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SOIL CHEMISTRY

Changes in Soil Physical and Chemical Properties during the Process of Alpine Meadow Degradation along the Eastern Qinghai-Tibet Plateau[1]

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Abstract—Soil moisture, nutrients and environmental conditions have extremely vital effects on vegetation growth and microbial activities in terrestrial ecosystems. To study the changes of soil physical and chemical properties as affected by degradation along the eastern margin of the Tibetan Plateau, using the largest wetland in Ruoergai as the research sample for two consecutive years, we tested the soil bulk density, the soil moisture content, the pH value, the content of organic C, total N and total P of 0~20 cm and 20~40 cm in different degradation degree (light, moderate, serious and non-degraded alpine meadow). The results show that: (1) Degradation had profound effects on the soil physical properties and chemical properties. with the intensification of the alpine meadow degradation in the eastern margin of the Qinghai-Tibet Plateau, the soil organic carbon, total nitrogen, total phosphorus and soil water content decreased significantly but soil bulk density increased significantly. (2) the soil organic carbon, total nitrogen, total phosphorus contents and soil water content increased with the increase of soil depth, however, the soil bulk density show the opposite regular. (3) The correlation analysis indicated that there was an extremely significant positive correlation between soil organic carbon and total nitrogen, total phosphorus, soil water, and the correlation coefficients were 0.822, 0.907 and 0.885 respectively ($P < 0.01$). There was an extremely significant positive relationship between the pH and the soil bulk density ($r = 0.488$, $p < 0.01$), while a significant negative relationship between pH and soil water ($r = -0.387$, $p < 0.05$). Overall, these results suggested that soil degradation not only changed the soil physical properties but also affected the soil chemical properties indirectly. Protecting surface vegetation and reducing wind erosion could be a good way to curb degradation.

Keywords: The Eastern Qinghai-Tibet Plateau, Ruoergai wetland, meadow degradation, soil physical properties, soil chemical properties, change mechanism

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INTRODUCTION

Soil organic carbon, nitrogen and phosphorus, which distribute unevenly in different areas, play major roles in land ecosystem by influencing the soil fertility, plant growth and soil microbial activities [14, 21]. In contrast to other soil elements, soil organic carbon, nitrogen and phosphorus are thought to be key elements that can curb the soil productivity [7, 15]. The study of soil organic carbon, nitrogen and phosphorus content and the relationship between soil and alpine meadow degradation is very important for assessing land degradation at different scales, such as regional, national and global [4, 34].

The Tibetan Plateau is an important water conservation area of China's Yangtze River and Yellow River, and it has a large area of grasslands, serving as the fifth largest livestock production base in China. In addition, there is the most extensive distribution of high-altitude peat bogs, which act an essential role in the ecological environment safety for China and even the world [10, 23]. Due to its high elevation and brittle cold environment, the eastern edge of the Qinghai-Tibet plateau is highly susceptible to global environmental change and human disturbance [22]. Currently, investigations have revealed that the meadow degradation has become one of the most severe environmental problems of this region, threatening its ecological environment. Moreover, as a result of climate change, overgrazing and artificial drainage, the total area of the Zoige peat-wetlands has shrunk rapidly and the water table has severely declined since the 1980s [20, 30]. All of these factors have seriously restricted the local social and economic sustainable

[1] The article is published in the original.

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development and weaken the area's ecological function. Consequently, it is of great significance to study the relationship between the alpine grassland degradation and the contents of soil organic carbon, nitrogen and phosphorus.

Over the past decades, many studies have been conducted to investigate or test the soil organic carbon, nitrogen and phosphorus content in different regions, which were necessary to the study of wetland ecosystems. Studies by B.M. Lex [12] indicate that crop-livestock production systems are the biggest human causes in altering the global nitrogen and phosphorus cycles. With the increase in the demand for beef and mutton, to meet the needs for forage grass, herders increased the amount of fertilizer application. From the beginning of the 20th century to the early 21st century, nitrogen and phosphorus content in soil ecosystems have shown a surplus globally, and this trend is predicted to continue until 2050. As essential elements of protein and genetic material, the nitrogen and phosphorus cycles are often limited in the Ruoergai alpine wetland ecosystem with little disturbance. So, is the nitrogen and phosphorus contents of this region consistent with that of the whole world? The changes of the soil organic carbon and the total nitrogen in the process of the desertification in Horqin Sandy Land were studied by H.L. Zhao [34]. The results show that along with the development of desertification, the soil carbon and nitrogen contents in Horqin Sandy Land decreased apparently. Then, in the eastern edge of the Qinghai-Tibet Plateau, where the ecological environment is very fragile and degradation is intensifying, do the soil carbon and total nitrogen content follow the same rule? Here, an analysis [25] is presented that the effects of grassland desertification on the soil particle composition, the soil potassium and the phosphorus in Northwest Sichuan Hongyuan County. The statistical analysis shows that the change of the total soil phosphorus content in different degrees of degradation was not apparent. With the increase of degradation, the total soil phosphorus content showed a decreasing tendency. Does this rule apply to the Ruoergai Wetland in the eastern edge of the Qinghai-Tibet Plateau? In addition, can the contents of soil organic carbon, nitrogen and phosphorus indirectly reflect the degree of the alpine meadow's degradation?

