



## High positive correlation between soil temperature and NDVI from 1982 to 2006 in alpine meadow of the Three-River Source Region on the Qinghai-Tibetan Plateau

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### ABSTRACT

Using satellite-observed Normalized Difference Vegetation Index (NDVI) data and Rotated Empirical Orthogonal Function (REOF) method, we analyzed the spatio-temporal variation of vegetation during growing seasons from May to September in the Three-River Source Region, alpine meadow in the Qinghai-Tibetan Plateau from 1982 to 2006. We found that NDVI in the centre and east of the region, where the vegetation cover is low, showed a consistent but slight increase before 2003 and remarkable increase in 2004 and 2005. Impact factors analysis indicated that among air temperature, precipitation, humid index, soil surface temperature, and soil temperature at 10 cm and 20 cm depth, annual variation of NDVI was highly positive correlated with the soil surface temperature of the period from March to July. Further analysis revealed that the correlation between the vegetation and temperature was insignificant before 1995, but statistically significant from 1995. The study indicates that temperature is the major controlling factor of vegetation change in the Three-River Source Region, and the currently increase of temperature may increase vegetation coverage and/or density in the area. In addition, ecological restoration project started from 2005 in Three-River Source Region has a certain role in promoting the recovery of vegetation.

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### 1. Introduction

The Three-River Source Region (TRSR), the source region of Yangtze River, Yellow River and Mekong River, is located in central part of the Qinghai-Tibetan Plateau. TRSR has a typical continental plateau climate, with cold (annual mean air temperature is about  $-0.9^{\circ}\text{C}$ ), dry, larger diurnal variation of temperature, and strong radiation. The vegetation is mainly composed of alpine meadow, alpine swamp and alpine grass. In general, soils are not developed well in this region, and soil is thin with a depth about 30–50 cm due to the impacts of high elevation and cold weather (Liu et al., 2006). The population is about 568,000 and most of the residents are Tibetan with a nomadic lifestyle. The ecosystem stability and con-

servation of biota, particularly the response of vegetation change to climate change in TRSR have attracted the attention of international scholars (Yang et al., 2006).

Global temperature is distinct increasing in recent decades (IPCC, 2007). The increasing rate of temperature in the Three-River Source Region, or on the plateau is obviously greater than other regions of the world in recent decades (Duan et al., 2006; Li and Kang, 2006; Lin and Zhao, 1996; Liu and Chen, 2000), and there may be a trend with more warming in the future (Kang et al., 2010; Liu et al., 2009). Climate warming has brought great influences on the terrestrial biosphere (Walther et al., 2002). The pronounced surface warming may have promoted vegetation growth in northern mid- and high-latitude regions in recent decades (Myneni et al., 1997; Zhou et al., 2001). Therefore, climate warming could have significant impact on the vegetation change in the Three-River Source Region.

Observations have shown grassland productivity decline, soil erosion and serious desertification in the region in recent decades (Liu et al., 2006, 2008; Yan et al., 2004; Wang et al., 2001). Some

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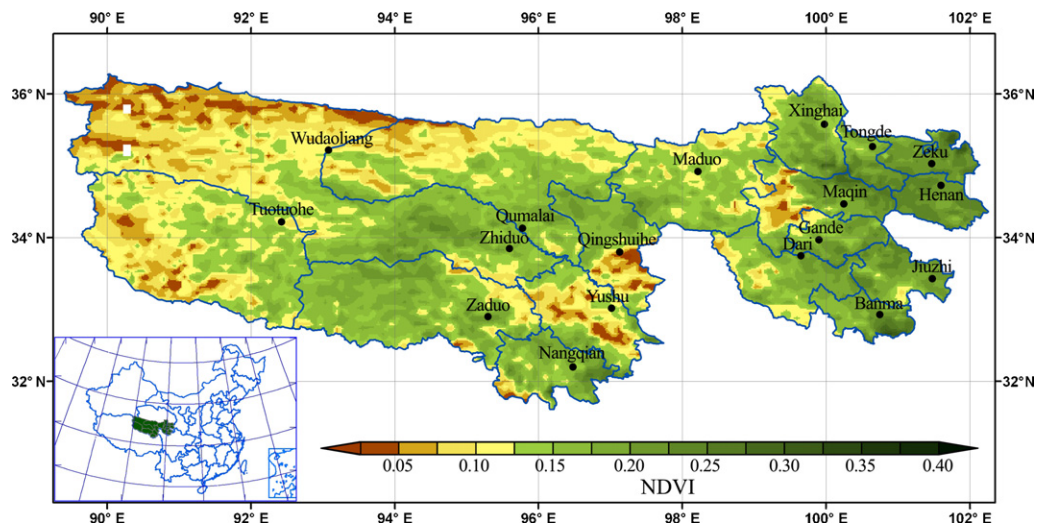


