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Climate changes and its impact on tundra ecosystem in Qinghai-Tibet Plateau, China

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Abstract Alpine ecosystems in permafrost region are extremely sensitive to climate change. The headwater regions of Yangtze River and Yellow River of the Qinghai-Tibet plateau permafrost area were selected. Spatial-temporal shifts in the extent and distribution of tundra ecosystems were investigated for the period 1967–2000 by landscape ecological method and aerial photographs for 1967, and satellite remote sensing data (the Landsat's TM) for 1986 and 2000. The relationships were analyzed between climate change and the distribution area variation of tundra ecosystems and between the permafrost change and tundra ecosystems. The responding model of tundra ecosystem to the combined effects of climate and permafrost changes was established by using statistic regression method, and the contribution of climate changes and permafrost variation to the degradation of tundra ecosystems was estimated. The regional climate exhibited a tendency towards significant warming and desiccation with the air temperature increased by 0.4–0.67°C/10a and relative stable precipitation over the last 45 years. Owing to the climate continuous warming, the intensity of surface heat source (*HI*) increased at the average of 0.45 W/m^2 per year, the difference of surface soil temperature and air temperature (DT) increased at the range of 4.1°C–4.5°C, and the 20-cm depth soil temperature within the active layer increased at the range of 1.1°C–1.4°C. The alpine meadow and alpine swamp meadow were more sensitive to permafrost changes than alpine steppe. The area of alpine swamp meadow decreased by 13.6–28.9%, while the alpine meadow area decreased by 13.5–21.3% from 1967 to 2000. The contributions of climate change to the degradation of the alpine meadow and alpine swamp was 58–68% and 59–65%

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between 1967 and 2000. The synergic effects of climate change and permafrost variation were the major drivers for the observed degradation in tundra ecosystems of the Qinghai-Tibet plateau.

1 Introduction

Global climate change has significantly affected the natural ecosystems in many regions of the world. In alpine or high-latitude regions, the freeze–thaw cycles lead to temporal variations in soil moisture and heat, forming frost or permafrost ecosystems (Wu et al. 2001; Walker et al. 2003). The tundra ecosystems are arguably among the most sensitive to the climate change owing to the sensitivity of the permafrost environment to warming (Walker et al. 2003; Christensen et al. 2004). Climatic change can alter permafrost directly through changes in air temperatures and heat exchange between soil and the overlying atmosphere. The degradation of permafrost can induce significant changes in ecosystems, land use and infrastructure, which rely on permafrost as their foundation (Osterkamp and Romanovsky 1999; Romanovsky and Osterkamp 2001). Furthermore, evidence continues to mount that the warming has been affecting the structure and function of terrestrial ecosystems in this region (McGuire et al. 2003; Stow et al. 2004; Hinzman et al. 2005). In arctic regions, larger expansions of the shrub cover and general trends of greening were observed over last 50 years corresponding to warmer temperatures (Tape et al. 2006; Payette 2006; Stow et al. 2004). Under a global mean warming of 2°C, forest extent is predicted by BIOME4 biogeochemistry biogeography model to increase in the Arctic on the order of 55% with a corresponding 42% reduction in tundra area. Tundra types generally also shift north with the largest reductions in the prostrate dwarf-shrub tundra, where nearly 60% of habitat is lost (Kaplan and New 2006).

The tundra was distributed from arctic to Qinghai-Tibet Plateau (QTP). Under the climatic warming, tree line advances into tundra had been documented in Russia, Canada and Alaska over the last half century (Lloyd and Fastie 2003; Esper and Schweingruber 2004; Tape et al. 2006; Payette 2006). Baker and Moseley found that the woody vegetation advanced into alpine meadow in southeastern QTP (Baker and Moseley 2007). The strongest signals of ecosystem change appeared to be the expansion of tundra shrubs and the decreases in the extent of ACS meadows in arctic tundra over the past 50 years (Sturm et al. 2001; Stow et al. 2004). Over the last 50 years, climate change in the Qinghai-Tibet plateau has largely paralleled that of the whole country, where air temperature rising for 0.4–0.6°C in last decade (Wang et al. 2007; Li and Wu 2005). The alpine vegetation plays a significant role in the lives of humans and animals of Qinghai-Tibet Plateau, and in the global energy balance and carbon budget (Li and Zhou 1998; Zhou 2001). The energy and water balance of the Qinghai-Tibet Plateau has an important influence on the Asian monsoon system, and thus is an important component of the energy and water cycles of the global climate (Zhang et al. 2003). Oppositely, the global climate may also be influenced by the strong response of the alpine or tundra ecosystems of the Qinghai-Tibet Plateau to the global climate change. Therefore, the changes in the plateau's unique alpine tundra ecosystems during recent 50 years under the climate changes have common concern to ecologists, social-economists, hydrologists and global change researchers. So far there are few studies to answer the question: how do the alpine ecosystems in the Qinghai-Tibetan Plateau response to climate change over last 50 years? The changes in extent and distribution of tundra ecosystems of the Qinghai-Tibet Plateau under the climate change and its major drivers are still unclear (Zhou 2001; Wang et al. 2007).

The main purpose of this study was to explore the long-term changes (1967–2004) in both alpine tundra ecosystems of the Qinghai-Tibet Plateau and their relationship with the climate change. Specifically, we sought to address the following questions: (i) what spatial-temporal shifts in the alpine tundra ecosystem and distribution occurred under the climate changes? (ii) How do these changes correlate with the climate change and how do permafrost response to the climate change?

2 Study area and tundra ecosystems

The headwater portion of the Yangtze River watershed has an area of 13.78×10^4 km^2, and lies between 90°43′–96°45′E and 32°30′–35°35′N, while that of the Yellow River at 6.48×10^4 km^2, lies between 33°00′–35°35′N and 96°00′–99°45′E (Fig. 1). The landform of this region is dominated by tall hills and a well-developed network of watercourses. The headwaters of the Yangtze River and Yellow River are located in a transitional region of alpine semiarid climatic zones, and are characterized by a mean annual temperature of −1.3–5.5°C and a mean annual precipitation of 270–520 mm (Wang et al. 2004; Wang et al. 2006). Permafrost is well developed in the headwater area of the Yangtze River, averaging between 50 and 120 m in depth,

