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Spatio-temporal changes of NDVI and its relation with climatic variables in the source regions of the Yangtze and Yellow rivers

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Abstract: The source regions of the Yangtze and Yellow rivers are important water conservation areas of China. In recent years, ecological deterioration trend of the source regions caused by global climate change and unreasonable resource development increased gradually. In this paper, the spatial distribution and dynamic change of vegetation cover in the source regions of the Yangtze and Yellow rivers are analyzed in recent 10 years based on 1-km resolution multi-temporal SPOTVGT-DN data from 1998 to 2007. Meanwhile, the correlation relationships between air temperature, precipitation, shallow ground temperature and NDVI, which is 3×3 pixel at the center of Wudaoliang, Tuotuohe, Qumalai, Maduo, and Dari meteorological stations were analyzed. The results show that the NDVI values in these two source regions are increasing in recent 10 years. Spatial distribution of NDVI which was consistent with hydrothermal condition decreased from southeast to northwest of the source regions. NDVI with a value over 0.54 was mainly distributed in the southeastern source region of the Yellow River, and most NDVI values in the northwestern source region of the Yangtze River were less than 0.22. Spatial changing trend of NDVI has great difference and most parts in the source regions of the Yangtze and Yellow rivers witnessed indistinct change. The regions with marked increasing trend were mainly distributed on the south side of the Tongtian River, some part of Keqianqu, Tongtian, Chumaer, and Tuotuo rivers in the source region of the Yangtze River and Xingsuhai, and southern Dari county in the source region of the Yellow River. The regions with very marked increasing tendency were mainly distributed on the south side of Tongtian Rriver and sporadically distributed in hinterland of the source region of the Yangtze River. The north side of Tangula Range in the source region of the Yangtze River and Dari and Maduo counties in the source region of the Yellow River were areas in which NDVI changed with marked decreasing tendency. The NDVI change was

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positively correlated with average temperature, precipitation and shallow ground temperature. Shallow ground temperature had the greatest effect on NDVI change, and the second greatest factor influencing NDVI was average temperature. The correlation between NDVI and shallow ground temperature in the source regions of the Yangtze and Yellow rivers increased significantly with the depth of soil layer.

Keywords: source regions of the Yangtze and Yellow rivers; NDVI; spatio-temporal change; temperature; precipitation; shallow ground temperature

1 Introduction

The earth is experiencing dramatic changes in climate (Ding and Dai, 1994). Rates of warming are pronounced during the last three decades and are predicted to persist over the next century (IPCC, 2007). The Qinghai-Tibet Plateau is a pilot region of climatic fluctuation which is extremely sensitive to global climate change (Feng *et al*., 1998). Climate change has caused public concern over the last several decades and greater attention has been paid to its impact on the terrestrial ecosystems. Changes of vegetation coverage and its eco-environment effect are always one of the research hot spots in the field of global change (Anyamba and Tucker, 2005; Raynolds *et al*., 2006).

The source regions of the Yangtze and Yellow rivers are important water conservation areas of China, which are extremely sensitive to ecological changes and they are also areas with abundant biodiversity in high altitude region (Wang *et al*., 2004). In recent years, grassland degradation, desertification, and soil erosion were aggravating and wetland area was decreasing caused by global climate change and unreasonable resource development, indicating ecological deterioration trend of the source regions increased gradually (Yang *et al*., 2004; Zhang *et al*., 2006). Research work about eco-environment effects of climate change was mainly carried out before 2000 and focused on dynamic change of vegetation in the source regions of the Yangtze and Yellow rivers (Pan *et al*., 2004; Yang *et al*., 2005); while there have been relatively few investigations since 2000.

Normalized difference vegetation index (NDVI) is a ratio that uses the NIR and red bands, which is an indicator of vegetation cover density and plant growth condition. NDVI has been widely utilized to measure canopy attributes such as net primary production (NPP) (Sun *et al*., 2002), percentage of absorbed photosynthetically active radiations (APAR) (Sellers *et al*., 1992), leaf area index (LAI) (Johnson *et al*., 2003) and phytomass (Raynolds *et al*., 2006). Based on such findings, NDVI has then been used to describe vegetation pattern (Zhang *et al*., 2009) and dynamic (Anyamba and Tucker, 2005), to explore responses to global changes (Guo *et al*., 2008) at regional and global scales. In this study, the spatial distribution and dynamic change of vegetation cover in the source regions of the Yangtze and Yellow rivers are analyzed in recent 10 years based on 1-km resolution multi-temporal SPOTVGT-DN data from 1998 to 2007. The primary objectives of this study was to (1) analyze the spatio-temporal patterns of NDVI in the source regions of the Yangtze and Yellow rivers; (2) explore the relationships between NDVI and air temperature, precipitation, and shallow ground temperature. The study will offer scientific basis for the eco-environmental protection in the source regions of the Yangtze and Yellow rivers and for the study of the response of alpine ecosystems to global climate change.

2 Materials and methods

2.1 Study site description

The headwaters of the Yangtze River are located between 32°30′–35°40′N and 90°30′–96°00′E. The watershed area is 12.12×10^4 km^2. The headwater region of the Yellow River is situated between 33°00′–35°35′N and 96°00′–102°35′E, with a watershed area of 6.37×10^4 km^2 (Pan *et al*., 2004). Both areas are on the Qinghai-Tibet Plateau (Figure 1), and the mean height above sea level exceeds 4500 m.

