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Influences of alpine ecosystem responses to climatic change on soil properties on the Qinghai–Tibet Plateau, China

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Abstract

Alpine ecosystems are quite sensitive to global climatic changes. Drawing from two sets of remote sensing data (1986 and 2000) and field investigations, the ecological index method was used to document ecosystem changes in the Yangtze and Yellow River source regions of central Qinghai–Tibet. Although crucial to understanding alpine ecosystem responses to global climatic changes, and in assessing the potential for their rehabilitation, the impact of such changes on alpine soil characteristics, including structure, composition, water retention, as well as chemical and nutrient contents, is poorly understood. Over a 15-year period (1986–2000), climatic changes led to considerable degradation of alpine meadows and steppes. In the meadows, the surface layers of the soil became coarser, bulk density, porosity and saturated hydraulic conductivity rose, while water-holding capacity decreased. In comparison, steppe soils showed little changes in soil physical properties. Degradation of alpine ecosystems led to large losses in soil available Fe, Mn and Zn. Important losses in soil organic matter (SOM) and total nitrogen (TN) occurred in badly degraded ecosystems. Climate warming in the Qinghai–Tibet Plateau, caused by the impact of greenhouse gas, has resulted in changes of cold alpine ecosystem such as the significant alteration of the soil C and N cycles.

Keywords: Alpine ecosystem; Response to climatic change; Soil properties; Degradation; Qinghai–Tibet Plateau

1. Introduction

Global climatic changes have significantly affected natural ecosystems in many regions of the world. These changes include alterations in plant community structure, composition, biological productivity, biodiversity and spatial patterns (Foley et al., 1996; McGuire, 2002). As the global climate warms, glaciers and frozen soils in some sensitive regions are significantly altered, thereby accelerating the degradation of alpine ecosystems (Jorgenson et al., 2001; McGuire et al., 2003). Transects within the cryosphere of arctic regions have shown that alpine ecosystems are quite sensitive to the global climate changes. Alterations in these ecosystems lead to dramatic changes in soil physical properties, soil and surface water dynamics and in the soil carbon cycle, which in turn exert a profound influence on the entire biosphere (Christensen et al., 2004; Weller et al., 1995; Jorgenson et al., 2001.

The headwaters region of the Yangtze and Yellow River, located in the interior of the Qinghai–Tibet Plateau, represents a distinct cryospheric environment, housing a number of typical alpine ecosystems including alpine meadows and alpine steppes. Such ecosystems are quite sensitive to global climatic changes, which have observably impacted the region's environment and altered its water cycle (Li and Zhou, 1998; Wang et al., 2001a,b). The Qinghai–Tibet Plateau's alpine ecosystems' climatic change-driven degradation over the past 40 years has been mainly manifested in a decrease in vegetative cover and shrinkage of alpine meadows (Wang et al., 2001a,b; Dong et al., 2002). This region presents a unique natural environment, serving specific ecological functions critical for water conservation in the large headwaters, abundant in natural resources, and diversified in species and germplasm resources that, in turn, strongly influence the entire catchment's environment (Liu, 1996; Li and Zhou, 1998; Wang et al., 2001a,b). Therefore, the

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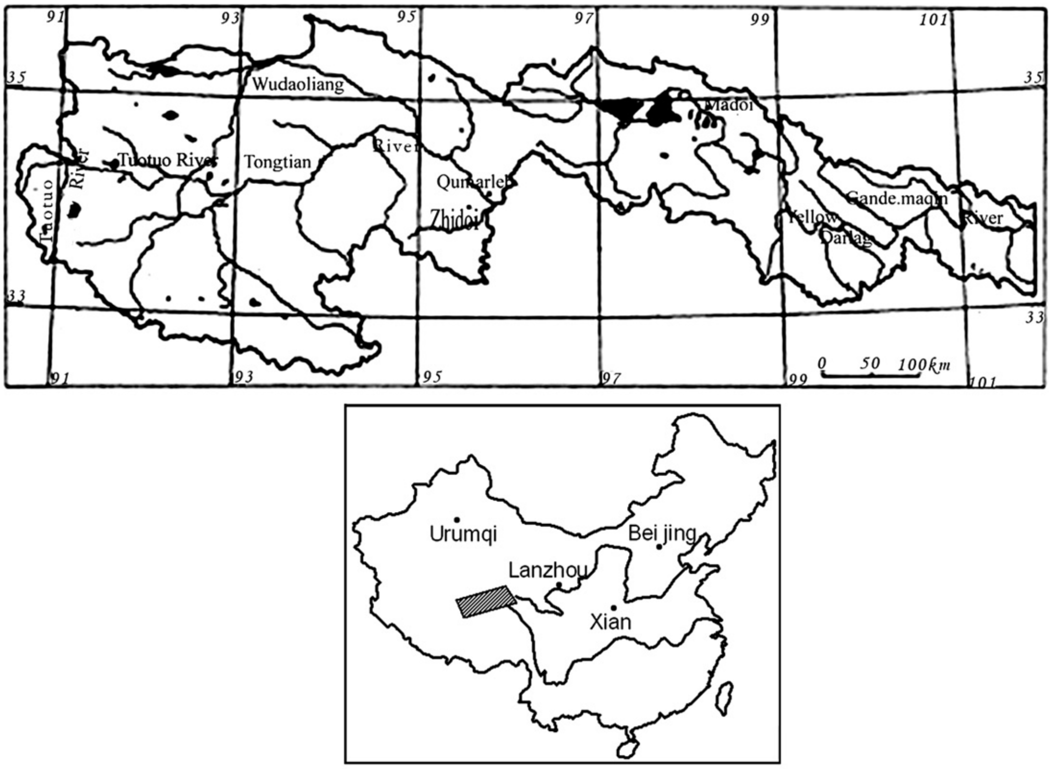