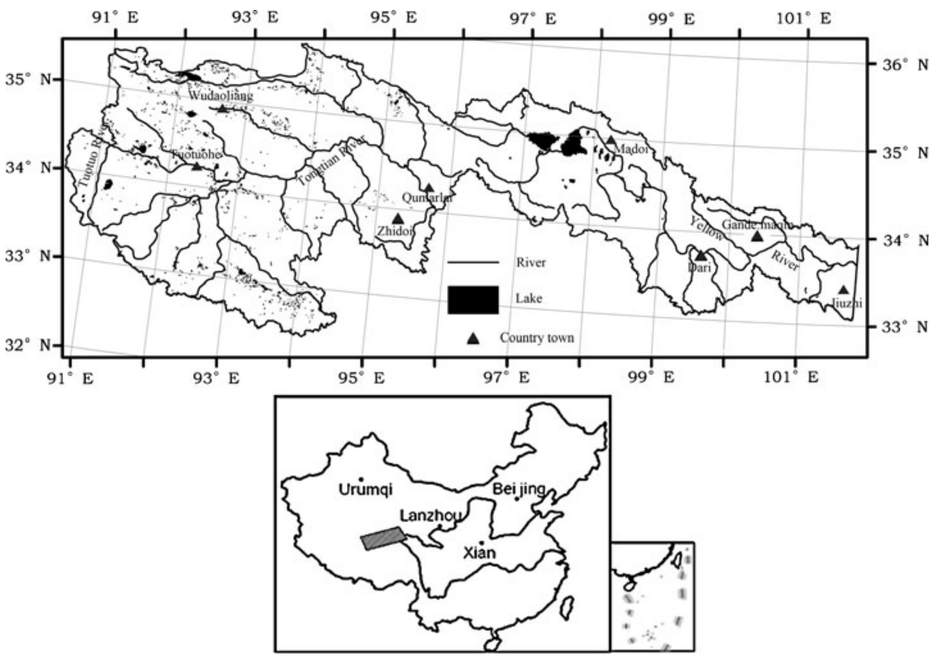

Fig. 1 Location of the study area

Table 1 Landscape types their distribution in the study region of Qinghai-Tibet plateau (2000)

	AC meadow	AC steppe	ACS meadow	SAND lands	BRS&S land	SAL land	Rivers & lakes	GL&PS land
Area (km^2)	27,589.84	14,695.03	5,158.24	3,393.03	27,504.75	142.53	5,270.69	1,163.39
Percent %	32.05	32.73	4.26	2.8	22.7	0.12	4.35	0.96

AC meadow alpine cold meadow, *ACS meadow* alpine cold swamp meadow, *AC steppe* alpine cold steppe, *SAND lands* mobile and semifixed sandy lands, *SAL lands* saline-alkali land, *BRS&S lands* bare rock, soil and shoaly land, *Rivers & Lakes* river and lakes and GL&PS lands, glacier and permanent snow cover lands

with an active layer of 0.8–1.5 m and permafrost temperature between −1.5 and −3.7°C (Zhou et al. 2000). In the headwater area of the Yellow River, permafrost was discontinuous and sporadic, with the depth below 50 m (Zhou et al. 2000).

The main native alpine tundra ecosystems in this region are alpine cold steppe, meadow, and swamp. Sparse alpine *Myricaria* shrub cover occurs locally in river valleys, and provides sparse anti-erosive cover on the upper mountains (Li and Zhou 1998; Wang et al. 2004). Alpine cold steppe ecosystems, consisting of hardy perennial xeric herbs and dwarf shrubs, are dominated by the species of *Stipa purpurea Grisebach steppe, Carex moorcroftii Falc. ex Boott. steppe* and *Dalea racemosa steppe* etc. Alpine cold meadow ecosystems consist mainly of cold mesophytic perennial herbs growing under moderate water stress conditions, where the soil is unsaturated. Meadows are dominated by *Kobresia pygmaea* (C.B. Clarke) C. B. Clarke, *Kobresia humilis* (C. A. Mey.) Serg., *Kobresia tibetica*. Formed in areas with permanent waterlog or where the soil is saturated, the alpine cold swamp meadow ecosystems support hardy perennial hydrophilous or hydro-mesophytic herbs (Li and Zhou 1998; Wang et al. 2004; Zhou 2001; Zhou and Song 1990).

Based on the principles of landscape-ecotypes classification (Jorgenson et al. 1999; Xiao et al. 1997), the nature of the land cover, and the interpretation of satellite and remote sensing images, the study area could be categorized into eight landscape-ecotypes: (i) alpine cold meadow (AC meadow), (ii) alpine cold swamp meadow (ACS meadow), (iii) alpine cold steppe (AC steppe), (iv) mobile and semi-fixed sandy lands (SAND lands), (v) saline-alkali land (SAL lands), (vi) bare rock, soil and shoaly land (BRS&S lands), (vii) river and lakes (Rivers & Lakes), and (viii) glacier and permanent snow cover lands (GL&PS lands). The details in identifying and classifying land cover types can be found in research by Wang et al. (2004, 2007). The distribution of land cover types across the study region (Table 1) showed three main tundra ecosystems: AC meadow, AC steppe, and ACS meadow. These three types respectively accounted for 32, 33, and 4.3% of the total area, or collectively for 70% of the study area (Table 1).

3 Methods and data sets

3.1 Field investigation and remote sensing data analysis

For field investigation, a vegetation distribution map of the region (Zhou and Song 1990) was used to obtain basic information regarding the spatial distribution of the three main types of vegetation: AC meadow, AC steppe and ACS meadow. Using

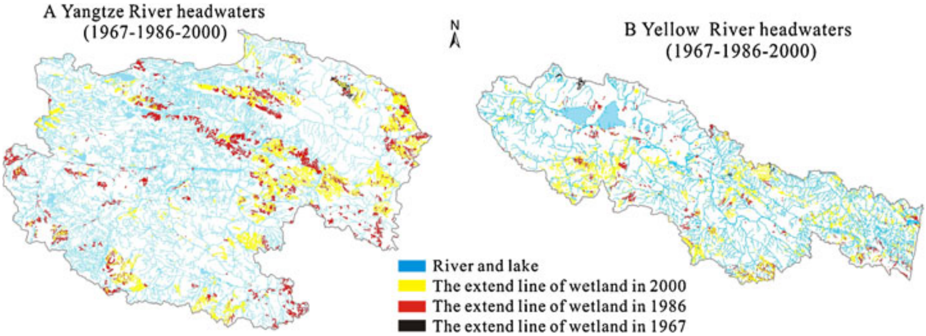

Fig. 2 Images of the spatial pattern variation of alpine swamp in the Qinghai-Tibet plateau region from 1967 to 2000

a sample belt transect method, the transects were arranged in two positions: (i) sub-zones were divided according to the map-assessed distribution of land cover type sub-regions and transects were arranged so as to run through these different sub-regions. (ii) belt transects were arranged according to landform units and degree of land cover within the same type of ecosystem sub-region, perpendicular to the first set of belts. Four to seven sampling sites were arranged in each of the secondary transect belts. Figure 2 shows the sketch of transects and sample distribution.

From three to five 1.0 m × 1.0 m sampling quadrates, oriented in different directions were set up at each site arranged in the transect belts (Fig. 2). The sampling quadrates at each site were chosen based on different land cover types, landforms, and the sub-division of land cover types (e.g., AC meadow was divided into three sub-types according to coverage). The plant species, abundance, community cover, total coverage, biomass, soil structure, and soil moisture were quantified for each sampling site. The remote sensing interpretation marker database contained 246 marker points of the eight landscape-ecotypes was established after the field investigation.

In the headwaters of the Yangtze and Yellow rivers, supported by a remote sensing interpretation marker database established on the basis of transect surveys, three sets of remote sensed data, including 1967 aero photographic data and satellite TM image data for 1986 and 2000, were processed using ERDAS IMAGE and ARC/INFO software. Based on a 1:100,000 topographic base map, raw data were run through a series of treatments including TM[ETM] radiation calibration, geometric rectification, UTM geographical coordinate image rectification, and topographic map (1:100,000) rectification, so as to attain an accuracy of RMS < 1 pixel.

