

Correlation of alpine vegetation degradation and soil nutrient status of permafrost in the source regions of the Yangtze River, China

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Abstract The impacts of alpine vegetation degradation on the main soil nutrients in the permafrost were studied by the comparative analysis of typical plots in the source regions of the Yangtze River. It is found that vegetation degradation has a severe effect on the content of the main soil nutrients, especially in the topsoil (0–10 cm) where the soil nutrients content were changed. There are good correlations between soil organic matter (SOM) and total nitrogen (TN), total phosphorus (TP) and total potassium (TK) in alpine soil. The change to soil nutrients increases concomitantly with the increasing intensity of vegetation degradation. Soil nutrients change dramatically in the thermokarst lakes in the surrounding area where vegetation is severely degraded. The ratio of SOM, TN, TP and TK in different soil layers of the adjacent thermokarst lakes is 5.88, 5.14, 3.86 and 4.43, respectively. The vegetation degradation accelerates the degradation of alpine soil environment in alpine frozen soil.

Keywords Yangtze River · Permafrost ·
Alpine vegetation · Soil nutrients

Introduction

The Qinghai-Tibet Plateau, the largest geomorphologic unit on the Eurasian continent, is an important part of the global terrestrial ecosystem, and the largest low-latitude permafrost region in the world. Beside its sensitivity to global climate change, the region plays an active role in moderating such changes at an Asian and even at global level (Cheng et al. 1997). The widely distributed alpine meadows, alpine steppes and alpine swamp meadows that cover most of the area of the Qinghai-Tibet Plateau are the naturally occurring vegetation ecotone and are representative of much of the land area in the Eurasian continent (Li and Zhou 1998). Being located in the interior of the Qinghai-Tibet Plateau, widespread permafrost exists naturally in the headwater regions of the Yangtze River and the Yellow River.

The distribution and variation of permafrost is a major environmental element in the Qinghai-Tibet Plateau, and has a significant effect on the regional vegetation community, and the wetland ecology development and distribution (Wang et al. 2001). According to a recent report by the World Wide Fund for Nature (WWF), the Qinghai-Tibet Plateau will become 3.8°C warmer by the end of the twenty-first century and this will cause permafrost degradation. As a result, the active layers will deepen with the increased groundwater infiltration; thus, the roots of native vegetation will not be able to reach the new aquifer and this area will suffer from drought, causing grassland degradation (WWF 2008).

Either the degradation of soil or the reconstruction of degenerated land will cause a tremendous change in the original ecosystem. These processes will change the biomass productivity rates of soil organic matter (SOM) accumulation and decomposition, which will in turn affect

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the carbon and nitrogen cycle and soil carbon storage in the ecosystem (Lal et al. 1995). From the perspective of global change, carbon sequestration and release in the Plateau soils are more sensitive to global change; thus, they play an important role in the carbon balance of the regional ecosystem (Wang et al. 2007). Based on a GIS study, the alpine grassland in northern Tibet which has degraded in recent years accounts for half of the entire grassland region in 2004 (Gao et al. 2010). In another study, the daily wind erosion rate increased sharply with the increase of the rate of grassland degradation (Li et al. 2005).

At present, the degradation of grassland in the Qinghai-Tibet Plateau is serious. According to an early study by Ma et al. (1999a, b), the degraded grassland has an approximate area of $0.45 \times 10^8 \text{ km}^2$, which is one-third of the total area of Qinghai-Tibet Plateau. The most seriously degraded area is the secondary bare land—"black beach", accounting for 16.5% of the total area of degraded grassland. Grassland degradation has threatened the local ecosystem, biodiversity conservation and economic development of livestock (Li and Zhou 1998; Zhou et al. 2003, 2005). Essentially, the degradation of grassland means the degradation of the Vegetation-Soil system (Chen and Wang 2000).

