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ORIGINAL ARTICLE

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Spatial and temporal of variations of alpine vegetation cover in the source regions of the Yangtze and Yellow Rivers of the Tibetan Plateau from 1982 to 2001

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Abstract Spatial and temporal variations in alpine vegetation cover have been analyzed between 1982 and 2001 in the source regions of the Yangtze and Yellow Rivers on the Tibetan Plateau. The analysis was done using a calibrated-NDVI (Normalized Difference Vegetative Index) temporal series from NOAA-AVHRR images. The spatial and temporal resolutions of images are 8 km and 10 days, respectively. In general, there was no significant trend in alpine vegetation over this time period, although it continued to degrade severely in certain local areas around Zhaling and Eling Lakes, in areas north of these lakes, along the northern foot of Bayankala Mountain in the headwaters of the Yellow River, in small areas in the Geladandong region, in a few places between TuoTuohe and WuDaoliang, and in the QuMalai and Zhiduo belts in the headwaters of the Yangtze River. Degradation behaves as vegetation coverage reduced, soil was uncovered in local areas, and over-ground biomass decreased in grassland. The extent of degradation ranges from 0 to 20%. Areas of 3×3 pixels centered on Wudaoliang, TuoTuohe, QuMalai, MaDuo, and DaRi meteorological stations were selected for statistical analysis. The authors obtained simple correlations between air temperature, precipitation, ground temperature and NDVI in these areas and constructed multivariate statistical models, including and excluding the effect of ground temperature. The results show that vegetation cover is sensitive to variations in temperature, and especially in the ground temperature at depths of ~40 cm. Permafrost is distributed widely in the study area. The resulting freezing and thawing are related to ground temperature change, and also affect the soil moisture content. Thus, degradation of permafrost directly influences alpine vegetation growth in the study area.

Keywords Source regions of the Yangtze and Yellow Rivers · NDVI · Alpine vegetation cover change · China

Introduction

Numerous studies have noted an incremental change in vegetation cover in different ecosystems of China and of the Northern Hemisphere between 1982 and 1999 (Keeling et al. 1996; Ciais et al. 2000; Bradley et al. 1999; Menzel and Fabian 1999; Fang et al. 2001, 2003; Pacala 2001; Melillo et al.1993; Schimel et al. 2000; Cao et al. 2003). The extent of vegetation cover is increasing significantly in West China. NDVI (Normalized Difference Vegetative Index) data, e.g., show that, between 1981 and 2001, vegetation cover increased 26.8 and 8.6% in the Xinjiang Uygur Autonomous Region and in Qinghai Province, respectively (Fang et al. 2003). Vegetation cover has also increased, on average, throughout China.

In the source regions of the Yangtze and Yellow Rivers, Wang et al. (2004) studied recent variations in several typical alpine grassland ecosystems using 1986 and 2000 Landsat TM data. Their study showed that distributing areas of high-cold grassland dominated by *Stipa purpurea*, *Carex moorcroftii*, and *Littledalea racemosa* species and alpine meadow, in which *Kobresia pygmaea, Kobresia humilis, Kobresia tibetica* are dominant species, with higher vegetation cover decreased 15.82 and 5.15%, respectively. High-cold grassland and alpine meadow are two primary categories of alpine vegetation in the study regions. This ecosystem has deteriorated severely. Herein, the relation between the degradation of grassland ecosystems and changes in alpine vegetation in this area were studied. Calibrated-NDVI multi-temporal series data from NOAA-AVHRR images were used to analyze the temporal and spatial variation in vegetation cover and its relation to meteorological factors. The data were analyzed with the use of the NDVI developed by Rouse et al. (1974). This index has been used extensively to study changes in vegetation cover over land surfaces on global and regional scales.

Data and analysis techniques

Description of the study region

The headwaters of the Yangtze River are between 32°30′ and 35°40′N and between 90°30′ and 96°00′E. The watershed area is 12.24×10^4 km^2. The headwater region of the Yellow River is between 33°00′ and 35°35′N and between 96°00′ and 99°40′E. Its watershed covers 4.49×10^4 km^2 (Ding et al. 2003). Both areas are on the Tibetan Plateau (Fig. 1). The mean height above sea level is >4,000 m.

NDVI

The NDVI is a ratio involving the amounts of reflectance in the near infrared (NIR) and red (RED) portions of the electromagnetic spectrum (ranges 0.72–1.10 and 0.58–0.68 μm, respectively), thus

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}. \tag{1}$$

Thus, $-1 < \mathrm{NDVI} < +1.0$. Positive NDVI values (NIR > RED) indicate green, vegetated surfaces, and higher values indicate greater amounts of green vegetation. Low values indicate sparse vegetation.