After interpreting and mapping, different sites were randomly selected for different landscape types to recheck the precision of vegetation types. Mapping error was limited to 14%, 11%, 16% and 18% in alpine cold swamp meadow, alpine steppe, alpine cold meadow and "Black-soil" meadow or weed meadow, respectively, with most errors occurring in distinguishing between alpine cold swamp meadow and high-cover alpine cold meadow, lower-cover alpine cold meadow and high-cover alpine steppe, and lower-cover alpine cold meadow and "Black-soil" meadow or weed meadow. According to spot-check results, the transforming area between those landscapes types was revised by correcting for the mapping error.

3.2 Investigation of permafrost and climatic data sets

The indicators used for permafrost change analysis includes the thickness of active layer, permafrost thickness and permafrost ground temperature. EKKO100 geologic radar detector and direct current electrode depth gauge technique were used to determine the thaw depth over permafrost, groundwater level above frozen layer, and permafrost thickness in each transect and sampling points along the 1–1.5 km section of the Qinghai-Xizang (Tibet) highway. In addition, a large number of bore holes were drilled in the engineering exploration processes of the Qinghai-Tibet railway to collect the data of permafrost indicators such as the thickness of active layer, permafrost thickness, and permafrost temperature. The 17 observation points of permafrost temperature were arranged in the permafrost region along the Qinghai-Tibet railway to collect the data of ground temperature and active layer thickness of different types of permafrost (Wu and Zhang 2008; Zhou et al. 2000).

Six meteorological stations were assigned in the Yangtze River and Yellow River headwater areas. These stations provided complete data of precipitation and air temperature for the period of 1960–2005. River runoff observation data of ACS meadow areas at the outlet of the Yangtze River and Yellow River headwater was available for the period of 1960–2005.

3.3 Analysis of tundra spatial pattern changes

Two landscape indexes were used to compare and analyze spatial-temporal shifts in tundra types, the variation in extent of land cover attributable to a specific tundra type, P_i and its rate of variation in time, R_i were defined as (Liu et al. 2002; Wang et al. 2004, 2007):

$$P_{\mathrm{i}} = \left[(LU_{kit1} - LU_{kit0}) \big/ LU_{kit0} \right] \times 100\% \tag{1}$$

$$R_{\mathrm{i}} = \frac{(LU_{kit1} - LU_{kit0})}{LU_{kit0}} \times \frac{1}{T} \times 100\% = P_i \times \frac{1}{T} \tag{2}$$

where,

i	subscript represents tundra ecosystem type,
k	subscript represents the sub-region,
t0, t1	subscript represents time of onset and end, respectively, of the time interval, T, under study,
LU_{kit0} and LU_{kit1}	represent the area of the ith tundra ecosystem in the kth sub-region at the start and end of the study period, respectively.

For assessing the discrete degree of spatial fragmentation of the tundra ecosystem, one can calculate the landscape fragmentation index and the degree of patch isolation, which can be viewed as potential influences on biodiversity. The fragmentation index of a tundra ecosystem is calculated based on the landscape fragmentation formula of Wang et al. (2004, 2007):

$$C_{ki} = n_{ki} / LU_{ki} \tag{3}$$

where,

n_{ki} is the area of the patch number corresponding to ith tundra ecosystem type in the kth sub-region,
C_{ki} is the fragmentation of the to ith tundra ecosystem in the kth sub-region, and
LU_{ki} is the area of to ith tundra ecosystem type in the kth sub-region.

The degree of the tundra ecosystem of patch isolation within the spatial distribution, S_{ki}, can be determined according to the method developed in landscape ecology (Wang et al. 2006).

$$S_{ki} = \left(0.5\sqrt{\frac{n_{ki}}{LU_{ki}}}\right) \Big/ \left(LU_{ki}/LU_k\right) \tag{4}$$

3.4 Relationship between climatic factors and changes in tundra ecosystem

The distribution areas of the two main tundra ecosystem types, AC meadow (including alpine swamp) and alpine steppe, were correlated, and they were analyzed against the climate change parameters to obtain a relationship in the period between 1967 and 2000. Because regional changes in alpine grassland area may also affected by population changes (Wang et al. 2001), in this study, a population-based piecewise linear interpolation method was developed to simulate the dynamics of alpine grassland (AC meadow and AC steppe) area change using a 3-year moving average as the weight of the linear interpolation:

$$LU_{it} = LU_{i,t-1} + r_{jt} \Delta LU_{ij} \tag{5}$$

where,

j is the date interval number,
r_{jt} is the mean population growth/economic policy weighing factor at year t within the jth interval.
ΔLU_{ij} is the difference in tundra ecosystem area of the ith region between the beginning and end of the jth interval;
LU_{it}, $LU_{i,t-1}$ are the areas of the ith tundra ecosystem type in the study region, at times t and $t-1$, respectively.

The relationship of tundra ecosystem area changes and climatic factors (air temperature and precipitation) were then analyzed, and a regression model linking tundra ecosystem area and climatic factors was formed from mean annual series data collected by function (5). Analysis of variance (ANOVA) was used to assess the significance of models. All statistical analysis was performed using SAS 8.1 software (SAS Institute 2000).

3.5 Analysis of permafrost response to climate changes and its relationship with the tundra ecosystem

The change of subsurface temperature and permafrost temperature exhibited a similar trend to the change of the air temperature. Under the climate warming, the active layer was incremented by 3.0–8.4 cm/year, and the permafrost temperature rising ratio was more than 0.05°C/year from 1995 to 2000 (Wu and Zhang 2008). In fact, the climate change would affect the thermal regime of the permafrost, and thus result in a great change in active layer thickness, permafrost temperature, and active soil water regime. Therefore, we selected the intensity of surface heat source, *HI*, the soil temperature in active layer (20 cm in depth) and the difference of surface soil temperature and air temperature, DT, to indicate potential changes of permafrost thermal regime caused by climate change (Ji et al. 1998; Li et al. 2003):

$$HI = H + LE = Rn - Gs \tag{6}$$

where H and LE are the sensible heat flux and latent heat flux, respectively. The total heat $HI = H{+}LE$ is defined as the intensity of surface heat source. *Rn* is the net radiation. *Gs* is the soil surface heat flux. The values of *Rn* and *Gs* were obtained from the six meteorological stations. The value of DT was calculated by surface soil temperature (5 cm in depth) minus the surface air temperature (1.0 m in height). Based on the gradient observational data of the atmospheric surface layer from 1993 to 2000 collected by an Automatic Weather Station (AWS) installed in Wudaoliang region, together with the observation data from the GAME/Tibet program (1996–2000), the *HI* was calculated using an empirical formula as fellow (Ji et al. 1998; Li et al. 2003; Li 2005):

$$HI = a + b\,T_s + cT_a + dE_s \tag{7}$$

where, T_s and T_a are the surface and air temperature (°C), respectively. E_s is vapour pressure (hPa). Constants of a, b, c, and d are the empirical coefficients.