Soil nutrients including soil organic carbon (SOC), N, P and S are important plant nutrients which participate in almost all ecosystem processes (Harrison 1985; Juan and Romon 1997). Many studies have shown that soil nutrients such as SOC, N and P would decrease with the increased tillage and soil depth (Urioste et al. 2006). Soil active organic carbon (SAOC) content decreases with the increase of soil depth in different types of land use. The allocation ratio of SAOC decreases with the increase of soil depth, while the allocation ratio of dissolved organic carbon (DOC) increases with the increase of soil depth (Yu et al. 2007). Tillage leads to the rapid decrease of light fraction organic carbon (LFOC) (Zhao et al. 2006). Overall, returning crop residues along with zero tillage improved the aggregation of SOC and nitrogen, while burning in combination with conventional tillage resulted in the deterioration of these soil properties. According to the study, SOC storage in the Qinghai-Tibet Plateau accounted for 2.6 or 2.4% of the world SOC pool (1,500 Gt) (Fang et al. 1996; Wang et al. 2002; Tao et al. 2006). Grassland SOC content across the entire Qinghai-Tibet Plateau totals about 33.5 Pg, of which 12.3 Pg (37%) is stored in the permafrost region (Wang et al. 2002; Luo et al. 2000).

At the same time, a large number of studies have shown that permafrost is gradually being degraded, presumably due to global warming. Thawing permafrost creates thermokarst terrain—uneven surface topography including pits, troughs, mounds and depressions, which can fill with water. Ponding of water in depressions creates thermokarst lakes, which may expand as a result of both thermal and

mechanical erosion over time with scales of decades to centuries (Czudek and Demek 1970).

Thermokarst lakes are common features of ice-rich permafrost landscapes. Thermokarst damages agricultural fields and ecosystems such as forests by drying in mounded areas and flooding in low-lying zones. Furthermore, it can contribute to erosion and increase sedimentation and siltation of rivers, which poses additional environmental concerns. Numerical simulation in typical thermokarst lakes in Alaska has shown that the evolution of thermokarst lakes and climate change are closely related, which induces the variation of permafrost in the adjacent thermokarst lakes (Ling and Zhang 2003). The thermokarst process has a significant impact on the ecological environment in permafrost, and it also accelerates the organic decomposition process which can release soluble substances in permafrost, thus affecting the chemical properties of soil mass and surface runoff (Truett and Kertell 1992; Kokelj and Lewkowicz 1999; Kokelj et al. 2002). A previous study showed that CH_4 bubbling from newly forming thermokarst lakes comprised 33–87% of the high-latitude increase in atmospheric methane concentration (Walter et al. 2007). There are signs that the formation of thermokarst lakes can affect SOM in frozen soil.

Currently, research on the response of soil nutrients to the degraded grassland in the Qinghai-Tibet Plateau as well as on the change to soil nutrients in regional vegetation caused by thermokarst lakes is scarce. Therefore, it is crucial to understand the nutrient cycling in permafrost-affected soils in the Plateau in order to evaluate the biogeochemical response to global climate change objectively.

Consequently, the objectives of this study aim to: (1) analyze the response of soil nutrients to grassland degradation in the permafrost region of the Qinghai-Tibet Plateau; (2) compare the differences between the changes to soil nutrients caused by thermokarst lakes and natural degradation conditions.

Material and methods

The study area description

The study area is in the source region of the Yangtze River which is in the centre of the Qinghai-Tibet Plateau, located between $32^\circ 30' - 35^\circ 40' \text{N}$ and $90^\circ 30' - 95^\circ 35' \text{E}$, with an area of $1.212 \times 10^5 \text{ km}^2$. The mean elevation of the area ranges from 4,315 to 5,126 m (Wang et al. 2001, 2008; Yao 2002). The area is dominated by a typical continental alpine climate with mean annual air temperature (MAAT) ranging from -3 to -7°C which depends on the elevation and the thickness of frozen soil. The mean annual precipitation (MAP) ranges from 150 to 540 mm and centers on

