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Influence of land cover changes on the physical and chemical properties of alpine meadow soil

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Abstract **Taking the alpine cold meadow grassland in the southeastern part of the Qinghai-Tibetan Plateau as an example, this research deals with the characteristics of alpine meadow soil property changes, including soil nutrients, soil physical properties and soil moisture content under different land coverage conditions. With the degradation of grassland vegetation and the decline of vegetation coverage, soil compactness reduces, gravel content increases and bulk density increases. The originally dense root-system layer is gradually denuded, making the soil coarse and gravel. The change of the organic matter contents with the vegetation coverage change in the surface soil layer (0—20 cm) has shown an obvious cubic polynomial curve process. The organic matter contents increase rapidly when land coverage is above 60%, contrarily decreases on a large scale when land coverage is below 30%. Between 30%—60% of land coverage the organic matter contents remain stable. The total N and organic matter contents in soil have shown quite similar change regularity. Following this the mathematic equations are derived to describe such change processes. Moisture content in soil changes sharply with the vegetation coverage change. Soil moisture content change with the vegetation coverage change has shown a quadratic parabola process. Results have shown that organic matter content and the total N content of the alpine meadow soil decrease by 14890 kg/hm^2 and 5505 kg/hm^2 respectively as the vegetation coverage reduces from 90% to less than 30%. The heavy changes of soil physical and chemical properties with grassland degradation have made the recovery of alpine meadow ecological system impossible. The protection of alpine meadow vegetation is of vital importance to the maintenance of the regional soil environment and the regional ecological system.**

Keywords: land cover change, alpine meadow soil, soil property, grassland degradation, Qinghai-Tibetan Plateau.

Land use and land cover changes (LUCC) were considered as the main components and chief causes of global environmental change[1,2]. The influence of human activities on soil environment is the central content of the study of global environmental change and sustainable development[3,4]. Anthropogenic soil environmental changes are the important indicators for measuring and reflecting the qualities of regional soil resources and environment[4]. Numerous studies have shown that ways of land use and managerial measures could affect the direction and degree of soil environmental changes[5—7]. Land cover is the syntheses of natural and man-made land coverage, which mainly includes the land and vegetation types, the vegetation density, the dynamic characteristics of vegetation growth seasons and the biophysical characteristics of land coverage[1,5]. Land cover, unlike land use, emphasizes the natural features of the land. Land use results in the land cover change that directly influences the terrestrial ecosystem and biogeochemical processes[6,7]. Meanwhile, land cover changes lead to soil loss and soil degradation by changing soil characteristics[5,6]. IAHS selected this issue as a main topic of two symposiums and the most prominent aspects were placed on the quantitative simulation and prediction of dynamical tendency of soil nutrient migration on regional or basin scale under different climate, landform and land use/ground cover conditions[8—10].

Soil characteristics are synthetic reflections of a series of soil physic-chemical features, and show the basic regimes of soil environment including soil physic texture and composition, soil chemic and nutrient characteristics, soil moisture, etc. Comparatively, the changes in forest soil and farmland soil under different land-use and management conditions were studied earlier than those of grassland soil. Especially the changes in soil physico-chemical properties and environmental features under different climates and landform conditions have been extensively studied[7]. Some pilot studies showed that the grassland cover changes, like forest cover change, have a great influence on soil water cycle and soil nutrient transformation[8—10]. However, very little research has been carried out on the alpine meadow soils widely distributed in the Qinghai-Tibetan Plateau and the inland mountain regions of China. Since the alpine cold meadow and grassland soils on the Qinghai-Tibetan Plateau have conspicuous water and heat changes, the vegetation system is highly sensitive to climate changes and the land is mainly used for grazing, they are valuable to the researches on global changes and soil-vegetation-atmosphere interactions of the region[11,12]. In addition, because the alpine meadow grasslands are mostly distributed in the source areas of many rivers and the changes in soil moisture behavior are closely related to the hydrological processes of the basins, it seems very necessary to study the response of alpine meadow soil properties to ground cover/land use changes.