Fig. 1 Geographical location of the study area in China and meteorological stations in the area, The *arrowheads* show the running direction in rivers

The NDVI time series were derived from the AVHRR 10-day composite images. These images were obtained from Environment & Ecology Scientific Data Center of western China, National Natural Science Foundation of China (http://www.westdc.westgis.ac.cn). The time series spans 20 years, from 1982 to 2001. The temporal and spatial resolutions of the images are 10 days and 8 km, respectively. The Maximum Value Composite, MVC (Holben 1986), is used in processing the NDVI data. Maximum NDVI value was extracted in each month from per pixel in per image. The maximum NDVI value is the monthly NDVI value.

Meteorological observations associated with livestock grazing show that herbage begins to turn green in the second 10 days of April, to wither and turn yellow in the first and the second 10 days of September, and to have died completely by the second and the third 10 days of October (Zhang et al. 1999). Thus, the period from April to October was defined as the growing season and the period from November to March of the following year as the non-growing season. NDVI data is unreliable during the non-growing period because vegetation cover is very poor and seasonal snow covers the land surface. Therefore, only monthly NDVI value in each month of the growing season was evaluated using MVC. Then, these monthly NDVI values are averaged. The mean NDVI value is used to represent vegetation cover during the growing season of a year. The annual NDVI in the following text is the mean NDVI value.

Meteorological data

The meteorological stations in the source region of the Yangtze River are Wudaoliang, Tuotuohe, and Qumalai. Those in the headwaters of the Yellow River are Maduo and Dari. Meteorological data used in this work include monthly mean air temperature and monthly precipitation between 1981 and 2000, and monthly ground temperatures at 0, 10, 20, and 40 cm depth between 1981 and 1998 at these stations.

Class of annual NDVI value in each pixel

A linear correlation with time was used to examine the change in NDVI in each pixel over the 20 years period. The trend in NDVI, β, is calculated from

$$\beta = \frac{20\Gamma}{m}100, \tag{2}$$

Where Γ 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 20 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 seven classes: (1) very marked increase or decrease ($\alpha \le 0.01$), (2) marked increase or decrease ($0.01 < \alpha \le 0.05$), (3) indistinct increase or decrease ($0.05 < \alpha \le 0.25$), and (7) basically unchanged ($\alpha > 0.25$).

Inter-annual variations of alpine vegetation cover in the source regions

Three-year mean NDVI values were calculated between 1982 and 1984, μ, and between 1998 and 2000, v, respectively. The former represents vegetation cover in the early 1980s and the latter, the same at the end of the 1990s (Fig. 2a, b). The fractional change over the past 20 years, $(v-\mu)/\mu$ was also calculated (Fig. 2c).

Annual NDVI values in the early 1980s and at the end of the 1990s decrease from southeast to northwest. Values range from 0.25 to 0.49 in the southeast from 0.1 to 0.25 in the northwest. Annual NDVI values are very low in the northern areas and along the western edges of the headwaters of the Yangtze River. Vegetation in these areas is sparse. The source region of the Yellow River, east of the Yangtze, is warmer and wetter. Thus, annual NDVI values are generally higher here, reflecting better vegetation cover.

In the Yellow River basin, NDVI values have increased in the southeasterly part of the area, while they dropped significantly along the edges of Zhaling and Eling Lakes in the north.

In the Yangtze River headwaters, NDVI values generally increased ~8% in northern areas and along the western edge of the area. This is partly because of the very low initial NDVI values. The increase ranges between 0 and 8% in the headwaters of most rivers in the southeasterly part of the area and exceeds 8% in several watersheds. In the spacious middle of the Yangtze River drainage, annual NDVI generally decreased, although it increased in some areas. The decrease ranged from 0 to 8% in areas around Qumalai and Zhiduo, and rises to as much as 16% locally.

NDVI variations in the Yellow River drainage differ from those in the Yangtze drainage. There is marked decrease in northeasterly and southwesterly parts of the Yellow River drainage and an increase in the middle and easterly parts (Fig. 2c). The increase in NDVI is ~5% in the east and equals or exceeds 10% locally. The decrease in NDVI along the edges of Zhaling and Eling Lakes is the highest observed, exceeding 14%. The NDVI decrease is also larger along the northern foot of the highest peak in the Bayankala Mountain, ranging between 4 and 9%. Overall, compared with mean annual NDVI in the early 1980s, the annual mean NDVI increases by 3.72% in the source region of the Yangtze