the period from June to August, more in the form of summer storms and less in snow. The annual evaporation is 1,204–1,327 mm, which far exceeds the MAP; thus, the aridity index is high (8–20). The freeze period is up to 7–8 months per year, from September to April. Soil type in the study area is classified according to the Chinese soil taxonomy (NSSO 1998). The major types of soil are alpine meadow soil, alpine steppe meadow soil, alpine swamp meadow soil and alpine grassland soil. Soil develops slowly in highly cold environments with high altitude and hypoxia, and the soil genetic horizons are generally thin and fragile; thus, it is difficult to recover if the soil is degraded (Li and Zhou 1998; Wang et al. 2001, 2008; Li et al. 2010). Soil degradation is serious in the study area, and soil erosion is one of the main causes of soil degradation (Wang et al. 2008). The main types of erosion are divided into freeze–thaw erosion, wind erosion and water erosion (Li et al. 2009). There are different sizes of thermokarst lakes occurring as a result of permafrost degradation in the studied area; some are perennial waterlogged, some are seasonal waterlogged. Severe vegetation degradation occurs around the thermokarst lakes; in some parts, the mineral soil is completely exposed.

The types of vegetation community in the studied area mainly consist of two categories: alpine cold meadow and alpine cold swamp meadow, and the dominant species include *Kobresia pygmaea*, *K. humilis*, *K. capillifolia*, *K. tibetica*, *Stipa aliena*, *Festuca ovina*, *Poa annua*, *Elymus nutans*, *Ptilagrostis dichotoma*, *Carex atrofusca*, *Leontopodium leontopodioides*.

Soil sampling and treatments

According to vegetation ecology and the degree of degradation, the study area is classified into different types, and three to five sampling transects in each study area at Fenghuo Mountain in the source region of the Yangtze River are selected. The actual sample size of the sampling transects is 10 × 10 m in width separated by a distance of 3–5 m, and then took samples at three depths (0–10, 10–20, 20–30 cm) from each transect. Firstly, three replicate samples were taken using the 100 ml metal ring at each transect, and stored them in aluminum boxes. Afterward, the soil moisture content and bulk density were determined by oven drying the samples at 105°C on average. At the same time, approximately 1 kg of soil samples in sealed plastic bags was transported to the laboratory, for further physical and chemical analysis. In areas where the soil thickness was only about 10 cm and there was only sand and gravel below this depth, only sampled two layers as the soil depth was insufficient for three samples. (Note: The data were collected in July 2007 and August 2008).

Analytical methods

The soil chemical analyses include SOM, total nitrogen (TN), total phosphorus (TP) and total potassium (TK) in the soil. SOM was measured using the Potassium Bichromate Titrimetric Method (Ji 2005). The TN was measured using the Semi-Micro Macro Kjeldahl Method (Ma et al. 1999a, b). The TP was measured with the HClO₄–H₂SO₄ Method (Zhou 1996) and the TK was measured with NaOH fusion-flame spectrometry. For the measurement of SOM, TN, TP and TK determination, three replications were taken from each soil layer.

Data analysis

SPSS13.0 and other geostatistic methods were used to analyze the correlation of experimental data.

Results and discussion

Correlation among soil nutrients and soil moisture content

Soil nutrients are the key factors of stable soil environment in permafrost, and the relationship among soil nutrients is one of the main indicators of soil environment. It can be seen from Table 1 that the correlation between SOM and TN is the strongest in the soil depth between 0 and 10 cm ($r = 0.9876$, $P \leq 0.05$), followed by the correlation between TP and TK ($r = 0.8138$, $P \leq 0.05$). The correlation between the other components is not significant. The results show that the variations of SOM and TN, TP and TK are most closely related to the soil surface horizons, along with the change of soil environmental effect between each other. Table 1 also shows that the correlation between

Table 1 Correlation coefficient for relationships among soil nutrients

Soil depth (cm)	Item	SOM	TN	TP	TK
0–10	SOM	1			
	TN	0.9876	1		
	TP	0.1636	0.1275	1	
	TK	0.1522	0.3763	0.8138	1
10–20	SOM	1			
	TN	0.9764	1		
	TP	0.2822	0.2692	1	
	TK	0.2055	0.1823	0.9257	1
20–30	SOM	1			
	TN	0.9578	1		
	TP	0.0719	0.0437	1	
	TK	0.1816	0.1799	0.8478	1

TK and TN is poor ($r = 0.3763$, $P \leq 0.05$) and even weaker between SOM and TP, TK. The above analysis illustrates that the interdependence among other components of soil nutrients is poor, apart from between SOM and TN, TP and TK in the topsoil of the permafrost region in an alpine cold environment.