According to the above scientific problems, we hypothesized that in an alpine meadow ecosystem, the degradation could significantly affect the contents of soil organic carbon, nitrogen and phosphorus, and the nutrient content would vary with the degree of degradation. To verify the above assumptions, we choose the largest wetland in the eastern margin of the Qinghai-Tibet Plateau, the Ruoergai Wetland, as the research area. We used the typical sampling method to stratify the soil at different degradation sample plots. Then, brought soil specimens to the lab, and analyzed the characteristics of the soil index, which can reveal the accumulation characteristics of the soil organic carbon, total nitrogen, total phosphorus and the ecological effect of the different levels of degradation. The result came from our survey and experiment will not only promote the research of the variation of the ecological environment but will provide basal information for control of the alpine meadow soil degradation in the eastern Qinghai-Tibet Plateau.

MATERIALS AND METHODS

Study Area

The research region situated in the eastern edge of the Qinghai-Tibet Plateau, the Zoige wetland, where China's Gansu province and Sichuan province meet. It lies between latitudes 33°25′ N and 24°80′ N and between longitudes 102°29′ E and 102°59′ E [9]. The terrain is tilted from south to north, with a mean altitude of 3500 m. The climate belongs to semi-arid continental monsoon climate of a plateau cold temperate zone and is characterized by a long winter and a relatively short summer [20]. The mean annual precipitation ranges from 654 mm to 780 mm, about 85% of the rainfall appearing during the wet-season from June to September, and the mean annual potential evaporation ranges from 1110 mm to 1273 mm [27]. The average annual temperature is about 1.1°C, and there is no absolutely frost-free season. This region has a long period of sunshine and sufficient solar radiation, with a total annual solar radiation of approximately 6194 MJ/m^2 [31]. The vegetation is a representative alpine meadow and wetland vegetation, reigned by plants such as *Carexpraeclara*, *Carexatrata*, and *Ajaniapotaninii*.

Field Sampling and Investigation

The study began in July 2016 when the meadow vegetation is the most vigorous. On the basis of field investigations, we choose the place where the degradation phenomenon is relatively concentrated as the experimental field. The different degraded levels of the alpine meadow were classified based on the criteria [24, 32] as shown in Table 1: the lightly degraded meadow (LDM), the moderately degraded meadow (MDM), and the seriously degraded meadow (SDM). In addition, a non-degraded meadow (NDM) was selected as a control.

Plant litters were moved from the topsoil before the sampling. In all the sample plot, soil specimens were gathered from the depth of 0 to 20 cm and 20 to 40 cm. Each sample was collected using five-point sampling method [36]. soil specimens were put in plastic packaging bags. The soil cores (10 cm radius) were also gotten at each sampling plot. At the laboratory, each soil sample was sieved to 2 mm mesh to wipe off the kinds of sundries. The rest part of sieved sample was air-dried for testing selected chemical properties. Finally,

Table 1. Different degradation levels in the alpine meadow along the Eastern Qinghai-Tibet Plateau

Classification	Characteristics of meadow
NDM	Thick soil, rich in species, no sand dunes or blowouts.
LDM	Vegetation coverage is greater than 41% and yield of grassland is slightly reduced. Plant population change is not obvious. No sand activities.
MDM	Vegetation coverage is 25–40%, and yield of grassland is decreased by 20%. Plant population change is not obvious; although weeds are apparent in the grassland. The sand-flow activities are not obvious.
SDM	Vegetation coverage is 10–25%. Native vegetation is greatly reduced. Sand flow or quicksand is obviously visible in the texture.