Fig. 1. Location of the study area.

region has currently become the focus of public concern and received considerable attention from scientists (Chen and Gou 2002; Dong et al. 2002; Wang et al., 2001a,b). However, two crucial issues are poorly documented and must be resolved: (i) what influence will significant changes in the regions' cold alpine ecosystem exert on the region's environmental status; (ii) what potential exists to restore the regions' degraded ecosystems. The specific objectives of this study with regards to the central Qinghai–Tibet Plateau were to: (i) assess the changes of alpine ecosystems caused by climate warming; (ii) characterize the major soil property change driven by alpine-cold ecosystem changes; (iii) evaluate the functionality of ecosystems, and their retention of vital system resources, such as soil and water, critical to their potential for restoration.

2. Methods and materials

2.1. Characteristics of the study area

The headwaters region of the Yangtze and Yellow Rivers, located in the interior of the Qinghai–Tibet Plateau, was selected for this study. Located between 32°30′N and 35°35′N

Table 1
Soil groups and normal profile texture, vegetation situation in the study region

Soil group in Chinese soil taxonomy	FAO/UNESCO taxonomy	Subgroups in study region (Chinese taxonomy)	Profile fabric (Chinese taxonomy)	Vegetation types and coverage
Alpine steppe soils (cryic calcic aridisols)	Cambisols	Lit-calcic aridisols	Ac, 0–5(8) cm A, 5(8)–15(19) cm Bk, 15(19)–30 cm BC, 30–40(45) cm	*Carex moorcroftii*, *Stipa purperea* and *Littledelea racemosa*; 10–50%
		Typ-calcic aridisols	Ac, 0–7(9) cm A, 7(9)–17(20) cm Bx, 17(20)–30 cm Bk, 30–45(50) cm	*Stipa purperea*, *Carex moorcroftii* and *Littledelea racemosa*; 20–70%
Alpine meadow soils (mattic cryic cambisols)	Cambisols	Cal-mattic cryic cambisols	Oo, 0–7(10) cm A, 7–25(30) cm ABk, 25–42(47) cm BC, 42–50(70) cm	*Kobresia pygmaea*, *K. tibetica*, *K. humilis*, and *Poapailolepis*; 40–95%
		Typ-mattic cryic cambisols	Oo, 0–5(9) cm A, 5–18(20) cm AB, 18–32(40) cm BC, 32–45(50) cm	

Table 2
Ecosystem grades, associated survey quadrats and distribution of soil samples

	Vegetative coverage, %					Quadrat point/soil sample distribution				
Alpine meadow	>85	85–65	65–45	45–20	<20	9/21	12/26	9/25	11/26	7/14
Alpine steppe	>70	70–50	50–30	30–15	<15	7/18	9/21	6/16	7/18	5/10
Classification code	I	II	III	IV	V	I	II	III	IV	V

and 90°43′ and 99°45′E, it represents an area of 18.6×10^4 km^2 (Fig. 1), where permafrost in the Qinghai–Tibet Plateau mainly occurs. The region's main geomorphologic types include vast high plains and open valley plains with relatively small variations in elevation (Wang et al., 2001a,b; Zhou, 2001). Mean annual precipitation in the Qinghai–Tibet Plateau differs greatly, ranging from 230–320 mm in the more arid alpine steppe regions, to 420–530 mm in the semiarid alpine meadows area. Mean annual temperature in the region range from −1.3 to −4.1 °C. On the whole, the climate is cold and dry. The region's natural alpine ecosystems are of three main types: steppe, meadow, and swampy meadow (Chen and Gou, 2002; Li and Zhou, 1998; Wang et al., 2001a,b). Among these, steppes cover the greatest area, and are characterized by vegetation dominated by hardy perennial xeric herbs and dwarf shrubs, principally *Stipa purperea* Grisebach*, Carex moorcroftii* Falc. and *Littledelea racemosa*. Meadow ecosystems are the second most widespread and consist mainly of cold meso-perennial herbs growing under moderate water availability conditions. These are, generally dominated by *Kobresia pygmaea* C.B. Clarke and *K. humilis* (C.A. Mey.) Serg. Swampy meadow, populated by hardy perennial hygrophilous or hygro-mesophilic herbs under waterlogged or moist soil conditions, mainly occurs in patches or strips in the mountains, wide-valley terraces and rounded hills, that represent only a small portion of the study region, are dominated by *K. tibetica* Maxim (Zhou, 2001). Given its adjacent distribution and small area, swampy meadow ecosystems are discussed along with meadow ecosystems.

Based on the data from China's second national soil survey (NSSO, 1998), the soil types in the study region were mainly classified into Cryic Calcic Aridisols (Alpine steppe soil, as Cambisols in FAO/UNESCO taxonomy) and Mattic Cryic Cambisols (Alpine meadow soil, as Cambisols in FAO/UNESCO taxonomy) (Chinese taxonomy, Table 1), and the soil profile texture of each subgroup was shown in Table 1. The most significant characteristic is that there are Mattic epipedon (Oo) in Alpine meadow soil and Crustic epipedon (Ac) in alpine steppe soil.