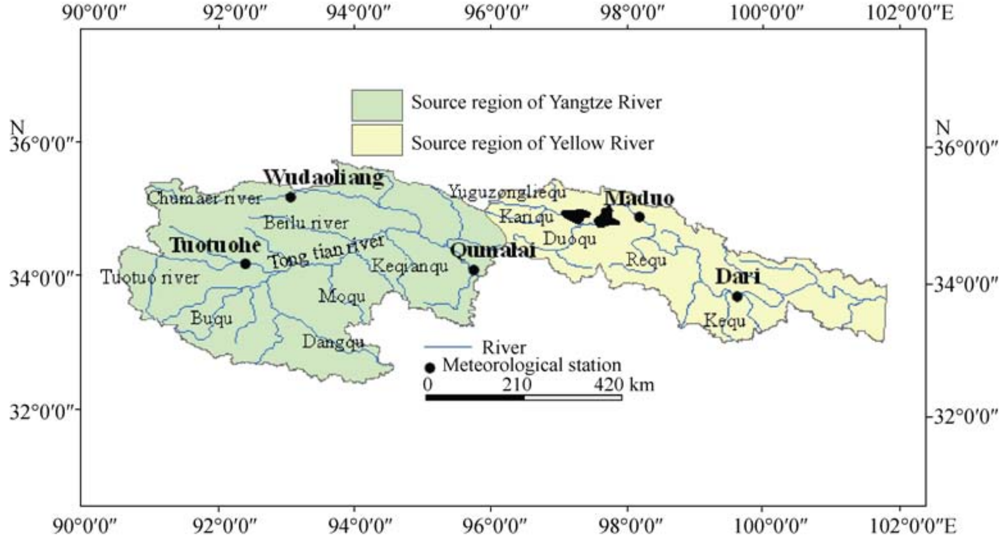

Figure 1 Location of the study area

Its climate is cold with average annual air temperature less than –0.4℃ and freezing period extends from September to April of next year. Prevailing wind direction is west with mean wind speed of 3.0–5.0 m/s. Precipitation in the source regions of the Yangtze and Yellow rivers changed greatly, which decreased from 515.0 mm in the southeastern source regions to 221.5 mm in the northwestern source regions. Mean annual evaporation was 1300–1400 mm. Soils were predominantly Mattic cryic cambisols (NSSO, 1998) under Chinese taxonomy. These soils are characterized by the presence of a Mattic epipedon and the clay and silt composition content increased and soil organic matter (SOM) decreased with the depth. Ecosystem types distributed most widely in the regions were alpine meadow and alpine steppe, of which alpine meadow was distributed widely in the region of the Yellow River, and alpine steppe was mainly located in the region of the Yangtze River. The alpine meadow was dominated by *Kobresia schoenoides*, while the alpine steppe was dominated by *Stipa purpurea*. Permafrost is widespread in the source regions, especially in the source region of the Yangtze River.

2.2 Acquired data

The ten-day composited NDVI data from May to October derived from the sensor VEGETATION on board the SPOT satellite platforms were acquired from the ‘Vlaamse

Instelling Voor Technologish Onderzoek' (VITO, http://www.vgt.vito.be/). The SPOT-VGT S10 (10-day) NDVI composites at full resolution of 1 km are generated from primary SPOT-VGT products that were corrected for surface reflectance, molecular and aerosol scattering and water vapour, ozone and other gas absorption following procedures described by Duchemin *et al*. (2002). Air temperature and precipitation for the period 1998–2007 was obtained from the China Meteorological Bureau (http://www.cma.gov.cn/). Shallow ground temperature of permafrost obtained from Observation and Research Station of the Qinghai-Tibet Plateau, CAREERI.

2.3 Data analysis

The maximum value compositing (MVC) procedure as described by Holben (1986) was used to merge NDVI values from 10 consecutive days to get NDVI in every year and every month. The maximum value compositing for the synthesis of daily NDVI-values was found to be a reliable procedure for change detection of the vegetation cover (Cuomo *et al*., 2001; Lanfredi *et al*., 2003).

To get NDVI values in the whole source regions and typical regions (3×3 pixels at the center of meteorological stations and permafrost observation stations), mean value of all pixels were calculated in the statistical region. A linear correlation with time was used to examine the change in NDVI in each pixel over the 10 years period. The trend in NDVI, CR, is calculated from $CR=10\times S\times 100/M$, where CR is the change rate in NDVI of every pixel, S is the slope of the linear regression between the annual mean NDVI values and time per pixel, and M is the mean annual NDVI over the 10 years. The F test was used to examine the significance of these trends. Depending on the significance level of a trend, the pixel was put into one of the six classes: very marked increase or decrease ($\alpha\leq 0.01$), marked increase or decrease ($0.01<\alpha\leq 0.05$), indistinct increase or decrease ($\alpha>0.05$) (Li and He 2009).

Daily air temperature and precipitation from May to October in meteorological stations was analyzed to get mean air temperature and precipitation matching the NDVI in different periods. The meteorological stations in the source region of the Yellow River are Dari, Maduo, and in the Yangtze River are Wudaoliang, Tuotuohe and Qumalai. The correlation between mean air temperature, precipitation and NDVI was studied by regression analysis. The shallow ground temperature of permafrost observation stations located at Wudaoliang, Fenghuo Mountain and Kunlun Mountains was used to investigate the relationship between NDVI and shallow ground temperature.

3 Results

3.1 Spatio-temporal pattern of NDVI in the source regions of the Yangtze and Yellow rivers

For the purpose of getting good knowledge about vegetation dynamic in the source regions of the Yangtze and Yellow rivers from 1998 to 2007, the mean value from the annual-maximum-NDVI during 1998–2000 and 2005–2007 were calculated, which represented vegetation cover at the beginning and ending of the study period (Figure 2). The results showed that vegetation cover in the source region of the Yellow River was better than that in the Yangtze River source region, and mean NDVI values decreased from southeast to northwest of the source regions which were consistent with hydrothermal condition. NDVI with value over 0.54 was mainly distributed in the southeastern source region of the Yellow River, and most NDVI values in the northwestern source region of the Yangtze River were less than 0.22. Alpine meadow and alpine shrub with high vegetation coverage dominated the southeastern source regions, while alpine steppe and alpine desert steppe were mainly distributed in the northwestern source regions. The difference in vegetation types exerted important effects on NDVI pattern.

Change curve and trend line of annual mean NDVI in the source regions of the Yangtze River and Yellow rivers from 1998 to 2007 were calculated respectively (Figure 3). Trend line could filter the effects of short-term fluctuation in climate on vegetation cover

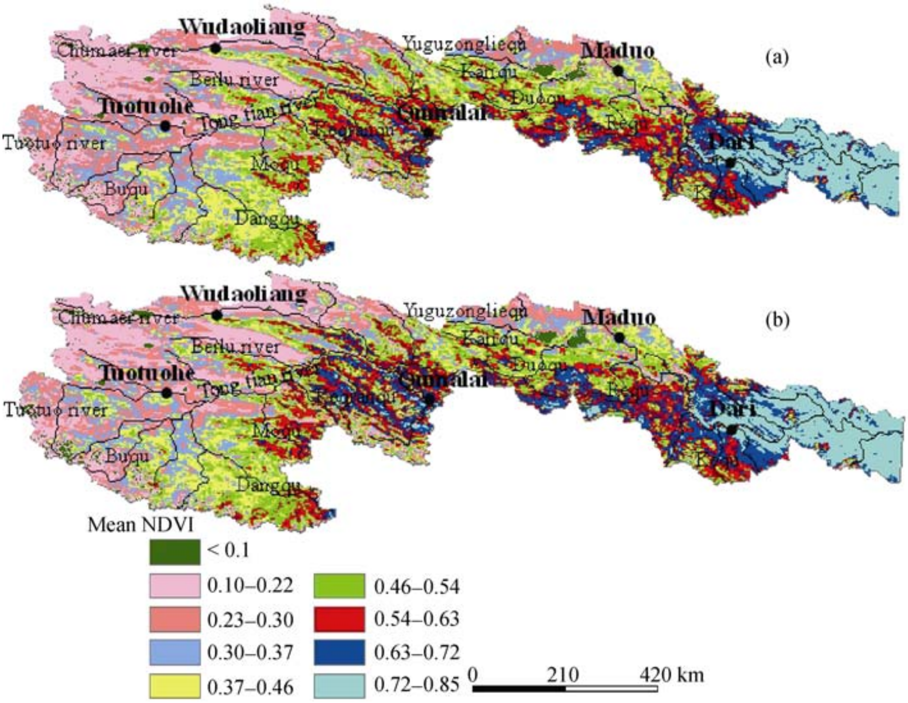

Figure 2 Mean NDVI distribution in the source regions of the Yangtze and Yellow rivers during 1998–2000 (a) and 2005–2007 (b)

