yr^{-1}, R^2 = 0.57, P<0.05)

3.3.2 Impacts of climate change on NDVI

The impacts from climate change on NDVI were analyzed through the linear regression, with the independent variable(s) of temperature, precipitation and their combination (Fig. 9 and Table 2). The NDVI is more positively correlated with temperature than precipitation, though it was significantly correlated with each the two variables. For example, over the whole region, the temperature can explain 25.6% (P < 0.01) of variability in the NDVI while only 1.7% (P < 0.01) is explained by precipitation, and 26.6% (P < 0.01) by their combination, according to the multiple correlation coefficient (R^2) as shown in Table 2.

Among the three parks, the climate change can explain the most variability in the NDVI time series in Yellow River Park (R^2 = 0.33, P < 0.01), followed by Yangtze River Park (R^2 = 0.18, P < 0.01), and the R^2 was below 0.10 in Lancang River Park, though its change was significant based on the statistic P < 0.01.

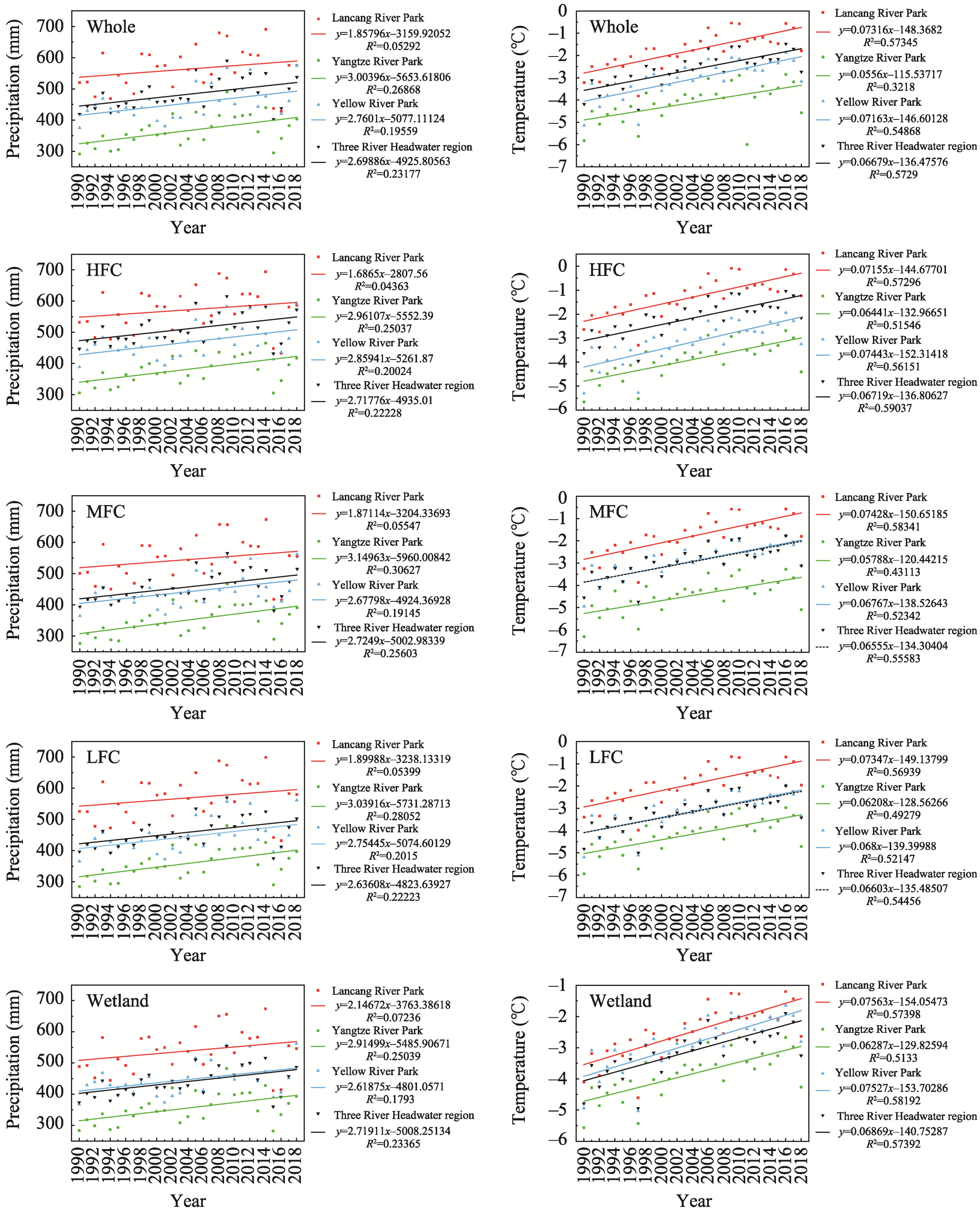

Fig. 8 Interannual changes of precipitation and air temperature for the grassland with higher, median and lower coverage fractions and the wetland in the period from 1990 to 2018 in the Three-River Headwaters region.