The study region has a population of 36.5×10^4 (1999), who are mainly Tibetan pastoralists. Livestock grazing is the main economic activity. Investigations in Zhiduo, Zaduo and other counties in the region suggest that there exists a large surplus of grassland and only 30–80% of the carrying capacity has been exploited (Wang et al., 2001a,b; Dong et al., 2002), Thus, grazing has only a limited impact on grassland ecosystems.

2.2. Ecological transect survey and soil sampling

A 1990 vegetation map of the region (Zhou and Song, 1990), depicting the spatial distribution of alpine-cold meadows, steppe and swampy meadows, served as basic information for field investigations. Sample transects were organized in two ways: (i) based on the vegetation map study sub-regions were portioned off according to the distribution of the main ecosystem types, then transects arranged to run through different ecosystem sub-regions; (ii) in the same sub-regions, for the three different cold alpine ecosystem types (meadow, steppe, swamp meadow), transects were arranged according to landform units and degree of land cover, and ran perpendicular to the first belt. In regions with common ecosystem types the transects covered various subzones of the same ecological type. In addition, some additional transects were made in different regions. Quadrats, each 20 m × 20 m in size, were arranged in each transect according to microtopographic features, plant community types and structure as well as gradient changes. The distribution of quadrats in the regions of different ecological types and different vegetation covers is shown in Table 2. Some 3–4 sampling plots, each 1 m × 1 m in size, were randomly located and oriented within each quadrat and the plant species, frequency, community cover, total vegetative cover and soil structure were surveyed.

The Landsat's Thematic Mapper (TM) remote sensing data obtained in 1986–1987 and 1999–2000 were processed using ERDAS IMAGE and ARC/INFO software (with ArcView 3.1, ESRI Ltd.), based on 1:100,000 topographic maps. A remote sensing interpretation mark database consisting of 246 mark points of 11 types was established on the basis of transect surveys. Using remote sensing analytical schemes to develop 8 vegetation types and 35 subtypes within grassland-dominated ecosystems, an evaluation was made of changes in the region's alpine ecosystems over the past 15 years. Furthermore the normalized difference vegetation index (NDVI) values calculated from AVHRR and the vegetative cover obtained from

Table 3
Vegetative cover, standing index (I) and integrated ecological index (S_L) of alpine meadow ecosystems (%) on the Qinghai–Tibet Plateau

Vegetative coverage	>85	85–65				65–45			45–20		<20
I	>80	60–80	60–40	40–20	<20	40–20	20–10	<10	20–10	<10	<5
S_L	>79	65–79	52–62	39–49	29–24	32–47	26–29	22–24	23–27	14–16	<10
Evaluation	Non	Slight	Slight	Moderate	Severe	Moderate	Severe	Severe	Severe	Extreme	Extreme

Table 4
Vegetative cover, standing index (I) and integrated ecological index (S_L) of alpine steppe ecosystems (%) on the Qinghai–Tibet Plateau

Vegetative cover	>70	70–50			50–30			30–15		<15
I	>80	80–60	60–50	50–40	80–60	60–50	50–40	50–30	<30	<30
S_L	>79	61–67	52–58	42–48	35–44	29–36	23–27	20–25	14–19	<12
Evaluation	Non	Slight	Slight	Moderate	Moderate	Moderate	Severe	Severe	Extreme	Extreme

quadrat surveys were used to assess the level of degradation of different degraded regions (Table 2).

In each quadrat, soil samples were collected in 2–3 randomly selected sample plots. Due to the soil profile texture as shown in Table 1, soil natural horizons of cryic calcic aridisols were divided into 0–8(9) cm (Ac), 8(9)–19(20) cm (A), 19(20)–30 cm (Bk or Bx), 30–45(50) cm (Bc or Bk) and below 50 cm (BC or C). The soil natural horizons of mattic cryic cambisols were divided to 0–9(10) cm (Oo), 9(10)–20 (30) cm (A), 20(30)–40 cm (AB) and 40–50(70) cm (BC). Soil samples were collected at depths of the 5 layers. Samples were stored in bags and transported to the laboratory for particle-size analysis and the determinations of soil organic matter, total N and P contents. In addition, soil bulk densities were determined by the cylinder ring method at various sampling points. Field surveys and sampling were carried out between July and August, in both 2002 and 2003. The distribution of soil samples from different ecological zones and vegetative covers is shown in Table 1.

2.3. Evaluation of ecosystem variations

The degradation of alpine ecosystems is manifested in changes of ecosystem structure and composition as well as a reduction in vegetative cover (Li and Zhou, 1998; Wang et al., 2001a,b). It can be described by three indexes: vegetative cover, ecosystem variability, and dominant species standing (Zhou, 2001; Wang et al., 2005), of which the latter is the integration of original plant species number and their frequency (Wang et al., 2005):

$$I = 1 + \sum_{i=1}^{n} P_i \quad (1)$$

where,

- I is the standing index of the dominant species of the original cold alpine ecosystem.
- P_i is the frequency of the original dominant species (relative abundance or relative importance value of dominant species) i (in this study the relative abundance is used).
- n is the total number of species.

The index of ecosystem variability is determined by a number of factors including grassland vegetation cover, species diversity, climax species number and frequency. It quantitatively reveals the degree of variation of the current ecosystem relative to the original situation. The integrated ecological character of ecosystems in different zones can thus be quantitatively evaluated as:

$$S_L = \alpha F_c + \beta I \quad (2)$$

where,

- F_c is the vegetative cover index.
- S_L is the ecological variability index (range 0.1–1.0).
- α is the weight coefficient for vegetative cover.
- β is the weight coefficient for the standing index of the dominant species.