The variations of active soil depth and temperature are the main indicators for permafrost change. They are derived by surface soil heat regime, and thereby result in the variation of the soil moisture within active layer (Li et al. 1996; Zhou et al. 2000; Wu and Zhang 2008). The DT and *HI* determine the soil heat regime of active layer, which was the important driving factor of permafrost change (Li et al. 1996; Li and Wu 2004). Because of lacking the observational data of the regional permafrost change, the permafrost thermal regime index *HI* and DT should be used to indicate the permafrost variation under climate change. However, as the DT value and its dynamics are determined by *HI*, it is inappropriate to include both DT and *HI* in the regression analysis as independent variables. Therefore, we only selected the intensity of surface heat source *HI* to indicate the permafrost thermal regime change. The permafrost thermal regime change controls the thickness of active soil layer, which might be the main factor affecting soil moisture regime. The soil moisture and temperature and their dynamics within active layer had a great effect on alpine cold vegetation (Wang et al. 2007). Therefore, the variation of permafrost thermal regime can be used to analyze the impact of permafrost change on alpine ecosystems.

To analyze the relationship between permafrost and tundra ecosystems, we first correlated the thickness of active layer to the ecological index (vegetation coverage or production capacity) based on the data of permafrost investigation and the ecosystem investigation from field sampling quadrates. The analysis results were used to determine what ecosystem type had an affinity with permafrost. Then we established the duplicate responding model (Eq. 8) of tundra ecosystem to permafrost changes under the combined effects of climate changes based on Eqs. 5 and 7:

$$F_i = C_i + \alpha_i\,(T_a) + \beta_i\,(HI) \tag{8}$$

where F_i is the area of ith type ecosystem; C_i is the constant; α_i and β_i are discrete weighted values of the response function of climatic change (air temperature Ta), and permafrost change (indicated by the thermal index, *HI*), respectively, as determined according to their correlation coefficient of multiple regression method and the non-linear least squares method. The relative weight or contribution of permafrost and climate changes to tundra ecosystem was determined by standardized coefficients or path coefficient based on Eq. 8.

4 Results

4.1 Changes in the spatial distribution of alpine tundra ecosystems

4.1.1 Changes in spatial distribution of ACS meadow

Figure 2 shows the changes in spatial distribution of ACS meadow ecosystems in the source region of the Yangtze River and Yellow River between 1967 and 2000. The shrinkage of alpine swamp area mainly occurred in the source region of Yangtze River and during the period from 1986 to 2000. Figure 3 indicates that the changes in ACS meadow ecosystems of the headwater regions were minor prior to the mid 1980s. From 1986 to 2000, dramatic changes in the spatial distribution of ACS meadow ecosystems took place, such that by the year 2000 a large area of ACS meadows had disappeared from the central and southeastern portions of the region. The situation was similar in the Yellow River headwater region, where small changes in ACS meadow distribution were occurred between 1967 and 1986, but the change became significant over almost the entire region between 1986 and 2000.

As a typical area of the Qinghai-Tibetan plateau and predominantly located in the headwater region of the Yangtze River, the area of ACS meadows decreased by 29% (0.93% year^{-1}) between 1967 and 2000 (Table 2). Roughly 96% of the loss took place between 1986 and 2000, a rate of 1.87% year^{-1}. Similarly, the area of ACS meadow in the headwater of the Yellow River decreased by 13.55% between 1967 and 2000 (0.44% year^{-1}, i.e. roughly half the rate of the Yangtze headwater region), with the majority of the drop occurred between 1986 and 2000.

Fig. 3 Changes in the typical ACS meadows area in the headwater regions of the Yangtze River and Yellow River of the Qinghai-Tibet Plateau

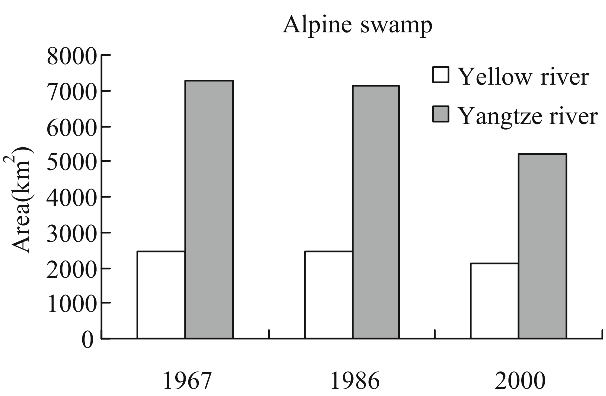

Table 2 Changes in spatial distribution characteristics of ACS meadow and AC meadow systems in the source regions of Yangtze River and Yellow River of the Qinghai-Tibet Plateau

Index		P_i			R_i		
		Swamp	Meadow	Steppe	Swamp	Meadow	Steppe
Yangtze source region	1967–1986	−5.2	−2.5	−0.1	−0.3	−0.1	−0.1
	1986–2000	−25.0	−11.3	−3.4	−1.7	−0.8	−0.2
	1967–2000	−28.9	−13.5	−3.6	−0.9	−0.4	−0.1
Yellow source region	1967–1986	−0.2	−2.5	−1.6	−0.01	−0.1	−0.1
	1986–2000	−13.4	−21.2	−5.5	−0.9	−1.4	−0.4
	1967–2000	−13.6	−23.1	−7.0	−0.4	−0.7	−0.2

The fragmentation and patch isolation indexes of ACS meadows in the Yellow River headwater region were greater than those in Yangtze River headwater region, indicating that swamp distribution was relatively scattered in the Yellow River headwater region (Table 3). The fragmental distribution pattern of ACS meadow in the Yellow River headwater rendered it to be more vulnerable to the disturbance by environmental change. Therefore, the level of patch isolation and fragmentation of alpine swamps of the Yellow River headwaters increased continually after 1967, particularly after mid-1980s (Table 3). Unlike the changes in Yellow River headwater regions, ACS meadow ecosystems in the Yangtze River headwater region exhibited decreasing fragmentation index and patch isolation index, suggesting that the degradation of ACS meadows caused disappearance of some small-scattered swamp patches.

4.1.2 Changes in spatial patterns of AC meadow and alpine steppe

The zonal alpine cold meadow and steppe landscape in the headwater area of the Yangtze River and Yellow River changed significantly from 1967 to 2000 (Fig. 4). As the area percentages of AC meadow and AC steppe ecotypes decreased, there was increase trend in newly formed landscape ecotypes, namely degraded grassland such as lower coverage alpine cold sparse steppe, black-soil (lower cover than 30%), and weed meadow. From 1967 to 2000, the AC meadow area with higher cover (vegetation cover more than 70%) was significantly decreased due to meadow degradation in Yangtze River and Yellow River headwater regions; 13.5% and 21.3% of the alpine cold meadow area were transformed into lower cover and weed meadow landscapes, respectively (Table 2). The AC steppe showed a similar decline.