Note: The HFC, MFC and LFC indicate higher, median and lower fractions of grassland coverage, respectively.

The impacts of climate change decreased along with the coverage fraction from the higher to the median, and then to the lower levels (Fig. 9). For example, for the whole region, the climate change can explain 23% of the variability in the NDVI time series of the higher fraction of grassland coverage, while it was only 22% for the median fraction and 16% for the lower fraction. The wetland in Yellow River Park was more strongly impacted by climate change as indicated by the highest R^2 of 0.165, which was followed by Yangtze River Park (R^2 = 0.163).

4 Discussion

The Three-River Headwaters region, as the first national park pilots in China, is becoming a research hot spot but its vegetation changes over the longer-term, especially when using the changes in the 1990s as the baseline, is very important

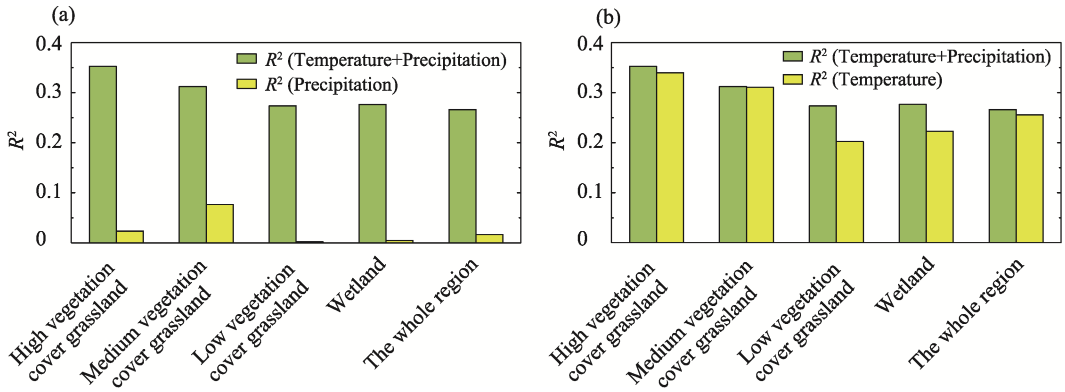

Fig. 9 Multiple correlation coefficients from the linear regression for the NDVI with the climatic factors time series from 1990 to 2018 for each of the major vegetation types in the Three-River Headwaters region.

Table 2 Correlation between NDVI and climatic factors in the Three-Rivers Headwater region