Fig. 1. The average NDVI in growing season for 1982–2006 and the locations of meteorological stations (black cycle symbols) in the Three-River Source Region.

studies report however that there is an increase trend in vegetation in some areas of the region (Zhong et al., 2010; Piao et al., 2006; Yang et al., 2006; Fang et al., 2003). The different results may be obtained at different location and size of study site since there is a significant spatio-temporal heterogeneity in the response of vegetation to climatic change in Three-River Source Region. Some studies indicate that the differences in spatial and/or temporal scale have a great influence on the results of vegetation response to climate change (Stein et al., 2001; Reginald, 1995; Furnas and Bederson, 1995). Therefore, the choice of spatio-temporal scale is important to assessing the response of vegetation to climate change and determining the key factors affecting vegetation change. In addition, the impact of human activities on vegetation change cannot be neglected, and should be taken into account in the Qinghai-Tibetan Plateau (Yang et al., 2004; Miller, 1999).

We urgently need the detailed information for the Three-River Source region since it is an ecologically vulnerable zone and also the important nature reserve. In this study, we therefore focused on the spatio-temporal variation of vegetation and its impact factors in the large nature reserve of the Qinghai-Tibetan Plateau. We are to address how the vegetation changed during the last 25 years before 2006 and what is the major determining factor for the possible changes. To avoid the influence of study site on result, the method of Rotated Empirical Orthogonal Function (REOF) was used to determine the spatial area which has the same characteristics of vegetation change.

## 2. Data and methods

### 2.1. Outline of investigated region

The Three-River Source Region is located in the south of Qinghai province, China, with a total area of 302,500 km<sup>2</sup> (31°39′–36°12′N, 89°45′–102°23′E, see Fig. 1). Most of the areas have at least 4000 m altitude and is characterized by low temperature, with annual average temperature of  $-5.4$  to  $4.2$  °C. The annual precipitation ranges from 770 mm in the southeast to 260 mm in the northwest. The vegetation coverage gradually reduces from the southeast to the northwest (Fig. 1). The ecosystems may be more frangible and sensitive to climate changes than low-elevation ecosystems due to its high elevation. Since there are more meteorological stations in the TRSR compared with other regions of the Qinghai-Tibetan Plateau, the continuous observation data can be used to better understand the response of vegetation to climate change.

### 2.2. Data

#### 2.2.1. NDVI

The Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) and processed by the Global Inventory Monitoring and Modeling Studies (GIMMS), available at <http://daac.gsfc.nasa.gov/>, was used as an indicator to monitor the vegetation activity. This dataset has taken into account of the effects such as satellite calibration, geometric correction and volcanic eruption, and reduced it preferably, especially in the field of the depressed errors that produced from satellite alternation. The original data was organized at 8 km by 8 km spatial resolution with a 15-day time interval, NDVI is generally expressed on a scale from 0.0 to 0.7 and the higher value indicates the increasing amounts of green vegetation (Pinzon et al., 2005; Pinzon, 2002; Tucker et al., 2005). The average NDVI during the growing season from May to September is considered as the indicator of vegetation growth status overall one-year in the Three-River Source Region (Xu et al., 2005; Zhang et al., 2007). Fig. 1 shows the mean NDVI climatology during the growing season from 1982 to 2006 in the TRSR.

#### 2.2.2. Observed meteorological data

The measured meteorological data was obtained from the Climatic Information Center of Qinghai Province, China, and the monthly air temperature, precipitation, wind speed, relative humidity and soil temperature at 0 cm (surface), 10 cm and 20 cm depth were collected from 18 meteorological stations (shown in Fig. 1) in the Three-Rivers Source Region from 1982 to 2006.

#### 2.2.3. Livestock numbers

Livestock numbers in Three-River Source Region was obtained from Qinghai Statistical Yearbook 1980–2006, published by Qinghai Statistical Bureau.

### 2.3. Methods

#### 2.3.1. Spatial re-sampling of NDVI

High resolution NDVI can be used to better describe the characteristics of the vegetation in local-scale, but it is not suitable for use in large-scale due to the strong high frequency noise (Schulze, 2000; Romeny, 1996). Therefore, the choice of effective resolution should be determined according to the spatial scale of study (Bestelmeyer et al., 2006; Stein et al., 2001). The Three-River Source Region covers

**Table 1**  
Correlation coefficients between time series of first eigenvector field of Rotated Empirical Orthogonal Function (REOF) of and environmental factors for whole time intervals.