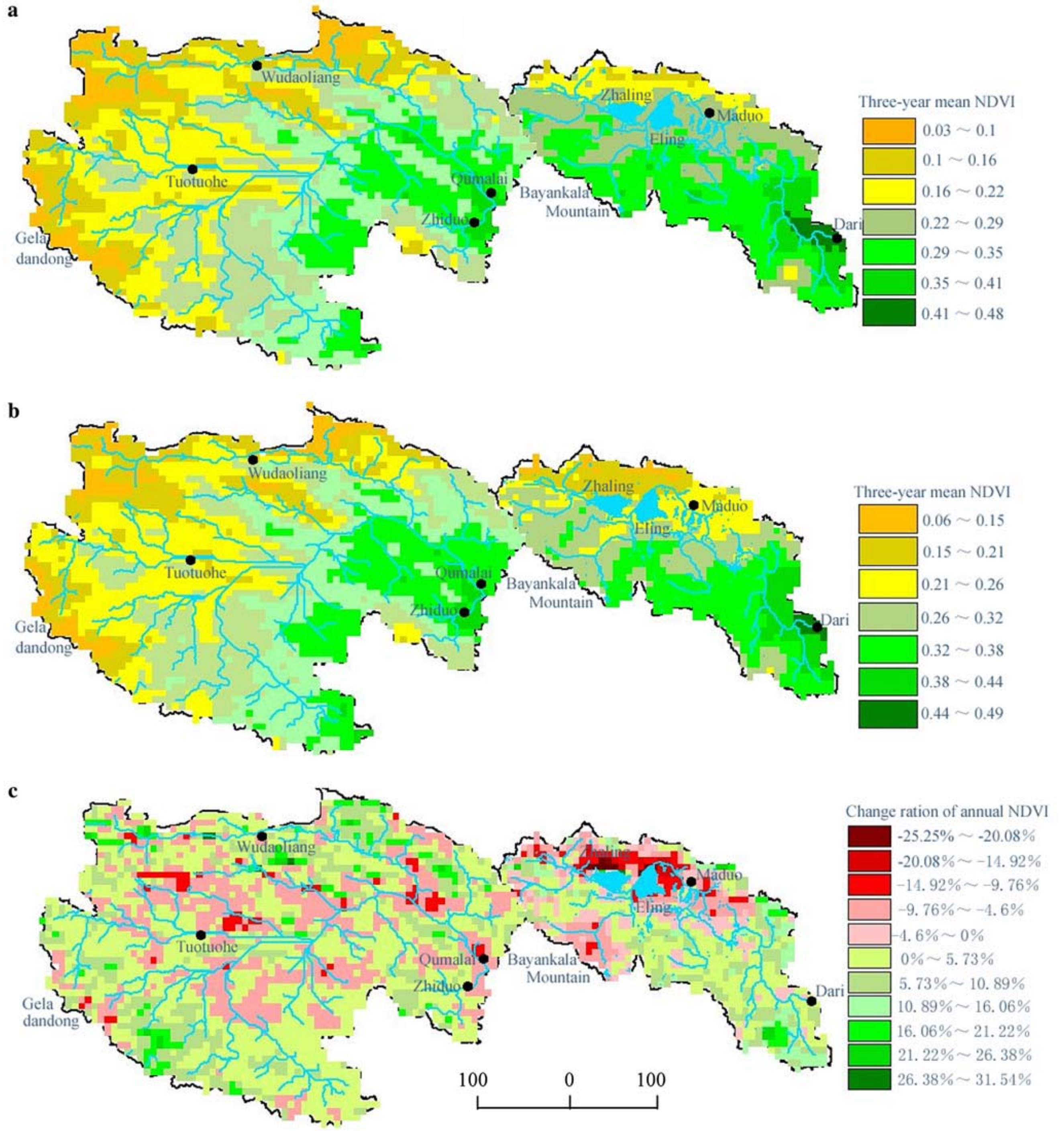

Fig. 2 Spatial distributions in annual NDVI in the source regions of the Yangtze and Yellow Rivers: **a** the early 1980s, μ; **b** the end of the 1990s, v; **c** the ratio $(v-\mu)/\mu$

River and by 2.05% in the source region of the Yellow River at the end of the 1990s (Table 1). These small increases are probably within the limits of uncertainty in the measurements; therefore, the authors cannot conclude that vegetation cover increases necessarily at present.

Figure 3 shows the short-term trends in the mean annual NDVI values, averaged over the entire watershed, against time. In the source region of the Yangtze River, annual values range from 0.19 to 0.25 (Fig. 3a). The maximum was in 1994 and indicates that vegetation cover over the land surface was superb that

Table 1 Changes in annual mean NDVI in the source regions of the Yangtze and Yellow Rivers between 1982 and 2001

	The early 1980s	The end of the 1990s	Change ratio (%)
The source region of the Yangtze River	0.215	0.223	+3.72
The source region of the Yellow River	0.293	0.299	+2.05

year. Although the slope of the regression line is slightly positive (0.0002 year^{-1}), the vegetation cover at present is slightly worse than it was in the early 1980s, and is much worse than in the early 1990s.

In the source region of the Yellow River, annual NDVI ranges from 0.26 to 0.35 (Fig. 3b). The fluctuations, however, are similar to those in the Yangtze drainage. Annual NDVI has a slightly decreasing trend (−0.0002 year^{-1}) in the Yellow River drainage in the period from 1982 to 2001. As noted, vegetation cover is generally better in the Yellow River drainage than in the Yangtze River watershed. Vegetation activity is not marked and vegetation cover change is not apparent in the study areas over the past 20 years.

