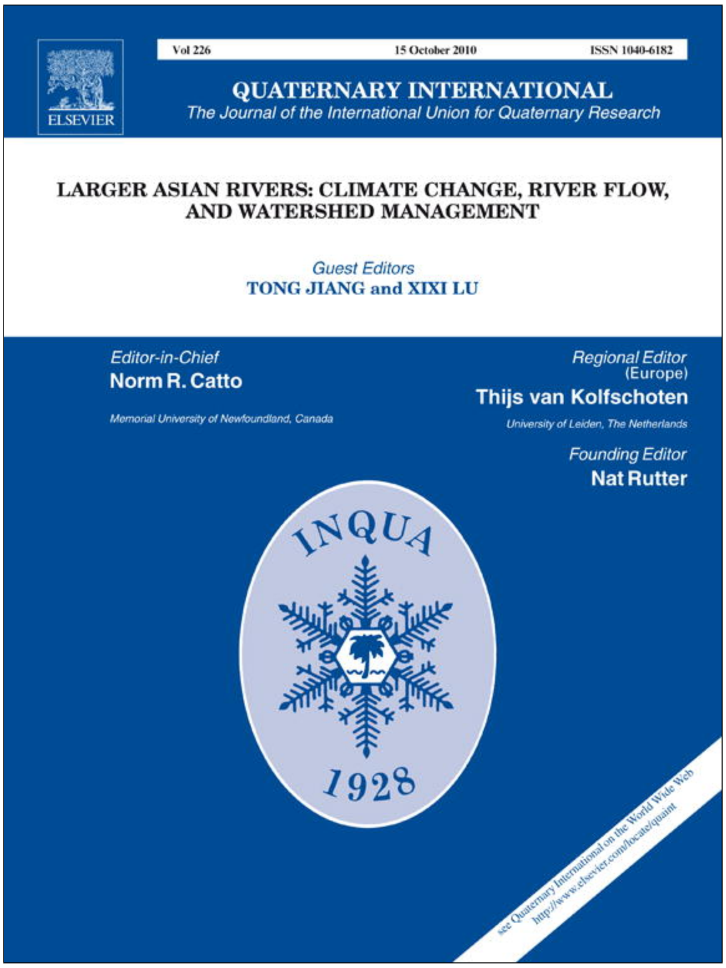
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Alpine grassland degradation index and its response to recent climate variability in Northern Tibet, China

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ABSTRACT

Northern Tibet is the headstream region for the Yangtze, Nu (Salween River), and Lancang (Mekong River). Sustaining the environmental conditions in the region is vital for Tibet and, as the source of many rivers, the whole of China and much of Asia. The study combines remote sensing data with data from other sources and national standards of grassland degradation index to assess alpine grassland degradation index between 1981 and 2004 in Northern Tibet. A Geographical Information System (GIS) was used to examine trends in grassland degradation index and its response to climate variability, including precipitation, temperature, and solar radiation. The results show that degradation has been very serious. The areas with a significant grassland degradation index trend accounted for 23.3% of the total grasslands in Northern Tibet. During 1981–2004, precipitation variability has benefited the recovery and protection of the grasslands, while temperature and solar radiation variability exacerbated grassland degradation index in Northern Tibet. The impact of regional climate change on grassland degradation index was on the balance more detrimental than positive from 1981 to 2004.

1. Introduction

The region of Northern Tibet (Nagqu) is the source of three major rivers in China and Asia; the Yangtze, Nu (headstream of Salween) and Lancang (Mekong) Rivers. Alpine grassland is the main rather fragile ecosystem in Northern Tibet (Gao et al., 2009a). The natural environment is extremely harsh, and the soil is generally quite thin. Once the alpine grassland vegetation is disturbed or degraded it is difficult to get it to recover (Zhang et al., 1998). Under the dual influence of a harsh natural environment and increased human pressures, a large area of the alpine grassland has become severely degraded in Northern Tibet (Gao et al., 2005). Alpine grassland degradation index has a direct impact upon the local people's livelihoods and affects the steady development of the local economy. In addition, grassland degradation index contributes to a warming and drying of the climate of the local and surrounding areas (Liu et al., 1999). The variations of grassland degradation index in headstream area could be varying its contribution to changing hydrological processes in the large rivers (Liu et al., 1999; Li, 2000; Piao and Fang, 2002; Gao et al., 2006a; Harris, 2009).