Time intervals	Factors					
	$T_a$	Precipitation	Humid Index	$T_{s0}$	$T_{s10}$	$T_{s20}$
March	0.2248	0.2447	0.1031	0.6151***	0.5505***	0.5504***
April	0.0566	-0.0870	-0.1497	0.3985	0.3673	0.4227**
May	-0.0454	-0.2212	-0.2661	0.2462	0.2566	0.3672
June	-0.0294	0.0100	0.0027	0.1110	0.1114	0.1627
July	0.4474**	0.1371	-0.0800	0.5574***	0.5300**	0.5438***
August	0.6044***	0.3196	0.0276	0.5377***	0.5433***	0.5878***
September	0.4109	0.0881	-0.2400	0.5191**	0.4818**	0.4742**
October	0.1551	0.0339	-0.0445	0.5472***	0.4739**	0.4846**
April–May	0.0179	-0.2634	-0.2701	0.4125	0.3841	0.4266**
May–June	-0.0465	-0.0958	-0.1678	0.2085	0.1951	0.2910
June–July	0.2520	0.0997	-0.0597	0.4622**	0.4073	0.4345**
July–August	0.6372***	0.3230	-0.0182	0.6829***	0.6016***	0.6351***
August–September	0.5829***	0.3024	-0.0986	0.6560***	0.5919***	0.6030***
March–May	0.1168	-0.1821	-0.2384	0.5394***	0.4663**	0.4827**
April–June	-0.0039	-0.1163	-0.1957	0.3534	0.3155	0.3817
May–Jul.	0.1727	0.0220	-0.1195	0.4508**	0.3980	0.4508**
June–August	0.4975**	0.2585	-0.0101	0.6250***	0.5166**	0.5504***
July–September	0.6249***	0.3140	-0.1384	0.7162***	0.6417***	0.6568***
March–June	0.0857	-0.0833	-0.1712	0.4580**	0.4000	0.4468**
April–July	0.1726	0.0045	-0.1426	0.5306**	0.4612**	0.4921**
May–August	0.3886	0.1733	-0.0706	0.5907***	0.5040**	0.5433***
June–September	0.5317**	0.2624	-0.0964	0.6895***	0.5914***	0.6071***
March–July	0.2024	0.0300	-0.1163	0.6120***	0.5048**	0.5318**
April–August	0.3310	0.1574	-0.0683	0.6178***	0.5144**	0.5536***
May–September	0.4721**	0.1900	-0.1503	0.6666***	0.5575***	0.5865***

$T_a$  is air temperature;  $T_{s0}$ ,  $T_{s10}$  and  $T_{s20}$  are soil temperatures at 0 cm, 10 cm and 20 cm depth respectively.

\*\* Correlation coefficient at 0.05 significant level.

\*\*\* Correlation coefficient at 0.01 significant level.

about 12 longitudes with an area of above 302,500 km<sup>2</sup>, NDVI data of 8 km × 8 km had been downscaled to a dataset with resolution of 0.15° × 0.15° in this study.

### 2.3.2. Humid index

The water and heat matching is a key to vegetation variation over a region. In this study, humid index is considered as one of potential impact factors of vegetation change. It is calculated by the following equation:

$$K = \frac{R}{ET} \quad (1)$$

where  $R$  is the monthly precipitation (mm) and  $ET$  is the monthly potential evapotranspiration (mm).

$ET$  is calculated based on an improved version of dynamic model proposed by Liu and Wang (1999) as follow;

$$ET_i = \frac{22d_i(1.6 + U_i^{1/2})W_{oi}(1 - h_i)}{P_i^{1/2}(273.2 + t_i)^{1/4}} \quad (2)$$

where  $i$  is the  $i$ th month,  $d$  is the number of days in  $i$ th month,  $U_i$  is  $i$ th month average wind speed at 10 m (m/s),  $P_i$  is the mean pressure of the  $i$ th month (mb),  $t_i$  is the  $i$ th month mean air temperature (°C),  $W_{oi}$  is  $i$ th month saturated vapor pressure at  $t_i$  (mmHg),  $h_i$  is  $i$ th month relative humidity.

As a calculating method of Ecological and Meteorological Monitoring Standard recommended by China Meteorological Administration (Chinese Meteorological Administration, 2005), the  $ET_i$  calculated by Eq. (2) is much closer to actual situation in this area since it not only takes into account of the pressure, but also the potential impact caused by low temperature in high-altitude area.