Spatial variation of alpine vegetation cover in the source regions

While the long-term trends in NDVI are negligible, there is substantial spatial heterogeneity. To study this, the spatial distributions of trends per pixel (Fig. 4a) were determined and the spatial distributions of their significance level (Fig. 4b). With ≥99% confidence, the authors can say that there are no areas in which the NDVI increases fall in the class of “very marked‘’. A few patches of “marked” increase, with confidence levels between 95 and 99%, are found here and there. The total area of these is only 0.95 and 1.57% of the total area in the Yangtze and Yellow River drainages, respectively. However, the 20-year change in annual NDVI in these areas is large, ranging from 12.86 and 27.22%. Areas of “indistinct increase”, in which the significance level is less than 95% are also distributed throughout the region. Their total area is only 1.12 and 1.01% of the total in the Yangtze and Yellow River drainages, respectively.

In the Yangtze River drainage, the annual NDVI decreases markedly in the Geladandong area and in some areas between Tuotuohe and Wudaoliang. In the Yellow River drainage, marked decreases are found to the north and the east of Zhaling and Eling Lakes and along the northern foot of Bayankala Mountain. The significance level in these areas is ≥ 95%, but their total area is only 0.49 and 4.38% of the total area of the Yangtze and Yellow River drainages, respectively. However, the change in these areas is quite large, ranging between −12.5 and −56.0%. The annual NDVI is basically unchanged over 96.81 and 89.32%, respectively, of the total area of the upper Yangtze and Yellow River drainages (Fig. 4b). Thus, there are only a few local areas of markedly increasing or decreasing annual NDVI in the study area.

Annual NDVI variations and relation between NDVI and meteorological factors

Annual NDVI variations near meteorological stations

For further analysis, areas of 3×3 pixels centered on the Wudaoliang, TuoTuohe, QuMalai, MaDuo, and DaRi meteorological stations were selected. At Wudaoliang in the Yangtze drainage and at Dari in the Yellow drainage, annual NDVI fluctuated, increasing slightly over the 20-year time period, but the increase is very small. Annual NDVI decreased very slightly at Tuotuohe and Qumalai in the Yangtze drainage and at Maduo in the Yellow drainage.

Relationship of NDVI and meteorological factors

Inter-annual variations in vegetation cover are affected primarily by climate and human activity. The ecosystem in the study area is that of alpine vegetation growing

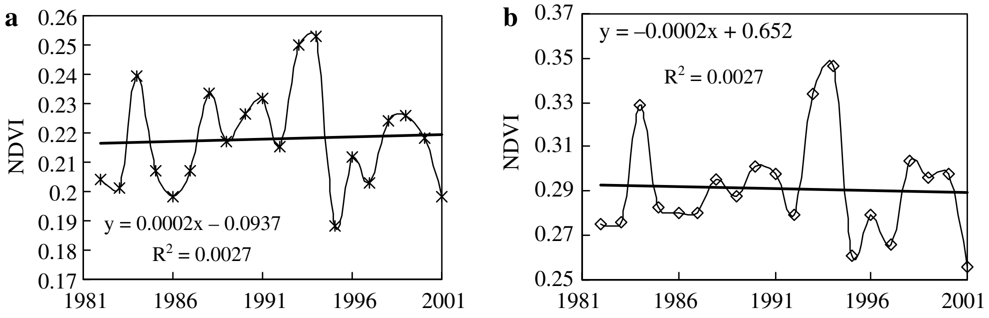

Fig. 3 Annual NDVI changes averaged over the source regions of the **a** Yangtze and **b** Yellow Rivers

