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ORIGINAL ARTICLE

Eco-environmental degradation in the northeastern margin of the Qinghai–Tibetan Plateau and comprehensive ecological protection planning

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Abstract The regional hydrology and ecosystems of the northeastern margin of the Qinghai–Tibetan Plateau have changed over the past 40 years driven by intense human activity and regional climate changes. Annual mean air temperature has increased in the region. Streamflow from the northeastern margin of the Qinghai–Tibetan Plateau has decreased significantly. Overall, a number of Alpine step meadows and Alpine frigid meadows have seriously degraded. Degeneration of vegetation and grassland led to desertification and frequently induced dust storms. With the continuous increase in cultivated land area, grassland area in the region has dropped significantly since the 1960s. At present, degraded grassland occupies about 83% of total usable grassland area. As the number of livestock increased, range condition deteriorated and the carrying capacity was reduced. The forest area in the northeastern margin of the Qinghai–Tibetan Plateau has decreased by 20%, and the local ecosystem has become very fragile. Given the relatively stable weather conditions, the northeastern margin of the Qinghai–Tibetan Plateau can be characterized by its three major ecosystems: grassland ecosystem, forest ecosystem and wetland ecosystem, which are crucial in maintaining the ecological stability. Changes in these ecosystems could influence sustainable development in the region. To avoid further deterioration of the environment and ecosystems, it is important to establish and implement ecosystem protection planning. Some effective measures are essential in this respect, including technical and political considerations.

Keywords Climate change · The Qinghai–Tibetan Plateau · Grassland · Source region of Yellow River

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Introduction

Environmental changes caused by human activities and regional climate changes have long been recognized throughout the world (Chen and Qu 1992; Ye et al. 1998; Wang and Cheng 1999; Chen and Kang 2001; Shi et al. 2001; Umar et al. 2001; Feng et al. 2006). During the past half-century, drastic environmental changes have occurred, which have invoked concerns. In the northeastern margin of the Qinghai–Tibetan Plateau, like elsewhere in the world, environmental changes can be classified into two categories, i.e. natural and human factors. The former includes tectonic uplift and a monsoon climate (Zhang et al. 2000a). The latter involves population explosion and human activities (Zhang et al. 2000b). The formation of the fragile eco-environment in northwestern China is a result of long-term natural evolution, superimposed by human activities in recent times. The northeastern margin of the Qinghai–Tibetan Plateau is one area severely affected by these changes. As a part of the Yellow River basin, the northeastern margin of the Qinghai–Tibetan Plateau is one of the most important inland bodies of water for the Yellow River, with about 18.6% of the runoff coming from this region. The source region's eco-environmental changes and related land degradation have a strong influence on the hydrological conditions and the environments of the middle and lower reaches of the river. The repeated drying up of the Yellow River since 1990s has led to in-depth studies of eco-environmental problems in the catchment of the Yellow River (Tian 1995; Liu 1996; Xi 1997; Yang 1997). Previous studies in the upper reaches and the catchment region of the Yellow River are focused mainly on water resource utilization and soil erosion, and relatively little research has been carried out on the effects or causes of regional eco-environmental changes (Tian 1995; Liu 1996). Some preliminary results show that eco-environmental changes in the source region of the Yellow River not only greatly affect the region's sustainable development but also aggravate soil erosion (Liu 1996; Chen and Liang 1998; Cheng and Wang 1998). Viewed holistically, as part of the whole river catchment area, the eco-environmental changes and their significance for hydrology have a strong influence on the hydrological conditions and the environments of the middle and lower reaches (Feng et al. 2006). In this study, we use changes in plant communities as indicators of eco-environmental evolution caused by climatic changes (Cheng et al. 1997; Cheng and Wang 1998) and human factors, and to ascertain evolutionary trend of this fragile ecosystem. We also outline strategies that could contribute to ecological sustainability in the northeastern margin of the Qinghai–Tibetan Plateau.

Study area

The region is located between 100°45′45″ and 104°45′30″ E, and 33°06′30″ and 35°34′00″ N. It covers an area of approximately 97,000 km^2. A city and three counties of Gansu province lie in the region, namely Hezuo City, Maqu County, Luqu County, and Xiahe County (Fig. 1). The region contains three large hydrographic systems, namely, Yellow River, Tao River and Daxia River.

Geographically, the northeastern margin of the Qinghai–Tibetan Plateau belongs to stratum drape system of Qin Moutain, with a downward inclination from south to north. The southern mountains are characterized by a remarkable vertical zonality (Wu 2000). The water source area is mainly concentrated on their upper and middle sections with an elevation ranging from 1,300 to 3,500 m above sea level, and a mean annual precipitation ranging from ≤200 mm in the lower-mountain or foothill zones to ≥600 mm in the higher-mountain zone. Macroscopically, the northeastern margin of the Qinghai–Tibetan Plateau is a fragile ecosystem because of three main factors: (1) severe water loss and soil erosion, (2) grassland desertification, and (3) atrophying and extinction of swamp land.

Study method and data source

The vegetation, land (soil, land use/land cover), hydrology (including aquatic ecosystems) are the main aspects reflecting environmental changes (Wang et al. 2003). Based on information accumulated from the past 40 years in the northeastern margin of the Qinghai–Tibetan Plateau, including 40 years of hydrological records made by the Gansu Hydrology Reconnaissance Bureau, and streamflow data from previous studies, detailed analyses on environment degradation of the Yellow River resource were conducted. The evaluation of the eco-environmental degradation was further aided by Landsat images and the field investigation. The primary information for this study was obtained from eight counties' false color composites made up of bands 4, 3 and 2 (R, G, B) of Landsat^{TM} (Thematic Map) imagery of September 1982 and 2001. The spatial resolution of the TM images was 30 m× 30 m. The geometrical correction of the images was made by using the Erdas Imagine provided by ERDAS, and its accuracy was achieved within one pixel (30 m). The details of the satellite image processing were described by Navas and Machin (1997), Valle et al. (1998), Bocco et al. (2001) and Vasconcelos et al. (2002). In addition, investigations were carried out to reveal the trend of eco-environmental changes in the region over the past 40 years. During 1994, 2000, and 2005, environmental field surveys of the Gannan catchment region were conducted at two levels of detail: (1) the main sampling transects focused on the three river systems to identify and compare plant communities, (2) more intense sampling within the main sampling transects sought to assess the current and ongoing situation with respect to vegetation types, land desertification, hydrology. Some historical records were used in the comparative study of land cover changes in the area. The following indices were selected to analyze the features of regional environment change for land, vegetation, and water factors, respectively. (1) Vegetation: forest and grassland coverage, degraded grassland (grass yields, grassland desertification, and carrying capacity); (2) landscape: the area of land desertification and land desertification processes, measured and analyzed by the field surveys and historical record data; and (3) water environments were quantified by long-term observation results.