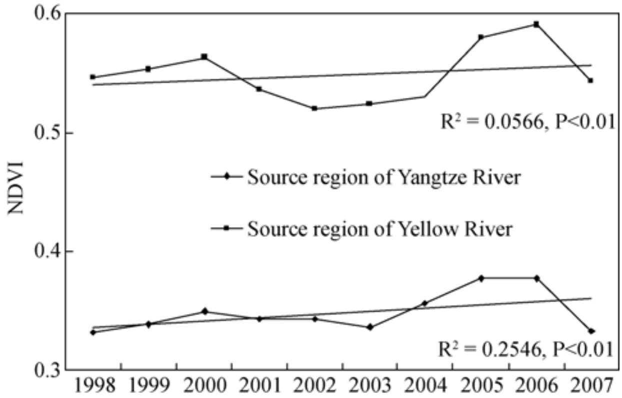

Figure 3 Variation of annual NDVI in the source regions of the Yangtze and Yellow rivers during 1998–2007

and reflected integrated effects of environmental change on vegetation dynamic. Annual mean NDVI in the source region of the Yellow River was 0.519–0.590 and that of the Yangtze River was 0.336–0.377. Vegetation cover in the source regions of the Yangtze and Yellow rivers had the same changing tendency, which increased from 1998 to 2000, then decreased till 2003, and the largest annual mean NDVI occurred in 2006 (Figure 3). Annual mean NDVI in the two source regions increased with fluctuation from 1998 to 2007. According to the statistical test, regression equations were with confidence levels of 99%. However, the correlation coefficients were very small, especially in the source region of the Yellow River, indicated vegetation activity in the source regions of the Yangtze and Yellow rivers increased weakly.

3.2 Changing trend of NDVI in the source regions of the Yangtze and Yellow rivers

NDVI changing trend during 1998–2007 showed clear spatial differentiation for the source regions of the Yangtze and Yellow rivers (Figure 4). In the source regions of the Yangtze and Yellow rivers, NDVI change rate per pixel was mainly between –15% and 15% and change rate ranging between 15%–35% was primarily distributed mosaically in the source region of the Yangtze River. NDVI changing trend of pixel in most regions was an indistinct

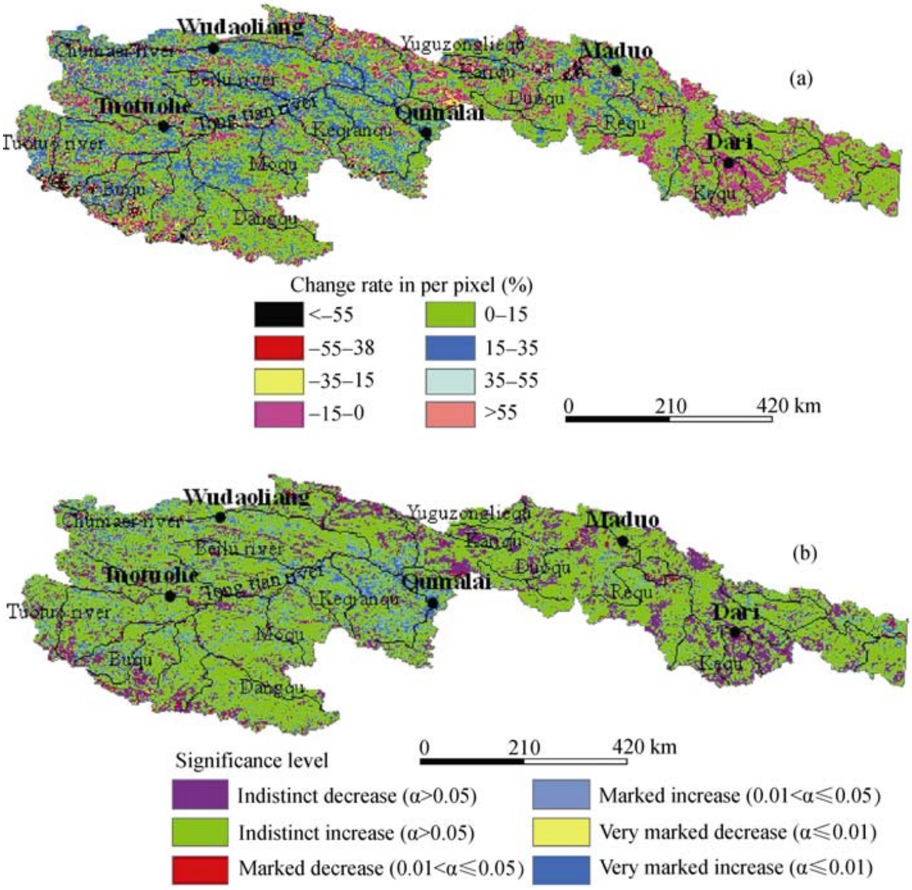

Figure 4 Spatial pattern of NDVI change rate (a) and significance level for NPP changing trend (b) in the source regions of the Yangtze and Yellow rivers during 1998–2007

increase or decrease, of which the pixel number of indistinct increase and indistinct decrease accounted for 63.98% and 22.28% of the total pixel numbers respectively. The pixel number of marked increase with confidence levels between 95 and 99% occupied 8.98% of the total pixel numbers. The area of very marked increasing regions with ≥99% confidence level was 3.42%, the pixel number of which was 7847. The percentage of pixel number with very marked decreasing tendency was very little, being only 0.32%.

The percentage of pixel number with very marked increasing and marked increasing tendency in the Yangtze River source region was bigger than that in the Yellow River source region. The regions with very marked increasing tendency were mainly distributed on the south side of the Tongtian River and sporadically distributed in hinterland of the source region of the Yangtze River. The regions with marked increasing tendency were mainly located along Xingsuhai and in the south of Dari county in the source region of the Yellow River and partial sections of Keqianqu, Tongtian, Chumaer and Tuotuo rivers in the source region of the Yangtze River. The north side of Tanggula Mountains in the source region of the Yangtze River and Dari and Maduo counties in the source region of the Yellow River were regions with marked decreasing tendency. The region with marked decreasing tendency was also sporadically distributed in hinterland of the source region of the Yangtze River.