In an integrated evaluation of ecosystem variation, S_L values were used as a criterion to grade ecosystem variability into five categories: I, $S_L \geq 80$, non-degraded; II, $80 > S_L \geq 50$, slightly degraded; III, $50 > S_L \geq 30$, moderately degraded; IV, $30 > S_L \geq 20$, severely degraded; and V, $S_L < 20$, extremely degraded. Integrating the results of the remote sensing analysis and evaluation criteria, the corresponding spatial distribution of different categories of degraded ecosystems was analyzed using ERDAS IMAGE and ARC/INFO software and their areas estimated.

2.4. Soil analyses and data analysis

The chemical compositions of soils were analyzed by standard methods (Ministry of Agriculture of China, 1993). Soil organic matter was determined by the Walkley–Black method. Soil pH was determined in a 1:1 (w/w) soil–water slurry by a potentiometric method. The semi-micro Kjeldahl method was used to analyze soil total N, and the Na_2O melting-molybdenum blue colorimetric method was used for total soil P. Soil trace elements, Zn, Fe, Mn, etc. were extracted with DTPA and then analyzed by atomic absorption spectrophotometry; available Mo was determined by a polarography method or a KSCN colorimetric method. By using the sample sifter, the soil granularity composition is divided into the larger than 2 mm faction and smaller than 2 mm faction. Soil particle-size composition (smaller than 2 mm faction) was determined on a

Table 5
The area (km^2) and variation in area (1986–2000) of alpine meadows and cold alpine grasslands of the Qinghai–Tibet Plateau at different levels of degradation

Degradation degree		Original	Slight	Moderate	Severe	Extreme
Alpine meadow	1986	25,627.5	7663.5	16,576.3	18,393.8	8059.3
	Variation	−746.5	−118.0	−99.8	175.8	152.2
Alpine steppe	1986	6527.1	3616.8	12,412.7	31,453.7	6834.9
	Variation	−130.8	−295.6	55.8	321.1	148.9

Table 6
Physical parameters and their changes in alpine meadow and steppe soils of the Qinghai–Tibet Plateau: ρ, bulk density; K_{sat}, saturated hydraulic conductivity

Level of degradation	Alpine meadow				Alpine steppe			
	ρ Mg/m^3	Granularity composition %		K_{sat} mm/h	ρ Mg/m^3	Granularity composition %		K_{sat} mm/h
		>0.5 mm [a]	<0.1 mm			>0.5 mm	<0.1 mm	
I	0.99±0.30	0.72/0.1	98.2	3.4	1.18±0.11	2.05	8.81	25.4
II	1.16±0.20	4.3/3.3	92.4	6.3	1.23±0.06	5.65	5.99	33.7
III	1.21±0.12	13.8/6.3	79.9	34.6	1.39±0.09	9.27	16.05	39.4
IV	1.33±0.13	32.7/9.9	57.4	61.2	1.38±0.10	11.45	17.19	38.7
V	1.35±0.21	33.9/9.5	56.6	63.7	1.49±0.07	15.1	14.2	41.3

[a] The number represents the composition of 0.5–2 mm/>2 mm.

CIS-50 grain-size analyzer (Ankersmic Co., Netherlands). All determinations were replicated twice.

Soil moisture volumetric contents were determined on site by time-domain reflectometry (TDR) (TRIME-FM, IMKO Gmbh, Germany), and soil gravimetric water contents determined by the oven-drying method (105 °C 2 h) using soil samples collected with a cutting cylinder. For the moisture determination, three replications were taken for each soil layer, and the soil bulk densities determined simultaneously. Soil saturated hydraulic conductivity was determined in each sampling plot using a Guelph-2800K1 infiltrator (Soil Moisture Equipment Corp. Santa Barbara, USA). Soil physiochemical property measurements were classified according to the S_L-based ecosystem variability categories, and correlation analyses to examine relationships between soil properties and ecosystem variations undertaken using multiple regressions and trend analysis of statistical methods in SAS 8.1 (SAS Institute 2000).

3. Results and discussion

3.1. Evaluation of changes in alpine ecosystems

The drop in the standing index of the original dominant species, I (Eq. (1)), and in the integrated ecological index, S_L (Eq. (2)) is shown in Tables 3 and 4, respectively. While the vegetative cover of the alpine meadows remained relatively high at 65–85%, the value of I generally varied between 80 and 20%, dropping below 20% with the appearance of secondary weeds in the meadows. Therefore, the degree of ecological degradation judged strictly on the basis of I is inconsistent with the actual situation facing the meadow ecosystems. Among the meadows where $85\% > I \geq 65\%$, there were slightly, moderately and severely degraded ecosystems. Where $65\% > I \geq 45\%$, there were no slightly degraded ecosystems, but mostly moderately and severely degraded ones. Where $I < 45\%$, ecological degradation in meadows was severe or extreme (Table 3).

Similar variations were noted for alpine steppe ecosystems (Table 4), where I generally varied between 80 and 30%, under a relative high coverage of 70–50%. However, the magnitude of S_L values varied considerably. Where vegetative cover exceeded 30%, the value of I remained at or above 40%, and degradation was slight or moderate. The extreme degradation occurred when vegetative coverage dropped below 20%.