1 Study area and methods

(ⅰ) Study area. The headwaters area of the Yellow River, Darlag County of Qinghai Province, was selected as the study area. Vegetation in the headwaters area is simple and dominated by alpine cold meadows. In the high-altitude zones there are cushion plants and sparse talus plants[11,12,14]. The dominant plant species are *K. humilis*, *K. capillifolia, K. pygmaea, Poa* sp., *Littledalea racemosa* and *Puccinella* spp., with a vegetative cover of 50%—90%[12,14]. The study area is located in the mid-east part of the Qinghai-Tibetan Plateau. It has an alpine cold and subhumid climate, with an annual mean temperature ranging from –0.1 to 3.5℃ and annual precipitation of 569 mm. Livestock grazing is the main economic activity of the area and practically no other way of land-use exists[12]. The selected study region, as a part of the southern Qinghai Plateau, is one of the regions with continuous alpine meadow soil distribution in the world. Owing to the spatial difference in water and heat conditions, the river valley, the bottomland, the sunny slopes and the semi-shady slopes of the mountains in the area below the height of 4300—4550 m a.s.l. are mostly covered by alpine cold meadow vegetation, and the shady slopes are covered by alpine cold shrub meadow vegetation. There are five soil types, i.e. alpine frozen soil, alpine meadow soil, alpine steppe soil, meadow soil and swamp meadow soil. Soil in the area is dominated by alpine meadow soil that is covered with alpine cold meadow vegetation, accounting for about 82.59% of the whole land area in this region. According to vegetation types and soil formation conditions they can be further divided in barbarism alpine meadow soil, alpine meadow soil, alpine shrub meadow soil and eroded alpine meadow soil, of which the barbarism alpine meadow soil was not included in the study range due to its small area. Their spatial distribution is shown in Fig. 1, and their basic characteristics are as follows[11,12]:

(1) Alpine meadow soil: the dominant soil in this area, whose layer is usually quite thin, about 30—60 cm in thickness. The parent materials of this soil are chiefly slope deposits and residual deposits. The soil texture is coarse: 1—0.01 mm grains generally account for 70% or so and gravels larger than 3 mm account for 10%—25%. In the layer of 0—10 cm, root systems are densely distributed with rich organic matter; soils are mostly sandy and humid due to the effect of the dense felty root system. In the layer of 10—30 cm is the humus layer with a dense root system; the soil is relatively loose and contains a small amount of semi-weathered gravels. Below 30 cm, root systems decrease but gravels increase.

(2) Eroded meadow soil: distributed generally on sunny gentle slopes of flats. Owing to the effects of rat damaging and human activities they have degraded seriously; vegetation coverage is less than 50% with weeds and *Kobresia* as the edificators. The soil is generally called “black soil shoal”. In the layer of 0—10 cm, soil is loose and contains gravels with rich root systems, generally belonging to gravelly medium loam. In 10—30 cm, soil layer has sparse root systems but numerous gravels and pores.

(3) Alpine shrub meadow soil: covered dominantly by alpine cold shrub vegetation including *Salix oritrepha, Dasiphora fruticosa, Kobresia bellardii*, *Poa alpina*, etc. is mainly distributed on the shady slope, with coverage of 80%—90%. In 0—20 cm, the soil layer contains a higher amount of humus; the soil is loose, without felty root system. 20—40 cm is light loamy and contains shrub root systems. The soil layer below 40 cm is light loamy, which is humid due to the freezing effect.

(ⅱ) Study methods. In methodology, the field survey was integrated with plot testing and experiments in laboratory. In regard to the vegetation and land types for land coverage issue, this study focuses on only one type of alpine cold meadow vegetation and alpine meadow soil. Topography (height, landforms, and so on) has some influence on the structure of vegetation, but it has little influence on vegetation types in the study area. In the same vegetation type, the land coverage changes are related to the degradation of vegetation and the directions of slopes. Therefore, the land coverage change is indicted by vegetation coverage changes caused by natural factors or human activities. Some of the soil physical parameters, such as soil density, soil moisture, soil unit weight and soil structure, and soil trophic state index (organic matter and nitrogen contents) are considered as variables to indict the soil characteristics.