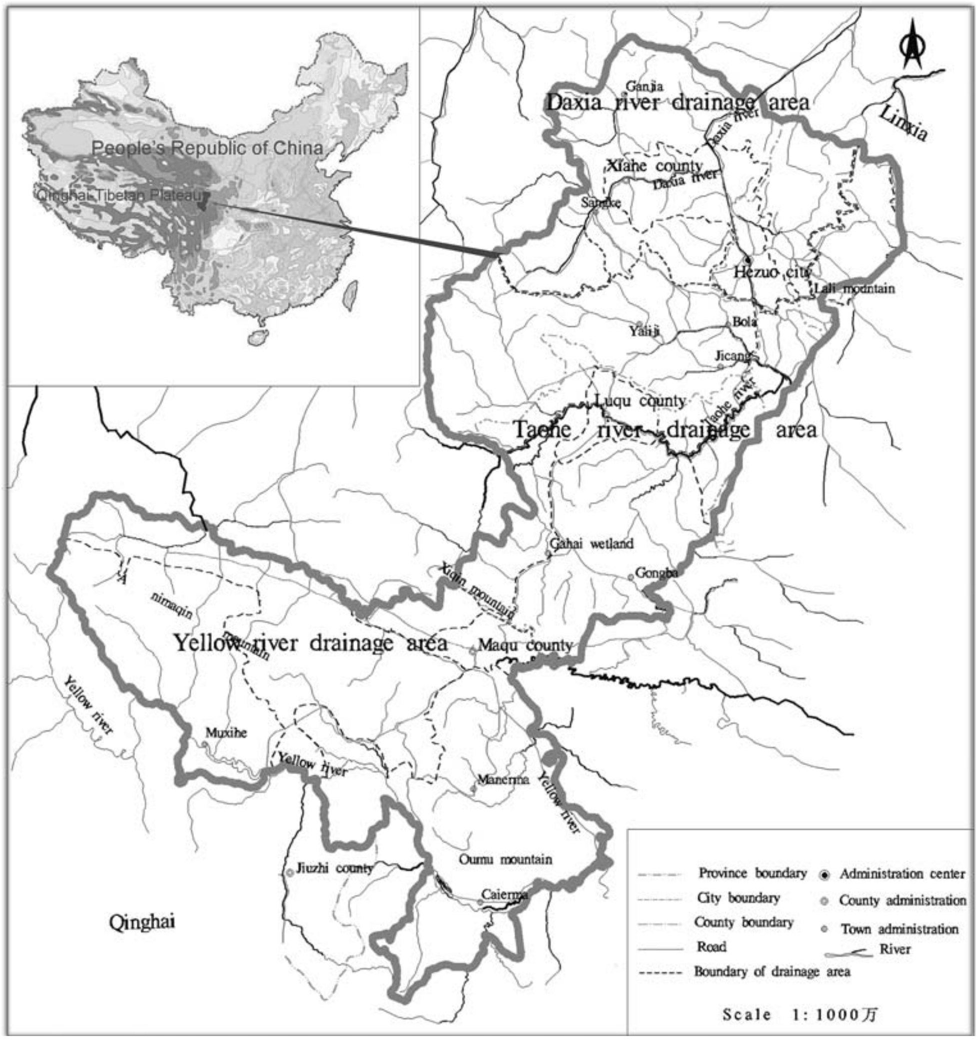

Fig. 1 The location of the northeastern margin of Qinghai–Tibetan Plateau

Results

Changes in regional water resources

Changes of surface water system

The northeastern margin of the Qinghai–Tibetan Plateau was the most important water reservation area and ecological shelter for the Yellow River basin, where rivers and swampland supply the Yellow River with large quantities of water. About 18.6% of the runoff comes from this region. During the past 40 years, due to the climate changes and irrigational water use, the surface water area in the region has decreased and water areas of most lakes and rivers were reduced. The lake water area shrank by 0.54% from 1970s to 1980s, and by 9.25% from 1980s to 1990s (Wang et al. 2001).

At the beginning of 1980s, the wetland area was 6,400,000 ha. However, at the end of 2004, the wetland area was only 1,900,000 ha, a decrease of 70.4% (Statistics yearbook of Ganan 2005; Gannan recorder 1998). In addition, the swampland drained away gradually in the northeastern margin of the Qinghai–Tibetan Plateau. Since the 1970s, the swampland vegetation was gradually replaced by meadow species, mesophytes and xerophytes (Wang et al. 2001). Swampland was 1,200,000 in 1980s and shrank to a mere 300,000 ha at the end of 2004, a reduction of 75.0% (Statistics yearbook of Ganan 2005; Gannan recorder 1998). Figures 2 and 3 represent a map showing the spatial distribution of wetland and swampland in the study areas, where there were 6.570,000 ha wetland and 1,340,000 ha swampland in 1982 (Fig. 2). By 2001, these figures shrank to 2,140,00 ha wetland and 356,000 ha swampland (Fig. 3). These represented 67.42 and 73.43% declines for wetland and swampland, respectively. In the Upland Plain Areas, some swamp plant species declined, and the peat was exposed to air (Peng 1987). The changes in wetland resulted in the disappearance of swamp species and a reduced biodiversity. The depth of the groundwater table was 20 m, at which level most plant species were incapable of utilizing the groundwater (Wang et al. 2001).