Table 3 Indexes of spatial pattern changes for typical ACS meadow and AC meadow in the source regions of Yangtze River and Yellow River of the Qinghai-Tibet Plateau

Region/year parameter/tundra type		Yangtze headwaters			Yellow headwaters		
		1967	1986	2000	1967	1986	2000
Fragmentation	Swamp	0.15	0.15	0.11	0.86	0.87	0.94
	Meadow	0.49	0.48	0.48	0.45	0.47	0.37
	Steppe	0.35	0.36	0.37	0.34	0.35	0.43
Patchisolation	Swamp	0.25	0.25	0.23	0.72	0.72	0.76
	Meadow	8.96	8.98	9.72	5.91	6.35	7.19
	Steppe	2.31	2.32	2.43	1.28	1.31	1.56

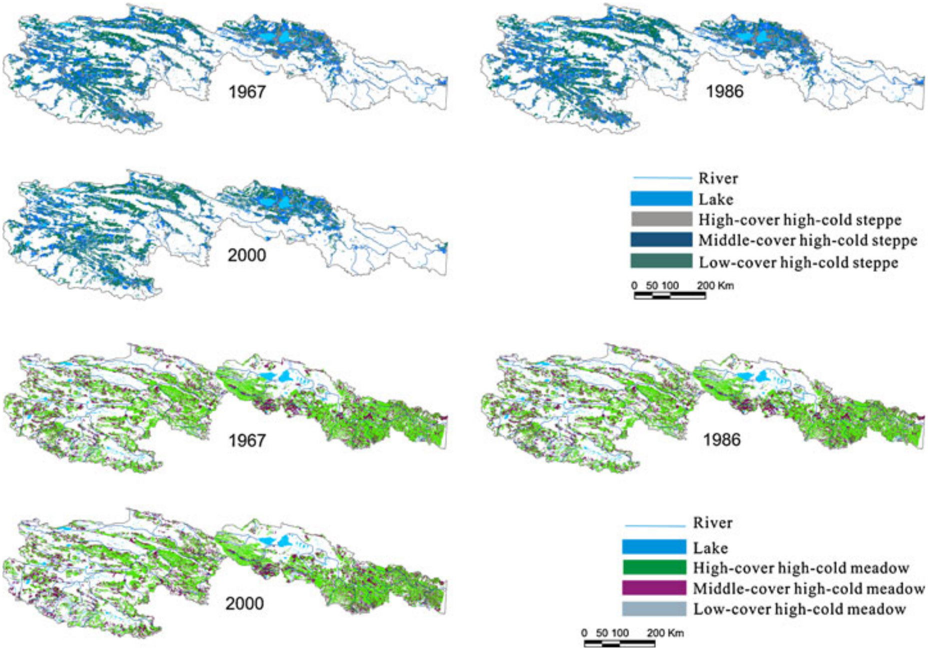

Fig. 4 Images of the spatial pattern variation of alpine meadow **a** and alpine steppe **b** in the headwater regions of the Yangtze River and Yellow River of the Qinghai-Tibet Plateau from 1967 to 2000

For the high cover area (vegetation cover more than 50%), 3.6% of them in the Yangtze River headwater regions and 7.0% of them in the Yellow River headwater region became either alpine cold sparse steppe and bare rock or soil and shoaly land (Table 2). Roughly 92% of AC meadow loss in Yellow River headwater region occurred between 1986 and 2000, a rate of 1.4% year^{-1} (Fig. 5). The area of alpine cold meadow in the Yangtze River headwater region decreased by the rate of 0.4%

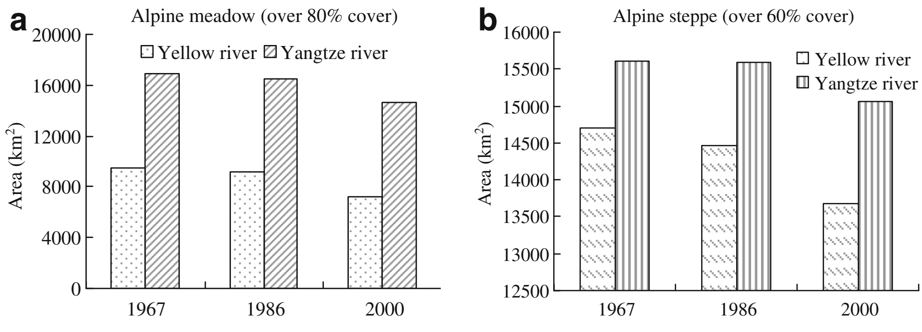

Fig. 5 Changes in the alpine meadow area **a** and alpine steppe area **b** from 1967–2000 in the headwater regions of the Yangtze River and Yellow River of the Qinghai-Tibet Plateau

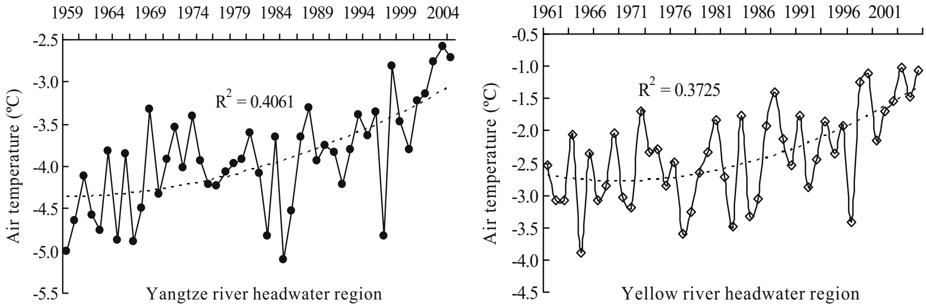

Fig. 6 Variation of air temperature from 1960 to 2005 in the headwater regions of the Yangtze River and Yellow River

year^{-1} between 1967 and 2000, with the majority of the drop occurred between 1986 and 2000, a decrease rate of 0.8% (Fig. 5, Table 2).

The fragmentation index of the AC meadows decreased in the Yangtze and Yellow River headwater regions from 1967 to 2000, while the patch isolation of the alpine meadows increased with the degradation of alpine cold meadow (Table 3). These changes indicated that the degradation of AC meadows resulted in disappearance of some small scattered meadow patches. Contrary to the AC meadow, the fragmentation and patch isolation indexes of the alpine steppes increased significantly from 1967 to 2000 in the river source regions, suggesting that the degradation of alpine steppes led to the shrinking and discretion of some large steppe patches.