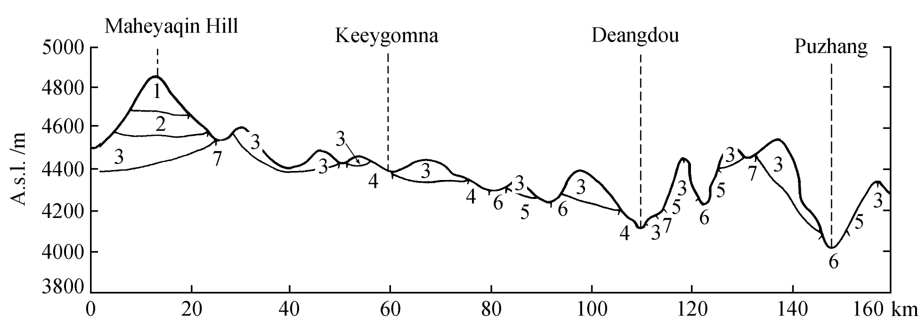

Fig. 1. Section plane of soil types and their spatial distribution. 1, Alpine rocky cold desert soils; 2, originality alpine meadow soils; 3, alpine meadow soils; 4, carbonate alpine meadow soils; 5, alpine shrubmeadow soils; 6, meadow soils; 7, swamp meadow soils.

With river basins as units, the investigation sections were arranged vertical to and parallel to the basin direction and the quadrates were arranged on each section in accordance with vegetation types and coverage changes. A series of investigation of sample plots have been carried out along with every section. Vegetation species composition, coverage, soil profile features, soil layer thickness, etc. were recorded, and soil moisture content, infiltration rate and evapo-transpiration were measured in every plot. In the meantime, soil samples were collected to determine soil nutrients and mechanical composition.

Soil moisture contents were determined using the time-domain reflection moisture meter (TDR). It can directly determine the volume moisture contents of different soil depths and is especially suitable for the moisture determination of coarse-grained soils of the study area. Each layer of the soils was parallelly determined three times. In the meantime, the weight moisture contents of soils were determined by the over-drying method. Soil bulk densities were determined by the ring-cutting method and HY-100 soil bulk density meter (produced from China) and the determined results were checked against each other.

Soil nutrient determination was limited to macro-analysis, including organic matter, total N, P and K, hydrolyzalbe N, available P and K, etc. Soil layer thickness in the study area generally varies from 40 cm to 60 cm, plant root systems mainly concentrate at the depths of 10—30 cm and shrub root systems could reach up to the depths of 60—70 cm. Hence, soil samples for nutrient analysis were collected from five depths, 10 cm, 20 cm, 30 cm, 40 cm and 60 cm. In order to reveal the difference between topsoil layer (0—30 cm) and subsoil layer (30—60 cm), the determined results of the two layers were gathered together in the comparative analysis of soil nutrient changes under different coverage conditions.

2 Study results

(ⅰ) Soil nutrient response to land cover changes. Soil organic matter and nitrogen are the main nutrient indexes of soil nutrients. Soil organic matter is also an important factor affecting soil structure, soil fertility, soil water retention ability, soil erosion resistance, soil temperature, etc. Hence it is an important indicator of soil characteristics[13]. The statistic results of soil organic matter and nitrogen at different depths under varied land coverage are shown in Tables 1 and 2. Fig. 1 shows the determined results of organic matter and total N of alpine clod meadow soil under different vegetation coverage conditions. Viewed from the scattering distribution tendency of soil organic matter contents of different vegetation coverages, the organic matter content in the topsoil layer (0—30 cm) of the alpine meadow soil showed a change regularity of cubic polynomial curve, and its fitting statistical curve equation is

$$Y = -5.2112+3.3854C-0.0789C^2+0.00055C^3, \quad (1)$$

where Y is soil organic matter content (g/kg) and C is the degree of land cover (%). The statistical check value of the equation $R^2 = 0.9394$. Since the equation has a higher statistical check value, it can reflect the general law of organic matter changes of alpine cold meadow soil with vegetation coverage changes.

It can be seen from Fig. 2 that, under the conditions of originally dense root systems and high meadow vegetation cover (coverage > 80%), soil organic matter content showed an approximately linear increase with vegetation coverage increasing. As the vegetation coverage reached

Table 1 Statistic of soil trophic state tested at 0—30 cm depths under varied land coverages

Coverage (%)	Soil organic matter content/g • kg^{-1}				Soil total N content/g • kg^{-1}			
	sample No.	average	max.	min.	sample No.	average	max.	min.
< 15	4	24.9	30.94	20.3	4	1.34	2.01	1.04
15—30	8	37.99	48.44	23.5	8	2.28	3.25	1.13
30—50	9	43.27	52.1	30.1	9	2.7	3.25	2.01
50—70	11	44.08	56.7	35.81	11	2.01	3.2	2.01
70—90	16	71.91	113.87	39.32	16	3.77	5.9	2.24
> 90	8	100.27	118.4	78.4	8	4.83	5.92	3.27