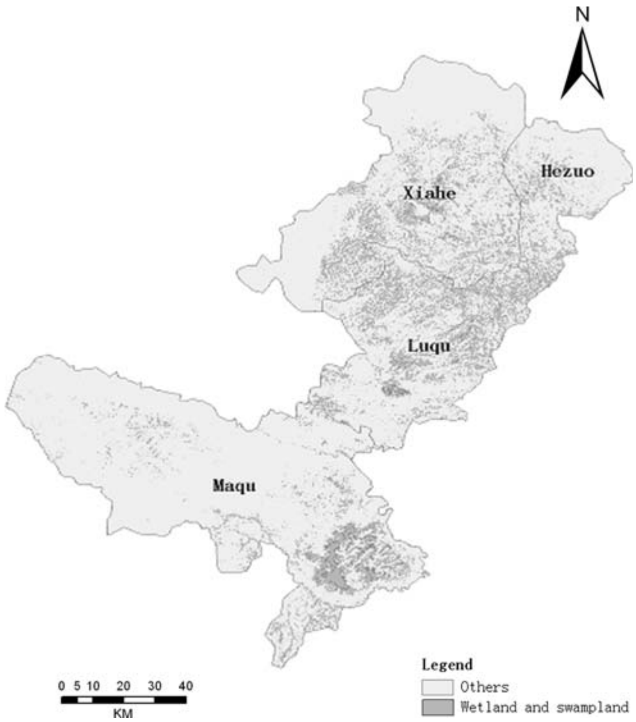

Fig. 2 A map of wetland and swampland spatial distribution in the northeastern margin of the Qinghai–Tibetan Plateau in 1982

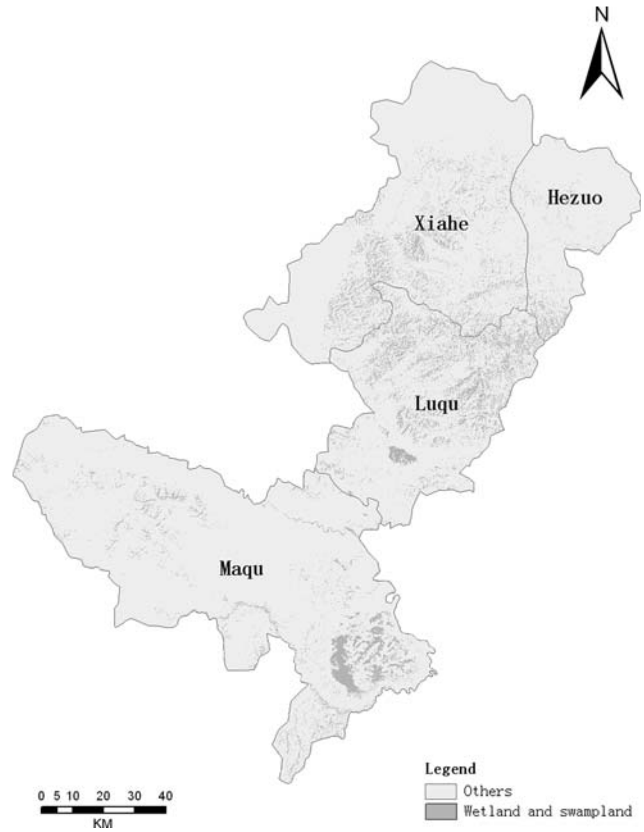

Fig. 3 A map of wetland and swampland spatial distribution in the northeastern margin of the Qinghai–Tibetan Plateau in 2001

Changes of water resource amount

The amount of water resource in the northeastern margin of the Qinghai–Tibetan Plateau has shown a steadily downward trend since 1950s (Fig. 4) (Gansu Hydrology 1972, 2005). According to Huang et al (2003), the northeastern margin of the Qinghai–Tibetan Plateau should be divided into four drainage basins, namely: Maqu, Maqu–Longyang Gorge, Daxia River and Tao River. The drainage basin area of Yellow River origin were 57,000, 29,000, 1,600 and 1,700 km^2 for Maqu, Maqu–Longyang Gorge, Daxia River and Taohe River, respectively. By analyzing hydrological data (1956–2004) of the study areas, their results showed that the multi-year variation of water resource of four catchment regions had similar patterns from 1956 to 2004. The maximum occurred at the middle and end of 1960s in all catchment regions, and declined thereafter. Tao River had the largest decrease, and a relatively lower decrease occurred in the other regions, including Daxia River region (Fig. 5). The reason for the sharp decrease in the Tao River watershed is because more grassland was cultivated to cropland (often irrigated) to meet increasing food demand of the growing population. There were high flow years in the northeastern margin of the Qinghai–Tibetan Plateau from 1956 to 1969 (Fig. 5). There were somewhat lower flow years from 1970 to 1979, and Daxia River showed a low flow year with a decrease of 15.8%. High flow years appeared in the Yellow River origin areas: Maqu and Maqu–Longyang Gorge had an increase of 13.0% from 1980 to 1989. Tao River and Daxia River had low flow years during the same period. There were serious low flow years from 1990s to 2004, a decrease of 29.03% of water resource compared to 1960s, and the average decrease from 1960s to 2004 was 14.69% (Table 1). The radial flow decreased after the 1990s.