In 1986 there were 6.7×10^4 km^2 of alpine meadow in the study region, of which moderately degraded, severely degraded and extremely degraded areas accounted for 24.8%, 27.5% and 12.0%, respectively (Table 5). In the ensuing 15 years, severely and extremely degraded meadow areas increased by 0.95% and 1.9%, respectively, whereas the non-degraded and slightly degraded area decreased by 2.9% and 1.5%, respectively (Table 5). In 1986 there were 5.48×10^4 km^2 of alpine steppe in the study region, of which moderately, severely and very severely degraded areas accounted for 22.6%, 57.4% and 12.5%, respectively. In the ensuing 15 years, the moderately, severely and extremely degraded steppe areas increased by 1.0% and 2.2%, respectively, while the slightly degraded steppe area decreased by 8.2% (Table 5).

In the Qinghai–Tibet Plateau continuous permafrost occurs mainly in the source region of the Yangtze and Yellow River basins. Since the mid-1970s the study area's temperature has shown a clear rise. For example from 1980 to 2000 periods the annual mean air temperature rose by 0.5 °C and the mean permafrost temperature increased by 0.2 °C. As a result, the area in permafrost has significantly decreased (Wu et al., 2002; Wang et al., 2001b). On average, over this period, the thickness of the active soil layer in the mid- to high-mountain, high plains,

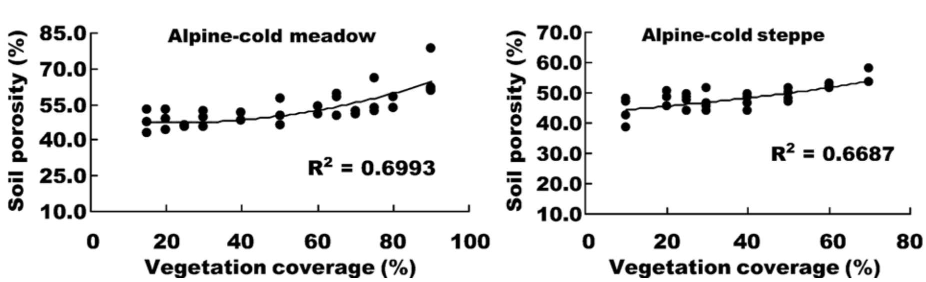

Fig. 2. Relation between soil porosity, vegetation type and cover.

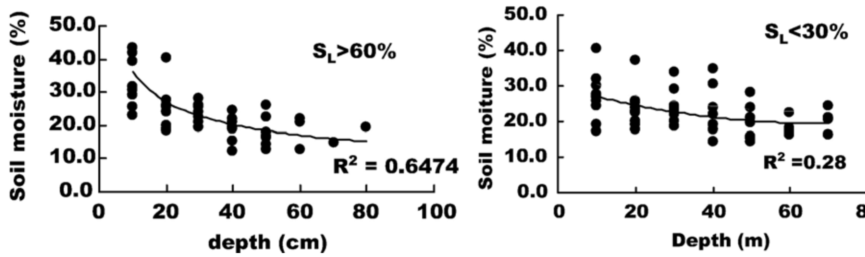

Fig. 3. Regularity in vertical distribution and variations in moisture content of alpine meadow soil.

and mid- to low-mountain regions has increased to 40–84 mm, 8–65 mm, and 30–50 mm, respectively (Zhao et al., 2000; Wu et al., 2001). Given that human activity in the study region is limited to livestock grazing and the population density is only 3 persons/km^2, one can conclude that climate change-induced changes in the extent of permafrost environments are the most important and direct factors leading to changes in the region's alpine ecosystems.

3.2. Changes of soil physical properties

3.2.1. Changes of soil structure and composition

Alpine meadow soils under high vegetative coverage belong to the mattic cryic cambisols type (Chinese soil taxonomy, Cambisols in FAO/UNESCO taxonomy). On these alpine meadow soils, when vegetative cover exceeded 70%, the fine sand and clay contents of the 0–0.30 m layer exceed 90%, a light sandy loam; however, below 0.30 m the layer was composed of gravel and the coarse contents increased with increasing depth, representing to medium–heavy loam or gravelly soils (Table 6). The most obvious physical variation is that the gravel content has increased in the surface layer, while the clay content has decreased, rendering the surface coarse. Where the S_L of alpine meadows decreased from 80% to 30%, the fine sand and clay content of the 0–0.30 m layer decreased, on average, by 37%, while the coarse sand and gravel content rose nearly 10-fold. This leads to the mechanical composition of the entire soil profile (0–1.0 m) which becomes uniform.

The coarser grain-size composition led to the increase in mean soil bulk density, ρ (Table 6). Where $S_L > 85\%$, the surface layer (0–0.30 m) bulk density of alpine meadow soils was 0.99±0.30 Mg/m^3 with roughly 84% of soil samples having $\rho < 1.1$ Mg/m^3. However, when $S_L < 30\%$, then $\rho = 1.35 \pm 0.21$ Mg/m^3, with about 67% samples having $\rho > 1.4$ Mg/m^3. On average, as S_L decreased by 55%, soil bulk density increased by 36.4%. Soil porosity of the 0–0.30 m soil layer also showed a significant change with changing S_L (Fig. 2). For meadows, increasing values of S_L led to a quadratic increase in mean porosity, followed by an even steeper rise at $S_L > 50\%$.