The influence of recent climate variability or change in high mountain and alpine ecosystems has become clear in recent years (Dirnböck et al., 2003; Alcamo et al., 2007). This change has been shown to be different in different areas, but future climate change in the regions may impose greater impacts on the alpine grassland ecosystem (Alcamo et al., 2007; Cruz et al., 2007). The Tibetan Plateau is a gigantic tectonic geomorphologic region of Earth (Zheng, 2003) and has experienced marked climate change and serious impacts on alpine grassland ecosystem in recent years (Du and Ma, 2004; Wu et al., 2005; Cruz et al., 2007; Wang et al., 2008). The unique vegetation and climate zones of the Plateau (especially Northern Tibet), along with relatively low intensity of human disturbance, make the region ideal for identifying the effects of recent climate change on ecosystems and their status (Piao et al., 2006). However, only very limited effort to date has been made to study the impact of climate change on the status and potential degradation of alpine grasslands. This paper aims to provide an assessment of recent changes in alpine grassland and trends in degradation, in relation to recent climate variability in this fragile and strategically important ecosystem. Such studies could provide evidence of, and scientific and technical support for the adaptation to future climate change, sustainable use, and scientific management and improvement of alpine grasslands.

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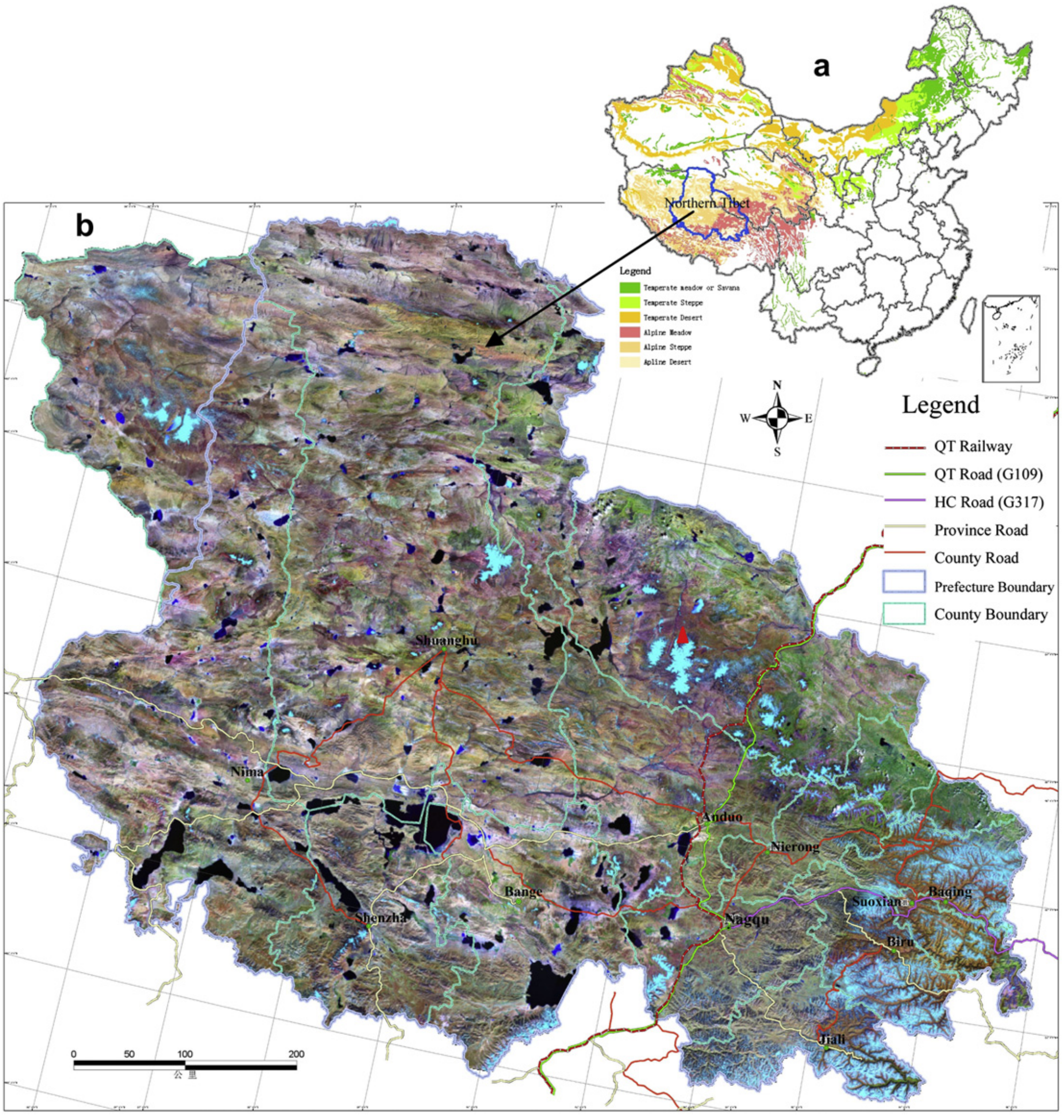

Fig. 1. Northern Tibet in China (a) Grassland distribution map of China and location of Northern Tibet in China (inside blue line). (b) Remote sensing map of Northern Tibet, QT Railway is Qinghai-Tibet Railway; QT Road (G109) is Qinghai-Tibet Road and also national road G109, HC Road (G317) is Hei-Chang Road and also called national road G317, ▲ is headstream of Yangtze River.