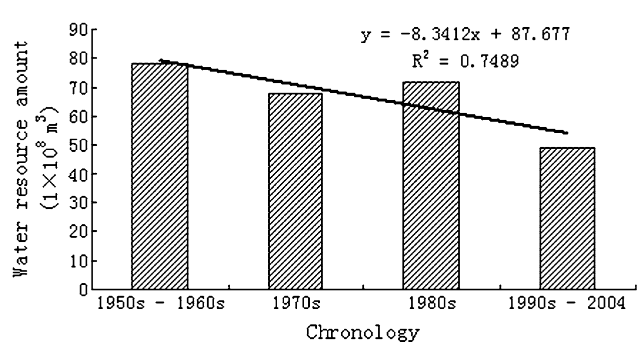

Fig. 4 The variation of the water resource amount in study region

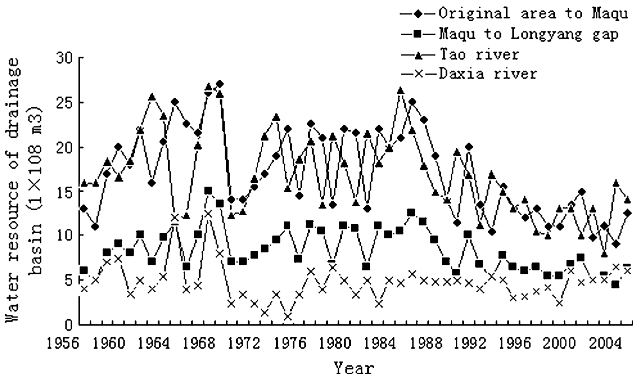

Fig. 5 Variation of annual water resource amount in sub-basin region

Changes in vegetation

Alpine meadow degradation

Under the natural conditions, when the depth of the groundwater table exceeds rooting depth, a number of Alpine step meadows and Alpine frigid meadows will die or seriously degenerate in the source regions. According to statistics (Wang et al. 2001), from the 1970s to the 1980s the areas of Alpine step meadows, Alpine frigid meadows and swamp meadows in the northeastern margin of the Qinghai–Tibetan Plateau decreased by 2.26, 3.73 and 24.53% respectively, whereas it decreased 6.64, 24.21 and 34.45%, respectively, from 1980s to 1990s. The vegetation cover on Alpine frigid meadow and shrub meadow on the river valley flats has decreased from 50 to 70% to less than 30%; and the degraded area increased from 24.5% in 1970s–1980s to 34.5% in the 1980s–1990s (Statistics yearbook of Ganan 2005). Deterioration in grassland vegetation led to land desertification and frequently induced sand storms.

Grassland ecosystems

With the continuous increase in cultivated land area and number of livestock, the area of degraded grasslands in the northeastern margin of the Qinghai–Tibetan Plateau had increased significantly since the 1950s (Fig. 6). In this region, there was about 2,960,000 ha of natural rangeland, and degraded grassland occupied about 83.20% of total usable grassland area, in which severe and moderate degraded grassland area was 814,000 ha and 1,370,000 ha, respectively; desertified grassland was 53,300 ha, and salt-affected grassland was 5,500 ha. The amount of quality forage declined from 70 to 45%. The areas invaded by noxious weeds had increased from 30 to 55% since 1980s (Yang 2004).

Table 1 Water resource amount decrease of northeastern margin of Qinghai–Tibetan Plateau at different temporal stage (1×10^8 m^3, %)

Region	1960s			1970s			1980s			1990–2004			Mean value		
	WRTA	DCCGC	RWRD	WRTA	DCCGC	RWRD	WRTA	DCCGC	RWRD	WRTA	DCCGC	RWRD	WRTA	DCCGC	RWRD
Gannan Yellow River Catchment Region	78.33	0	0	67.99	10.34	13.20	71.68	6.65	8.49	49.3	29.03	37.06	66.82	11.51	14.69
River original to Maqu	19.88	0	0	17.83	2.05	10.31	19.47	0.41	2.06	12.87	7.01	35.26	17.51	2.37	11.92
Maqu to Longyang Gap	9.33	0	0	8.37	0.96	10.29	9.13	0.20	2.14	6.04	3.29	35.26	8.22	1.11	11.90
Tao river	23.96	0	0	19.99	3.97	16.57	21.62	2.34	9.77	16.34	7.62	31.80	20.4775	3.48	14.53
Daxia river	3.79	0	0	3.13	0.66	17.41	3.55	0.24	6.33	2.979	0.81	21.40	3.36225	0.43	11.29

WRTA Water resource total amount; *DCCGC* A decrease compare and contrast given century with 1960s; *RWRD* The ratio of water resource decrease

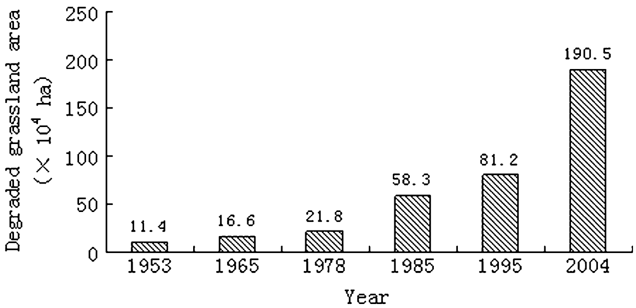

Fig. 6 Changes of degraded grassland in the study region

Changes of forest

The area of forest land in the northeastern margin of the Qinghai–Tibetan Plateau has dropped significantly since the 1950s (Fig. 7). This region had the largest forest land in the entire Gansu province. The woodland area and standing wood accumulation in the region made up 30 and 45% of the total in Gansu (Zhang et al. 2000c). Since 1950s, 18 timber factories were established and 1952 workers employed in the timber industry (Gannan 50 years 2005). At the end of 1998, the northeastern margin of the Qinghai–Tibetan Plateau had lost 23,000 ha forest area and 26,270,000 m^3 wood accumulation, representing 35.11 and 32.59% reduction, respectively (Gansu Forestry inventory and planning Institute 2006; Yang 2004). That made forest line shrink by 20 km on the average (Gannan Record 1998) and 30 km in some part of the region (Li 2000). However, a slight increase was observed since 1999 due to implementation of state forest policy (Fig. 7).