Table 2 Statistic of soil trophic state tested at 30—60 cm depths under varied land coverages

Coverage (%)	Soil organic matter content/g • kg^{-1}				Soil total N content/g • kg^{-1}			
	sample No.	average	max.	min.	sample No.	average	max.	min.
<15	4	15.34	17.71	12.5	4	1.03	1.21	0.91
15—30	7	16.51	22.65	12.5	7	1.16	1.51	0.86
30—50	8	20.47	27.1	9.59	8	1.25	1.51	0.66
50—70	11	22.58	37.9	12.9	11	1.29	1.72	0.9
70—90	15	33.18	49.6	12.99	15	1.81	3.03	0.89
> 90	8	44.95	97.5	26.03	8	2.35	4.24	0.53

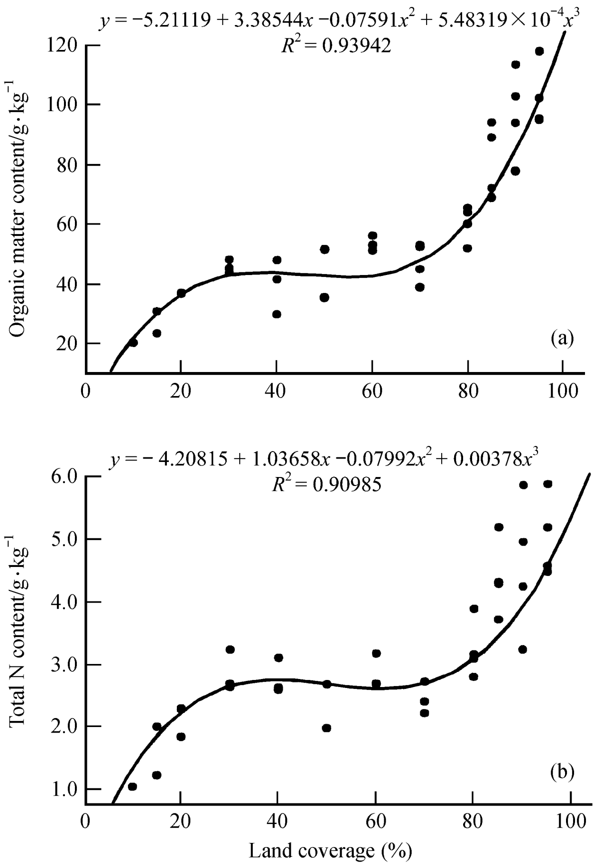

Fig. 2. Tendency of organic matter and total N contents in surface soil layer (0—30 cm) of alpine meadow soil with the changes of vegetation coverage.

95%, the organic matter content increased by 1.5 times, compared to the time when the soil had 70% vegetation coverage. The original alpine cold meadow vegetation in the study area had a higher coverage and organic matter content. As shown in Fig. 2, as the vegetation coverage exceeds 90%, the organic matter content is higher than 70 g/kg. For the moderately degraded alpine cold meadow grassland, its vegetation coverage reduced from more than 90% to 60%—70%, the organic matter content in the topsoil layer (0—30 cm) sharply decreased by 30%—55%. What is interesting is that as the alpine cold meadow vegetation coverage varied between 30%—60%, the organic matter content in topsoil layer almost showed no change and stabilized between 45—50 g/kg. From field investigation we found that soils with a vegetation coverage of 30%—60% entirely belonged to erosion-induced degraded alpine meadow soil type. They generally occurred on the river banks and gentle mountain slopes with secondary weeds as the main edificators. As the land cover further became worse and the vegetation coverage was less than 30%, serious water erosion gullies and dense subsoil piles formed by rat digging could be seen on the surface, and the soil surface obviously became coarse and gravelly. In such a case, organic matter content in the topsoil layer also showed a decreasing tendency, with an average decrease of 10—15 g/kg, and the vegetation coverage reduced by 10%.