2. Data and methods

2.1. Study area

Northern Tibet is located between the Tibetan Gangdise and the northern part of the Nyainqentanglha mountain ranges, extending from 30°27′–35°39′ N, 83°41′–95°10′ E (Fig. 1). The total land area is around 446 000 km^2 and covers 37.1% of the total area of the Tibet Autonomous Region in China. Northern Tibet forms the highest part of the Tibetan Plateau with an average elevation over 4500 m asl. The region supports the headwaters of many important Asian and Chinese rivers such as the Yangtze, Nu (Salween) and Lancang (Mekong) Rivers and numerous internal draining rivers and lakes in Northern Tibet. Within the region, alpine grassland is the most important ecosystem, mainly comprised of alpine meadow and alpine steppe. These vegetation complexes are dominated by *Kobresia tibetica*, *Kobresia humilis*

Table 1
Evaluation criteria and integrated evaluation indices of remote sensing monitoring of grassland degradation index in Northern Tibet.

Spatial or temporal averaged grassland degradation index	Status of grassland degradation index	Grassland degradation index grading criteria and score on grid cell by remote sensing monitoring
$GDI \le 1$	Un-degraded (UD)	Grassland Vegetation Coverage (GVC) up to 90% or more of UD GVC (the maximal GVC of the early 1980s in Northern Tibet), grade score = 1
$1 < GDI \le 2$	Lightly degraded (LD)	GVC up to 75–90% of UD GVC, grade score = 2
$2 < GDI \le 3$	Moderately degraded (MD)	GVC up to 60–75% of UD GVC, grade score = 3
$3 < GDI \le 4$	Severely degraded (SD)	GVC only up to 30–60% of UD GVC, grade score = 4
$GDI > 4$	Grievous severely degraded (GSD)	GVC only below 30% of UD GVC, grade score = 5

Table 2
The change characters of annual mean temperature, precipitation and solar radiation in different areas of Northern Tibet.

Period		Nagqu			Anduo		Bange		Shenzha		Suoxian	
		R (MJ m^{-2})	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)
1980s	Mean value	5477.7	−1.2	442.9	−2.8	450.5	−0.8	332.6	0.0	289.9	1.8	602
	Increment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0
	CV	13.8	45.0	15.1	23.0	15.1	76.2	18.3	1321.2	17.0	36.9	12.4
1990s	Mean value	6109.5	−0.8	453.0	−2.8	443.7	−0.5	315.9	0.2	303.5	1.8	557.6
	Increment	631.8	0.4	10.1	0.0	−6.8	0.3	−16.7	0.2	13.6	0	−44.4
	CV	22.7	101.7	16.6	31.2	10.4	136.6	19.1	283.0	23.5	42.7	16.8
2000s	Mean value	7152.1	−0.4	508.0	−2.1	543.0	−0.2	342.7	0.5	382.1	2.5	652.1
	Increment	1674.4	0.8	65.2	0.7	92.6	0.6	10.1	0.5	92.2	0.7	50.1
	CV	2.3	21.4	2.2	8.6	14.3	222.0	26.6	22.2	12.6	2.9	20.9
1981–2004	Mean value	5984.9	−0.9	449.6	−2.7	459.6	−0.6	326.6	0.2	307.8	1.9	589.2
	CV	21.2	−72.9	16.1	−27.1	14.5	−109.1	19.0	287.7	21.0	36.8	15.7

In this table, Increment = $A_i - A_{1981-1990}$; CV is the coefficient of variation. R is annual total solar radiation (MJ m^{-2}); T is annual mean temperature(°C); P is annual total precipitation (mm).