Alpine steppe soils bearing alpine steppe vegetation were dominated by cryic calcic aridisols (Chinese soil taxonomy, Cambisols in FAO/UNESCO taxonomy). Since such soils were formed in more arid and cold climatic conditions than alpine meadow soils, the biological and chemical weathering was even weaker; hence surface soil layers have a greater coarse grain change to greater gravel content. Even in the steppe regions where vegetative cover exceeds 70%, the soil fine particle content is generally less than 15% (Table 6). With a decrease in S_L, the coarse sand and gravel content in the steppe surface soil layer tended to increase. For example, as S_L decreased from 70–50% to 15%, coarse sand and gravel contents increased 5-fold and 1.6-fold respectively, but fine particle (fine sand and clay) content changed little (Table 6). The bulk density of the alpine steppe soil was significantly higher than that of the alpine meadow soil. For steppes where $S_L > 70\%$, the mean surface layer (0–0.30 m) bulk density of the steppe soil was roughly the same as that for soils of meadows where S_L ranged from 70 to 65%. Where steppe $S_L < 15\%$, 76% of soil samples had $\rho > 1.5$, and where steppe vegetative cover decreased by 75%, soil bulk density increased by 27.1%. The porosity of alpine steppe soils showed a similar but less steep quadratic increase with increasing S_L than did meadow soils (Fig. 2). For the steppes fine particle content showed almost no difference with S_L, which formed a basis for the restoration of the degraded alpine steppe.

3.2.2. Variation in soil water properties

Soil saturated hydraulic conductivity, K_{sat}, reflects water percolation capacity and is closely related to soil structure, bulk density, and porosity. Alpine meadows locations where $S_L > 50\%$ had lower K_{sat} values (generally $K_{sat} < 7$ mm/h) than locations where $S_L < 50\%$ (Table 6), reflecting the fact that at higher S_L values, surface layers of these meadow soils had a lower infiltration capacity. As S_L decreased, the surface layer K_{sat} of meadow soil increased significantly. When S_L decreased by 67%, K_{sat} increased, on average, by 12 to 17-fold (Table 6). This increase in K_{sat} promoted downward seepage of water from surface soil layers into deeper layer. In alpine steppe soil, however, the K_{sat} changed little when S_L dropped from 80% to

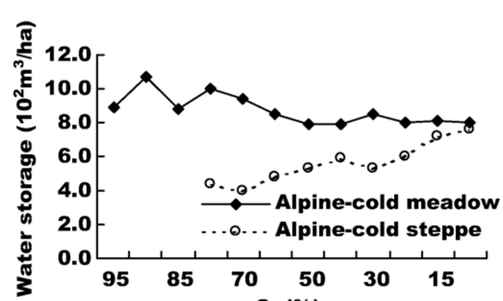

Fig. 4. Variations in water storage in topsoil (0–0.3 m) of alpine meadow and alpine steppe.

Table 7
Chemical properties of alpine meadow and steppe soils of the Qinghai–Tibet Plateau

Vegetation type	Soil type (Chinese soil taxonomy) vegetation cover[a]	pH	Available trace elements (ppm)				$CaCO_3$%	CEC cmol/kg
			Fe	Mo	Zn	Mn		
Alpine meadow	Mattic cryic cambisols I–II	6.9–7.5	145.6	0.09	1.36	26.7	1.26	28.93
	Mattic cryic cambisols IV–V	7.5–8.2	87.33	0.12	1.05	17.8	0.61	23.35
Alpine steppe	Cryic calcic aridisols I–II	7.5–8.0	21.46	0.21	0.79	14.0	9.2	10.28
	Cryic calcic aridisols IV–V	8.0–8.3	16.34	0.27	0.54	10.6	10.13	9.75

[a] See Table 2.

below 15% (Table 6). Thus, changes in S_L had little influence on the K_{sat} of alpine steppe soils.

Moisture content in the upper 0.3 m layer of alpine meadow soil showed a strong regularity (the direct proportionality between moisture and S_L) with changes in S_L. For $S_L > 60\%$, the accumulation of soil moisture in the surface layers of alpine meadows was high (Fig. 3). With increasing soil depth, the soil moisture content decreased exponentially, particularly below 0.3 m in depth. On average, moisture content decreased by 46.6% within the first 0.50 m of soil. For degraded meadows, as S_L decreased below 30%, the relationship between moisture and S_L became more variable. The greater variability in vertical moisture distribution within the soil of degraded alpine meadows with low S_L values resulted in an increase in deep seepage of water, which was closely related to the high K_{sat} of the low-coverage meadow soil. Soil moisture content in alpine steppe can be affected by a number of factors such as local precipitation, terrain conditions and soil texture, and its spatial distribution is irregular.

Water-storage capacity (=soil gravimetric water content × soil bulk density × soil depth × estimating area) in surface soil layers is of great importance to the growth of vegetation. Dense root systems and high evapotranspiration of alpine meadow vegetation require a large water supply in the root zone (Zhou, 2001). In such meadows, the upper 0.30 m soil layer had a high water-storage capacity ($8.7–11.4 \times 10^2$ m^3 water/ha) when $S_L > 70\%$, indicating high retention of water in the surface layer of these meadow soils. With the degradation of such meadows and the concomitant reduction in S_L, the surface soil layers' water-storage capacity decreased. When S_L dropped below 50%, the mean water storage in the upper 0.3 m soil layer was $7.6–8.45 \times 10^2$ m^3 water/ha. However, soil water storage showed no significant changes when S_L varied between 50 and 10%. The change in water storage in the surface layer (0–0.30 m) of alpine steppe soils was just the contrary of that in alpine meadow. Water storage in the root layer of high vegetative cover steppe soil was low, generally ranging from 3.8 to 4.8×10^2 m^3 water/ha (Fig. 4). With the degradation of alpine steppe and the reduction in S_L, water storage in surface soil layers tended to increase. As S_L declined from 60% to 10%, mean soil water storage increased by 61%. When S_L slipped below 15%, the water storage in surface soil layers of severely or extremely degraded steppe and alpine meadow tended to become the same (Fig. 4).