Like the soil organic matter, the total N content and its distribution in soil are related to vegetation, water and heat conditions. It is not only a fertility indicator, but also an important soil characteristic mark. The total N content changes in the upper layer (0—30 cm) of alpine meadow soils with vegetation coverage changes are quite similar to the changes of soil organic matter (Fig. 2). In statistical terms, it can be expressed by the cubic polynomial tendency equation:

$$N = -4.208 + 1.037C - 0.0799C^2 + 0.0038C^3, \quad (2)$$

where N is the total N content (g/kg), and statistic check $R^2 = 0.9098$. Eqs. (1) and (2) are the same in form. This suggests that the total N contents of soil with vegetation coverage changes exhibit an obvious cubic polynomial tendency, too. In the cases of high and low vegetation coverage, it changed sharply but in the case of medium vegetation coverage it was relatively stable. What is different is that as the vegetation coverage was higher than 85%, the determined total N contents greatly deviated from the regression curve as compared to the organic matter contents, and the determined N values showed a sharp change. When vegetation coverage reduced from 95% to 85%, the total N content on an average decreased by 35%—40% and the decreased amplitude was significantly higher than that of soil organic matter content. In the alpine meadow soil, which was dominated by *Kobresia*, the forms over 95% of the soil N were the organic N, and the organic N had a high aminating action[14]. That led to rapid loss of soil N content with the degradation of alpine meadow vegetation.

Organic matter and the total N contents in the subsoil layer (30—60 cm) with vegetation coverage changes are shown in Fig. 3. Although the organic matter and total N contents in the area of high vegetation coverage (>80%) are higher, they have no obvious correlation. The changes of organic matter and the total N contents are more complex in the subsoil layer than in the topsoil layer. That suggests that there are more factors affecting soil nutrient content in the subsoil layer and the influence of vegetation coverage is not decisive.

According to the above analysis, calculated on the basis of 30 cm soil thickness and 90% of undisturbed mean coverage, the nutrient losses of alpine meadow soils with different degrees of degraded vegetation and different bulk densities are presented in Table 3. It can be seen that the nutrient contents of alpine meadow soils showed a marked response to vegetation coverage. Slightly degraded vegetation resulted in a soil organic matter loss of

8370 kg/hm^2 and N loss of 1590 kg/hm^2. Seriously degraded vegetation resulted in a soil organic loss of 14890 kg/hm^2 and N loss of 5505 kg/hm^2.

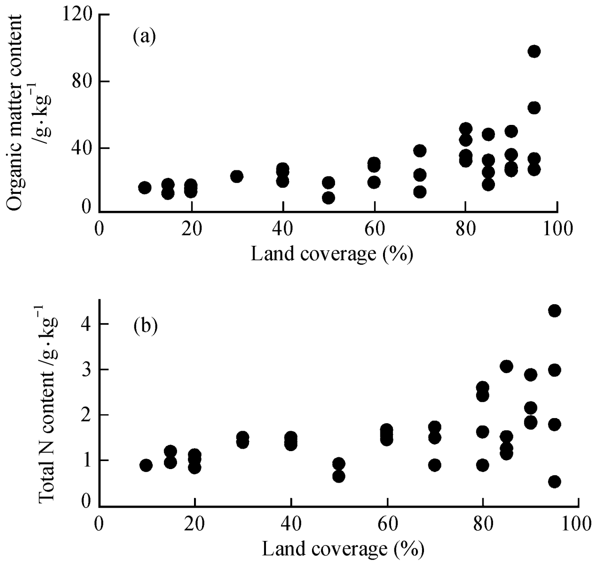

Fig. 3. Organic matter and total N contents in subsoil layer (30—60 cm) with vegetation coverage Changes.

(ii) Influences of vegetation cover on physical properties of alpine meadow soils. In the alpine cold region, when alpine meadow coverage is decreased, the nutrient loss of alpine meadow soils was very serious. In addition, the reduction in meadow vegetation coverage led to the invasion of rats. They browsed plant roots and stems, dug out a large amount of subsoil and thus formed densely distributed soil piles. Such soil piles buried vegetation and formed bare lands under the influences of soil erosion by water and wind. With the increase in subsurface hole density, soils became loose and susceptible to erosion[14,15]. As a result, soil physical properties also obviously changed. Table 4 lists several soil physical indexes under different vegetation coverage conditions. Root systems in a 0—10 cm layer of primary alpine cold meadow soils were dense and formed felty turf, and the mean ratio between grass and soil in a 0—20 cm soil layer was 1∶4.5. The soil density was great but its bulk density was small. The largest soil bulk density in the study area was 1.04 g/cm^3 and the content of gravels was small. When the grassland was degraded, the coverage of vegetation was reduced from over 90% to lower than 60% and secondary weeds replaced the primary *Kobresia*, soil compactness lowered, and surface soil density was reduced to 0.38 kg/cm^2 under a vegetation coverage of less than 30%[12,15]. With gradual denudation of dense root system layer, grass content in soil significantly decreased, soil-stabilizing root systems also decreased, soil and water losses increased, soil bulk density enhanced, gravel content increased, thus making the soil coarse and gravelly.