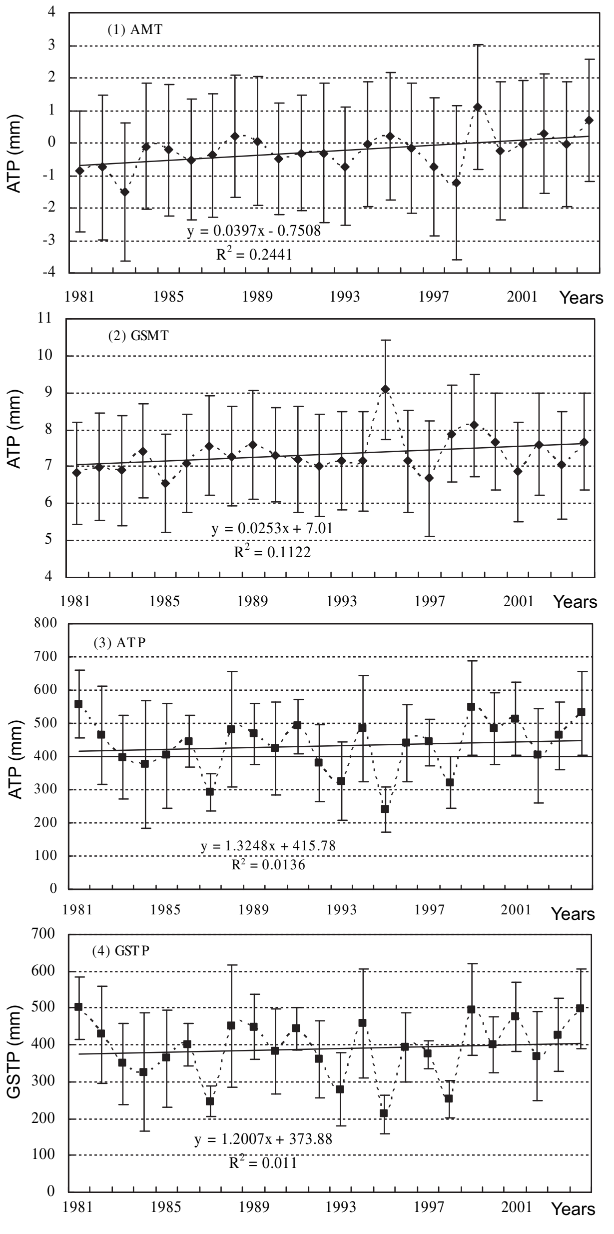

Fig. 2. Annual changes of mean temperature and precipitation in Northern Tibet. (AMT is the annual mean temperature, GSMT is the growing seasonal mean temperature, ATP is the annual total precipitation, and GSTP is the growing seasonal total precipitation, dashed lines show the changes of mean value ofclimatic factors from five meteorological stations, and straight real lines are the trendline of climate factors).

and *Stipa purpurea*. The region is very cold and dry with mean annual temperatures ranging from −2.8 to 1.6 °C and annual precipitation from 247 mm to 514 mm (1960–2004). Under the influence of atmospheric circulation and topography, precipitation declines from east to west and from south to north (Liu et al., 2003). The annual evaporation (measured by evaporation pan) rises from 1500 mm in the southeast to 2300 mm in the northwest.

2.2. Data and pre-handling

NDVI (normalized difference vegetation index) data include every-10-day AVHRR-NDVI Data (with 8 km × 8 km spatial resolution) between July and December, 2001 (http://glcf.umiacs.umd.edu/data/gimms/), and every-10-day MODIS-NDVI Data for the growing season (May–September) between 2002 and 2004 (with 0.25 km × 0.25 km spatial resolution).

Meteorological data include daily data (precipitation, air temperature, solar radiation) collected from six weather stations (Bange, Anduo, Nagqu, Shenzha, Suoxian, and Biru, solar radiation data is only available at Nagqu) in Northern Tibet; and monthly meteorological data collected from 740 weather stations in whole China from 1981 to 2004.

Other related data include historical alpine grassland survey made by the Nagqu Grassland Station; a digital topographic map of the Nagqu District at a scale of 1:250 000; a China vegetation map at a scale of 1:1 000 000; administrative zoning map of the Nagqu District, and some other maps and data on vegetation and soil.

NDVI data is processed to meet the required criteria, such as geometric correction in line with the digital topographic map of Nagqu Prefecture at a scale of 1:250 000. Monthly values were calculated based on meteorological data, and spatial interpolation was made using a geographic information system (Yu et al., 2004),

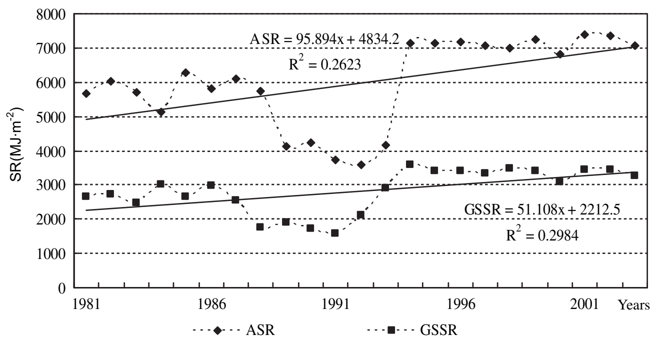

Fig. 3. Changes of annual solar radiation (ASR) and growing seasonal solar radiation (GSSR) in Northern Tibet.