3.3. Soil chemical and nutrient changes

The mattic cryic cambisols of the alpine meadows generally exhibited a weak acidity: 86% of the soil samples were measured to have a $7.5 > pH > 6.9$. The $CaCO_3$ content in surface soil layers was also low, averaging 1.36% (Table 7), but the cation exchange capacity (CEC) was relatively high. With the degradation of alpine meadows, when S_L dropped below 30%, soils turned weakly alkaline ($pH > 7.5$), and the CEC decreased significantly. Alpine steppe soils of non-degraded steppe exhibited a weak alkalinity and a surface soil layer $CaCO_3$ content ($\geq 9.0\%$) far greater than that of meadow soils. When S_L decreased due to degradation, the $CaCO_3$ content of steppe soils tended to increase, but CEC did not change significantly, although it remained higher than that of equivalent meadow soils (Table 7).

Alpine meadow soils (mattic cryic cambisols) were markedly enriched in Fe and Mn, the mean Fe and Mn contents of non-degraded meadow soils reaching 145.6 ppm and 26.7 ppm respectively, some 7- and 2-fold greater than in equivalent steppe soils (Table 7). Similarly, Zn content in meadow soils was 1.7-fold greater than in equivalent alpine steppe soils (cryic calcic aridisols). With the degradation of alpine meadows, their Fe, Mn and Zn contents significantly decreased. As the S_L decreased from >70% to <30%, their available Fe and Mn

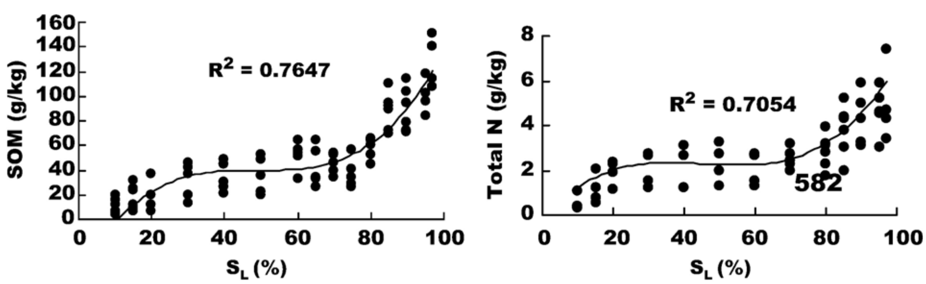

Fig. 5. Variations of soil organic matter and total N contents of alpine meadow soils with different integrated ecological indexes (S_L).

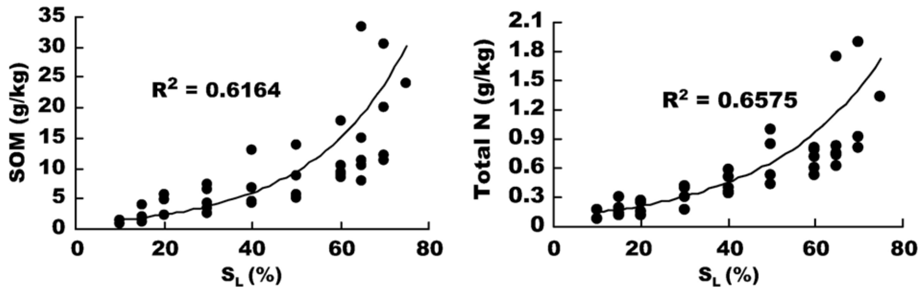

Fig. 6. Variations of soil organic matter and total N contents of alpine steppe soils with different integrated ecological indexes (S_L).

contents decreased, on average, by 40% and 33.3%, respectively. Available trace elements levels in alpine steppe soils (cryic calcic aridisols) were low overall; however, as with meadow soils, their Fe and Mn contents were relatively greater than those of Zn and Mo. With the degradation of alpine steppe and the concomitant decrease in S_L, available Fe, Mn and Zn tended to decrease, Fe and Mn decreasing by 23.8% and 24.3%, respectively. In contrast, available Mo contents in soils of both alpine meadows and steppe tended to increase with decreasing S_L (Table 7). Thus, overall, meadow degradation promoted the soil's shift from weak acidity to weak alkalinity, and a decrease in CEC and trace elements such as Fe, Mn and Zn. The changes in alkalinity, CEC and trace element contents of alpine steppe soils were similar to those of alpine meadow soils.

Variations in soil nutrients are important indicators of soil chemical properties. A plot of soil organic matter (SOM) and total N (TN) of alpine meadow soils under different S_L values, shows that both SOM and TN show a similar curvilinear relationship with S_L (Fig. 5), despite differences in moisture and temperature between sampling sites. For $65\% < S_L$ and $S_L < 30\%$, SOM and TN significantly increased with the increase S_L, whereas, for $60\% > S_L > 35\%$, SOM and TN only changed weakly with S_L. Overall, when S_L decreased from 90% to 15%, the mean SOM and TN of meadow soil decreased by 84% and 77%, respectively, most of this drop occurring from S_L values of 90% to values of 50–60%. Based on these observations, it was estimated that SOM and TN decreased by 63.6% and 51%, respectively, for moderately degraded vs. non-degraded alpine meadow.