3.3 NDVI change and correlation between NDVI and environmental factors in typical regions

3.3.1 NDVI change in typical regions

Mean NDVI of 3×3 pixels at the center of weather stations were analyzed, based on which the vegetation dynamic around the weather stations was investigated (Figure 5). NDVI near all meteorological stations fluctuated, increasing during 1998–2007, while it differed greatly on slope of the trend line at different meteorological stations. The increasing trend of NDVI near meteorological stations in the source region of the Yangtze River was more obvious than that in the source region of the Yellow River, which was mainly caused by the difference of vegetation status between the two source regions. Vegetation coverage was lower in the source region of the Yangtze River compared to that in the source region of the Yellow River and slight change in NDVI could lead to a great change rate. NDVI near Maduo fluctuated greatly with the lowest value occurring in 2001. Vegetation status near Dari meteorological station was good and NDVI value was high, which, to a great extent, led to an unclear changing trend with correlation coefficient being only 0.2. The increasing trend of NDVI near Qumalai meteorological station located in the southwestern source region of the Yangtze River was most obvious. The slope of linear regression equation of Qumalai meteorological station was the highest with a value of 0.0117, and the correlation coefficient was 0.83. Vegetation coverage near Wudaoliang and Tuotuohe meteorological stations was low and the NDVI was 0.15–0.25. Lags are thought to be common features of some ecosystems. Vegetation NDVI in eastern China maximally responds to the variation of temperature with a lag of about 10 days, and it maximally responds to the variation of precipitation with a lag of about 30 days (Cui *et al.*, 2009). The vegetation index of the Red River Basin has a time lag effect that NDVI responds to the rainfall and temperature changes, the range of the lag time is between 15 and 165 days (Li and He, 2009). Interannual variation of annual NDVI across northern Patagonia was little correlated with annual precipitation, either current or previous; however, it was highly and widely correlated with precipitation accumulated during a few months of the previous growing season (Fabricante *et al.*, 2009). On mesic sites in a temperate mixed deciduous forest, interannual variation in productivity and C allocation was related to annual growing season precipitation; however, this effect was delayed until the following growing season (Gregory *et al.*, 2006). Notably, a significant decline in leaf production was observed in 2000 following a moderate drought in 1999 (Gregory *et al.*, 2006). The lowest NDVI value occurred around 2001 at each meteorological station and the lowest air temperature occurred in 2000, based on which we deduced the lowest NDVI value was consistent with the lowest air temperature better by considering lag effect of climate change on vegetation.

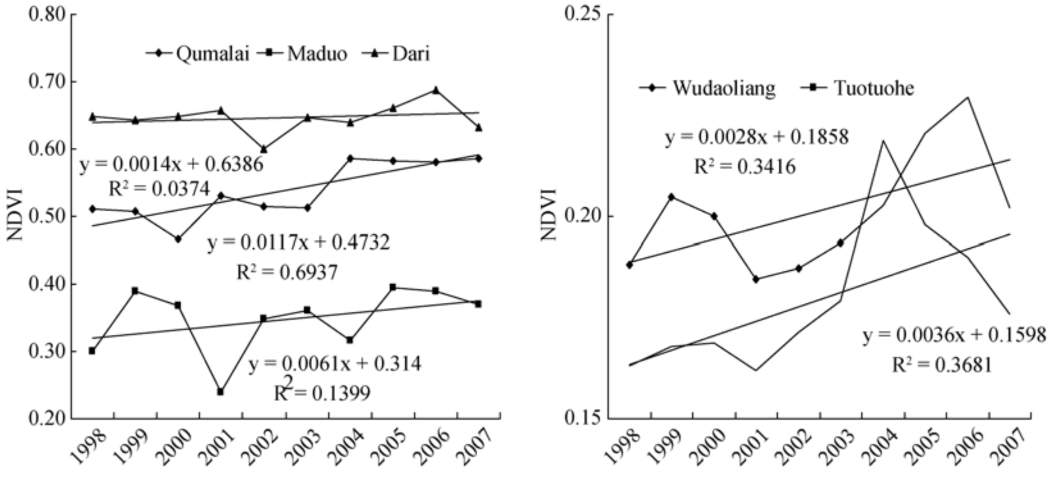

Figure 5 NDVI changing trend in typical regions

3.3.2 Correlations between NDVI and climatic factors

The relation between mean monthly NDVI in the growing season and mean monthly air temperature, monthly precipitation at meteorological stations is shown in Figure 6. It is clear that there is a good positive correlation between mean monthly air temperature, monthly precipitation and NDVI at monthly scale, and their correlativity could be described as quadratic equation. Qumalai had the largest correlation coefficient between NDVI and monthly precipitation and it was 0.71, while correlation coefficient at other meteorological stations was about 0.57. Correlation between NDVI and mean monthly air temperature at Dari meteorological station was the largest with correlation coefficient being 0.84, and Qumalai had the second largest correlation coefficient of 0.76. By comparing correlation coefficients between NDVI and mean monthly air temperature, and monthly precipitation, we found that correlation between NDVI and mean monthly air temperature was far robust than that between NDVI and monthly precipitation. Thus, conclusion that temperature appears to be the primary factor determining plant growth by contrast with precipitation could be obtained.

3.3.3 Correlations between NDVI and shallow ground temperature

In this research, shallow ground temperature matching NDVI data, provided by three observation stations of permafrost, was utilized. The three observation stations of permafrost was

Wudaoliang, Fenghuo Mountain and Kunlun Mountains, which was dominated by alpine steppe, alpine meadow and alpine desert steppe respectively. There are no long-term con-