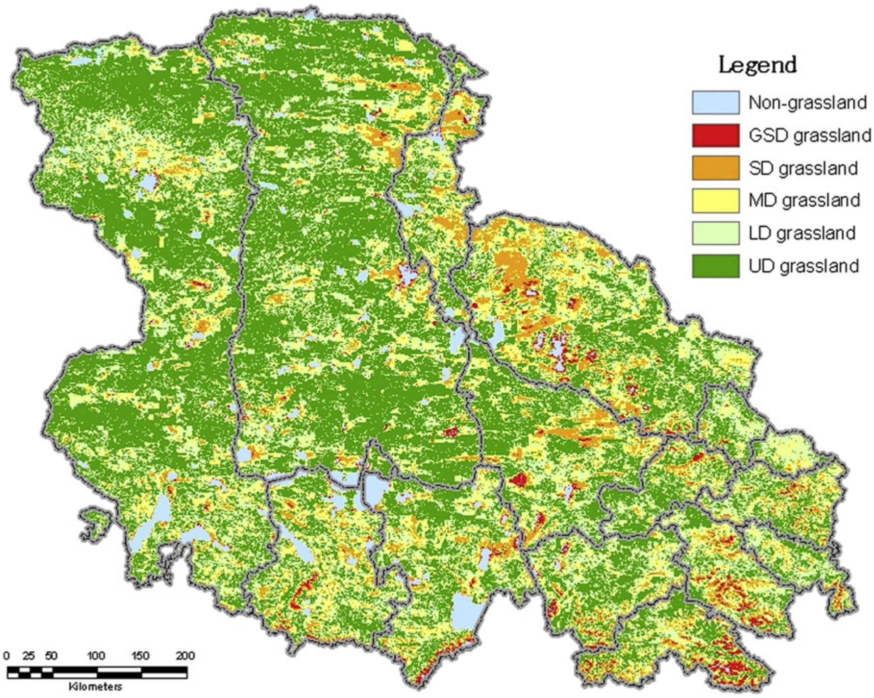

Fig. 4. Spatial distribution of grassland degradation index in Northern Tibet at 2004.

from which a raster map (1 km × 1 km) of meteorological elements was derived for the whole of China. The data were processed with the assistance of ERDAS Imagine8.6 and ArcInfo9.0 software.

2.3. Remote sensing (RS) monitoring of alpine grassland degradation index

There is a significant linear correlation between vegetation coverage and NDVI (Wittich and Hansing, 1995; Purevdorj et al., 1998; Leprieur et al., 2000). Such relationships can be used to estimate the regional vegetation coverage for the accurate assessment of rangeland vegetation cover (e.g. Geerken et al., 2005). The vegetation coverage of alpine grassland was calculated using the relationship between vegetation coverage and NDVI (Gao et al., 2006b). Based on the national standards of "Parameters for Degradation, Sandification and Salification of Rangelands" (GB19377-2003) taken from General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (2004), the maximum alpine grassland vegetation coverage of Northern Tibet in the early 1980s (1981–1985) was chosen to represent un-degraded alpine grassland conditions in order to classify grades of higher degradation in the region (Gao et al., 2005). The Delphi method was adopted to classify 5 grades of alpine grassland degradation index: un-degraded (UD), lightly degraded (LD), moderately degraded (MD), severely degraded (SD) and grievous severely degraded (GSD) according to actual field surveys and validations (Table 1). Spatial or temporal averaged grassland degradation index (GDI) were calculated in Northern Tibet (Gao et al., 2006b). From 16th to 26th August, 2004, a total of 16 grassland sample plots in the eastern region and 18 grassland sample plots in the western region were investigated, with records of the geographical location, vegetation cover, topography, and grassland degradation index grades of each sample plot for validating the remote sensing monitoring of grassland degradation index in Northern Tibet (Wan et al., 2006).

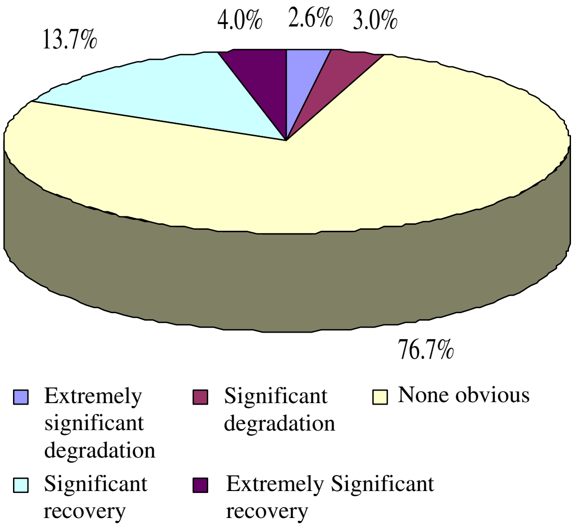

Fig. 5. Proportion of trend of grassland degradation index in Northern Tibet.