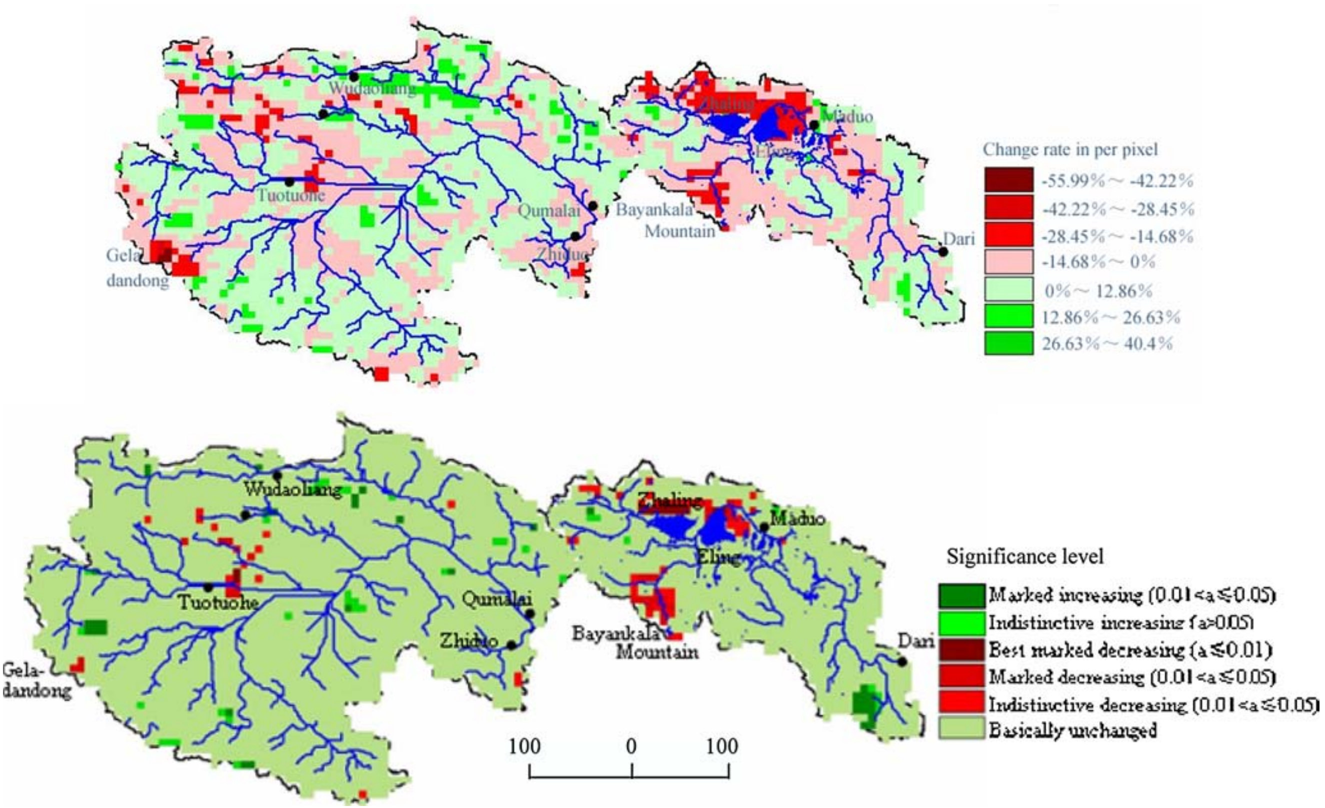

Fig. 4 Spatial patterns of change and of the significance level of the change in the source regions of the Yangtze and Yellow Rivers from 1982 to 2001 **a** change per pixel; **b** significance level of change

over the permafrost. This vegetation has adapted to a cold climate over geologic time. In addition to air temperature and precipitation, heat and moisture conditions in the permafrost also have an effect on the vegetation. Unfortunately, there are still no long-term continuous measurements of permafrost moisture content. Thus, herein the authors can only discuss the relation of the NDVI to mean monthly air temperature, monthly precipitation, and mean monthly ground temperature.

Relation between mean monthly NDVI in the growing season and meteorological factors

The relation between mean monthly NDVI in the growing season and mean monthly air temperature, monthly precipitation, and mean monthly ground temperature at Dari is shown in Fig. 5. The situation at Dari is typical of that at the other meteorological stations, which are therefore not illustrated. It is clear that on a monthly scale there is a good positive correlation between NDVI and these parameters, but correlation with precipitation is far less robust than that with the other variables. Thus, temperature appears to be the primary factor determining plant growth. Also, the correlation of NDVI with ground temperature between 10 and 40 cm depth is far better than that with air temperature. Thus, ground temperature is one of the principal factors influencing alpine vegetation cover over permafrost. Lack of data on soil water content limits the ability to carry this analysis further.

Thus, in order of decreasing importance, the factors influencing vegetation growth are ground temperature between 10 and 40 cm depth, air temperature, and lastly precipitation.

Integrated response of NDVI to influencing factors

The analyses in the preceding paragraph indicate that there is a direct statistical relation between monthly NDVI during the growing season and monthly precipitation, mean monthly air temperature, and mean monthly ground temperature. Though some correlations are good, others are weak. However, linear correlations are artificial, and do not necessarily capture all possible interactions among the variables. Thus, the possibility of nonlinear relations is explored next, such as