Non-degraded meadow (NDM); The lightly degraded meadow (LDM); The moderately degraded meadow (MDM); The seriously degraded meadow (SDM)

soil specimens were used to determine both the content of total soil nitrogen, phosphorus and other soil physical properties.

Laboratory and Statistical Analyses

The soil organic carbon content was measured by the Walkley-Black $K_2Cr_2O_7$–H_2SO_4 oxidation method [18]. The total soil nitrogen content (g/kg) was analyzed using the Kjeldahl digestion procedure [1]. The total soil phosphorus content (g/kg) was tested using alkaline digestion (NaOH 2 g, 0.25 mm soil 0.25 g, 400°C–15 min and 720°C–15 min) followed by molybdate colorimetric measurement [16]. The soil pH level was tested in a mixture of soil and water (soil water ratio was 1 : 5) by a glass electrode [5]. Undisturbed soil bulk density were drying at 105°C for ten hours, then weighed and figure out the soil bulk density (g/cm^{-3}) [17].

All data were analyzed using the SPSS software. One-way analysis of variance was used to compare the differences of variables in different degrees of degraded soils.Pearson correlation coefficients were used to assess the correlations between the corresponding variables. Excel 2016 was used to draw charts.

RESULTS

The Changes of The Soil Physical Properties and pH in The Process of Meadow Soil Degradation

Soil water content and soil bulk density were important indicators for measuring soil physical properties. With the aggravation of degradation of the alpine meadow, the soil water content decreased significantly ($P < 0.05$), showing that:

NDM > LDM > MDM > SDM (Table 2). Compared with the non-degraded meadow, the soil water content of 0–20 cm soil layer in the lightly, moderately and severely degraded meadow decreased by 30, 51 and 64% respectively; the soil water content of subsurface 20–40 cm decreased by 32, 44 and 63% respectively. On the vertical profile of the soil, the soil water content was characterized by second layers > the first layer. In contrast to the soil moisture content, the soil bulk density increased significantly with the aggravation of degradation, and the soil bulk density in the 0–20 cm soil layer increased significantly ($P < 0.05$), and the variation of soil bulk density in the subsurface 20–40 cm was not significant ($P > 0.05$). Soil bulk density in the soil profile showed as follows: the first layer > second layers. The lowest pH value of soil was 7.77 in the non-degraded stage, and the highest value was 8.27 in the moderate degradation stage, so it gradually tended to be alkaline. On the soil profile, soil pH did not change regularly.

The Changes of the Soil Organic Carbon Content in the Process of Meadow Soil Degradation

With the intensification of degradation in the alpine meadow, soil organic carbon content gradually decreased,showing that: NDM > LDM > MDM > SDM (Fig. 1). Compared with non-degraded meadow, the loss of surface 0–20 cm soil organic carbon in lightly, moderately and severely degraded meadow was 1.24, 16.48 and 23.18 g/kg respectively; The loss of organic carbon in subsurface 20–40 cm was 2.09, 16.39 and 24.18 g/kg, respectively.

Table 2. Soil water content, pH value and soil bulk density under different degradation levels

Stage	Soil Depth, cm	NDM	LDM	MDM	SDM
Soil Moisture Content (%)	0–20	11.64 ± 0.01^a	8.11 ± 0.01^b	5.73 ± 0.01^c	4.23 ± 0.01^c
	20–40	12.96 ± 0.01^a	8.84 ± 0.01^b	7.26 ± 0.01^b	$4.82\% \pm 0.01^c$
pH Value	0–20	7.77 ± 0.19^a	8.12 ± 0.04^a	8.27 ± 0.19^a	8.17 ± 0.09^a
	20–40	7.8 ± 0.11^b	8.08 ± 0.04^{ab}	8.3 ± 0.1^a	8.03 ± 0.09^{ab}
Soil Bulk Density (g/cm^3)	0–20	1.60 ± 0.02^c	1.64 ± 0.01^b	1.64 ± 0.01^b	1.69 ± 0.01^a
	20–40	1.58 ± 0.02^a	1.61 ± 0.02^a	1.63 ± 0.03^a	1.65 ± 0.01^a

Different lowercase letters in the same column means significant difference at 5% level.
Means ± Std error ($P < 0.05$).

On the soil profile, relative losses indicated that soil organic carbon content in 0–20 cm soil layer was greatly affected by degradation. Compared with the second layer 20–40 cm, the content of organic carbon of the first soil layer 0–20 cm in none degraded meadow, lightly degraded meadow, moderately degraded meadow, and seriously degraded meadow decreased by 12, 10, 24 and 33%, with an average decrease of 20%.