Causative analysis of eco-environmental changes

Air temperature changes

In the most recent four decades the climate in the northeastern margin of the Qinghai–Tibetan Plateau had showed a warming trend (Fig. 8), with the air temperature

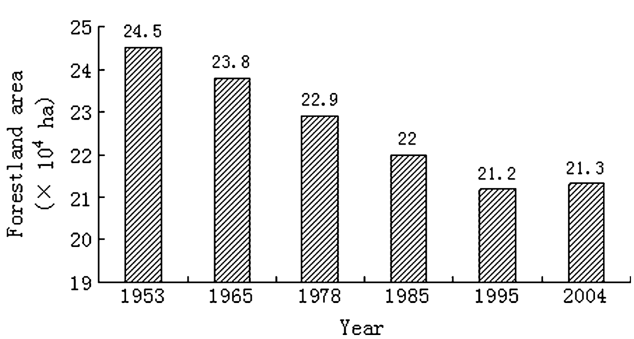

Fig. 7 Changes of decreased forest area in the northeastern margin of Qinghai–Tibetan Plateau

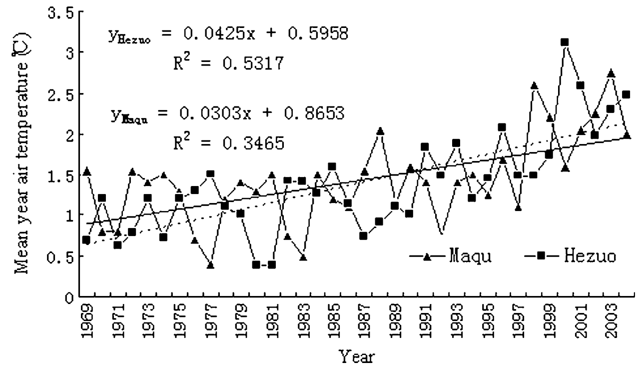

Fig. 8 The variation of annual average air temperature of Maqu and Hezuo

increasing by 0.70°C (Table 2). On an average, the temperature increased by 0.275°C for each 10 year period (An and Li 2003). According to the meteorological data of Maqu county and Hezuo city, annual average air temperature over the past 40 years fluctuated along an upward linear curve (Fig. 8).

Average air temperature showed a fairly rapid increase after 1990s. The mean annual air temperature increased by 0.1–0.2, 0.1–0.5 and 0.3–0.6°C, for the periods of 1960–1970, 1970–1980, 1980–1990, respectively (Table 2). The annual air temperature was unchanged from 1960s to

Table 2 The decade average of mean air temperature departure in the northeastern margin of the Qinghai–Tibetan Plateau (°C)

Year and season	Chronology	County and city			
		Maqu	Luqu	Xiahe	Hezuo
Mean annual	1960s	–0.3		–0.4	–0.4
	1970s	–0.1	–0.2	–0.3	–0.2
	1980s	0.0	–0.1	0.0	0.0
	1990s	0.3	0.2	0.5	0.5
Winter	1960s	–0.7		–0.5	–0.6
	1970s	–0.2	–0.2	–0.3	–0.1
	1980s	0.2	0.1	0.3	0.2
	1990s	0.1	0.0	0.4	0.6
Spring	1960s	0.0		0.0	–0.1
	1970s	0.0	0.1	0.0	0.0
	1980s	–0.4	–0.3	–0.4	–0.3
	1990s	0.3	0.4	0.4	0.5
Summer	1960s	–0.3		–0.3	–0.4
	1970s	–0.3	–0.4	–0.3	–0.2
	1980s	0.0	–0.1	0.1	0.1
	1990s	0.4	0.4	0.6	0.5
Autumn	1960s	–0.3		–0.5	–0.4
	1970s	–0.3	–0.2	–0.3	–0.3
	1980s	0.2	–0.1	0.1	0.2
	1990s	0.4	0.2	0.6	0.7

1970s, and it decreased by 0.3–0.4°C in 1980s. However, air temperature was higher by 0.6–0.8°C in 1990s compared to 1980s. Mean summer temperature showed an ascending trend from 1960s to 1990s for all four regions surveyed with maximums which occurred in 1990s (Table 2). The mean winter temperature was also higher during 1980s and 1990s than in 1960s and 1970s (Table 2). The magnitude of temperature increase was ranked according to the order of Hezuo > Xiahe > Maqu > Luqu. The greater magnitude of temperature increase in Hezuo city and Xiahe county may partially reflect the urbanization and population growth in this lower latitude zone, due to close proximity to the interior regions of Gansu province and well developed commerce in these regions. However, the assessment of general increase in air temperature in the plateau may have to be placed under a global perspective, i.e. as a sign of global warming in the world's highest plateau. Rising temperature may also be a direct result of population explosion (from 0.55 to 1.3 billion since 1949) and increasing greenhouse gas emission in the northeastern margin of the Qinghai–Tibetan Plateau, especially during the almost three decades of booming economic growth.

Precipitation

Over the past four decades the annual precipitation in the headwater area showed no noticeable changes or it remained stable (Wang et al. 2001). The annual precipitation in the study areas did not show any distinct patterns. The precipitation in the autumn was lowest in 1990s, and highest in the winter months during the same period (Table 3). Figure 9 showed a temporal pattern of annual precipitation variation.

Increased land–surface air temperature

The assessment of general increase in air temperature in the Plateau may have to be placed under a global perspective and anthropogenic causes. First, average global surface temperature has increased by approximately 0.6°C since the late nineteenth century, with 95% confidence limits of close to 0.4 and 0.8°C (Houghtou et al. 2001). Most of this increase had occurred in two periods, from about 1910 to 1945 and since 1976 (Houghtou et al. 2001). The period 1946 to 1975 had no significant change of temperature, though there was a small non-significant, but regionally more marked, cooling over the Northern Hemisphere (Parker et al. 1994). 1983 and 1998 were influenced by the strong 1982/83 and 1997/98 El Niño. The warming influence of El Niño on global temperature is empirically well attested (Jones 1994). Average air temperature showed a fairly rapid increase since 1990s in the northeastern margin of the Qinghai–Tibetan Plateau. The decade of mean air temperature departure was –0.4 to –0.3, –0.3 to –0.1, –0.1 to 0 and 0.2 to 0.5°C, for the periods of 1960–1970, 1970–1980, 1980–1990, respectively (Table 2). The annual air temperature decreased by –0.4 to –0.1°C from 1960s to 1970s, and the air temperature was unchanged during 1980s. However, air temperature was higher by 0.2–0.5°C in 1990s than 1980s (Table 2). The observed meteorological data was significantly consistent with Houghtou et al. (2001), Parker et al. (1994) and Jones (1994) research's result. Second, Rising temperature may also be a direct result of population explosion (from 0.55 to 1.3 billion