### 2.3.3. REOF

The method of Empirical Orthogonal Function (EOF) analysis or Rotated Empirical Orthogonal Function (REOF) is decomposition of signal or data set in terms of orthogonal basis functions (North, 1984; Richman, 1986). It is often used in data reduction to identify a

small number of factors that explain most of the variance observed in a much larger number of manifest variables (Hannachi et al., 2007; Munoz et al., 2008). REOF analysis is a useful method for statistical analysis of large data sets and has been widely used in meteorology and climate research. REOF has obvious advantages over EOF, with a more clear meaning in distribution of geographic regions and fewer errors resulted from different sample numbers. In fact, REOF can be considered as an analysis to the loadings of rotated factors in Factors Analysis (Rencher, 2002).

There is no unified method to specify a threshold value for spatial division using REOF factor loading. According to the previous studies, the value was given as larger than 0.5 (Rosemblat et al., 2006; Collantes, 2005), while other as larger than 0.4 (Liu et al., 2003). Actually, REOF is a method for computing correlation coefficients between multi-variables, and it can transform complex relationships existed in “ $i$ ” variables into a few comprehensive factors (REOF eigenvectors) and achieve a simple structure. It can be demonstrated mathematically that the REOF factor loadings is the correlation coefficient between  $i$ th variable and  $j$ th factor (Rencher, 2002). Therefore, the threshold of 0.36 was obtained using the 0.10 level of significance test in this study (25 samples). Furthermore, at 0.05 and 0.01 level of significance test, 0.42 and 0.54 are used to distinguish the significant zone and typical zone, respectively.

Usually, many eigenvectors will be obtained from REOF decomposition, but it does not mean that all of the REOF eigenvectors have physical meaning. The validity test is particularly important when the number of spatial points in variable field is larger than that of samples. The validity test is performed by calculating the error range of eigenvalue (North et al., 1982).

### 2.3.4. Time interval combination

To examine the climatic factors affecting vegetation variation, we analyzed the relationships between average NDVI in growing season and six environmental factors (including air temperature, precipitation, humid index and soil temperature at 0 cm, 10 cm and 20 cm depth) in each time interval (Table 1). Furthermore, the

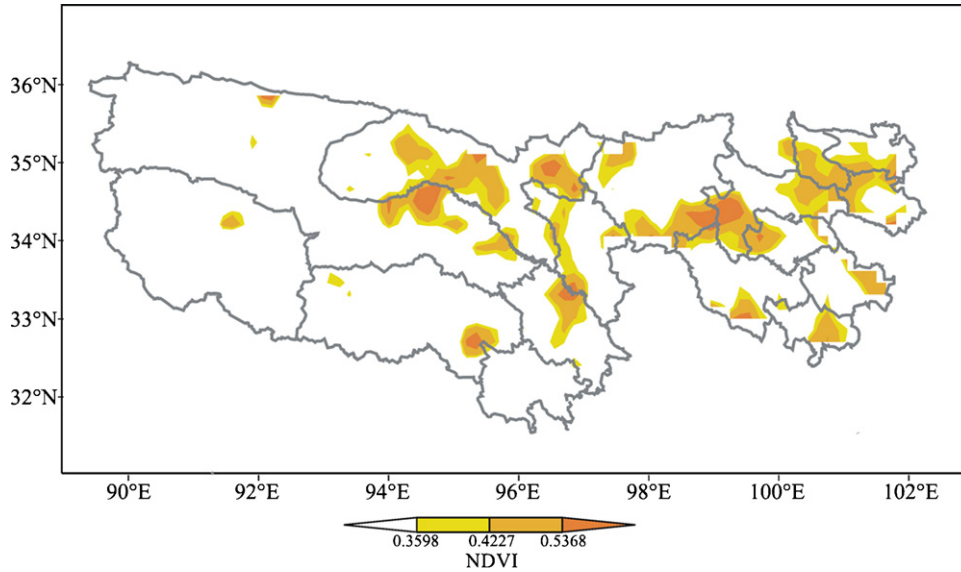


Fig. 2. The first eigenvector field of REOF (divided by a threshold of 0.36) in Three-River Source Region for 1982–2006.

response of vegetation to environmental factors with a two-month lag was assumed because the vegetation change usually lags behind environment change in the Qinghai-Tibetan Plateau (Zhong et al., 2010; Xu and Liu, 2007). In fact, the effect of climatic factors from March to September on vegetation change was considered in this study. At the same time, the average values of environment factors on the given each time interval (one-month, two-month, three-month, four-month and five-month) were calculated to analyze the effect of environment factors on the vegetation change. There are 25 time interval combinations and six climatic factors, so that the dataset is made up of 150 potential factors affecting vegetation change (Table 1).