$$\mathrm{NDVI} = f(P) + f(T) + f(\mathrm{GT}), \tag{3}$$

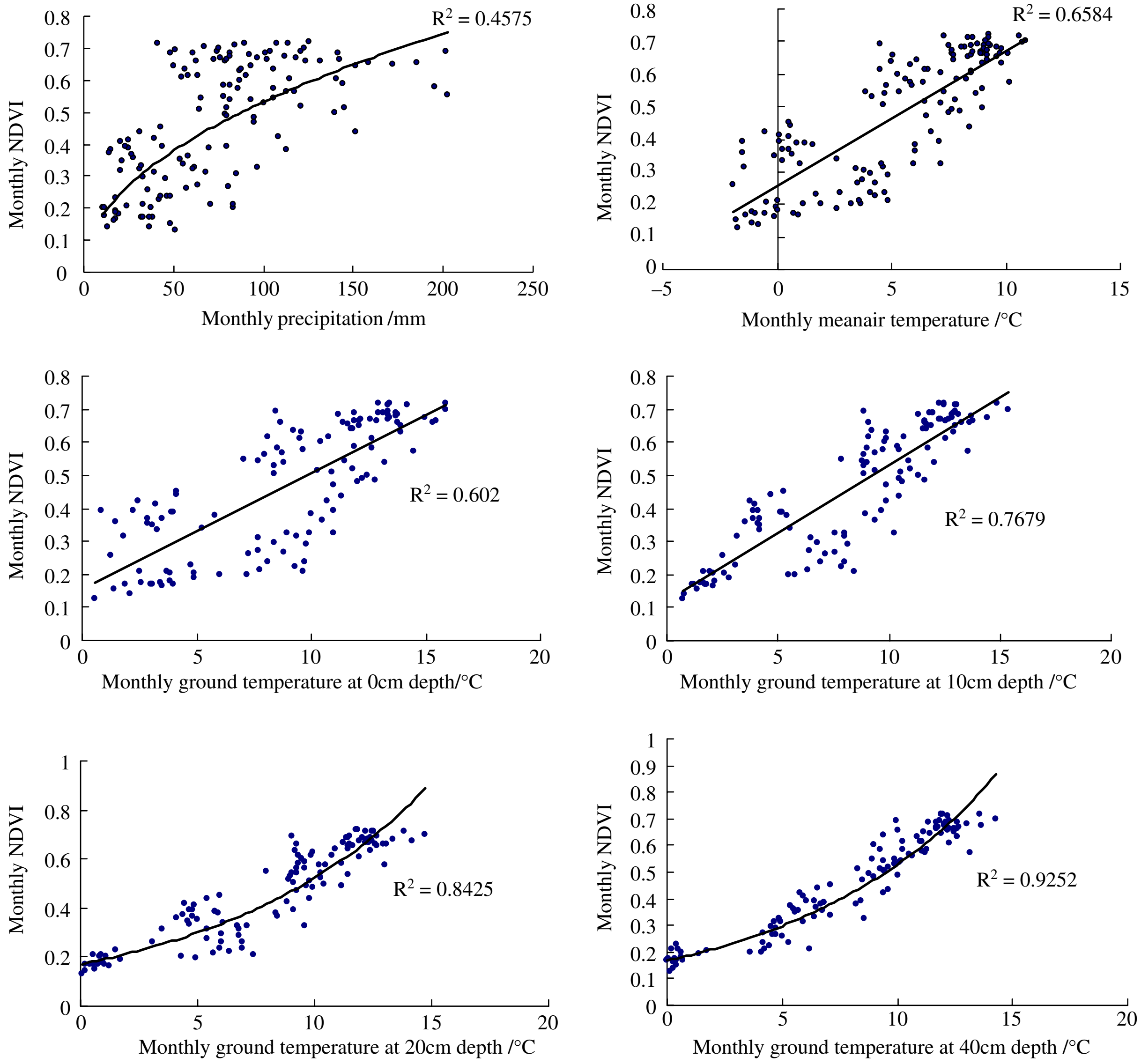

Fig. 5 Relation between monthly NDVI and monthly precipitation, mean monthly air temperature, and mean monthly ground temperatures at various depths during the growing season at Dari meteorological station in the source region of the Yellow River

where P is the precipitation, T, the air temperature, and GT the ground temperature at different depths. Model parameters are fit using the Gauss–Newton numerical iterative method (Levenberg 1944). The function used to estimate the quality of the simulated result is the determinate coefficient, NSE (Nash and Sutcliffe 1970):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (\mathrm{NDVI}_{i\mathrm{obs}} - \mathrm{NDVI}_{i\mathrm{mod}})^2}{\sum_{i=1}^{n} \left(\mathrm{NDVI}_{i\mathrm{obs}} - \overline{\mathrm{NDVI}_{\mathrm{obs}}}\right)^2}. \tag{4}$$

Here $\mathrm{NDVI}_{i\mathrm{obs}}$ is measured NDVI during the ith month from image data, $\mathrm{NDVI}_{i\mathrm{mod}}$ is the simulated NDVI in the ith month, $\overline{\mathrm{NDVI}_{\mathrm{obs}}}$ is the average value over the measured time series, and n is the length of the time series length. When $\mathrm{NSE} = 1$, the simulated result is perfect (Loumagne et al. 1996).