Table 3 The decade average of mean precipitation anomaly in the northeastern margin of the Qinghai–Tibetan Plateau (mm)

Year and season	Chronology	County and city			
		Maqu	Luqu	Xiahe	Hezuo
Mean annual	1960s	1		–3	4
	1970s	2	4	0	–2
	1980s	0	3	0	–1
	1990s	–2	1	1	–1
Winter	1960s	–24		–53	–43
	1970s	–2	–28	–32	–17
	1980s	2	–3	–25	25
	1990s	22	24	87	35
Spring	1960s	–4		–3	11
	1970s	2	–5	–7	–12
	1980s	–5	10	12	6
	1990s	4	–2	–3	–4
Summer	1960s	1		–q2	–3
	1970s	–1	8	3	5
	1980s	1	0	–7	–5
	1990s	–8	7	3	1
Autumn	1960s	6		–2	17
	1970s	8	7	0	–9
	1980s	3	7	7	0
	1990s	0	–1	0	0

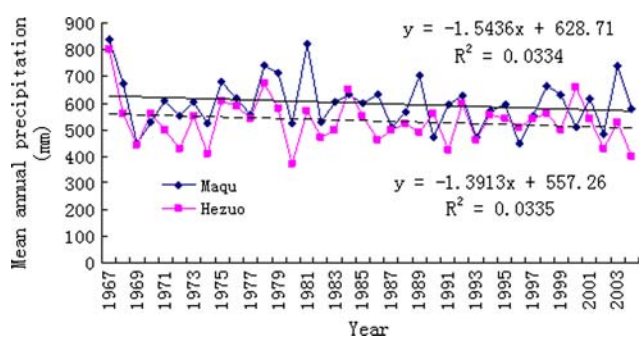

Fig. 9 Variation of average annual precipitation of Maqu and Hezuo

since 1949) and increasing greenhouse gas emission in the northeastern margin of the Qinghai–Tibetan Plateau especially, during the almost three decades of booming economic growth. Current anthropogenic emissions of CO_2 are primarily the result of the consumption of energy from fossil fuels (Keeling and Whorf 2000). About 10 to 30% of the current total anthropogenic emissions of CO_2 were estimated to be caused by land-use/cover conversion. Changes in land use/cover and management affected the amount of carbon in plant biomass and soils. Historical cumulative carbon lost is due to changes in land use (Matthews 1983; Leemans 1990; de Fries et al. 1999). Land use responds to social and economic pressures to provide food, fuel and wood products, for subsistence use or for export. Land clearing can lead to soil degradation, erosion and leaching of nutrients, and may therefore reduce the subsequent ability of the ecosystem to act as a carbon sink (Taylor and Lloyd 1992). Betts et al. (1997, 2000), Chase et al. (2000) and Zhao et al. (2001) studies' results demonstrate that land cover can have an impact on the regional scale climate but suggestions that land clearance had an impact on the global scale climate is currently speculative. Evidence from palaeoclimate and modelling work indicated that land use/cover changes in vegetation may lead to very significant local and regional scale climate changes which, in some cases, may be equivalent to those due to increasing CO_2 (Pitman and Zhao 2000). Population growth and the demand for economic development had led to regional scale changes in vegetation type and vegetation fraction in the northeastern margin of the Qinghai–Tibetan Plateau, such as deforestation, agriculture area expansion and grassland degradation (Figs. 6, 7).

Permafrost degradation and its influence

Compared with the decade average of mean air temperature 1960s the air temperature in the northeastern margin of the Qinghai–Tibetan Plateau increased by 0.4–0.9°C (Table 2). The increased temperature has caused the degradation of permafrost. The uppermost layer of ground above permafrost, which experiences seasonal thawing, was called the active layer. The most distinct feature of land–atmosphere interactions in permafrost regions is that mass exchange was usually limited to this relatively shallow active layer, with complex transfers of heat by conduction and percolation across the ice/water interface. Recent studies indicated that by the middle of the twentieth century, climatic warming resulted in a 12–15% reduction of the near-surface permafrost area and a 15–30% increase of the active layer thickness (Anisimov and Nelson 1996, 1997; Anisimov et al. 1997). Wang (1991) study had shown that if the mean air temperature is increased by 0.2–0.3°C, the thickness of the permafrost could be decreased by 3–5 m. This might cause such problems as the downward shift of the frozen soil layer and even its disappearance, water loss from the surface soil, a lowering of the water table (Wang and Cheng 1999), release of greenhouse gases from thawing permafrost (Goulden et al. 1998) and changes in the vegetation associated with the thickening of the active layer. The first contributes directly to the global radiative force, while the second alters parameters of the radiation balance and surface hydrology. In the northeastern margin of the Qinghai–Tibetan Plateau, the lake water area in the region has decreased and water areas of most lakes and rivers were reduced. The lake water area shrank by 0.54% from 1970s to 1980s, and by 9.25% from 1980s to 1990s (Wang et al. 2001). Zhang et al. (2004) indicated that there was a positive correlation between the actual evaporation and air temperature, and soil moisture was in negative equilibrium state in the northeastern margin of the Qinghai–Tibetan Plateau. The supply of soil moisture depended on the water height of the lakes. The lakes, the permafrost and wetland had a great role in regulating radial flow of rivers (Li et al. 2001). The higher air temperature thawed frozen soil, increased soil evaporation, resulting in declined ground water table and water levels of the lakes, hence reduced water supply of baseflow from the ground water and lake water (Chen et al. 2004). Furthermore, there was a significantly positive correlation between water resource total amount and the decade average of mean air temperature departure in the northeastern margin of the Qinghai–Tibetan Plateau. For example, water resource total amount (the decade average of mean air temperature departure) was 783,000,000 m^3 (–0.37°C) in 1960s, 680,000,000 m^3 (–0.20°C) in 1970s, 717,000,000 m^3 (–0.025°C) in 1980s and 493,000,000 m^3 (0.375°C) during 1990 to 2004, respectively.