2.3.5. Multicollinearity and dominant factors analysis

Since there are relationships among 150 potential factors to some extent, the multicollinearity may eliminate important explanatory variables in analysis, and cause different analysis results (Velleman and Welsch, 1982; Velleman et al., 1977). Step-wise regression can reduce the impact of multicollinearity among factors to a certain degree and determine the significance of each factor to given dependent variables. But the regression equation is quite easy to meet the *F*-test or correlation coefficient test when there are many dependent variables (Rencher, 2002; Harrell, 2001). Latent Root Regression (LRR), proposed by Webster and Mason (1974), takes into account the impact of dependent variables on the multicollinearity brings from original independent variables, which can reveal the relationships between independent and dependent variables. But there is no clear criterion for LRR to determine the number of available variables.

In this study, linear correlation, latent root regression and step-wise regression are used to analyze the impact of environment factors on vegetation change in sequence.

3. Results

The average NDVI data of May–September from 1982 to 2006 were collected in the Three-River Source Region, except the area with  $NDVI \leq 0.0$  (e.g., water bodies), and 1521 spatial cells in effective area are used by EOF method. The REOF eigenvector field was obtained when the varimax method of orthogonal rotation is applied to the first 14 eigenvectors with cumulative percentage of variance explained over 85%. The variance explained by first REOF

eigenvector field (REOF1) was 22.2% with an eigenvalue of 337.4, it passed the validity test by the method of North et al. (1982) since the difference (119.2) in eigenvalue between first REOF and second REOF was greater than 94.5. The results suggest that REOF1 revealed the most significant variation in vegetation in the Three-River Source Region for 1982–2006.

3.1. Spatial distribution of vegetation

Fig. 2 shows the spatial distribution of vegetation divided by a threshold of 0.36 in Three-River Source Region for 1982–2006. It covers about 22% of Three-River Source Region, and is discontinuously distributed in mid-eastern region with 34°–35°N and 94°–102°E. The mean NDVI was 0.31 from May to September, indicating that the REOF1 has relatively low vegetation coverage.

3.2. Temporal variation of vegetation

REOF1 time series shows the temporal dynamic characteristics of the vegetation change for 1982–2006 (Fig. 3). The obvious phase variation of vegetation was found in this area, and a dramatic change occurred in 2003. The vegetation appeared to remain relatively steady and slightly increased from 1982 to 2003. However, it increased rapidly from 2003, and had significant higher vegetation coverage for 2004–2006. Therefore, the temporal variation

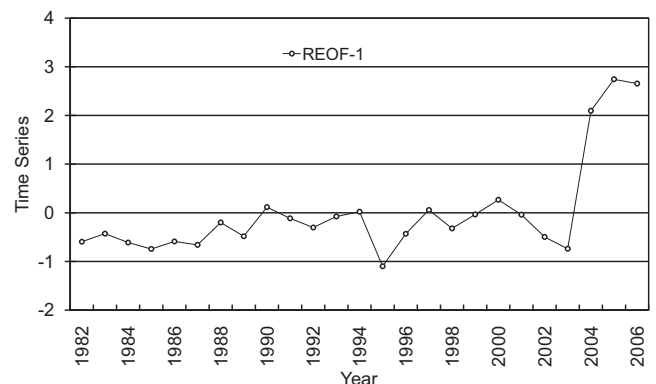


Fig. 3. The time series of the first eigenvector field of REOF.

**Table 2**

The first 10 impact factors and equation parameters obtained by latent root regression.

Regression parameters	$R^2$					$Ra^2$					F-test	Sig.
	0.8779					0.85					6.09	0.025
Variables	$T_{a-7-9}$	$T_{s20-8-9}$	$T_{s0-3-7}$	$T_{s0-4-8}$	$T_{a-8}$	$T_{a-7-8}$	$T_{s20-7-9}$	$T_{s0-3}$	$T_{s0-7-9}$	$T_{s10-6-9}$		
Standardized coefficients	-1.0103	0.8774	0.8388	0.7402	0.684	-0.5453	-0.4403	0.4257	-0.4175	-0.4106		

Notes:  $T_{a-7-9}$  means air temperature averaged for July–September,  $T_{s20-8-9}$  is soil temperature at 20 cm depth averaged for August–September,  $T_{s0-3-7}$  is surface soil temperature averaged for March–July,  $T_{s0-4-8}$  is surface soil temperature averaged for April–August,  $T_{a-8}$  is August mean air temperature,  $T_{a-7-8}$  is air temperature averaged for July–August,  $T_{s20-7-9}$  is soil temperature at 20 cm depth averaged for July–September,  $T_{s0-3}$  is March mean surface soil temperature,  $T_{s0-7-9}$  is surface soil temperature averaged for July–September,  $T_{s10-6-9}$  is soil temperature at 10 cm depth averaged for June–September.

**Table 3**

Remained impact factors and equation parameters obtained by stepwise regression.