In the first model, the authors do not include ground temperature. The simulated results are then good at Wudaoliang, Tuotuohe, and Qumalai in the Yangtze drainage and at Maduo and Dari in the Yellow River drainage (Fig. 6). The regression equations are

$$\mathrm{NDVI}_{\mathrm{Wudaoliang}} = 0.000029P + 0.046\exp(0.185T) + 0.100 \tag{5}$$

$$\mathrm{NSE} = 0.55,$$

$$\mathrm{NDVI}_{\mathrm{Tuotuohe}} = 0.00013P + 0.036\exp(0.157T) + 0.108 \quad \mathrm{NSE} = 0.51, \tag{6}$$

$$\mathrm{NDVI}_{\mathrm{Qumalai}} = 0.00043P + 0.134\exp(0.127T) + 0.069 \quad \mathrm{NSE} = 0.68, \tag{7}$$

$$\mathrm{NDVI}_{\mathrm{Maduo}} = 0.00019P + 0.198\exp(0.106T) + 0.047 \quad \mathrm{NSE} = 0.65, \tag{8}$$

$$\mathrm{NDVI}_{\mathrm{Dari}} = 0.00031P + 0.322\exp(0.082T) - 0.066 \quad \mathrm{NSE} = 0.67. \tag{9}$$

The NSE values in Eqs. 5–9 are relatively low, however, because the effect of ground temperature is not included. Because ground temperature data from the Wudaoliang and Tuotuohe stations are discontinuous, the authors only generated complete models for the Qumalai, Maduo, and Dari stations, thus

$$\mathrm{NDVI}_{\mathrm{Qumalai}} \underset{\mathrm{NSE}=0.89}{=} 0.00211\log(P) - 0.0081T + 0.2418\exp(0.0921\mathrm{GT}_{40}) - 0.1595, \tag{10}$$

$$\mathrm{NDVI}_{\mathrm{Maduo}} \underset{\mathrm{NSE}=0.80}{=} 0.0025\log(P) + 0.0003T + 0.5932\exp(0.0544\mathrm{GT}_{40}) - 0.4711, \tag{11}$$

$$\mathrm{NDVI}_{\mathrm{Dari}} \underset{\mathrm{NSE}=0.93}{=} -0.0145\log(P) - 0.0042T + 0.6228\exp(0.0537\mathrm{GT}_{40}) - 0.4326. \tag{12}$$

Here, the subscript of GT is the depth in centimeters. Results for the Qumalai and Dari stations are shown in Fig. 7.

Comparison of the simulations under the two conditions shows that monthly precipitation and monthly mean air temperature have important effects on vegetation growth. However, the effect of ground temperature is even more significant. *NSE* values in Eqs. 10–12 are noticeably greater than those in Eqs. 7–9. This indicates that monthly NDVI values can be simulated using monthly precipitation, monthly mean air temperature, and monthly mean ground temperature at 40 cm depth.

The authors attempted many additional numerical simulations and found that the effect of air temperature is small in Eqs. 10–12, the effect of ground temperature between the surface and 10 cm depth is also relatively small, and the effect of ground temperature at greater depths is more significant. At present the authors have ground temperature data only between 0 and 40 cm depth, so this effect cannot be explored further.

There is a good linear correlation of air temperature with ground temperature between 0 and 10 cm. However, at greater depths this correlation becomes worse. The small contribution of air temperature and ground temperature between 0 and 10 cm to the quality of the simulations indicates that the key factor influencing alpine vegetation cover is the ground temperature in deeper layers. The contribution of precipitation to the simulations is also small. Although the authors have no measured data on soil moisture content; in the course of field investigations in the study area it was found that it is generally adequate, especially in alpine meadows. There are stagnant water puddles and some surface runoff in these meadows.

The above analyses indicate that the most important factor affecting NDVI in the source regions of the Yangtze and Yellow Rivers is ground temperature in deeper layers. The authors intend, next, to explore the question of which ground-temperature depth is most important. Freezing-thawing processes in frozen soil are not only closely related to ground temperature variations, but also influence soil moisture content. Thus, permafrost degradation will affect alpine vegetation growth directly.

Conclusion and discussion

NDVI variations show that as a whole alpine vegetation cover has no marked increasing or decreasing trend. However, it has worsened in local areas of the source regions of the Yangtze and Yellow Rivers over the past 20 years. Changes in NDVI are noticeably different from one region to another, however, and display considerable spatial heterogeneity. Factors affecting NDVI variations are air temperature, precipitation, and ground temperature. Simple correlations of NDVI and each of these factors indicates that precipitation is not a limiting factor for alpine vegetation growth, but temperature is. A multivariate statistical model relating mean monthly NDVI simultaneously to mean monthly air temperature, to monthly precipitation, and to mean monthly ground temperature indicates that precipitation and air temperature are important in combination and that ground temperature is even more noticeable. The NDVI is sensitive to ground temperature variations at ~40 cm depth.