4.2 Climate changes and its relationship with the tundra decline

4.2.1 Climate changes and the permafrost responses

Over the last 40 years, the study area had exhibited an obvious warming trend (Fig. 6); mean temperatures hade increased by 0.37–0.45°C/10a between 1960 and 2005. However, there were different trends before and after 1980. Prior to the 1980, the changes of air temperature in Yangtze River headwater region slightly increased by 0.20°C/10a, and there was no significant change in the Yellow River headwater

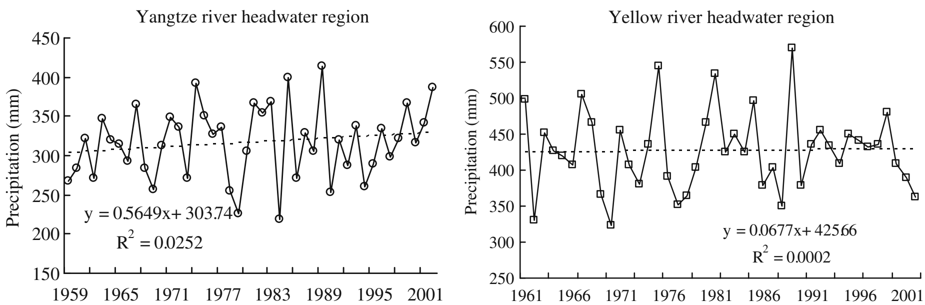

Fig. 7 Variation of precipitation from 1960 to 2002 in the headwater regions of the Yangtze River and Yellow River

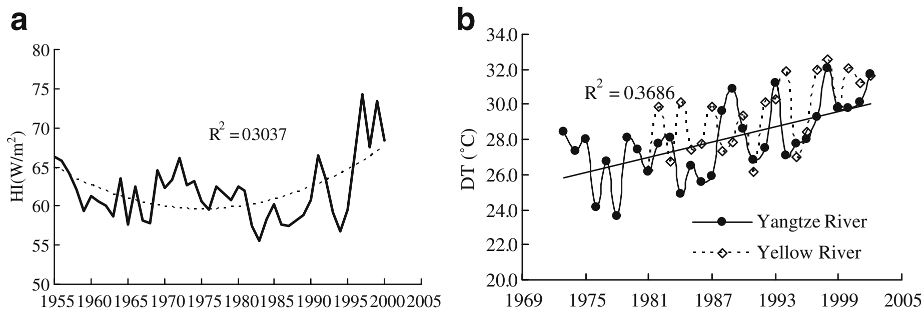

Fig. 8 Dynamic changes of surface heat capacity, *HI* (**a**) and the difference of surface soil temperature and air temperature, DT (**b**)

regions. From 1981 to 2005, dramatic changes in the air temperature took place in both Yangtze River and Yellow River headwater regions, such that by the year of 2005 the air temperature had increased by 1.60°C and 1.20°C in these two regions, respectively. The annual precipitation over the last 40 years had no noticeable change (Fig. 7, Wang et al. 2001). The region's climate exhibited a tendency towards desiccation, which seriously affected the normal growth and reproduction of vegetation (Li and Zhou 1998; Wang et al. 2001).

Owing to the influences of climate change, obvious changes were occurred in the surface heat capacity and the difference of soil and air temperatures (DT). As shown in Fig. 8, the *HI* and DT exhibited significant increasing trend. Similar to air temperature changes, the majority of the increase of *HI* and DT occurred between 1980 and 2005. During that period, the *HI* was increased by an average of 0.45 W/m^2 per year, and the DT was increased by averages of 4.50°C and 4.10°C in Yangtze River and Yellow River headwater regions, respectively (Fig. 8). Under *HI* and DT increase, the soil temperature within the active layer exhibited a notable increase trend. As shown in Fig. 9, the soil temperature within 20 cm in depth increased by averages of 1.40°C and 1.10°C in Yellow River and Yangtze River headwater regions, respectively (Fig. 9a). With the increases of *HI* and soil temperature within the active layer,

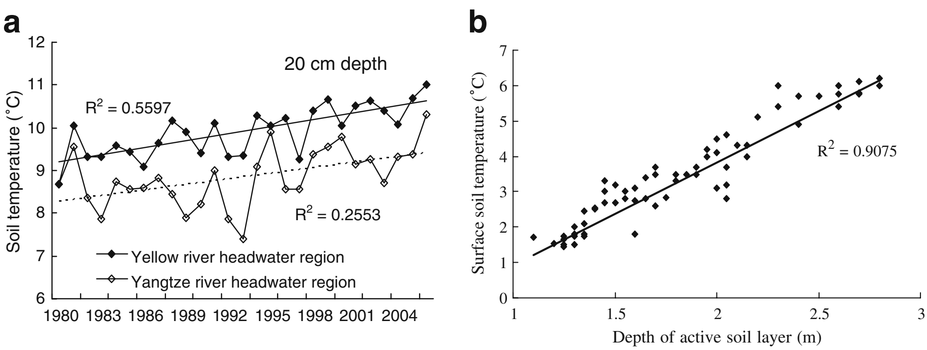

Fig. 9 Dynamic changes of soil temperature within the active layer 20 cm in depth, (**a**) and the relationship between surface soil temperature and the depth of active soil layer (**b**) in the study region

the mean permafrost temperature had evidently elevated by more than 0.05°C/10a over the last 20 years (Zhao et al. 2000; Wu and Liu 2004). In addition, the mean annual increment of active layer was about 0.8–8.4 cm/year and the relationship between surface soil temperature and the depth of active soil layer was positive liner (Fig. 9b, Wu and Liu 2004; Wu and Zhang 2008). The changes of the active layer and the thermal regime of the permafrost were consistent with the change of air temperature.

4.2.2 Correlations between tundra ecosystem degradation and climatic variables

To explore the correlation between the climate change and the areas of ACS meadow, AC meadow, and alpine steppe, the climatic variables of the mean annual air temperature, annual precipitation, mean air temperature and precipitation during the growing season (April–Sept.) were selected. The data series of ACS meadow area, high cover AC meadow area, and high cover alpine steppe area was obtained from Eq. 5. In the Yangtze River headwater region, alpine swamp area and AC meadow area were strongly correlated with the air temperature of the growing seasons ($R^2 = 0.53$ and 0.47, respectively, $P \leq 0.0001$) (Figs. 8b and 10a), and not correlated with mean annual air temperature ($R^2 = 0.19$ and $R^2 = 0.07$, respectively, $P \geq 0.044$). In the Yellow River headwater region, ACS area and AC meadow area

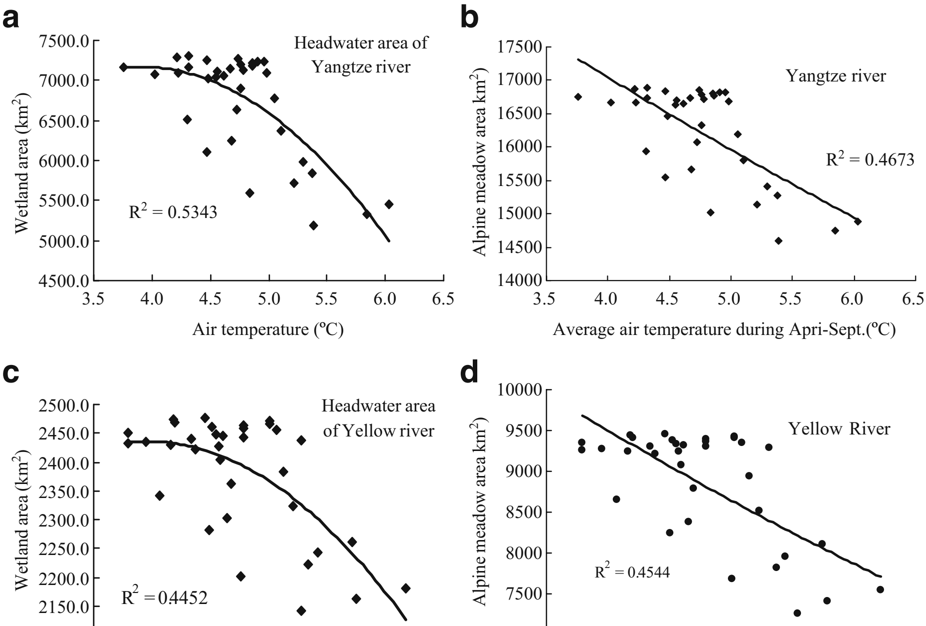

Fig. 10 Correlation relationships between air temperature changes and the variation of ACS meadow area (**a**), AC meadow area (**b**) in the headwater region of the Yangtze River, and the variation of ACS meadow area (**c**) and AC meadow area (**d**) in the headwater region of the Yellow River