The Changes of the Soil Total Nitrogen Content in the Process of Meadow Soil Degradation

The total soil nitrogen contents in the alpine meadow fall badly with the increasing of the degradation degree ($P < 0.05$) (Fig. 2). The results indicated that under different level of degradation, the mean total soil nitrogen content ranged from 0.07 to 0.63 g/kg. The mean total soil nitrogen content was the most abundant in the NDM soils (0.63 g/kg), followed by the LDM (0.19 g/kg), the MDM (0.11 g/kg), and the SDM (0.07 g/kg). Compared with undegraded meadow soil, the mean total soil nitrogen contents in lightly, moderately and severely degraded meadow decreased by 69, 83 and 89%, respectively.

On the vertical profile of the soil, the content of the total soil nitrogen tended to increase as the soil depth increased (Fig. 2). In the degradation process of the alpine meadow, the total nitrogen content of the non-degraded meadow, the lightly degraded meadow, the moderately degraded meadow, and the seriously degraded meadow ranged from 0.60 to 0.65 g/kg, from 0.17 to 0.21 g/kg, from 0.09 to 0.12 g/kg, and from 0.06 to 0.07 g/kg, respectively.

The Changes of the Soil Total Phosphorus Content in the Process of The Meadow Soil Degradation

With the exacerbation of degradation of the alpine meadow in Ruoergai, the total phosphorus content decreased gradually (Fig. 3), but the content of total phosphorus was more than 0.38 g/kg in every stage of degradation. Under the different stages of degradation, the mean total phosphorus content in the non-degraded meadow was the highest (2.38 g/kg) and the mean total phosphorus content in the seriously degraded meadow was the lowest (0.39 g/kg). The content of the total soil phosphorus in the lightly degraded meadow was higher than in the moderate degraded meadow. Compared to the control, the mean total phosphorus contents in the lightly, moderately and seriously degraded meadows decreased by 40, 76 and 84%, respectively.

Soil total phosphorus content had the same change regularity with soil organic carbon content and total nitrogen content in the soil profile. In the process of meadow soil degradation, the total phosphorus content of the non-degraded meadow, the lightly degraded meadow, the moderately degraded meadow,

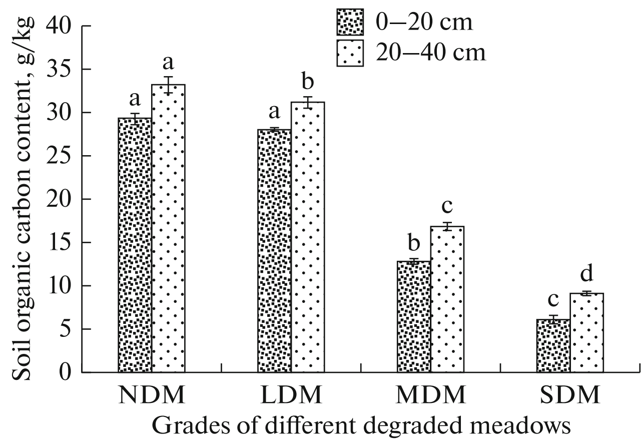

Fig. 1. Variation of the soil organic carbon contents under different degradation degrees.
Note: Different lowercase letters mean significant differences at $P < 0.05$ level.

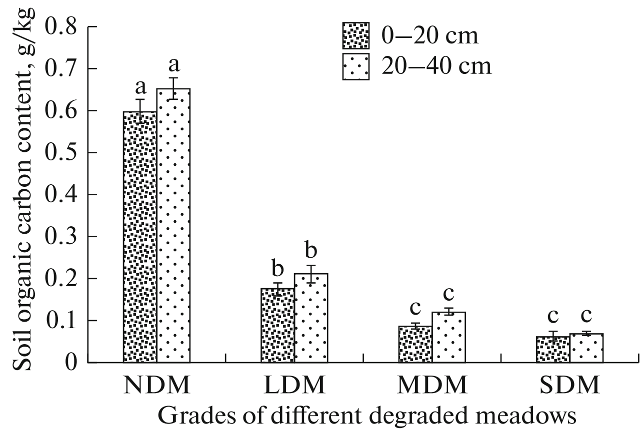

Fig. 2. Variation of the total soil nitrogen contents under different degradation degrees.
Note: Different lowercase letters mean significant differences at $P < 0.05$ level.

the seriously degraded meadow ranged from 2.34 to 2.43 g/kg, from 1.40 to 1.46 g/kg, from 0.55 to 0.58 g/kg, and from 0.38 to 0.39 g/kg, respectively. Similarly, the total phosphorus content increased as the soil depth increased.