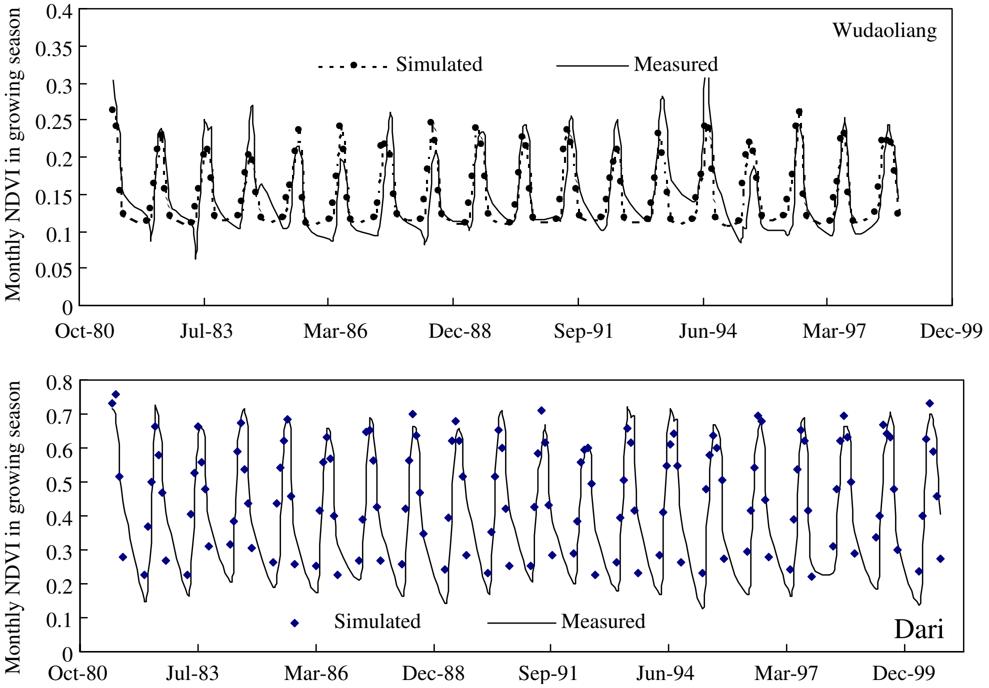

Fig. 6 Comparison of simulated and measured values of monthly NDVI during the growing season at Wudaoliang and Dari meteorological stations in the source regions of the Yangtze and Yellow Rivers, respectively, not considering ground temperature

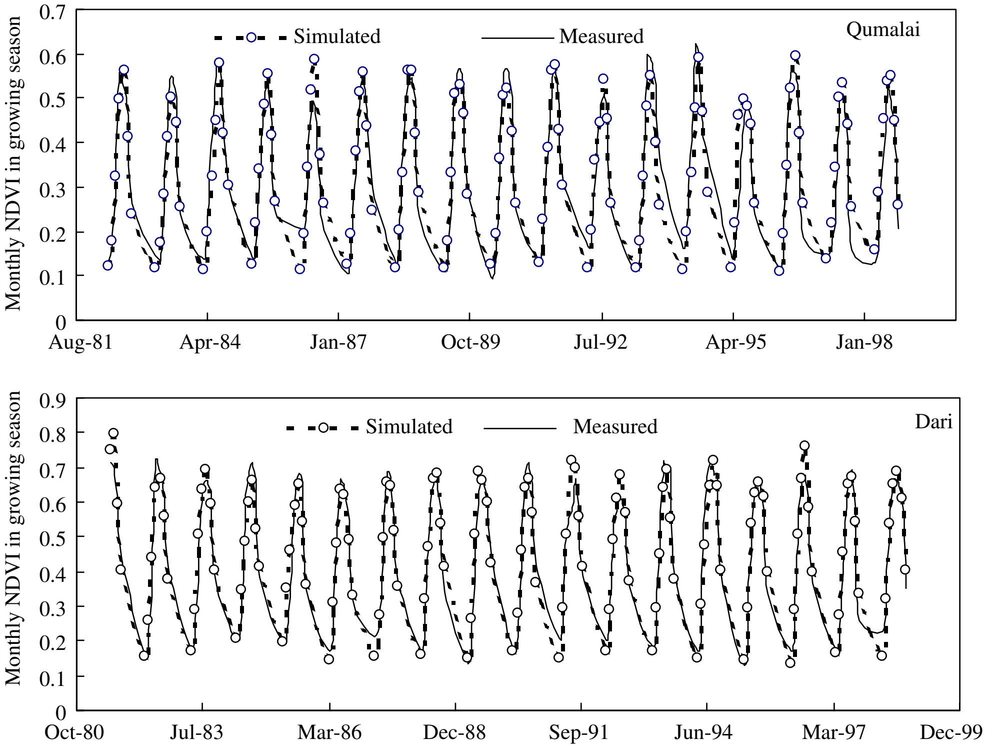

Fig. 7 Comparison of simulated and measured values of monthly NDVI during the growing season at Qumalai and Dari meteorological stations in the source regions of the Yangtze and Yellow Rivers, respectively, including effects of ground temperature at 40 cm depth

A rational interpretation is the following. Herbaceous plants are one of the primary vegetation components in this permafrost region. The root systems of these plants are distributed between the surface and 40 cm depth. When the thaw extends downward to near 40 cm, a great variety of climatic and water conditions, to which alpine vegetation growth has adapted, begin to operate. Thawing of frozen soils is not only closely related to ground temperature variations, but also influences soil moisture content. Thus, permafrost degradation will affect alpine vegetation growth directly in the source regions of the Yangtze and Yellow Rivers.

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