Overgrazing

Grassland is vulnerable to subtle environmental and management changes that can lead to shifts in vegetation states (Scholes and Archer 1997). Livestock grazing on this land is the land use with the largest global areal extent (FAO 1993a). In the northeastern margin of the Qinghai–Tibetan Plateau, there was about 2,960,000 ha of natural rangeland, and the mean grass productivity was about 1,575 kg ha^{-1} per year (edible fresh grass) (Ren et al. 1982), so the grass production was 4,660,000,000 kg per year. Assuming the fodder consumption of 1,460 kg one sheep per year (fresh grass) (Ren et al. 1982), the theoretical carrying capacity of the northeastern margin of the Qinghai–Tibetan Plateau should be 3,190,000 sheep. In 1965, the actual livestock population was 1,360,000 sheep (Table 4), only 42% of the carrying capacity, and there was enough forage to raise livestock and to keep the pastures in good condition. In 1978, the actual livestock population was 3,640,000 sheep, the grassland was overstocked and overgrazed. After 1978, the actual livestock population exceeded the theoretical carrying capacity by a large margin (Table 4). In 1980s the grassland available per head of sheep was 0.91 ha, by 1990s it had decreased to 0.74 ha, by 2003 to 0.5 ha, and at present the figure ranges from 0.45 to 0.50 ha. All these resulted in degradation of the grassland ecosystem.

Land use/cover changes

There were two types of land-use/cover change in the northeastern margin of the Qinghai–Tibetan Plateau: direct anthropogenic change, such as deforestation and agriculture; and indirect change, where changes in climate or CO_2 concentration force changes in vegetation structure and function within biomes, or the migration of biomes themselves. With respect to direct anthropogenic change, population growth in this region and the demand for economic development had led to regional scale changes in vegetation type, vegetation fraction and soil properties (Henderson-Sellers et al. 1996; Ramankutty and Foley 1998). With respect to indirect effects of land-use changes, these were thought to represent about 10 to 30% of total anthropogenic CO_2 emissions (Houghtou et al. 2001). In the study area, the significant decrease of forestland and degradation of grassland, which adversely affected soil conservation, the area of water loss and soil erosion had reached 490,000 ha, the low-grade, middle-grade and high-grade soil and water loss area are 301,000, 147,000 and 41,700 ha, respectively (Gannan Statistics Yearbook 2005) (Table 5). Overgrazing resulted in degradation of the grassland ecosystem. In the northeastern margin of the Qinghai–Tibetan Plateau, degraded grassland occupies about 83.20% of total usable grassland area, in which severe and moderately degraded grassland area was 814,000 and 1,370,000 ha, respectively; desertified grassland was 53,300 ha, and salt-affected grassland was 5,500 ha (Gannan Statistics Yearbook 2005). Because

Table 4 The statistic data of the livestock population ($\times 10^4$ head) in northeastern margin of Qinghai–Tibetan Plateau

Items	Years														
	1965	1970	1978	1979	1981	1985	1988	1991	1995	1999	2000	2001	2002	2003	2004
Final total (sheep unit)	135.80	230.7	335.4	405.2	458.99	525.46	556.25	569.41	566.9	737.91	711.07	687.84	646.54	638.82	631.54
Hezuo city															
Total (sheep unit)	0	0	0	0	0	0	0	0	0	108.18	110.59	105.82	91.37	86.82	83.73
Yak	–	–	–	–	–	–	–	–	–	8.01	8.23	8.35	6.92	6.53	6.42
Sheep	–	–	–	–	–	–	–	–	–	14.48	14.79	14.72	14.87	15.12	14.13
Horse	–	–	–	–	–	–	–	–	–	1.36	1.35	0.76	0.73	0.64	0.54
Maqu county															
Total (sheep unit)	87.01	166.1	222.5	273.6	298.49	343.25	369.07	386.78	388.41	450.28	423.96	407.96	385.91	383.36	378.75
Yak	7.31	14.47	19.73	24.65	26.78	30.86	32.10	32.64	31.92	38.54	36.15	35.02	32.9	32.72	32.35
Sheep	10.11	15.67	18.41	19.17	18.69	21.45	24.67	29.18	30.61	32.38	33.06	33.26	33.31	32.56	32.15
Horse	0.38	0.57	0.68	0.79	1.2	1.32	2.34	3.12	3.86	3.25	2.94	2.45	2.36	2.36	2.31
Luqu county															
Total (sheep unit)	48.58	64.36	112.3	131.1	159.89	181.58	186.51	181.95	177.63	178.36	175.56	173.11	168.33	167.77	168.22
Yak	3.41	4.86	8.62	10.38	13.15	14.8	15.31	14.65	13.94	13.91	13.74	13.52	13.07	13.1	13.19
Sheep	12.38	13.46	20.73	21.86	22.29	27.28	26.71	28.65	29.63	28.36	28.56	28.41	28.33	28.07	27.92
Horse	0.21	0.23	0.54	0.54	0.61	0.63	0.67	0.68	0.86	1.09	0.96	0.95	0.93	0.87	0.84
Xiahe county															
Total (sheep unit)	0	0	28.88	10.39	28.92	22.04	29.17	34.42	36.37	51.05	53.75	58.96	65.91	63.95	65.4
Yak	–	–	2.41	0.57	2.39	1.63	2.09	2.51	2.5	3.76	3.91	4.35	5.25	5.12	5.24
Sheep	–	–	3.28	2.19	1.52	0.64	0.67	0.82	0.87	1.15	2.15	2.86	3.01	3.25	3.80
Horse	–	–	0.15	0.25	0.35	0.51	0.76	0.85	1.05	1.23	1.25	1.26	1.04	0.95	0.92