Region	LUCC	$y=a_1x_1+b_1$ (Temperature)			$y=a_2x_2+b_2$ (Precipitation)			$y=a_3x_3+a_4x_4+b_3$ (Temperature + Precipitation）				
		a_1	R^2	P	a_2	R^2	P	a_3	P	a_4	P	R^2
Lancang River Park	HFC	0.135	0.018	0.486	–0.305	0.093	0.104	0.307	0.164	–0.343	0.122	0.106
	MFC	0.306	0.094	0.106	0.134	0.018	0.189	0.269	0.225	–0.259	0.243	0.072
	LFC	0.077	0.006	0.691	–0.158	0.061	0.158	0.211	0.342	–0.272	0.223	0.062
	Wetland	0.117	0.014	0.545	–0.269	0.073	0.157	0.265	0.224	–0.311	0.155	0.089
	Whole	0.115	0.013	0.552	–0.285	0.070	0.134	0.269	0.222	–0.313	0.158	0.087
Yangtze River Park	HFC	0.341	0.116	0.071	0.069	0.005	0.721	0.404	0.051	–0.162	0.418	0.139
	MFC	0.392	0.154	0.036	0.280	0.078	0.141	0.391	0.050	0.003	0.988	0.154
	LFC	0.363	0.138	0.043	0.201	0.041	0.295	0.398	0.042	–0.100	0.631	0.140
	Wetland	0.374	0.140	0.046	0.146	0.021	0.451	0.436	0.033	–0.165	0.403	0.163
	Whole	0.341	0.116	0.041	0.136	0.019	0.481	0.323	0.054	–0.005	0.760	0.098
Yellow River Park	HFC	0.387	0.150	0.038	0.009	0.008	0.644	0.390	0.046	–0.007	0.969	0.150
	MFC	0.424	0.180	0.022	0.266	0.071	0.163	0.347	0.839	0.180	0.360	0.207
	LFC	0.405	0.164	0.029	0.236	0.056	0.219	0.333	0.100	0.171	0.388	0.188
	Wetland	0.355	0.420	0.046	–0.104	0.011	0.589	0.452	0.032	–0.219	0.283	0.165
	Whole	0.404	0.163	0.030	0.122	0.015	0.529	0.395	0.048	0.021	0.916	0.164
Three-River Head-water region	HFC	0.406	0.165	0.029	–0.114	0.013	0.555	0.540	0.009	–0.295	0.137	0.234
	MFC	0.456	0.207	0.013	0.084	0.007	0.665	0.505	0.014	–0.117	0.544	0.219
	LFC	0.363	0.202	0.043	–0.015	0.002	0.739	0.441	0.035	–0.186	0.357	0.160
	Wetland	0.304	0.223	0.023	–0.168	0.028	0.384	0.457	0.026	–0.362	0.073	0.200
	Whole	0.403	0.162	0.030	–0.076	0.017	0.397	0.518	0.013	–0.263	0.185	0.218

for assessing the relative effect with the ecological protection and restoration (Shao et al., 2016) or the ecological quality evaluation (Wang et al., 2019; He et al., 2020). In the previous study, a Landsat-based NDVI dataset was developed by the data fusion method, yielding data with a spatial resolution of 30 m and spanning the period of nearly 30 years from 1990 to 2018. This study applied the dataset to explore the changes of grassland in the Three-River Headwater region on Qinghai-Tibet Plateau, which can provide a good case study for further extending time series to the 1970s, which is the early stage of Landsat, and exploring vegetation status and changes based on a longer-term baseline.

According to such a long-term NDVI dataset, we found the NDVI was increasing in the study period from 1990 to 2018, as reported by Liu et al. (2017) and Chen et al. (2019), and the rate of increase was greater in the period after 2005 than the period before 2005 (Fig. 4). This acceleration could be attributed to the ecological protection and restoration projects implemented since 2005 and the climate change characterized as the warmer wetter trend (Wang et al., 2021). However, NDVI had decreasing trends over the two counties of Qumalai and Maduo, which would be due to the drought that occurred in those regions (Liu et al., 2014).

Another factor causing the decreasing trends of the NDVI could be human activity. A similar decreasing was found in the other three regions and the faster increase of the urbanization has been considered as the dominant reason (Liu et al., 2013).