2.4. Trend analysis of alpine grassland degradation index

For the period of 1981–2004 linear trend coefficient was used to identify any long term trends. The correlation coefficient between alpine grassland degradation index area and natural temporal sequence number 1, 2, 3, …, and n (Piao and Fang, 2002; Yang et al., 2007):

$$r_{xt} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(i - \bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(i - \bar{t})^2}} \quad (1)$$

where n is the annual sequence number, x_i is the score of grassland degradation index grade in i year, and $\bar{x}$ is the annual mean score of grassland degradation index grade, $\bar{t} = (n+1)/2$. When the value

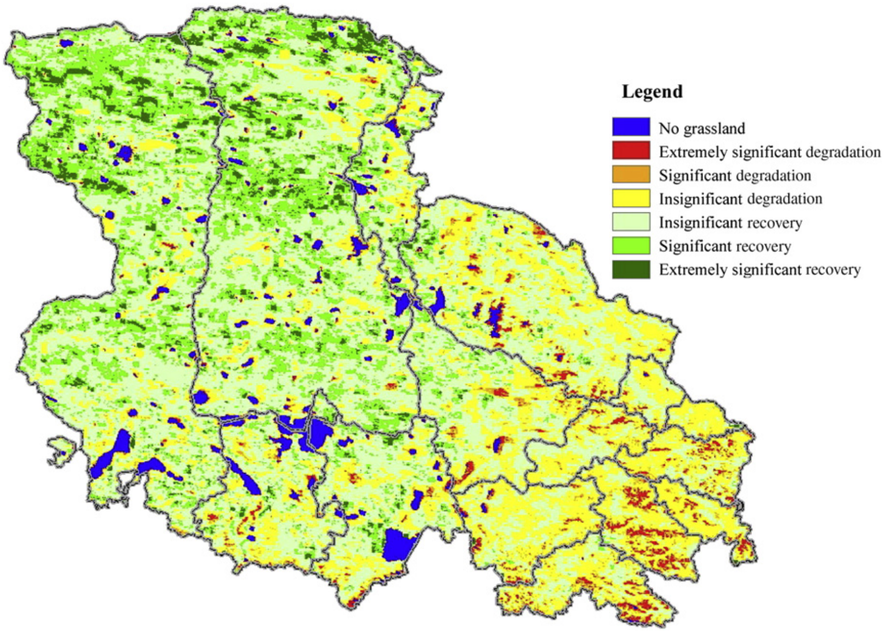

Fig. 6. Trend of Grassland degradation index in Northern Tibet.

is positive or negative, it represents a linear ascending or descending trend of grassland degradation index during a given time.

2.5. Climate change and its correlation with alpine grassland degradation index

For analysis of the interannual variability of climatic factors, the variability (coefficient of variation, CV) of climate factors in Northern Tibet was calculated as,

$$CV = (S_i/\bar{x}_i) \times 100\% \quad (2)$$

where CV is the coefficient of variation, $\bar{x}_i$ is the multi-year means for climate factors in the i period, S_i is the standard deviation of climate factors in the i period, and subscripts are the periods concerned.

Correlation coefficients were calculated between the status grassland degradation index and precipitation, temperature, and solar radiation using the gridded data. The calculation formula was as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (3)$$

Table 3
Proportion (%) of different correlation between grassland NPP and climatic factors in Northern Tibet.

Correlativity	Temperature	Precipitation	Solar radiation
Extremely significant level of negative correlation	0.54	2.10	1.17
Significant level of negative correlation	0.13	10.31	2.07
No significant level of correlation	96.15	87.51	81.01
Significant level of positive correlation	2.64	0.06	11.33
Extremely significant level of positive correlation	0.54	0.02	4.42

where y_i represents climate elements, such as annual precipitation (mm) annual mean temperature (°C), and annual solar radiation (MJ/m^2) in i year, and $\bar{y}$ is the multi-year climate means, other symbols are the same as in formula (1).

3. Results and discussion

3.1. Climate variability in Northern Tibet from 1981 to 2004

From 1981 to 2004, annual and growing seasonal (from May to September) mean temperature Northern Tibet shows an increasing trend, with a relatively large annual fluctuation (Table 2 and Fig. 2). The Nagqu station shows a significant increase (0.05 confidence level, and $n = 24$). Two noticeable fluctuations (1983 and 1997) in annual mean temperature occur, where temperatures are lower than in the preceding or following years (Fig. 2). A slight decline of annual mean temperature occurred in the mid and late 1990s, with a recovery since around 2000. The annual mean temperature increased by 0.0–0.41 °C from the 1980s to 1990s, and by 0.5–0.8 °C from the 1980s to 2000s. In summary, recent years have recorded a consistent increase in annual and growing seasonal mean temperature in the region (Fig. 2).