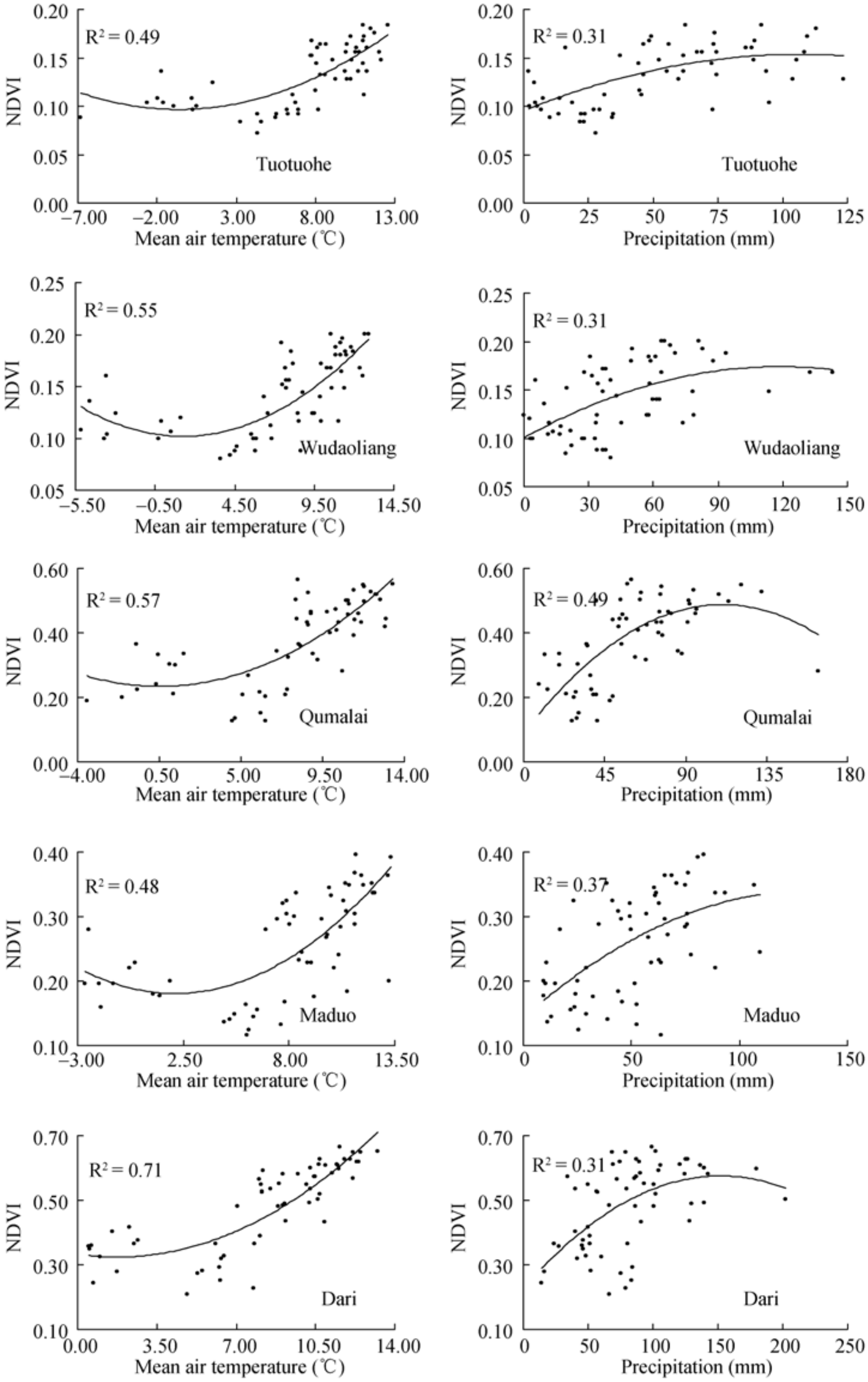

Figure 6 Correlations between NDVI and climatic factors

tinuous measurements of permafrost shallow ground temperature, so shallow ground temperature consistent with NDVI data at time scale was selected. Shallow ground temperature of three depths (0 cm, 20 cm, 40 cm) in 2005 and 2006 at Wudaoling, two depths (10 cm, 30 cm) in 2006 and 2007 at Kunlun Mountains, and two depths (10 cm, 20 cm) during 1999–2004 at Fenghuo Mountain were utilized. The correlation between mean monthly NDVI in the growing season and mean monthly shallow ground temperature is illustrated in Figure 7.