Step	Variable	Regression testing				Partial regress Testing			
		$R^2$	$Ra^2$	F-test	Sig.	Partial correlation coefficient	T-test	Sig.	
First step	$T_{s0-3-7}$	0.4784	0.4557	21.091	0.001	0.7598	5.4822	0.001	

of vegetation can be divided into two phases, i.e. 1982–2003 and 2004–2006.

3.3. Impact factors analyses

The dataset for 1982–2006 (150 potential factors) was used to examine the effect of climatic factors on vegetation change based on the three statistical methods (i.e., linear correlation, latent root regression and stepwise regression).

3.3.1. Linear correlation

We calculated the Pearson’s linear correlation coefficients between impact factors and REOF1 time series (Table 1). It was found that the vegetation change is closely related to thermal factors (i.e., temperatures), especially in the period from July to September, but shows a small effect of moisture (e.g. precipitation and humid index) on vegetation variation.

Table 1 indicates that the highest positive correlation coefficient with 0.72 was soil temperature at 0 cm depth of July–September. In addition, the correlation coefficients between vegetation and soil temperature are usually higher than those of air temperature in the same period. The results implied that soil temperatures may make a more important contribution to vegetation variation.

3.3.2. Latent root regression

36 factors are significant at 0.01 level in Table 1. To examine the effect of these factors on vegetation change, we tested the response of independent variables (36 climatic factors) to dependent variable (time series of REOF1) using the latent root regression by software (NOSA) from website <http://www.miforum.net/nosa/index.htm>. According to the standardized coefficients, we can determine the sensitivity of climatic factors to vegetation change. The first 10 main factors are presented in Table 2. It can be seen that the 88% of vegetation variation can be explained by first 10 factors, indicating that these factors play an important role in controlling vegetation variation. The results suggest that vegetation change was closely related to the July–September air temperature, March–July and April–August soil surface temperature, August–September soil temperature at 20 cm depth.

However, it must be noted that the vegetation change was negatively associated with July–September air temperature, July–September soil temperature at 20 cm depth, July–September soil surface temperature, and June–September soil temperature at 10 cm depth, and showed the opposite results with the linear correlation. The results indicate that LRR method eliminated the effect of multicollinearity among independent variables on regression anal-

ysis. The results may accurately reflect the relationship between vegetation change and independent variables, i.e. temperature rise in July–August is not conducive to vegetation growth.

3.3.3. Stepwise regression

To reveal the dominant factors affecting the vegetation change, the variables listed in Table 2 were entered into stepwise regression calculated by SPSS version 13.0. Only the March–July soil temperature at 0 cm depth was retained on the 95% confidence interval as enter threshold and the 90% as remove threshold (Table 3). The square of correlation coefficient  $R^2$  reaches 0.48, indicating that this variable is the most important one for REOF1 zone because the about 48% of the vegetation change information might be explained by this variable in 1982–2006.

3.4. Time phase of vegetation change and response

Average NDVI for May–September and soil surface temperature of March–July in REOF1 zone for 1982–2006 are presented in Fig. 4. The NDVI appeared to remain relatively steady ranged from 0.29 to 0.33 in 1982–2003, but with a slightly increasing trend. The NDVI, however, increased quickly after 2003 and reached 0.34 in 2004, and then maintained the higher vegetation coverage in 2004–2006, which consisted with the REOF1 time series in Fig. 3. The average NDVI in 2004–2006 was 18.5% higher than that in 1982–2003.

Soil temperature at 0 cm depth in March–July ( $T_{s0-3-7}$ ) showed an obviously increasing trend with 0.62/10a from 1982 to 2006

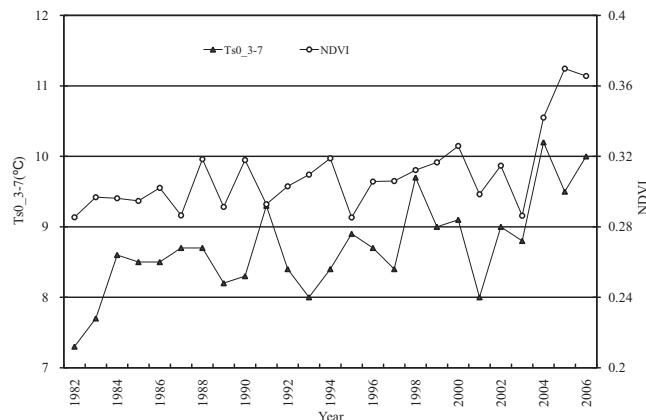
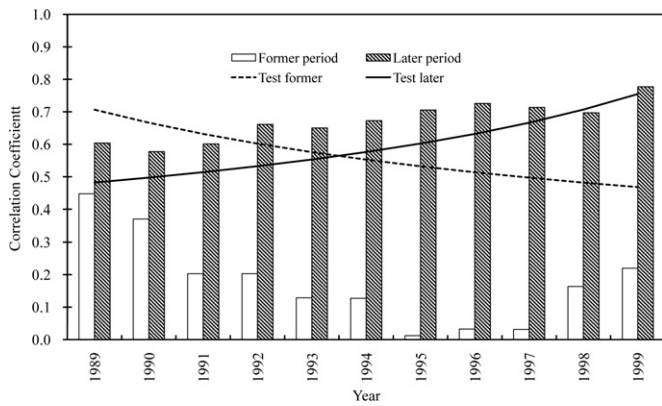