Vegetation growth is sensitive to climatic changes in the Three-River Headwaters region, which has been extensively studied in the past 20 years (Li et al., 2011; Zheng et al., 2017; Zheng et al., 2018; Chen et al., 2020; He et al., 2020). Our results showed the NDVI was more positively correlated with temperature than with precipitation. In Mongolia and Xinjiang province, the main climate control factor of alpine grassland is precipitation (Zhou et al., 2014; Wang et al., 2021). The reasons why that study's results are different from this study are that the different regions have different vegetation types, and the dominant factors of climate are also different. In Mongolia and Xinjiang, the precipitation is relatively lacking, so the NDVI there was more stressed by temperature than precipitation, although it has been reported in previous studies that vegetation is more influenced by temperature because the precipitation is considered to be sufficient in the Three-River Headwaters region (Liu et al., 2013; Wei et al., 2015).

In this paper, a few insufficiencies remain. Firstly, there are many factors that influence vegetation growth, such as the fertilization effect of CO_2 and soil properties (soil total carbon, soil total phosphorus, and soil water content). Attention should be paid to the relationships between vegetation and those factors in future studies. Secondly, in addition to NDVI, many other vegetation indices can also reflect vegetation dynamics. It is important to note that the results of vegetation changes may be different because of the differences in the resolution and quality of the different vegetation dynamic datasets. Therefore, it is essential to make an in-depth study of whether the data reflecting vegetation dynamics changes have the same or similar results and to increase the credibility of the results. In addition, human activities may also have a greater impact on NDVI, so it is necessary to conduct a quantitative analysis of the impacts of human activities on the changes in NDVI in future research. In spite of these insufficiencies in the current study, this work has provided a prime understanding of the spatio-temporal variation characteristics of vegetation and its response to climate in the Three-River Headwaters region.

5 Conclusions

This study applied a 30-m NDVI product spanning the 30 years from 1990 to 2018, and analyzed the spatiotemporal changes of NDVI and the impacts from climate change in the Three-River Headwaters region in the past 30 years, which is the first time for such an analysis in light of the spatial resolution and time span used for this region. A warming and wetting climate change has happened in the study area in the period from 1990 to 2018. In response to the climate change, the annual NDVI showed an upward trending during the period, and in the period of 2005 to 2018, the increasing rate of NDVI was 2.3 times that in 1990–2004, however, the increase in the rate varied among the regions. This work has provided an understanding of the spatio-temporal variation of alpine grassland and its response to climate, which would be fully implemented for the further management and ecological quality assessment based on a long-term baseline for the Qinghai-Tibet Plateau.

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基于 30m 归一化植被指数的近 30 年三江源高寒草地植被时空变化及气候影响研究

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摘　要：植被长期变化及其对气候变化的响应一直是生态学研究的热点。本研究应用前期基于 Landsat 数据融合得到的青藏高原三江源区 1990–2018 年近 30 年 30 m 空间分辨率归一化植被指数（NDVI），以 Theil-Sen 中值法和线性回归，分析了近 30 年高寒草地时空变化及气候变化影响。结果表明:（1）研究区 NDVI 呈从东南到西北逐渐降低的空间格局，全区平均 NDVI 为 0.39，其中澜沧江源 NDVI 最高（0.43），其次是黄河源（0.38）和长江源（0.23）。（2）研究期间，全区 NDVI 以 0.0031yr^{-1} 的速率呈上升趋势（$R^2 = 0.62$，$P < 0.01$），后期（2005–2018 年）增长速度为 0.00649 yr^{-1}（$R^2 = 0.71$，$P < 0.01$），是前期（1990–2005 年间）速率 0.00284 yr^{-1}（$R^2 = 0.31$，$P < 0.01$）的近 2.3 倍，说明后期（2005–2018 年）植被变绿加速，且不同流域间增速在 2.3 至 63 倍间。（3）NDVI 与温度的相关性高于与降水的相关性，气候变化可解释高、中、低覆盖度草地 NDVI 年际变化的 34%、31%和 20%，从高覆盖到低覆盖草地气候变化的影响依次减小。本研究首次分析了近 30 年青藏高原三江源地区高寒草地时空变化及气候影响，为基于长时间序列数据为基准进行生态管理成效评价和草地生态质量评价，提供了较高空间分辨率和较长时间序列的数据基础，研究结果也为青藏高原高寒草地保护和恢复提供科学依据。

关键词：归一化植被指数（NDVI）；三江源；高寒草地；气候变化