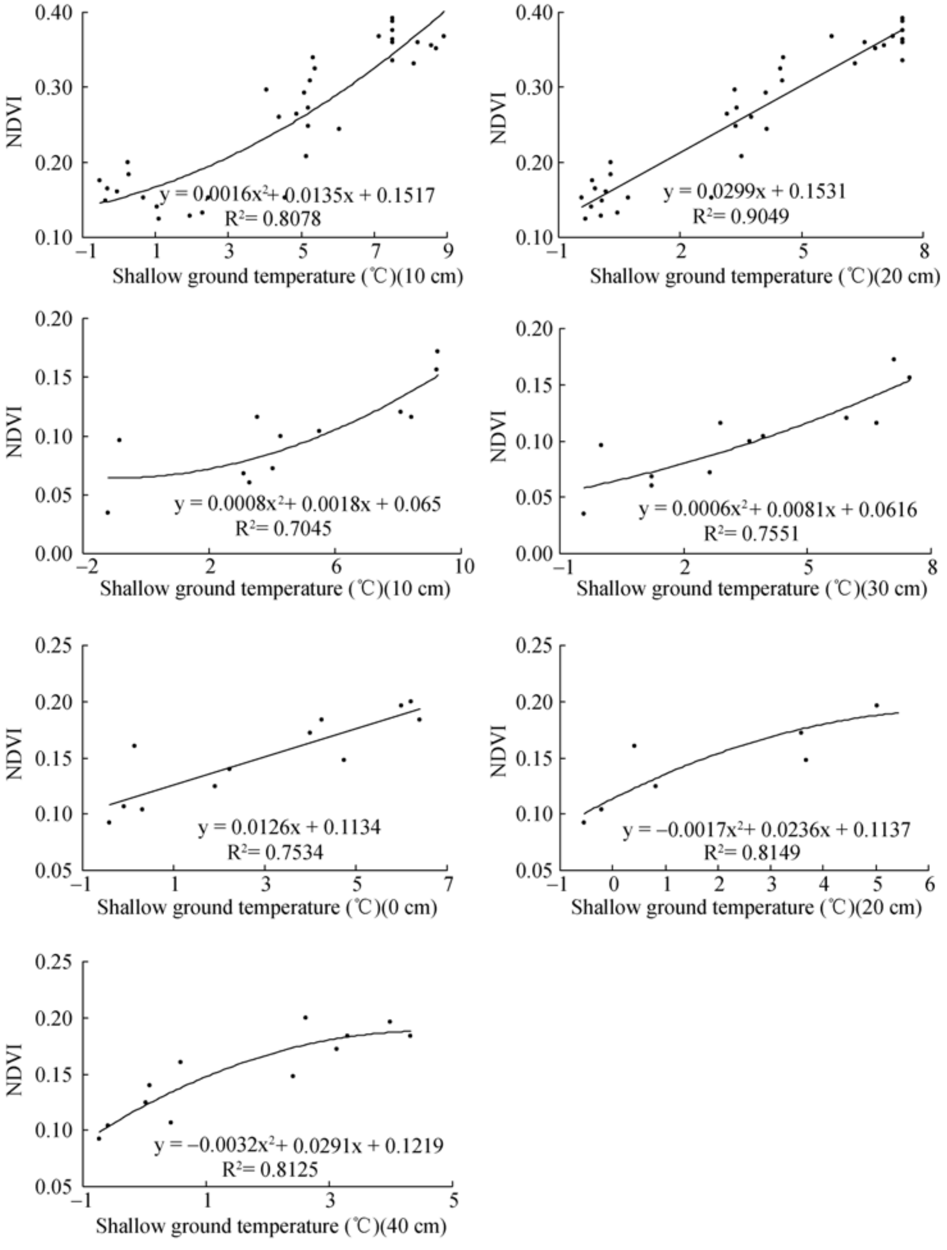

Figure 7 Correlations between NDVI and shallow ground temperature

Regarding correlation between NDVI in the growing season and shallow ground temperature, Fenghuo Mountain had the largest correlation coefficient at approximately corresponding depths; Wudaoliang had the second largest correlation coefficient, and the correlation coefficient in Kunlun Mountains was the lowest. Few studies demonstrated that active layer was significantly positive with ground temperature of permafrost (Wu *et al.*, 2003; Guglielmin *et al.*, 2008). In this research, Fenghuo Mountain, Wudaoliang and Kunlun Mountains were in the order of increasing active layer depth; and combined the correlation of NDVI with shallow ground temperature the conclusion that active layer depth of permafrost related with NDVI closely was drawn. Active layer depth in alpine meadow was the lowest, and in alpine desert steppe was the largest. We could deduce that alpine meadow was most sensitive to permafrost degradation caused by global warming.

The increasing trend of correlation coefficient with the depth was detected in every observation station of permafrost. Making further comparison of the correlation coefficient in Fenghuo Mountain and Wudaoliang, the correlation of NDVI with ground temperature at a depth of 20 cm appeared to be the largest. During our field investigation, we found plant roots were mainly distributed at a depth of 0–20 cm, therefore, ground temperature at 20 cm would exert the largest effects on ecological characteristics of roots, which probably caused the largest correlation between NDVI and ground temperature at a depth of 20 cm.

4 Discussion

Permafrost was distributed widely in the source regions of the Yangtze and Yellow rivers, especially in hinterland of the source region of the Yangtze River which was occupied by large area of continuous permafrost (Wang *et al.*, 2001). Permafrost plays a significant role on vegetation production in the alpine grassland ecosystem in permafrost areas due to the fact that permafrost as a semi-permeable layer could prevent soil moisture infiltrating and supply an ample water resource for plant growth. Meanwhile, permafrost is beneficial for plant survival and organism remaining in soil and plays an important role in nutrients cycling (Li *et al.*, 2005). Climate warming over past decades has caused wide and fast degradation of permafrost, resulting in the retrogressive succession of alpine vegetation on the Qinghai-Tibet Plateau (Guo *et al.*, 2007). Alpine swamps changed into alpine meadows, then into alpine steppe and finally into alpine desert steppes in the process of permafrost degradation on the Qinghai-Tibet Plateau (Guo *et al.*, 2007). Results obtained using static analogic approach indicated vegetation coverage decreased gradually, based on which the conclusion could be drawn that NDVI in permafrost areas on the Qinghai-Tibet Plateau should decrease in theory during permafrost degradation in the context of global warming. However, the results obtained in our study showed that changing trend of NDVI in the source regions of the Yangtze and Yellow rivers was increasing; even if in hinterland of the source region of the Yangtze River which was occupied by large area of continuous permafrost, the percentage of area with an increasing trend was larger than that of area with a decreasing trend. There existed discrepancy between results obtained from this study and from theoretical analysis.

The response of alpine ecosystem to permafrost degradation existed lag effect, which was the primary factor causing the discrepancy between results obtained from this study and from theoretical analysis. Decreased soil moisture during permafrost degradation caused alpine swamps to change into alpine meadows, which was validated adequately in field investigation. Permafrost degradation was a long-term dynamic process and so was the response of alpine grassland ecosystem in permafrost areas to permafrost degradation. Therefore, in the process of retrogressive succession of alpine ecosystem during permafrost degradiation, the swamp water surface and soil moisture decreased gradually. During our field investigation in permafrost areas, we found though water surface lowered at the beginning of permafrost degradation, vegetation coverage changed little, which caused no change in NDIV during permafrost degradation.

Spatial resolution of SPOT-VGT NDVI was too large to detect little change in ecosystem degradation at local scale. Permafrost degradation exhibited more modes such as active layer thickening, ground temperature increasing, continuous permafrost changing into island permafrost, thawy interlayer and lower boundary change (Li and Cheng, 1999; Jin *et al*., 2000). Spatial distribution of permafrost was controlled by landform, physiognomy, altitude and vegetation status and possessed large variability. Thus, the response of vegetation to permafrost degradation varied. The response of vegetation to permafrost degradation at smaller scale was filtered and only extensive change process was reflected at pixel scale, which could also cause increasing trend in NDVI in the context of permafrost degradation.

Ground temperature increased gradually during permafrost degradation (Kattsov *et al*., 2005). Increased ground temperature in the process of permafrost degradation weakened the stress effect of low temperature and lengthened growing season, which were beneficial to plant growth. An important indirect effect was that increased soil temperature resulting in improved nutrient mineralization and more soil nitrogen could be utilized which caused the increase of vegetation activity, and increase of NDVI eventually (Jonasson *et al*., 1999; Mack *et al*., 2004; Schuur *et al*., 2007).

Permafrost is the material foundation that permafrost ecosystem keeps ecological balance. Permafrost warming and degradation are associated with dramatic changes in below-ground conditions for plant growth (Cao *et al*., 2006; Hobbie *et al*., 2000). Study on role of vegetation and climate in permafrost active layer depth in Arctic tundra showed warmer permafrost had high vegetation cover (Kelley *et al*., 2004). Coupled relationship between water and heat process was of great importance for plant growth (Wu *et al*., 2003). Rising ground temperatures may increase N mineralization rates (Waelbroeck *et al*., 1997), which was beneficial for plant growth. However, increasing ground temperature dropped down permafrost table which caused soil moisture decrease (Peng *et al*., 2003). Increasing shallow ground temperature had greater positive effect on vegetation activity in permafrost areas on the Qinghai-Tibet Plateau in short term. In the long-term point of view, permafrost will disappear with increasing ground temperature caused by rising air temperature, which will make soil much dryer with smaller water supply and generate extremely dry conditions for plant growth (Zhang *et al*., 2004). Sequentially, moderate hygrophilous plants are replaced by xerophilous plants, or even rodent damage (Liang *et al*., 2007). Air temperature as a main river for vegetation change influenced plant growth directly through change in length of growing season and indirectly through change in permafrost conditions including deepening of thaw depth and increasing of shallow ground temperature. Shallow ground temperature could be reviewed as mediating driver of air temperature for vegetation change, which exerted more effects on plant growth due to that belowground biomass mainly distributed at a depth of 0–40 cm in permafrost areas on the Qinghai-Tibet Plateau (Wang *et al*., 2006). It appears that vegetation coverage in permafrost areas on the Qinghai-Tibet Plateau responds to shallow ground temperature more dramatically compared with response to air temperature, which could be verified by correlation coefficient between NDVI and shallow ground temperature and mean air temperature in this study.