Fig. 4. The average NDVI and soil surface temperature in March–July ( $T_{s0-3-7}$ ) in REOF1 zone in 1982–2006.



**Fig. 5.** Correlation coefficients between NDVI and  $T_{50.3-7}$  and significant test at the 0.10 level in former period and later period divided by year from 1989 to 1999 respectively. Former period: correlation coefficients in the period from 1982 to the divided year; and later period: correlation coefficients in the period from the divided year to 2006.

(Fig. 4). However, there are large differences in correlation in different time intervals according to its relationship between NDVI and  $T_{50.3-7}$  in this study. To examine the different responses of vegetation to  $T_{50.3-7}$  in different time intervals, the study period was arbitrarily divided into any two sub-periods (defined as former period and later period here) by year between 1989 and 1999 successively (e.g., divided by 1994, i.e., former period with 1982–1994 and later period with 1994–2006). The correlation coefficients between NDVI and  $T_{50.3-7}$  for all sub-periods above (including 11 former and later periods respectively) were calculated and tested at the 0.05 level of significance (Fig. 5).

It could be found that correlation coefficients between NDVI and  $T_{50.3-7}$  in former periods are obviously lower than those in later periods (Fig. 5), the correlations were not significant in former periods, and significant in later periods at the 0.05 level. The results indicate that the responses of NDVI on  $T_{50.3-7}$  were different in different intervals although there was a significant relationship between NDVI and  $T_{50.3-7}$  in 1982–2006 showed in Table 3. Fig. 5 shows that the correlation coefficient in 1982–1995 period is the least one of all the coefficients with dividing year of 1995. However, the correlation coefficients reached 0.71 in 1995–2006, which is close to the value at the 0.01 level of significance, and the difference of correlation coefficient between former and later periods is the largest. It shows that the different response of NDVI on  $T_{50.3-7}$  obviously occurred in near 1995, i.e., the response of the vegetation change to  $T_{50.3-7}$  was insensitive before 1995, but sensitive after 1995.

#### 4. Discussion

In this study, it is shown that the vegetation coverage appeared to be increasing trend in the typical region of Three-River Source Region from 1982 to 2006. While, some studies reported that the vegetation has been degraded in different levels based on the satellite data in Three-River Source Region in recent decades (Zhang et al., 2007; Yang et al., 2006; Liu et al., 2006; Yan et al., 2004), which is apparently contrary to our results. By analyzing, it was found that one of the most important reasons is the difference in location of study area and size between our study and others. Three-River Source Region has diverse ecosystems, and the significant spatio-temporal differences in climate and vegetation types were detected based on the measured data. The previous studies show that the vegetation increased in some regions, but decreased in others in the recent decades (Xu et al., 2008; Wang et al., 2008; Liu et al., 2008; Yang et al., 2006), indicating that the different selection of study area and time interval can result in different conclusions.

It is easy to find out that the data before 2003 was used in previous studies. However, the data from 1982 to 2006 are presented in this study, showing that the most significant vegetation change occurred after 2003 in the TRSR. Wang et al. (2008) reported the short-term variation of vegetation in TRSR based on the MODIS satellite data in 2001–2006, the conclusions with increased trend of vegetation supported our result to certain extent. In addition, in our study, the study area is determined by using the method of REOF; it represents a typical region with the same vegetation characteristics, and can reflect the vegetation information in TRSR. Therefore, both the temporal data and spatial region provide a new understanding of vegetation variation in TRSR in recent years.