(iii) Influences of land cover on soil moisture content. The determined results of soil moisture distribution in soil profile showed that soil moisture content is closely related to the vegetation coverage (Table 5). Fig. 4 shows the soil moisture contents at 20 cm and 50 cm depths with vegetation coverage changes. The data analyses at all observation sites showed that soil moisture content at 20 cm depth with vegetation coverage has an obvious parabolic tendency and it is easy to obtain a statistical correlation equation:

$$W = 19.46619 - 0.08219C + 0.00667C^2, \qquad (3)$$

where W is soil moisture content (%), C is vegetation coverage (%) and correlation check R^2 = 0.9949. That shows there is a quantitative relation between vegetation coverage and soil moisture content. Furthermore, the soil moisture content changes slowly under the low vegetation coverage condition but varies sharply under the high vegetation coverage condition. However, the situation is somewhat different: soil moisture content within the 50 cm layer and vegetation coverage showed a scattering tendency as shown in Fig. 4(b), although the fitting correlation equation between vegetation coverage and soil

Table 3 Nutrient losses of alpine meadow caused by vegetation coverage changes

Vegetation coverage change	Under-gradation (90% coverage)	Slight degradation (70% coverage)	Moderate degradation (40% coverage)	Serious degradation (20% coverage)
Soil bulk density /g • cm^{-3}	1.04	1.21	1.38	1.55
Organic matter loss /kg • hm^{-2}	–	8370	9960	19890
N loss/kg • hm^{-2}	–	1590	1716	5505

Table 4 Relation between vegetation coverage of alpine cold meadow grassland and soil physical property changes

Vegetation coverage (%)	Surface soil density/kg • cm^{-2}	Grass to soil ratio (0—20 cm)	Soil bulk density/ g • cm^{-3} (0—20 cm)	Mean distribution density of rat[15] (individuals/hm^2)	>2 mm gravel content (%) (0—20 cm)
70—80	2.9	1∶8.9	1.17—1.22	82	3—16
40—60	2.30	1∶16.7	1.21—1.43	148	15—24
10—30	0.38	1∶21.8	1.36—1.57	48	25—57
Primary grassland	4.03	1∶4.5	0.69—1.04	25	0—8

Table 5 Statistics of alpine soil moisture tested at different depths under different land coverages

Coverage (%)	Sample No.	0—30 cm depth			30—50 cm depth		
		average	max.	min.	average	max.	min.
≤15	8	23.4	27.0	17.3	18.37	23.5	14.3
30	9	23.6	29.9	20.7	20.68	28.8	15.6
50	8	28.94	35.4	20.7	21.58	27.6	15.4
70	7	37.27	44.9	27.8	29.75	38.6	22.0
≥90	9	54.34	73.9	40.9	30.4	38.9	27.2

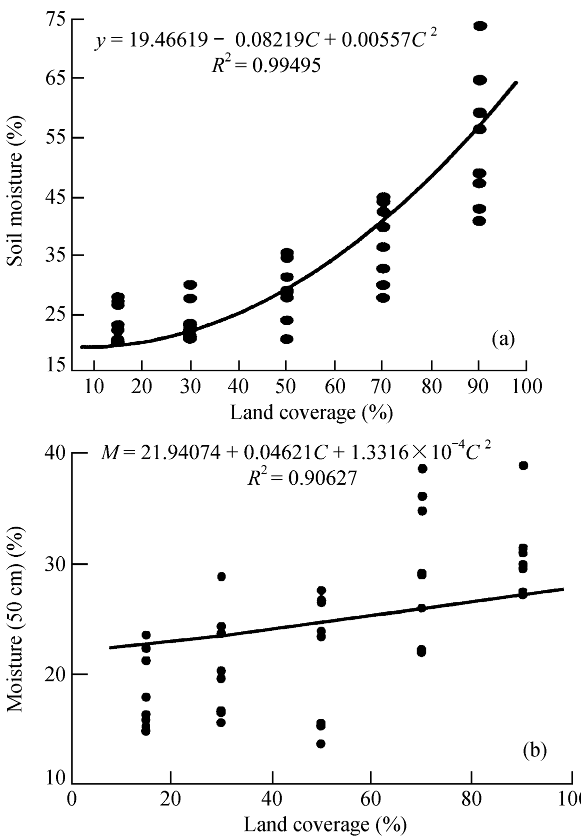

Fig. 4. Soil moisture contents at different depths along with vegetation coverage change.