5 Conclusions

In this paper, we have studied the spatial distribution and dynamic change of vegetation cover in the source regions of the Yangtze and Yellow rivers based on 1-km resolution multi-temporal SPOTVGT-DN data from 1998 to 2007, and the correlative relationships between mean monthly air temperature, monthly precipitation, shallow ground temperature and NDVI were analyzed. The results are as follows:

(1) Annual mean NDVI in the source region of the Yellow River was 0.519–0.590 and that in the source region of the Yangtze River was 0.336–0.377, which indicated vegetation cover in the Yellow River source region was better than that in Yangtze River source region. Mean NDVI values decreased from southeast to northwest of the source regions, which was consistent with hydrothermal condition. NDVI with a value over 0.54 was mainly distributed in the southeastern source region of the Yellow River, and most NDVI values in the northwestern source region of the Yangtze River were less than 0.22. Vegetation cover in the source regions of the Yangtze and Yellow rivers had the similar change curve.

(2) NDVI changing trend during 1998–2007 showed clear spatial differentiation for the source regions of the Yangtze and Yellow rivers. NDVI changing trend in most regions was indistinct increase or decrease, which the pixel number of indistinct increase and indistinct decrease accounted for 63.98% and 22.28% of the total pixel numbers respectively. The area of marked increase with confidence levels between 95 and 99% occupied 8.98% of the total pixel numbers, which was mainly distributed in Xingsuhai and the south of Dari county in the source region of the Yellow River and partial sections of Keqianqu, Tongtian, Chumaer and Tuotuo rivers in the source region of the Yangtze River. The regions with very marked increasing tendency were mainly distributed on the south side of Tongtian River and sporadically distributed in hinterland of the source region of the Yangtze River, which accounted for 3.42% of pixel number. The north side of Tanggula Mountains in the source region of the Yangtze River and Dari and Maduo counties in the source region of the Yellow River were regions with marked decreasing tendency. The proportion of area with very marked decreasing tendency occupied only 0.32%.

(3) It is clear that there is a good positive correlation between mean monthly air temperature, monthly precipitation and NDVI, and their correlativity could be described as quadratic equation. Correlation between NDVI and mean monthly air temperature was far robust than that between NDVI and monthly precipitation, showed temperature was a more important factor determining plant growth by contrast with precipitation. The increasing trend with the depth in the correlation coefficient of mean monthly NDVI in the growing season with mean monthly shallow ground temperature was detected in every observation station of permafrost. The correlation of NDVI with ground temperature at a depth of 20 cm appears to be the largest. Alpine meadow was most sensitive to permafrost degradation caused by global warming. The importance of shallow ground temperature, mean air temperature and precipitation which influenced vegetation cover was decreased orderly.

References

Anyamba A, Tucker C J, 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *Journal of Arid Environments*, 63: 596–614.

Cao W B, Wan L, Zeng Y J *et al.*, 2006. Impacts of global warming on the eco-environment in the headwater region of the Yellow River. *Earth Science Frontiers*, 13(1): 40–47. (in Chinese)

Cui L L, Shi J, Yang Y M *et al*., 2009. Ten-day response of vegetation NDVI to the variations of temperature and precipitation in eastern China. *Acta Geographica Sinica*, 64(7): 850–860. (in Chinese)

Cuomo V, Lanfredi M, Lasaponara R *et al*., 2001. Detection of interannual variation of vegetation in middle and southern Italy during 1985–99 with 1 km NOAA AVHRR NDVI data. *J. Geophys. Res*., 106(D16): 17863–17876.

Ding Y H, Dai X S, 1994. Temperature variation in China during the last 100 years. *Meteorological Monthly*, 12: 19–23. (in Chinese)

Duchemin B, Berthelot B, Dedieu G *et al*., 2002. Normalization of directional effects in 10-day global syntheses derived from VEGETATION/SPOT: II. Validation of an operational method on actual data sets. *Remote Sensing of Environment*, 81(1): 101–113.

Fabricante I, Oesterheld M, Paruelo J M, 2009. Annual and seasonal variation of NDVI explained by current and previous precipitation across Northern Patagonia. *Journal of Arid Environments*, 73:745–753.

Fang J Y, Piao S L, He J S *et al*., 2004. Increasing terrestrial vegetation activity in China, 1982–1999. *Science in China* (*Series C*), 47(3):229–240.

Feng S, Tang M C, Wang D M, 1998. New evidence for the Qinghai-Xizang (Tibet) Plateau as a pilot region of climatic fluctuation in China. *Chinese Science Bulletin*, 43(20): 1475–1479.

Gregory S N, Mary A A, Robert N M, 2006. Above- and belowground net primary production in a temperate mixed deciduous forest. *Ecosystems*, 9: 317–329.

Guglielmin M, Ellis Evans C J, Cannone N, 2008. Active layer thermal regime under different vegetation conditions in permafrost areas. A case study at Signy Island (Maritime Antarctica). *Geoderma*, 144: 73–85.

Guo W, Yang T, Dai J *et al*., 2008. Vegetation cover changes and their relationship to climate variation in the source region of the Yellow River, China, 1990–2000. *Int. J. Remote Sens*., 29: 2085–2103.

Guo Z G, Niu F J, Zhan H *et al*., 2007. Changes of grassland ecosystem due to degradation of permafrost frozen soil in the Qinghai-Tibet Plateau. *Acta Ecologica Sinica*, 27(8):3294–3301. (in Chinese)

Hobbie S E, Schimel J P, Trumbore S E, 2000. Controls over carbon storage and turnover in high-latitude soils. *Global Change Biology*, 6: 196–210.

Holben B N, 1986. Characteristics of maximum-value composite images for temporal AVHRR data. *International Journal of Remote Sensing*, 7: 1435–1445.

Hu L W, Yang G H, Feng Y Z *et al*., 2007. Tendency research of climate warm-dry in source regions of the Yangze River, Yellow River and Lantsang River. *Jour. of Northwest Sci-Tech Univ. of Agri and For.* (*Nat. Sci. Ed.*), 35(7): 141–147. (in Chinese)

IPCC, 2007. Intergovernmental Panel on Climate Change. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

Jin H J, Li S X, Wang S L *et al*., 2000. Impacts of climatic change on permafrost and cold regions environment in China. *Acta Geographica Sinica*, 55(2): 161–173. (in Chinese)

Jonasson S, Michelsen A, Schmidt I K *et al*., 1999. Responses in microbes and plants to changed the temperature, nutrient, and light regimes in the Arctic. *Ecology*, 80(6): 1828–1843.