The region experiences relatively high interannual variability in precipitation, ranging from 14. 5%–21.0%. Fig. 2 shows a maximum occurred in the late 1980s and early 1990s, with a slight decline in the late 1990s and recovery in recent years (Fig. 2). Between 1981 and 2004, the precipitation of Nagqu, Anduo, Suoxian, Bange, and Shenzha has generally increased (Table 2).

During the period 1981–2004, the total annual and growing season solar radiation has shown a decrease, with a historical minimum in 1992 followed by recovery (Fig. 3). The eruption of Mount Pinatubo in June 1991 resulted in a large increase in stratosphere aerosols over most parts of China, which significantly reduced the solar radiation over the Qinghai-Tibeten Plateau during the period of 1991–1992 (Piao and Fang, 2002). Overall, mean annual and growing season solar radiation shows a significant increasing trend (0.05 confidence level) in Northern Tibet.

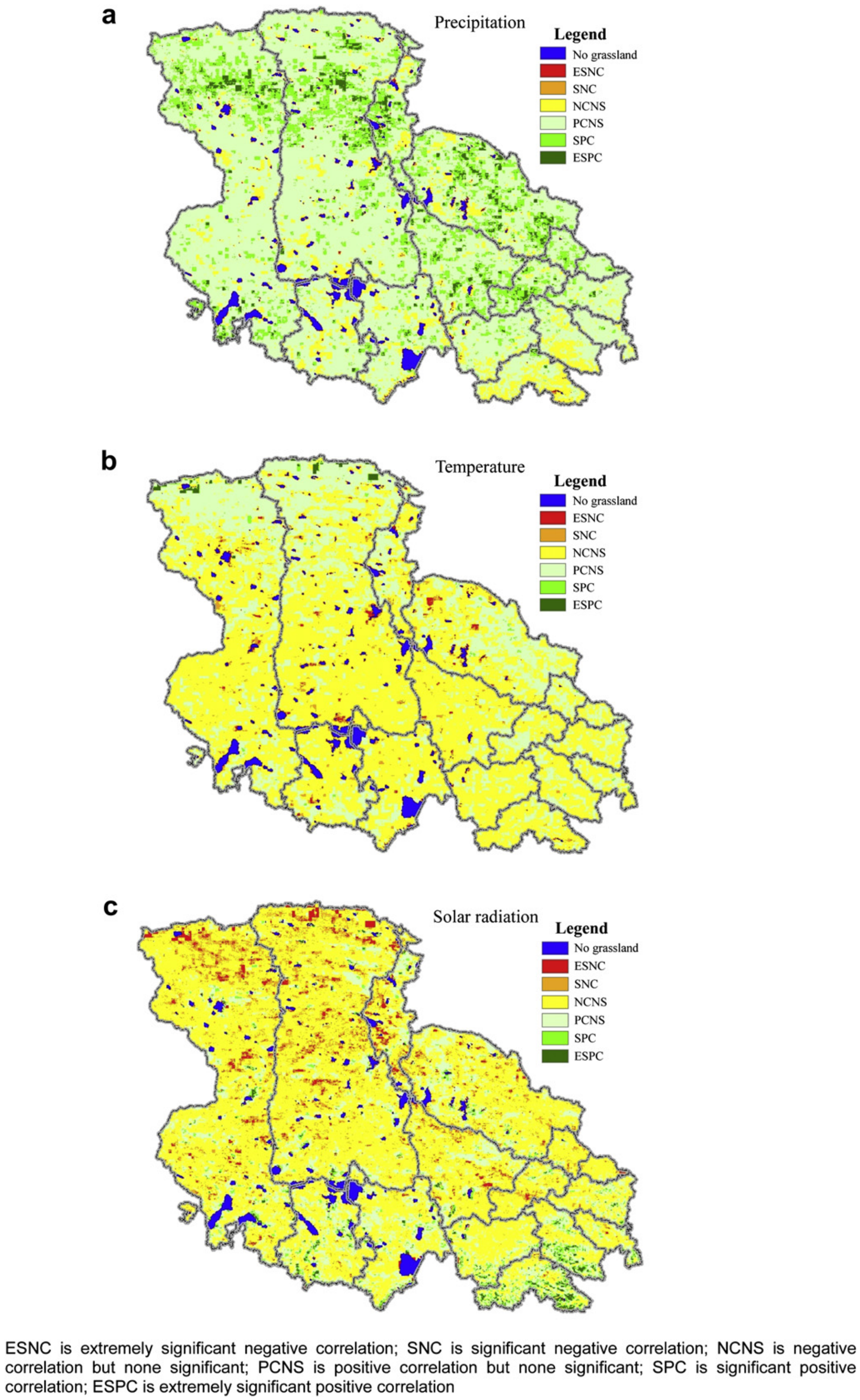

Fig. 7. Spatial correlations between grassland degradation index and annual climate factors in Northern Tibet.