The response of vegetation to climate change has been studied by many scientists, and the results are different according to climate and vegetations of study area. Several studies pointed out that the vegetation is influenced by thermal condition in the Three-River Source Region (Xu et al., 2008; Zhu et al., 2007), and Yang et al. (2006) indicated that soil temperature is the dominant influence on vegetation variation in the Yangtze and Yellow River source region, these results are consistent with our study. Others studies, however, showed that the vegetation variation is strongly correlated with either precipitation or temperature (Zhong et al., 2010; Wei et al., 2008; Zhou et al., 2007). Wang et al. (2009) pointed out that the increase in temperature and moisture will result in the increase in vegetation productivity, and the increase in temperature with decrease in humidity will cause the decrease in vegetation productivity. Karnieli et al. (2006) found the relationship between NDVI and land surface temperature varied from one type of ecosystem to another, and/or from low to high latitude because of the large differences in climate conditions with energy-limited or water-limited, respectively. Annual mean precipitation of 598 mm in REOF1 zone, of which more than 80% falls in the growing season, and annual mean air temperature, however, is only about 0.7 °C, and the mean air temperature in July and growing season (May–September) are 10.5 °C and 8.2 °C for REOF1 zone, respectively. The observed data suggest that the climate is characterized by relatively abundant precipitation and lower temperature, indicating that the effect of moisture on vegetation is much less than that of temperature in this region. A positive correlation exists between land surface temperature and NDVI when energy is the limiting factor for vegetation growth in the North America continent with higher latitudes and elevations (Karnieli et al., 2009), this is consistent with our results.

The time lag response of vegetation to the climate change is very different according to the vegetation type, growth phase of the plants, environmental factors, and so on (Schmidt and Karnieli, 2000). Zhong et al. (2010) indicated that the effect of vegetation on climatic factors has an accumulative effect over time, this is mainly reflected on the influence of climatic factors in former phase and vegetation growth in later phase. However, the lag response of vegetation to climate change has not been considered in most previous studies, but only examined the relationship between variables in the same stage (zero time lags). In this region, the soil water is unavailable to plants in the frozen-soil period from November to February of the following year. Frozen soil begins to thaw in April when average daily soil temperature at 5 cm depth rises above 0 °C (Gu et al., 2005). In May the plants usually start to grow, and grow quickly from June to July, after then, the plant growth begins to slow (Zhong et al., 2010). Therefore, the higher soil temperature in March–April will promote thawing the frozen soil. In this study, vegetation and  $T_{50.3-7}$  had the highest relationship, indicating that temperature in former period (March–April) plays an important role in vegetation variation of growing season. Our results imply the possibility that the growing season is extended by soil temperature rise in March–April. Temperature elevation on the Qinghai-Tibetan Plateau is higher than surrounding areas and the trend of increased in winter and/or before growing seasons is larger than that in

summer in recent years (Li and Kang, 2006; Zhang et al., 2006), indicating the plateau may be one of sensitive regions to global warming, which supported our results to some extent.

The effect of human activity on vegetation variation in Three-River Source Region is hotly debated (Zhang et al., 2007; Wang et al., 2008, 2001). However, the Three-Rivers Source Region was established as a National Nature Reserve in January 2003 and the implementation of ecological protection and restoration project was started from August 2005 which mainly included restricting livestock numbers and/or decreasing grazing intensity. As the livestock number is often used as an indicator detecting the impact of human activity on vegetation change, we assessed the impact of change in livestock numbers on vegetation change. The results showed that there were negative correlation between NDVI and livestock numbers for the same year, previous year and previous 2-year (Pearson's linear correlation coefficients  $r = -0.64$ ,  $p < 0.01$ ;  $r = -0.61$ ,  $p < 0.01$ ;  $r = -0.60$ ,  $p < 0.01$  respectively) in this study area. To examine the effect of these factors on vegetation change, latent root regression was used to determine the influence of independent variables (all 39 factors) to dependent variable (time series of REOF1), it was found that the livestock numbers only for previous 2-year has a certain influence on vegetation change. However, the impact of livestock numbers was firstly removed from the impact factors when the stepwise regression was carried out, and the  $T_{50-3-7}$  was the most important impact factor. The results suggest that the influence of temperature on vegetation change was much greater than that of livestock number, although the livestock number had impact on vegetation change at the 0.01 level of significance test from 1982 to 2006.

## 5. Conclusions

In this study, the typical vegetation zones were selected using the method of REOF based on the latest satellite dataset in Three-River Source Region for 1982–2006, the zones with a similar vegetation characteristics cover 22% area of the Three-River Source Region. The relationship between vegetation and climatic factors was studied in these typical zones. It was found that the vegetation change appeared to remain relatively steady, but with a slightly increasing trend in 1982–2003. The vegetation coverage, however, increased quickly after 2003, and maintained the higher value in 2004–2006. The results show that the impact of temperature change on vegetation variation is much larger than of water. Further study indicates that soil surface temperature in March–July is the dominant factor affecting the vegetation variation in Three-River Source Region. The results are important to understanding the response of vegetation variation to global warming not only in the Three-River Source Region but also on the Qinghai-Tibetan Plateau.

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