Table 5 The present status of water loss and soil erosion area in the Northeastern Margin of Qinghai–Tibetan Plateau ($\times 10^4$ ha)

Inventory unit	The gross area of water loss and soil erosion	Erosion degree		
		Low-grade	Middle-grade	High-grade
Total	48.98	30.10	14.71	4.17
Maqu county	21.15	12.61	7.54	1.01
Luqu county	15.11	9.61	3.99	1.51
Hezuo city	4.87	3.02	1.22	0.63
Xiahe county	7.86	4.87	1.96	1.02

water and soil loss are limiting factors in plant growth, increases in the water and soil loss had resulted in concomitant decreases in the number of plant species, along with their density, coverage and yield or biomass (Wang and Fu 2004).

Eco-environmental protection planning

The speed and magnitude of eco-environmental degradation (such as climatic warming, decreased precipitation, permafrost degradation, soil and water loss, desertification and land use/cover changes) affected the success of species, population, and community adaptation. The rate of eco-environmental degradation may exceed the rate of shifts in certain species ranges; these species could be seriously affected or even disappear because they were unable to adapt. Some plant and animal species (such as endangered species generally and species adapted to narrow niches for which habitat is discontinuous and barriers impede or block migration) and natural systems (such as prairie wetlands; remnant native grasslands; montane ecosystems near ridges and mountaintops; and ecosystems overlying permafrost) could be adversely affected by regional eco-environmental variations.

A sound environment was essential for human existence and sustainable economic development (Niu 1997; Wang et al. 2003). The structure and function of ecosystems were largely regulated along energy, moisture, nutrient, and disturbance gradients, and these gradients were affected by climate, physiography, soil, hydrology, flora, and fauna (Bailey 1996). The regional environment was an ecosystem organically composed of the state of various factors such as water, land (physiography, soil), vegetation, and climate (Walter 1979; Bailey 1996). As climatic factors globally accounted for the greatest variations in the ecosystem, physiographic factors, such as geological substrate and surface shape and relief, serve as boundary conditions that control the spatial arrangement and rate of geomorphic process (Jorgenson et al. 1999). Given the relatively stable weather conditions, the northeastern margin of the Qinghai–Tibetan Plateau should be characterized with the three major ecosystems: grassland ecosystem, forest ecosystem and wetland ecosystem, which are crucial in maintaining the ecological stability. Any disturbance or destruction of the ecosystems would adversely affect sustainable development of the region.

In this paper, based on information accumulated from the last 40 years in the northeastern margin of the Qinghai–Tibetan Plateau, plus results from these studies, the rehabilitation measures taken (including grassland, forestland and wetland system protection planning) in this area were significant not only for restoring degraded eco-environment but also for regional sustainable development.

Grassland ecosystems protection planning

The grassland area is 2,360,000 ha in the northeastern margin of the Qinghai–Tibetan Plateau, of which grassland area under utilization is 2,220,000 ha, or 93.8%. The grassland area damaged by rodents is 1,290,000 ha, including a severely damaged area of 853,000 ha. In order to improve grassland productivity and carrying capacity, an integrated rodent management program should be adopted. In some areas where animal husbandry has been predominant, and the grassland was over-cultivated to grow crops, some of this cultivated land should be converted back to grassland or artificial pastures. The number of grazing animals should be gradually reduced to a level that is below the current carrying capacity of the grassland. Other measures such as noxious weed control, fertilization, irrigation, rotational grazing system, temporary exclusion of some severely degraded pastures from grazing, protecting grassland from fire hazard should also be implemented. By adopting these measures, the grassland conditions can be improved and grassland productivity restored.

Forest ecosystems protection planning

Forest land is 477,000 ha in the northeastern margin of the Qinghai–Tibetan Plateau, and forest cover is 14.2%, higher than the average of Gansu province. By implementing the state forest protection policy, it is aimed to achieve the goal of the total forest area of 438,000 ha by 2010. This policy includes, but is not limited to, fire prevention measures, fire extinguishing team training and equipment supplies, and establishment of proper facilities in the fire prone areas.

Wetland ecosystems protection

Wetland area is 175,000 ha, in which, 27,700 ha river wetland, 138,000 ha swampland, 2,300 ha lake wetland and 6,500 ha beach wetland; swampland is the main type in this category. Through establishment of wetland natural protection zones, the wetland will be regularly monitored and researched, plant and animal species preserved, and the wetland will be well maintained as water reservoir of the Plateau. A goal is to achieve the total protected wetland area of 175,000 ha by 2010.

Conclusions

Dramatic changes have taken place in the environment in the northeastern margin of the Qinghai–Tibetan Plateau during the past 40 years, notably in the past 20 years. These changes have led to decreased land productivity and runoff reduction, and desertification in the northeastern margin of the Qinghai–Tibetan Plateau is accelerating. Such changes in the environment had their natural and anthropogenic causes. Climate changes (mainly the rising of temperature) not only intensified soil surface evaporation, but also caused the decrease of wetland area, and degradation of Alpine frigid meadow and swamp meadow. As a result, the supplies of surface runoff and groundwater level declined, which combined with overgrazing, reduced vegetation cover and led to grassland desertification. The predominating causes for ecological degeneration in the northeastern margin of the Qinghai–Tibetan Plateau are the rising air temperature and vegetation degeneration. Rising air temperature signals global warming in the highest Plateau of the world, which adds more evidence to the phenomenon of global climate change. The man-made causes are responsible for the current deterioration of the Plateau ecosystems, and resulting dwindling water resources for middle and lower reaches of the Yellow River. Therefore, to avoid further deterioration of these ecosystems, and its consequent impact on the entire Yellow River watershed, it is imperative to establish and implement an integrated protection program.

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