Kattsov V M, Kallén E, Cattle H, 2005. Future climate change: Modeling and scenarios for the Arctic. In: Arctic Climate Impact Assessment. New York: Cambridge University Press, 99–150.

Kelley A M, Epstein H E, Walker D A, 2004. Role of vegetation and climate in permafrost active layer depth in the Arctic tundra of northern Alaska and Canada. *Journal of Glaciology and Geocryology*, 26(suppl.): 269–274.

Lanfredi M, Lasaponara R, Simoniello T *et al*., 2003. Multiresolution spatial characterization of land degradation phenomena in Southern Italy from 1985 to 1999 using NOAA-AVHRR NDVI data. *Geophysical Research Letters*, 30: 1069–1072.

Leef J, 2003. Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard. *Australian Journal of Grape and Wine Research*, 9: 96–101.

Leprieur C, Verstraete M M, Pinty B, 1994. Evaluation of the performance of various vegetation indices to retrieve vegetation cover from AVHRR data. *Remote Sensing Review*, 10: 265–284.

Li X, Cheng G D, 1999. A GIS-aided response model of high-altitude permafrost to global change. *Science in China* (*Series D*), 42(1): 72–79.

Li Y G, He D M, 2009. The spatial and temporal variation of NDVI and its relationships to the climatic factors in Red River Basin. *Journal of Mountain Science*, 27(3): 333–340. (in Chinese)

Li Y N, Guan D G, Zhao L *et al.*, 2005. Seasonal frozen soil and its effect on vegetation production in Haibei alpine meadow. *Journal of Glaciology and Geocryology*, 27(3):311–319. (in Chinese)

Liang S H, Wang L, Li Z M *et al.*, 2007. The effect of permafrost on alpine vegetation in the source regions of the Yellow River. *Journal of Glaciology and Geocryology*, 29(1): 45–52. (in Chinese)

Mack M C, Schuur E A G, Bret-Harte M S *et al.*, 2004. Ecosystem carbon storage in Arctic tundra reduced by long-term nutrient fertilization. *Nature*, 431: 440–443.

Myneni R B, Nemani R R, Running S W, 1997. Estimation of global leaf area index and absorbed PAR using radiative transfer model. *IEEE Transactions on Geoscience and Remote Sensing*, 35(6): 1380–1393.

National Soil Survey Office (NSSO), 1998. Soil of China. Beijing: China Agricultural Press. (in Chinese)

Osterkamp T E, Viereck L, Shur Y *et al.*, 2000. Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. *Arctic*, *Antarctic*, *and Alpine Research*, 32(3): 303–315.

Pang J H, Liu J L, Wang J, 2004. RS/GIS-based study on the dynamic land use change in the source areas of the Yangze River and Yellow River. *Arid Land Geography*, 27(3): 419–425. (in Chinese)

Peng X M, Wu Q B, Tian M Z, 2003. The effect of groundwater table lowering on ecological environment in the headwaters of the Yellow River. *Journal of Glaciology and Geocryology*, 25(6): 667–671. (in Chinese)

Piao S L, Fang J Y, 2003. Seasonal changes in vegetation activity in response to climate changes in China between 1982 and 1999. *Acta Geographica Sinica*, 58(1): 119–125. (in Chinese)

Raynolds M K, Walker D A, Maier H A, 2006. NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment*, 102: 271–281.

Schuur E A G, Crummer K G, Vogel J G *et al.*, 2007. Plant species composition and productivity following permafrost thaw and thermokarst in Alaskan tundra. *Ecosystems*, 10:280–292.

Sellers P, Heiser M, Hall F, 1992. Relations between surface conductance and spectral vegetation indexes at intermediate (100 m^2 to 15 km^2) length scales. *J. Geophys. Res.*, 97: 19033–19059.

Sun R, Liu C M, Zhu Q J, 2002. Dynamic change of net primary productivity and fractional vegetation cover in the Yellow River Basin using multi-temporal AVHRR NDVI data. *Journal of Geographical Sciences*, 12(1): 29–34.

Waelbroeck C, Monfray P, Oechel W C *et al.*, 1997. The impact of permafrost thawing on the carbon dynamics of tundra. *Geophysical Research Letters*, 24: 229–232.

Wang D X, Li Y B, Yang G H, 2004. Progress in the study of the environment of the source regions of Yangze River, Yellow River and Lantsang River. *Jour. of Northwest Sci-Tech Univ. of Agri. and For.* (*Nat. Sci. Ed.*), 32(1): 5–10. (in Chinese)

Wang G X, Cheng G D, Shen Y P, 2001. Research on Ecological Environmental Change in the Changjiang-Yellow Rivers Source Regions and Their Integrated Protection. Lanzhou: Lanzhou University Press, 29–35. (in Chinese)

Wang W Y, Wang Q J, Jing Z C *et al.*, 2006. Effects of vegetation cover change of alpine Kobersia meadow on plant community structure and diversity in source region of the Yangtze and Yellow rivers. *Resources Science*, 28(2): 118–124. (in Chinese)

Woo M K, 1992. Impacts of climate variability and change on Canadian wetlands. *Canadian Water Resources Journal*, 17(1):63–69.

Wu Q B, Shen Y P, Shi B, 2003. Relationship between frozen soil together with its water-heat process and ecological environment in the Tibetan Plateau. *Journal of Glaciology and Geocryology*, 25(3): 250–255. (in Chinese)

Yang J P, Ding Y J, Chen R S, 2005. NDVI reflection of alpine vegetation changes in the source regions of the Yangze and Yellow rivers. *Acta Geographica Sinica*, 60(3): 467–478. (in Chinese)

Yang J P, Ding Y J, Shen Y P *et al.*, 2004. Climatic features of eco-environment change in the source regions of the Yangtze and Yellow rivers in recent 40 years. *Journal of Glaciology and Geocryology*, 26(1): 7–16. (in Chinese)

Zhang S Q, Wang Y G, Zhao Y Z *et al.*, 2004. Permafrost degradation and its environmental sequent in the source regions of the Yellow River. *Journal of Glaciology and Geocryology*, 26(1): 1–6. (in Chinese)

Zhang X Y, Hu Y F, Zhuang D F *et al.*, 2009. NDVI spatial pattern and its differentiation on the Mongolian Plateau. *Journal of Geographical Science*, 19: 403–415.

Zhang Y L, Liu L S, Bai W Q *et al.*, 2006. Grassland degradation in the source region of the Yellow River. *Acta Geographica Sinica*, 61(1): 3–14. (in Chinese)