At the depth of 10–20 cm, the correlation between SOM and TN is still the strongest ($r = 0.9764$, $P \leq 0.01$), followed by TP and TK ($r = 0.9257$, $P \leq 0.05$); TK and TN is insignificantly correlated ($r = 0.1799$, $P \leq 0.05$). In addition, correlation between other components and the surface is essentially the same; the correlation coefficient changes very slightly. In the second layer, the correlation coefficient between SOM and TN is slightly lower, but still a strong correlation occurs ($r = 0.9764$, $P \leq 0.01$); the correlation between TP and TK is stronger, and its correlation coefficient increases by 13.8%.

At the depth of 20–30 cm, the correlation between SOM and TN is still the strongest ($r = 0.9578$, $P \leq 0.01$); the correlation between TP and TK is still evident ($r = 0.8478$, $P \leq 0.05$). The correlation coefficient between TK and TN is lower ($P \leq 0.05$), but the correlation between SOM and TP, TK decreases by 11.6 and 74.5%, respectively. On one hand, the soil nutrients content of permafrost-affected soils reduces at the depth of 20–30 cm; on the other hand, some nutrients content would vary with the decrease of vegetation roots below 20 cm.

Overall, the correlation between SOM and TN changes slightly with the variation of soil depths, and the correlation coefficient ranges between 0.9578 and 0.9876 ($P \leq 0.05$). The result shows that SOM and TN are closely related in the soils of the source region of the Yangtze River, because most nitrogen is tied with the biomass, and this result is consistent with Wang et al. (2005) who found that the correlation coefficient between SOM and TN is 0.9786 ($P \leq 0.05$), and that meadow degradation is due to human activity, climate warming and permafrost degradation in the Qinghai-Tibet Plateau's permafrost region. The correlation between TP and TK increases at first and then decreases, and it reaches its peak in the second layer ($r = 0.9275$, $P \leq 0.05$); despite this, the general trend is still rising. The weathering process of phosphorus and potassium of soil is identical in the permafrost region of the source regions of the Yangtze River, both phosphorus and potassium are from the identical soil parent materials, and then convert to available phosphorus and potassium after long-term physical, chemical and biological weathering. Furthermore, the utilization of phosphorus and potassium for alpine vegetation is consistent. This distinctive correlation shows the particularity of the frozen soil environment.

Soil moisture has great importance with respect to total nutrient masses and their redistribution in the profile. Figure 1 shows that the moisture content in the upper

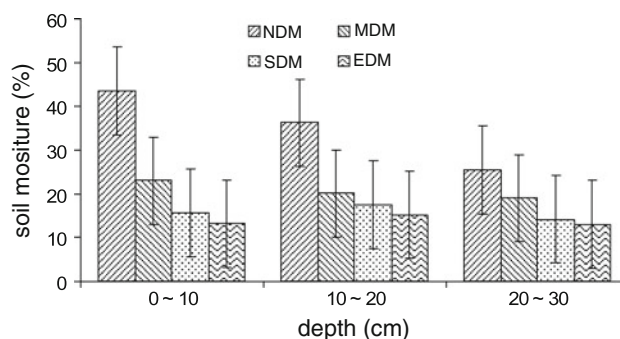


Fig. 1 Variation of soil moisture content in topsoil (0–30 cm) of alpine meadow

30 cm layer of alpine meadow soil showed a strong regularity with changes in the whole profile. With the increase of soil depth, the soil moisture content decreased quickly, particularly below 20 cm in depth. Soil moisture content in the 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 in topsoil 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 areas (Zhou 2001). With the degradation of such meadows and the concomitant reduction in MDM, SDM and EDM, the water-storage capacity of topsoil layers decreases as well. With the increase of the soil depth from 0–10 to 20–30 cm, mean moisture content decreases by 41, 17, 10 and 2% in NDM, MDM, SDM and EDM accordingly. It shows that the moisture content in topsoil layers of severely or extremely degraded alpine meadow tends to be similar.