3.2. Trends in alpine grassland degradation index

3.2.1. Status of alpine grassland degradation index in 2004

Using results from remote sensing monitoring of grassland degradation index in Northern Tibet, for 2004 the area of un-degraded alpine grassland accounted for 49.2% of the total grassland area (around 206 900 km^2). Severely and very severely degraded (SD and GVS) alpine grassland accounted for 8.0% and 1.7% respectively (Gao et al., 2005, 2006b). The spatial pattern of alpine grassland degradation index in 2004 (Fig. 4) shows more serious degradation in the middle, eastern and northern areas, whereas in the vast western area degradation is less serious. Degradation was most severe in three counties of Nagqu, Biru and Jiali, the headwaters of the Yangtze River (Galadandong Snow Mountain and glaciers and the Northwestern Sewu rural area), the area along the Qinghai-Tibet road and railway line, and that around the Tanggula Mountains and Nyainqentanglha snow mountain and glaciers. These patterns are interpreted as being due to the high sensitivity to recent climate variability in the snow covered mountain and glacial areas in Northern Tibet and the effects of higher levels of human activities around lines of communication and transport.

3.2.2. Spatial patterns in alpine grassland degradation index trend

Figs. 5 and 6 shows the spatial patterns and distribution in degradation change over the full period. In most areas of the region, the interannual variability is moderate, with no statistical trend. This area comprises 76.7% of the alpine grasslands in the region (Fig. 5). In contrast, the area with a significant grassland degradation index trend, including that having a grassland degradation index trend coefficient at a significant or an extremely significant level, only represents 23.3% of the grasslands in the region. In Northern Tibet, 5.6% of alpine grasslands has been rated as having significant degradation, of which extremely significant degradation is 2.6%, and significant degradation 3.0%. The area with a significant recovery reaches 17.7%, with 4.0% for an extremely significant recovery, and 13.7% for significant recovery (Fig. 5). As far as the spatial distribution pattern of alpine grassland degradation index trend in the region is concerned, significant degradation mainly occurs in the east section, with most significant recoveries in the west (Fig. 6).

3.3. Relationship between alpine grassland degradation index and climate variability

Table 3 and Fig. 7 show the correlation between alpine grassland degradation index (GDI) and annual mean temperature calculated by formula (3) using the gridded data. The area with insignificant correlations accounts for 96.2% of the total grassland area, and only 3.9% of the area shows significant correlations (both positive or negative) For annual precipitation, the area with insignificant correlations accounts for 87.5% of the total grassland area and only 0.1% of the area shows significant positive correlation (Table 3). The area with significant correlation accounts for 12.4% (mainly the Tanggula Mountains and uninhabited areas in the northwest). The increase of precipitation in these areas is associated with recovery of alpine grasslands and slows alpine grassland degradation index to some extent. For annual solar radiation, the area with insignificant correlations accounts for 81.0% of the total grassland area. The area with a significant positive correlation accounts for 15.75%, mostly in the mid and western areas and in the north of the Tanggula Mountains (Fig. 7).

Recent research on China's grassland productivity shows that significant impacts of climate change came from changes in the seasonality of temperature and precipitation change and from changes in evapotranspiration during the growing season (Piao and Fang, 2002; Piao et al., 2006, 2008; Gao et al., 2009b). According to this study, the increase of precipitation benefits the recovery of some areas of grassland because these area is semi-arid or arid area and water is one of important limiting factors to plants in these area. Rising temperatures may accelerate grassland degradation index in Northern Tibet and increase in total solar radiation in the region may increase degradation because the physical factors of more sunshine, higher temperature, lower humidity, and poorer soil moisture condition make these areas more vulnerable to degradation in Northern Tibet.

4. Conclusions

(1) In recent years, serious alpine grassland degradation index has been detected in Northern Tibet. Degraded grassland accounted for 50.8% of the total grassland area, and severely and grievous severely degraded grassland accounted for 8.0% and 1.7% respectively in 2004. The status of grassland degradation index in the middle, eastern and Northern regions of Northern Tibet were more serious. In comparison, the alpine grassland degradation index in the vast western region was relatively slight.

(2) From 1981 to 2004, the interannual variability of alpine grassland degradation index in most areas of Northern Tibet were not obvious across roughly 76.7% of the total grassland area, while areas with marked change only account for 23.3%. Significant degradation mainly occurs in the east section, and the most significant recovery happened in the west.

(3) Precipitation variation has benefited the reovery and protection of alpine grasslands in the region, while the variation of temperature and solar radiation has worsened alpine grassland degradation index in recent years. During 1981–2004, the importance of climate elements affecting alpine grassland degradation index was in the following order: total solar radiation > precipitation > temperature. In conclusion, the regional climate change has produced a more negative than positive impact on grassland degradation index in Northern Tibet.

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