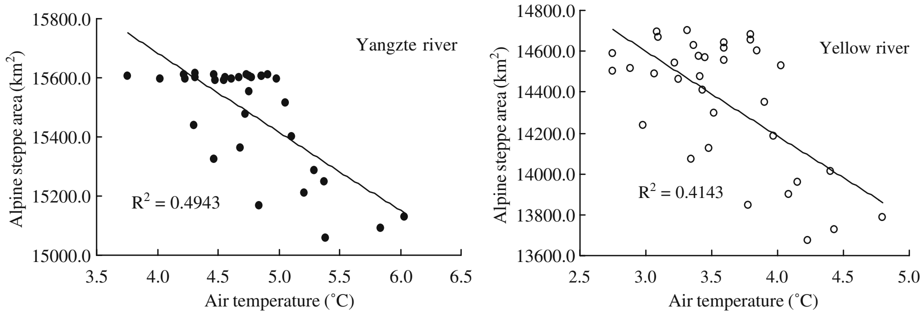

Fig. 11 Correlations between air temperature changes and the variation of alpine steppe area in the headwater regions of the Yangtze River and Yellow River

were closely correlated with the air temperature of the growing seasons ($R^2 = 0.44$ and 0.45, $P \leq 0.0001$) (Fig. 10c and d), and to a lesser extent with mean annual air temperature ($R^2 = 0.18$ and 0.22, $P \leq 0.021$). In contrast, alpine swamp area and AC meadow were not correlated with annual precipitation ($R^2 \leq 0.07$, $P \leq 0.38$) and mean growing season precipitation ($R^2 = 0.11$, $P \leq 0.19$) in the study region. The alpine steppe area was strongly correlated with the air temperature of the growing seasons ($R^2 = 0.49$ and 0.41, $P \leq 0.0001$) in the study region (Fig. 11). These strong correlations between the air temperature and alpine swamp area, AC meadow area, or steppe area demonstrated that the tundra ecosystems of the Qinghai-Tibet Plateau were strongly influenced by air temperature changes, particularly during the vegetation growing season. The degradation of the permafrost major tundra ecosystems (loss of area) was strongly linked to the rising air temperature of the growing seasons over the past 40 years.

4.2.3 Correlations between tundra ecosystem degradation and permafrost changes

There was a significant statistical correlation between vegetation cover and the thickness of active layer in the AC meadow and ACS meadow landscapes (Fig. 12a). As the thickness of the active layer increased, the vegetation cover of the AC

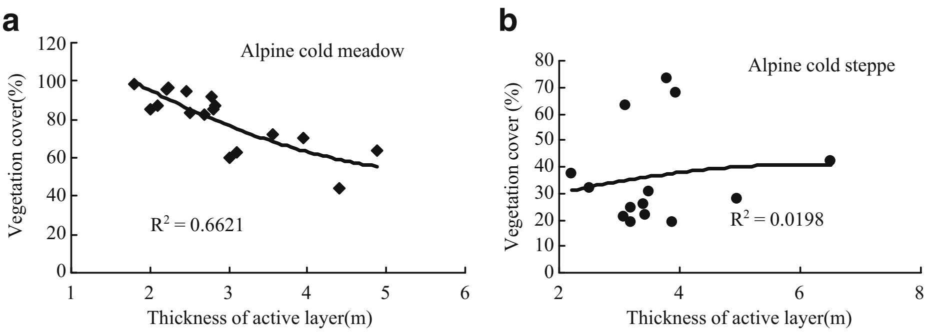

Fig. 12 Statistic correlations between vegetation cover and the thickness of active layer in alpine meadow (**a**) and alpine steppe (**b**)

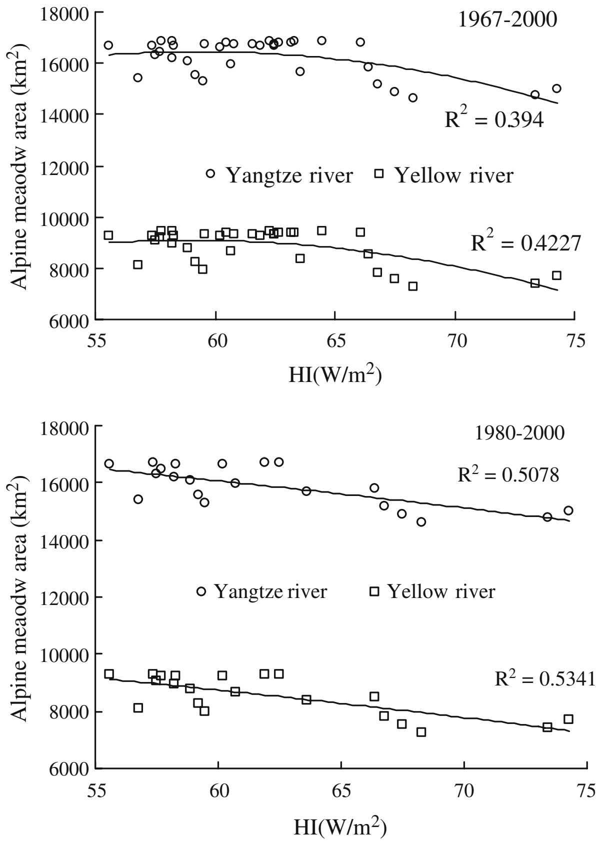

Fig. 13 Statistical correlation between AC meadow area and the surface heat capacity, *HI*

meadow and ACS meadow significantly decreased with a correlation coefficient of 0.81 ($P \leq 0.001$). However, there was no significant trend of alpine steppe coverage changes with the thickness of active layer (Fig. 12b). Apparently, the changes in permafrost environment had little effect on the distribution of alpine steppe. For this reason, the AC meadow and ACS meadow were more sensitive to the permafrost changes, while the alpine steppe was relatively stable (Wang et al. 2006).