Relationships between vegetation coverage and soil nutrients

Vegetation degradation is one of the primary causes of soil degradation in the alpine cold meadow of the Qinghai-Tibet Plateau, and soil degradation is bound to bring further degradation of vegetation (Zhou et al. 2005). However, soil degradation inevitably leads to changes in the soil nutrients content. A great number of studies indicate that there is a certain relationship between vegetation coverage and soil nutrients, but the relationship is not always invariable under different conditions. Wang et al. (2008) found that there is a high correlation between LFOC in SOM and vegetation coverage in the alpine meadow and alpine steppe, and that the relationships between total soil organic carbon (TOC) and its vegetation coverage are weak.

At the depth of 0–10 cm in the topsoil, there exists a very good correlation between vegetation coverage and different soil nutrients, particularly the SOM and TN. The

relationships between vegetation coverage and content of TP and TK are also strong (Fig. 2a). At the depth of 10–20 cm, there is still a strong correlation even though the relationships between vegetation coverage and SOM and TN increase slightly while the relationships between vegetation coverage and TP and TK decrease slightly (Fig. 2b). The correlation coefficients of each component in Fig. 2c are greatly reduced, which indicate that the variation of surface vegetation has little direct impact on soil nutrients in the 20–30 cm band and below. This differs with the findings of Alison et al. (1999) who found that the correlation coefficient between vegetation coverage and soil nutrients including TN, TP and TK is respectively -0.03 , -0.39 and 0.41 on an uninfluenced area in Igloolik

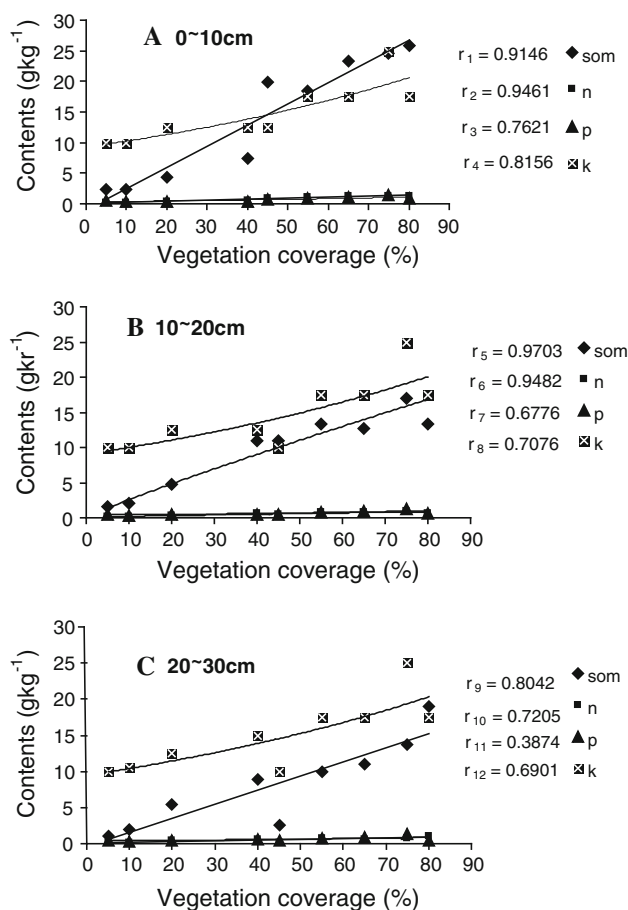


Fig. 2 Relationships between vegetation coverage and SOM, TN, TP and TK of the 0–10 cm (a), 10–20 cm (b) and 20–30 cm (c) layers of alpine cold meadow soils in the study area. r_1 , r_5 and r_9 are correlation coefficients for relationship between SOM and vegetation coverage in 0–10, 10–20 and 20–30 cm, respectively. r_2 , r_6 and r_{10} are correlation coefficients for relationship between TN and vegetation coverage in 0–10, 10–20 and 20–30 cm, respectively. r_3 , r_7 and r_{11} are correlation coefficients for relationship between TP and vegetation coverage in 0–10, 10–20 and 20–30 cm, respectively. Similarly, r_4 , r_8 and r_{12} are correlation coefficients for relationship between TK and vegetation coverage in 0–10, 10–20 and 20–30 cm, respectively

Island, Nunavut. This indicates that the relationship between vegetation and soil is different in middle-latitude and high-latitude alpine cold circumstance.