The variations of SOM and TN of alpine steppe soils also showed a significant correlation with S_L. The SOM and TN content of steppe soils showed an exponential increase with rising S_L values (Fig. 6). As the S_L of steppe lands decreased from 70% to 15%, SOM and TN decreased by 80.1% and 93.6%, respectively. Compared to non-degraded steppe, moderately degraded steppe, with $40 > S_L > 30$, mean SOM and NT were decreased by 73.8% and 72.5%, respectively.

The variation of the total soil P content in cryic soils is shown in Fig. 7. In spite of a lower correlation than SOM and total N, the total P content of alpine meadow soil also varied significantly with S_L. The total P content of meadow soils tended to increase as S_L increased. If severely degraded meadow, where S_L had dropped from above 90% to less than 15%, the mean total P content decreased by 66.5%, on average, while for moderately degraded meadow, where S_L had dropped by 50% or so, mean total P content decreased by 54.6%. However, vegetative cover and standing index of the dominant species appeared to have little influence on the total P content of steppe soils. Thus, in summary, SOM and TN contents in alpine meadow and to a somewhat lesser extent in steppe soils were significantly and positively correlated to the ecological index, S_L, which represents the ecological conditions.

4. Conclusions and discussion

In the past 15 years, under the influence of climatic changes, the typical alpine ecosystems in the headwater regions of the Yangtze River and Yellow River in the interior of the Qinghai–Tibet Plateau have been greatly altered. The original area of high vegetative cover alpine meadow ecosystems decreased by 746.5 km^2, while the extremely degraded meadow increased by 152.2 km^2. The original area of alpine steppe ecosystems decreased by 130.8 km^2, while severely and extremely degraded steppe areas together increased by 470 km^2. Alpine meadow soil of the Qinghai–Tibet Plateau showed a significant response to the changes in the cold alpine ecosystem. Meadow degradation

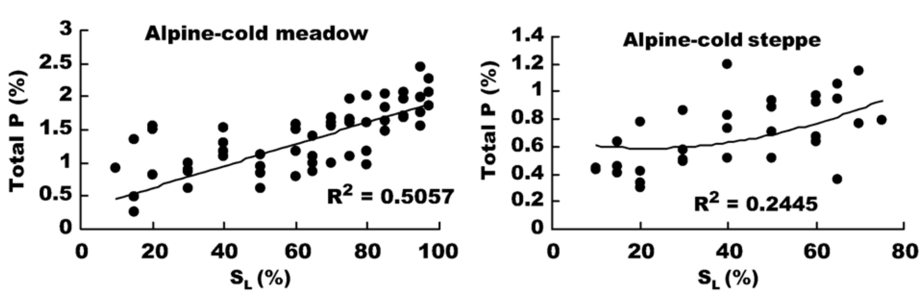

Fig. 7. Variations in total P content of alpine steppe soils with different integrated ecological indexes (S_L).

led to coarsening of the soil texture and increases in bulk density and porosity. However, the structure and mechanical characteristics of alpine steppe soil changed only slightly.

With respect to soil water-holding capacity, the K_{sat} of the topsoil layer (0–0.3 m) of alpine meadows dramatically increased with decreasing S_L, such that the accumulation of water in the topsoil layer no longer occurred. This decrease in water-storage capacity of the topsoil caused the severe degradation of meadow vegetation rendering it also more difficult to restore such lands to their former state. In contrast to meadow soils, the K_{sat} of alpine steppe soils showed no significant change, and the mean water storage in the topsoil actually increased with decreasing S_L. When the S_L dropped below 20%, water storage in meadow and steppe topsoils was similar. Overall, degraded steppes showed a greater potential for restoration than degraded meadows (Wang et al., 2005), the difference in the response of their soil physical properties to ecosystem changes being the main cause.

The changes of soil physical and chemical features implicated serious soil erosion occurred in the permafrost area of Qinghai–Tibet Plateau. By using the soil ^{137}Cs content variation data, Wang et al. identified that the soil erosion was linear with the alpine grassland coverage, and suggested that the alpine grassland degradation was one of the most important causes of soil erosion in the permafrost area of Qinghai–Tibet Plateau (Wang et al., in press). Climatic change caused the alpine grassland degradation, which resulted in soil erosion and soil physical properties changes, and soil properties changes interacted with soil erosion.

With the reduction of S_L, SOM and TN in alpine meadow and steppe soils decreased in a curvilinear manner, with some minor differences. Loss of soil organic carbon (SOC), derived from SOM using the van Bemmelen coefficient (SOM × 0.58 = -SOC; Duan et al., 1997; Cramer et al., 2001) when non-degraded high vegetative cover alpine meadows of the headwater regions of the Yangtze and Yellow Rivers underwent severe degradation over the past 15 years, was estimated to be 11.556 Tg or more, and the loss of soil N to be 1.69 Tg. The loss of SOC when non-degraded high vegetative cover alpine meadows underwent severe degradation was estimated to be 1.251 Tg, and the loss of soil N to be 0.13 Tg. Under the influences of global climatic changes, the SOM and TN contents of typical alpine meadow and steppe soils on the Qinghai–Tibet Plateau changed significantly, which coupled with effects on soil water retention properties, may have important effects on the global climatic changes.

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