In the study region, AC meadow area was correlated relatively weakly with *HI* index ($R^2 = 0.39$ and 0.42) in Yangtze River and Yellow River, respectively ($P = 0.004$) (Fig. 13a) during 1967–2000. However, the correlation became more

Table 4 The regression response model of tundra ecosystem to climate and permafrost changes and various parameters in the Yangtze River headwater region

Periods		Regression model	Correlation R	F-test	Standard α and β
Alpine meadow	1967–2000	$F = 22624.35 - 41.0HI - 808.68T_a$	0.698	14.69	−0.32, −0.68
	1980–2000	$F = 22809.83 - 58.06HI - 683.98T_a$	0.816	17.98	−0.47, −0.53
Alpine swamp	1967–2000	$F = 12717.56 - 41.51HI - 720.09T_a$	0.71	15.83	−0.35, −0.65
	1980–2000	$F = 12942.88 - 56.72HI - 620.145T_a$	0.82	19.6	−0.49, −0.51

Table 5 The regression response models of tundra ecosystem to climate and permafrost changes and various parameters in the Yellow River headwater region

Periods		Regression model	Correlation R	F-test	Standard α and β
Alpine meadow	1967–2000	$F = 14579.84 - 53.43HI - 673.13T_a$	0.71	15.0	−0.42, −0.58
	1980–2000	$F = 14783.68 - 65.46HI - 596.59T_a$	0.83	20.28	−0.52, −0.48
Alpine swamp	1967–2000	$F = 3212.849 - 7.618HI - 101.49T_a$	0.685	13.73	−0.41, −0.59
	1980–2000	$F = 13232.786 - 9.47HI - 87.09T_a$	0.83	19.93	−0.52, −0.48

significant during 1980–2000 (Fig. 13b), and the correlation coefficient R reached 0.51 and 0.53 in Yangtze River and Yellow River headwater regions, respectively ($P = 0.0017$).

Using the above-mentioned method, the duplicate responding model was established based on two factors, climatic change (change in air temperature) and the permafrost change (change in *HI*). The results of regression showed (Table 4) that the contributions of climate warming and the permafrost thermal changes to the decrease of AC meadow area was 68% and 32%, respectively, in the Yangtze River headwater regions during 1967–2000, compared to 53% and 47% for those contributions from 1980 to 2000. For alpine swamp ecosystem, the contributions of permafrost thermal changes was increased from 35% between 1967 and 2000 to 49% between 1980 and 2000, which was approximately equal to the contribution to the climate changes effects. In the Yellow River headwater regions, the contribution of permafrost thermal changes to tundra ecosystems was much stronger than that in Yangtze River headwater region. Between 1967 and 2000, the contributions of permafrost changes to AC meadow and alpine swamp were both more than 41%, and even reached 52%; both were greater than the contribution of climate changes between 1980 and 2000. The tundra ecosystems in the Yellow River headwater region were more responsive to permafrost changes than that in the Yangtze River headwater region. The effects of permafrost changes on tundra ecosystems were more significant and stronger after 1980 than that before 1980. Owing to the correlation coefficients were more than 0.8 for both Yangtze River and Yellow River headwater regions between 1980 and 2000, the correlation of tundra ecosystem changes with the synergic effects of climate and permafrost changes tended to much more significant after 1980s (Tables 4 and 5).

5 Discussion

Natural climatic conditions, permafrost environment, and human activities are probably the three major aspects that control the changes of alpine-cold ecosystem. Human activity in the study region mainly manifests in the livestock grazing activity. According to investigation in the study region, the density of population is only 2.1 people per km^2, and there is still large surplus of grassland carrying capacity, which in some places reaches up to 80% (Wang et al. 2001). Wang et al. (2009) determined that the contribution of nature factor including climate and permafrost changes to the alpine grassland ecosystems degradation reached to 82–86% in the headwater area of the Yangtze River. Therefore, the grazing might have an important impact on the alpine grassland ecosystem, but the effects were much weaker than that of climate change. As described above, the significant correlation between AC meadow ecosystem and the active layer thickness indicated the higher sensitivity of high-coverage AC meadow, especially the alpine-cold swamp meadow ecosystem, to the permafrost environment variations. The lower the upper limit of permafrost, the more rapid the degradation of the alpine cold swamp meadow and high-coverage alpine cold meadow. The existence of permafrost supported the development and expansion of AC meadow and alpine swamp ecosystems under the cold and semiarid (precipitation <400 mm) conditions. Permafrost is sensitive to climate changes; any changes in the climatic condition can cause profound variation of the frozen soil environment (Jorgenson et al. 2001; Christensen et al. 2004; Wu and Zhang 2008). The synergic effects of climate change and permafrost variation resulted in more serious degradation or larger area shrinkage of the alpine cold meadow and swamp meadow than the alpine steppe (Klein et al. 2005).

Vegetation cover variation has a significant influence on the net radiation *Rn* and the energy flux regime. The sensible heat flux *H* and soil surface heat fluxes *Gs* decreased with increasing vegetation cover (Ma et al. 2006). The differences of heat transmission and surface heat flux under different vegetation covers were related to different heat balance and heat consumption level. The variation of heat balance and soil surface heat flux that transferred into and from soil was significant with different vegetation covers and in different seasons. This might be the main factor to cause the variation of the soil–air temperature difference and soil temperature under different vegetation cover. Of the potential drivers considered here, the serious degradation of alpine ecosystem in large area since 1980 remains the most viable explanation for the significant increase of *HI* and DT in the study region. The maintenance of a high vegetation cover upon AC meadows is favourable to slow the heat cycling of the permafrost and minimize the impact of climate change on the permafrost.

6 Conclusions

In the permafrost region of Qinghai-Tibet Plateau, the air temperature has been increased by 0.4–0.54°C/10a over the last 45 years. The major increase of the air temperature took place during 1980–2005, when the air temperature increased by 1.2°C–1.6°C. Contrary to arctic tundra region, the precipitation showed no noticeable change. Therefore, the regional climate exhibited a tendency towards significant warming and desiccation. Owing to the influences of climate warming, dramatic changes of land surface and active soil thermal regime occurred in the Yangtze River and Yellow River headwater regions. The surface heat capacity, the difference of soil and air temperature, and the soil temperature within the active layer increased quickly, causing evident degradation of permafrost over the last 20 years.

Under the synergic impact of climate change and permafrost variation, the tundra ecosystems exhibited a noticeable degradation. Since the 1960s, ACS and AC meadow area with high vegetation cover had decreased by more than 14%, particularly ACS meadow in the Yangtze River headwater region, where the decline was 29% between 1967 and 2000. The degradation processes of tundra ecosystems were strongly correlated with the climate warming and permafrost variation. With the majority of the increase in air temperature and soil temperature within the active layer occurred between 1980 and 2000, more than 90% of the decreased tundra area was took place between 1980 and 2000. The degradation of tundra ecosystems in the Yellow River and Yangtze River headwaters caused fragmentation in their spatial distribution and a continuous increase in the degree of patch isolation after 1986, resulting in extreme vulnerability to the disturbance of climate change.

The impact of permafrost variation on AC meadow and ACS meadow ecosystems was more significant than alpine steppe ecosystem. Based on the primary estimation, the contributions of permafrost variation to AC meadow and ACS meadow between 1967 and 2000 was about 32–42% and 35–41%, respectively, but they were increased to 47–52% and 49–52% between 1980 and 2000. There was a close correlation among the climate, tundra vegetation, and permafrost. Under the climate warming, the variation of permafrost had a strong effect on tundra ecosystems.

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