Generally, the relationships between vegetation coverage and soil nutrients are weaker with the increase of depth, but there is no evident abrupt decrease in the 0–20 cm layer. Because the vegetation of grassland assigns the photosynthetic products to roots, the live roots, dead roots and coarse organic matter in the alpine region are concentrated in the 0–20 cm layer (Wang et al. 1998). Each correlation coefficient decreased abruptly in the 20–30 cm layer, which is mainly due to the low temperature in alpine region. The formation process of soil requires a long time; in an area where there is little annual precipitation, the organic matter of topsoil transported to the deep soil is little, the relative humidity of soil is comparatively large and the supply of deep nutrients is restricted. At the same time, owing to the relatively undersized alpine vegetation, the distribution of roots is shallow and the soil at a deeper level seldom gets material supply. The relationships between vegetation and SOM and TN are consistently strong in the entire transect at a depth between 0 and 30 cm; this demonstrates that surface vegetation is closely related to the content of SOM and TN, and demonstrates that SOM and TN of soil are major factors of alpine vegetation's growth and development.

Relationships between vegetation degradation and the variation of soil composition

Based on the degradation of the alpine meadow in the study area, we divided the meadow degradation into five levels: non-degraded alpine meadow (i.e., native vegetation), lightly degraded alpine meadow, moderately degraded alpine meadow, severely degraded alpine meadow and extremely degraded alpine meadow (Ma et al. 2002). Soil nutrients content and distribution pattern of meadow with different degradation in the vertical profile are different.

As shown in Table 2, in soil at a depth between 0 and 30 cm, SOM content decreases with the severity of alpine meadow degradation. The total profile SOM content of the non-degraded alpine meadow is 48.7 g/kg at its highest. SOM at the depth of 0–10 cm of NDM was up to six times greater than that in more degraded areas. In the same profile, SOM content significantly increases with depth reduction, while the SOM content in the same layer decreases with the intensification of the degradation. The SOM content in the soil depth between 0 and 10 cm is significantly higher than that in soil depth between 10–20 and 20–30 cm. In an alpine meadow under different degradation, the SOM content in the 0–10 cm level accounts for 43% of that in the soil depth between 0 and 30 cm and accounts for 74% of that in the soil depth between 0 and

Table 2 Soil nutrients differ from soil layer at different degraded alpine meadows (g/kg)

Soil nutrients	Soil depth (cm)	NDM	LDM	MDM	SDM	EDM
SOM	0–10	17.3	20.9	13.7	4.3	2.3
	10–20	15.1	13.0	10.9	4.8	1.8
	20–30	16.3	10.4	5.7	5.4	1.5
	0–30	48.7	44.3	30.3	14.5	5.6
TN	0–10	1.3	1.2	0.7	0.3	0.2
	10–20	0.8	0.7	0.5	0.3	0.2
	20–30	0.9	0.7	0.4	0.4	0.1
	0–30	3.0	2.5	1.5	1.0	0.5
TP	0–10	1.1	0.9	0.6	0.4	0.5
	10–20	1.0	0.8	0.5	0.5	0.4
	20–30	0.9	0.8	0.5	0.5	0.4
	0–30	3.0	2.5	1.6	1.4	1.3
TK	0–10	21.4	17.7	12.3	12.1	10.4
	10–20	21.2	17.5	12.0	12.5	10.0
	20–30	21.1	17.3	11.7	12.9	9.6
	0–30	63.7	52.5	36.0	37.5	30.0

The data in the table are shown by average values, but the value in 0–30 cm is the sum of 0–10, 10–20 and 20–30 cm

NDM non-degraded meadow, *LDM* lightly degraded meadow, *MDM* moderately degraded meadow, *SDM* severely degraded meadow, *EDM* extremely degraded meadow

20 cm. This trend in general agrees with that of Wang et al. (1998).