Correlation Analysis

Pearson correlation coefficients among the soil organic carbon, total soil nitrogen, the total soil phosphorus, and selected soil physical property factors were shown in Table 3. The correlation analysis showed there was an extremely significant positive correlation among soil organic carbon and total nitrogen, total phosphorus, water content, and the correlation coefficients between soil organic and other three soil index were 0.822, 0.907 and 0.885 respectively ($P < 0.01$). At the same time, there was a significant negative correlation between organic carbon and pH

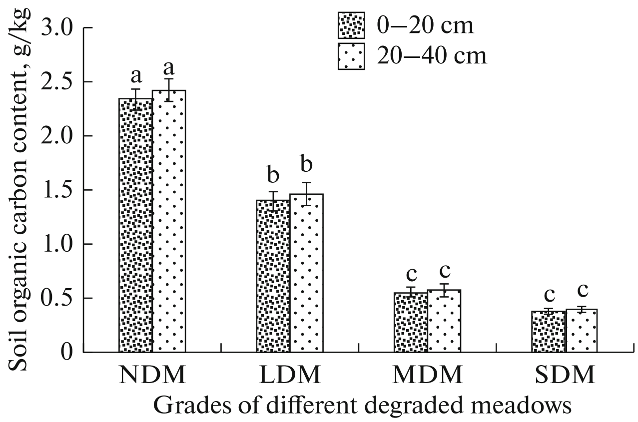

Fig. 3. Variation of the total soil phosphorus content under different degradation degrees.
Note: Different lowercase letters mean significant differences at $P < 0.05$ level.

value ($r = -0.431$, $P < 0.05$), and negatively correlated with bulk density ($r = -0.642$, $P < 0.01$). The total nitrogen was significant negative correlated with both pH value and soil bulk density ($r = -0.599$, -0.555, $P < 0.01$), while the total nitrogen and soil moisture content had a very significant positive correlation ($r = 0.866$, $P < 0.01$). The soil total phosphorus has a very significant negative correlation with pH and soil bulk density ($r = -0.557$, -0.622, $P < 0.01$), and has a very significant positive correlation with soil moisture content ($r = 0.887$, $P < 0.01$). There was a significant negative correlation between soil pH and water content ($r = -0.387$, $P < 0.05$) and a very significant positive correlation with soil bulk density ($r = 0.488$, $P < 0.01$). Soil moisture content was negatively correlated with soil bulk density ($r = -0.617$, $P < 0.01$). According to Figs. 1–3, the results showed that the degree of soil degradation was closely related to the content of soil organic carbon, total nitrogen, total phosphorus and other soil physical properties.

DISCUSSION AND CONCLUSION

The phenomenon of the degradation and the desertification of the alpine meadow is severe in Ruoergai of the eastern Qinghai-Tibet Plateau. Soil physical and chemical properties, which are essential environmental condition for plant growth, are important factors in ecological restoration and degradation control. The results are in line with the hypothesis mentioned above. The contents of the organic carbon, total nitrogen and the total phosphorus in the alpine meadow ecosystem were significantly correlated with the degree of degradation. With the intensification of the alpine meadow degradation, the soil organic carbon, nitrogen and phosphorus contents in the 0~20 cm and the 20~40 cm soil layers gradually decreased (Fig. 1–3).

Effects of Meadow Degradation on Soil Physical Properties and pH

Soil water content and soil bulk density, as important parameters of soil physical properties, affect soil water and fertilizer conservation and aeration capacity. This result showed that as the degradation deteriorated, soil water content decreased significantly and soil bulk density increased significantly ($P < 0.05$). From the process of none degradation to severe degradation, Soil water content decreased by 63% and soil bulk density increased by 5% in the 0–40 cm soil layer. Correlation analysis showed that soil bulk density had a very significant negative correlation with soil water content ($r = -0.617$, $P < 0.01$). This may be due to the deterioration of the alpine meadow degradation, the vegetation coverage and height decrease; then, the protective effect on the soil was weakened, resulting in the decrease of soil porosity, the weakening of water retention capacity and the increase of evaporation [28]. Soil pH has a direct effect on availability of soil nutrient, which can directly or indirectly affect the growth and development of vegetation on the surface [8]. The correlation analysis showed that soil pH and organic carbon had a significant negative correlation ($P < 0.05$), and soil pH had a very significant negative correlation with total nitrogen and total phosphorus ($r = -0.599$, -0.557, $P < 0.01$). This result supports the view of the relationship between soil pH and soil nutrients in previous studies [7, 23].