moisture content is also a quadratic polynomial as follows:

$$y = 21.94+0.0462C+0.000133C^2. \quad (4)$$

The correlation check R^2 = 0.9136. Compared with the changes of topsoil moisture content, it has a different equation, the scattering regularity is not evident and the relative moisture change is complicated. Eqs. (3) and (4) were established on the basis of experimental data statistics. Because the tested vegetation coverage varied between 15%—90%, one can use the above binomial to calculate the soil moisture contents at 20 and 50 cm depths.

The curve in Fig. 4 reflects not only the scattering tendency of the experimental data but also the simulation values of soil moisture content corresponding to the non-experimental coverage. At 40% of vegetation coverage, soil moisture contents within 20 and 50 cm depths were 26.85%±13.4% and 23.58%±11.9% respectively. The quantitative relation obtained from statistical data shows that the increase of vegetation coverage is favorable to enhancing moisture content of alpine cold meadow soil, and this is particularly obvious in the shallow soils (20 cm). When the vegetation coverage is above 60%, each 10% increase in vegetation coverage leads to a 5%—15% increase in the soil moisture content, which is significantly higher than the increase amplitude of moisture content of deep soil (50 cm, Fig. 4(b)). The reason for this is that as the coverage of meadow vegetation (including dwarf shrub meadow) increases, the water absorbed by the plant root system from soil is mainly concentrated in 20—40 cm soil layers with the dense root system[16]. In addition, because the high-coverage vegetation intercepts the precipitation and slows down the water infiltration into soil, the upper soil layer remains wet during most time of the year.

3 Conclusion and discussion

Alpine meadow soils in the Qinghai-Tibetan Plateau are of a special grassland soil type. They occur in the high-altitude region near the source areas of many rivers. The change of their properties is not only closely related to global changes but also significantly affects the hydrological processes of river runoff. The researches on soil nutrients, soil physical properties and soil moisture characteristics have shown that the changes in land cover of alpine cold meadow grassland caused significant changes of alpine meadow soil properties. For the moderately degraded alpine cold meadow soil, its vegetation coverage reduced from more than 90% to 60%—70%, organic matter content in surface soil layer decreased by 30%—35%. However, as the vegetation coverage varied between 30%—60%, organic matter in the surface soil layer maintained a relatively stable level of 45—50 g/kg and when the vegetation coverage reduced below 30%, the organic matter content in the surface soil layer showed a sharp decreasing tendency. The changes in soil total N and organic matter contents showed a similar regularity. However, the nutrient changes in the subsoil layer were complex; they showed no obvious dependence upon vegetation coverage.

The changes of soil moisture content with vegetation coverage in the surface soil layer and the subsoil layer were different, the moisture content in the surface soil layer varied slowly under the low vegetation coverage condition but changed sharply under the high vegetation coverage condition. When vegetation coverage was higher than 60%, each 10% increase in vegetation coverage led to a 5%—15% increase in moisture content of shallow soil, but the moisture content change in subsoil layer was complex. With the degradation of grassland vegetation, vegetation coverage reduced, soil compactness declined, originally dense root system layer was gradually denuded, soil grass yield significantly decreased, soil loss increased, soil bulk density enhanced, gravel content in soil increased, thus making the soil coarse and gravelly. According to calculation at 30 cm soil thickness, as vegetation coverage declined from 90% to 70%, soil organic matter loss was 8370 kg/hm^2 and soil N loss was 1590 kg/hm^2. As grassland seriously degraded and vegetation coverage reduced from 90% to 30%, soil organic matter loss was 14890 kg/hm^2 and soil N loss was 5505 kg/hm^2.

In the recent 30 years grassland degradation in the study area was continuously exacerbated by overgrazing and regional climate changes[17]. Soil water and heat conditions in the alpine cold meadow region are closely related to vegetation cover, so the changes in land cover reflect the changes of vegetation and soil water-heat conditions. The protection of alpine meadow vegetation ecology is greatly significant to the region's soil environment. In addition, owing to the high organic matter content in primary alpine meadow soil, large areas of meadow vegetation degradation will cause a large amount of organic matter loss. And CO_2 emission from soil, together with its influence on global change, is also a problem worthy of consideration and further study.

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