In the soil profile (0–30 cm), TN content decreases with the severity of alpine meadow degradation. The TN content value in the non-degraded alpine meadow is 1.3 g/kg at its highest, which is 1.1, 1.9, 4.3 and 6.5 times greater than the value of the lightly, moderately, severely and extremely degraded alpine meadows, respectively. It shows a similar but slower trend in the SOM content. A large amount of the TN content enriches in the topsoil. In each profile, the TN content in the surface accounts for more than 40% of the entire profile which is closely related to the SOM distribution. This shows that the TN in alpine soils is tied to the SOM due to the pattern of SOM accumulation and nutrient cycling.

In the soil profile (0–30 cm), TP content decreases with the severity of alpine meadow degradation and gradually becomes stabilized. The non-degraded alpine meadow has a highest TP content value of 1.1 g/kg, which is respectively 1.2, 1.8, 2.8 and 2.2 times greater than the value of the lightly, moderately, severely and extremely degraded alpine meadows. Such a trend can be interpreted as the result of erosion.

In the soil profile (0–30 cm), TK content is higher than SOM, TN and TP. TK content decreases with the severity of alpine meadow degradation. The highest TK content

value in the non-degraded alpine meadow is 63.7 g/kg, which is respectively 1.2, 1.8, 1.7 and 2.1 times greater than the values of the lightly, moderately, severely and extremely degraded alpine meadows. In the same profile which has the same vegetation characteristics, TK content does not change significantly with depth. This indicates that TK is the major soil nutrient least affected by degradation.

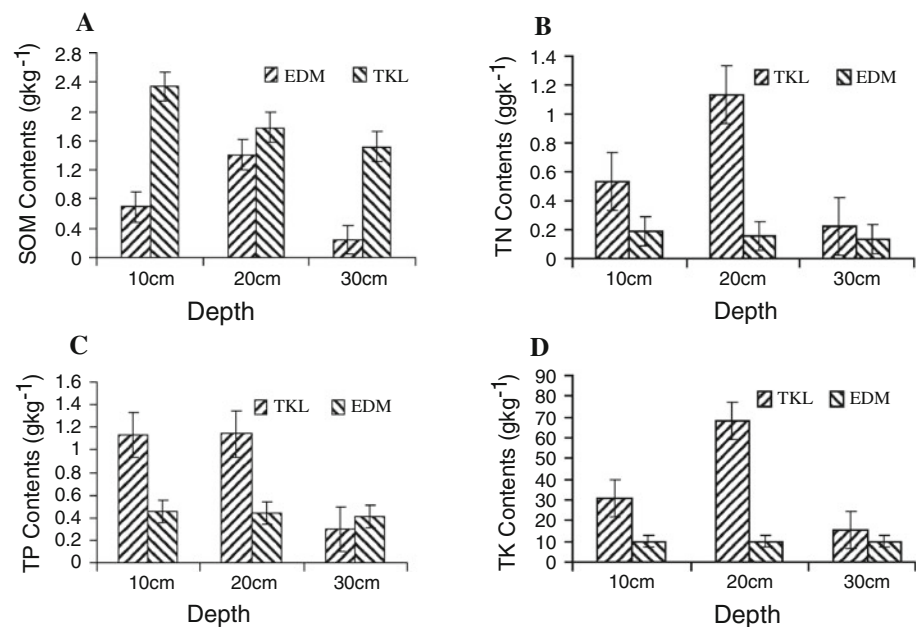
The nutrients content of soil decreases with the severity of alpine meadow degradation as follows: SOM (10.06) > TN (6.27) > TP (2.36) > TK (2.22) (lower intensity: in the soil at a depth of 0–30 cm, the ratio between non-degraded alpine meadow soil nutrient content and extremely degraded alpine meadow soil nutrients content). It indicates that the SOM is very sensitive to the degradation in alpine meadow. Due to the cold environment in the studied area, SOM decomposes slowly at a low temperature, which results in a net accumulation. Global warming and human activities influence the degradation of permafrost and lead to changes in soil nutrients. The soil nutrients content decreases with the degradation of grassland, which indicates that the vegetation and the soil nutrient content have a close relationship and mutual feedback.

Thermokarst lake and the soil nutrients

The permafrost region of the Qinghai-Tibet Plateau is very sensitive to global change. Under the global warming conditions, permafrost degradation occurs. Some of the melted water flows along the surface, gathers in the hollows and forms thermokarst lakes and these thermokarst lakes affect the surrounding environment strongly.