Soil water content is a dynamic indicator of soil evaporation and precipitation. With the deepening of the soil depth, the soil water content in the 0~20 cm

Table 3. Correlations among the soil indexes

Item	Organic Carbon	Total Nitrogen	Total Phosphorus	pH Value	Water Content	Soil Bulk Density
Organic Carbon	1	?	?	?	?	?
Total Nitrogen	0.822**	1				
Total Phosphorus	0.907**	0.929**	1			
pH Value	–0.431*	–0.599**	–0.557**	1		
Water Content	0.885**	0.866**	0.887**	–0.387*	1	
Soil Bulk Density	–0.642**	–0.555**	–0.622**	0.488**	–0.617**	1

* Indicate significant differences at the 0.05 level
** Indicate significant differences at the 0.01 level.

was lower than in the 20~40 cm, while soil bulk density is the opposite, Soil bulk density in 0~20 cm was higher than in the 20~40 cm. The reason is that 0–20 cm soil is exposed to sunlight and wind erosion for a long time, so the evaporation of soil water is faster than that of 20–40 cm soil, and the loss of soil water is greater [13]. The difference of soil bulk density between 0–20 and 20–40 cm may be related to the compaction of animals and the distribution of plant roots [2]. Soil pH has no regular change in vertical profile of soil.

Effects of Meadow Degradation on soil C N P Content

The content of soil carbon, nitrogen and phosphorus depends on the difference between input and loss [26]. The content of soil organic carbon, total nitrogen and total phosphorus in the 0–40 cm soil layer decreased significantly, reaching 76, 89 and 84%, respectively, of which organic carbon lost 23.68 g/kg, total nitrogen lost 0.56 g/kg, and total phosphorus lost 1.99 g/kg. There are two reasons for this phenomenon. The reason may be that, with the deterioration of degradation, the coverage of the plants community decreases, the input amount of organic matter is reduced as well as the protection to the soil is weakened, so that the soil carbon, nitrogen and phosphorus are lost in large amount. The result supports the view of T. Wan [29] and S.L. Jiang [10] regarding changes in the soil nitrogen characteristics during grassland degradation in Northwest Sichuan. In addition, this law is consistent with the changes of the soil nitrogen in the process of meadow degradation in arid and semi-arid zones of China found by Y.Q. Li [11] and H.L. Zhao [35]. These findings suggested that the change of the soil organic carbon, total nitrogen and total phosphorus in the alpine meadow of Ruoergai is similar to the semi-arid area of North China. The correlation analysis showed that there was a very significant correlation between soil carbon, nitrogen and phosphorus ($r = 0.822, 0.907, 0.929$, $P < 0.01$), which supported the view that there was a close relationship between various nutrients in the soil [6, 10].

Land degradation characterized by wind erosion is one of the types of grassland degradation [29]. It is generally believed that wind erosion causes nutrient loss in the surface soil of degradation meadow, resulting in the decline of soil productivity and destroying the balance of nutrient elements in grassland ecosystem. The study demonstrated that a large amount of carbon, nitrogen and phosphorus were lost in the 0~20 cm soil layer. Compared with 20–40 cm, soil C, N and P content decreased by 79, 89 and 84%, respectively in 0–20 cm soil depth, which indicate that degradation has a more significant effect on Soil Nutrients. There are two reasons for this phenomenon. First, the soil nutrient mainly came from the accumulation of litter in surface soil and artificial fertilizer, but the source of soil nutrient was scarce in the alpine meadow degradation areas in Ruoergai. Meanwhile, the nutrients necessary for plant growth mainly come from the 0~20 cm soil depth. Second, due to the unique geological conditions of Ruoergai, the wind erosion is serious, resulting in a rapid decrease of the nutrient content in the surface 0~20 cm soil [33, 37]. Other scholars have reached similar conclusions on different scales [3, 19, 38].

In summary, the results showed that soil degradation not only changed the soil physical properties but also indirectly affected the soil chemical properties. Protecting surface vegetation and reducing wind erosion could be a good way to curb degradation. The data collected from our research can provide basic data for the current condition of alpine meadow soil degradation in the Qinghai-Tibetan Plateau as well as facilitate the research on ecological environment.

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