According to a comparison between soil nutrients of the adjacent thermokarst lakes and the extremely degraded alpine meadow, we find that the levels of soil nutrients in the proximate thermokarst lakes are higher than those in the extremely degraded alpine meadow at the same depth (Fig. 3). The reason for this may be that the surrounding vegetation of the thermokarst lakes was seriously degraded, and the soil nutrients accumulate from the runoff. At the same time, the first layer suffered from heavy erosion resulting in loss of soil nutrients. The factor that affects soil nutrients of the third layer is mainly freeze–thaw erosion. Due to freeze–thaw erosion and leaching, the near-surface soil is subjected to the loosening affected by the freeze–thaw cycles. Ice segregation leads to heaving during the freezing process. Erodibility of soil increases in the winter, along with the soil moisture profile filling and the surface structure breaking down with freezing and thawing. The deposition occurs because of upwards water loss, similar to a caliche layer. Besides, the formation of the deposition is excluded from the ice lenses during the winter; nutrients gather in the deep layer and are deposited in the second

Fig. 3 Comparison of different soil nutrients between thermokarst lakes and extremely degraded meadow. *TKL* thermokarst lakes, *EDM* extremely degraded meadow. The data in the figure are showed by average values



layer. Thus, the soil nutrients appear to gather in the second layer. The changes ratio of SOM, TN, TP and TK in different soil layers of the thermokarst lakes is 5.88, 5.14, 3.86 and 4.43, respectively. Under natural conditions, the variation of SOM, TN, TP and TK is respectively 1.54, 1.46, 1.10 and 1.0 in the extremely degraded area. The surrounding thermokarst lakes have higher soil nutrients degradation rates than those occurring under natural condition.

As shown in Fig. 3, in the 0–30 cm soil layer, the SOM content of the adjacent thermokarst lakes is much less than that of the extremely degraded alpine meadow, while other soil nutrients (TN, TP, TK) are much higher than extremely degraded alpine meadow. The ratios are 0.41, 3.93, 1.97 and 3.81. This shows that the formation and development of the thermokarst lakes can influence alpine soil environment and it is a more serious threat than that of the natural degradation in the stability and security of the permafrost environment.

Conclusions

1. The soil nutrients content and distribution in the profile of the alpine meadow in the source region of the Yangtze River are affected by the degradation of vegetation. In the 0–30 cm soil layer, the SOM and TN have the strongest correlation ($r = 0.97$); the TP and TK correlation coefficient in soil is higher than 0.8; other components have poor correlation. The major nutrients of the alpine meadow are SOM and TN, other nutrients are relatively lower in content. The SOM and TN are the main elements that affect the stability of the alpine soil environment.

2. The soil nutrients content decreases with the severity of alpine meadow degradation. The intensity reduction order is: SOM > TN > TP > TK. Besides TK, soil nutrients content decreases with the soil depth in the same profile. Soil nutrients content at the same depth decreases with the severity of alpine meadow degradation. This indicates that in alpine regions of the Yangtze River, changes in soil environment and vegetation characteristics have a strong correlation. These two factors are interdependent and form a mutual influence control mechanism. Climate change and human activity have a serious impact on climate in this fragile alpine ecological environment.
3. Thermokarst lake is a special phenomenon of the degraded permafrost in the source regions of the Yangtze River. The formation of thermokarst lakes has severe influence on soil environment of alpine meadow. The SOM content in affected zone of thermokarst lake is less than the EDM, while other soil nutrients content (TN, TP, TK) are much more than EDM and less than MDM. Compared to the degradation of natural vegetation's impact on the soil environment, impact of thermokarst lake is quicker and more dramatic, it has also localized damage effect on soil environment of alpine meadow, and can induce rapid damage to soil environment.

Alpine meadow is one of the main ecological types in the source regions of the Yangtze River and studies on alpine meadow soil, vegetation and hydrological characteristics are of great practical significance. It is beneficial to understand deeply the alpine ecological environment in permafrost of the Qinghai-Tibet Plateau, and it is

conducive to the formulation and implementation of developmental, constructive and protective measures in the source regions of the Yangtze River.

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