Distribution characteristics of soil organic carbon and nitrogen in farmland and adjacent natural grassland in Tibet

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Abstract: Land-use significantly affects soil organic carbon (SOC) and nitrogen cycling, eventually leading to global climate change. The cold and arid climate conditions in Tibet are not conducive to transformation of SOC and nitrogen. Hence, research on SOC and nitrogen distribution under different land-use patterns in Tibet is an important basis to assess the soil carbon and nitrogen potential in the land ecosystem of this area. This study aims to explain the effects of two land-use patterns, namely, farmland and grassland, on SOC and nitrogen contents in the cold regions of Tibet. This study also seeks to provide a scientific basis for the agricultural and grass production system. To achieve these goals, the changing features of total nitrogen (TN), mineralized nitrogen (nitrate nitrogen (NN) and ammonium nitrogen (AN)), and SOC were analyzed in different soil depths (0-5, 5-10, 10-20, 20-30, 30-40, and 40-50 cm) in farmland and adjacent natural grassland. The differences in carbon and nitrogen contents between the farmland and grassland of the main agricultural area of Tibet were determined through combined field survey and lab analysis. Results showed that the contents of SOC, TN and mineralized nitrogen in the grassland and farmland decreased with increasing soil depth mainly in the surface with depth of 0-20 cm. The effects of the different land-use patterns on the contents of SOC and TN were primarily evident in the 0-10 cm surface layer. The contents of SOC and TN in the farmland were significantly lower than those in the grassland, with mean reduction by 28.36% for SOC and 20.76% for TN. When the soil layer is deeper than 10 cm, the contents of SOC and TN in the farmland were greater than those in the grassland. This finding indicated that the transformation from grassland to farmland in Tibet mainly influenced the SOC and TN in the 0-10 cm surface layer. Moreover, the results showed that the increment of carbon in the deep soil layers of the farmland partially offsets the SOC loss from the surface because of cultivation. The ratio of mineralized nitrogen to TN in the farmland was significantly higher than that in the grassland (p<0.001). Mineralized nitrogen in the farmland mainly existed in the form of NN, with a mean content of 2.7% in the 0-50 cm surface layer. By contrast, the difference in the ratio of AN to TN between the grassland and farmland was not significant. The results revealed that the land-use pattern in extremely cold agricultural areas mainly affects the contents of SOC and nitrogen in the 0-10 cm surface layer, and agricultural management is beneficial in increasing the SOC content in the deeper layers.

Keywords: Tibet, farmland, grassland, soil organic carbon, soil total nitrogen, nitrate nitrogen, ammonium nitrogen

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1 Introduction

Land-use is the main driving factor for soil organic carbon (SOC) storage and global carbon cycling[1] and has drawn the most attention because of the resulting CO_2 emission or fixation obtained from different land-use and its important effect on global climate change. A significant coupling relationship exists between SOC and nitrogen[2]. Land-use influences the content and form of nitrogen in soil[3], ultimately affects the sustainability of the use of land and its ecological environment.

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Therefore, under different land-use patterns, the contents of SOC and nitrogen, as well as of other key components gained considerable attention from many local and foreign scholars. These researchers include those who conducted small-scale studies on small watershed[4,5], as well as others who investigated on the national[6] or global scale[7]. The response of SOC and nitrogen to land-use patterns is significantly influenced by climate conditions and management levels.

Climate conditions significantly affect the accumulation and transformation of SOC, thus resulting in different response sensitivities of SOC under different land-use patterns. If natural grassland is reclaimed to farmland in tropical regions, the SOC content in the 0-20 cm surface layer will reduce by 10%. By contrast, the SOC content below 20 cm did not significantly change. This finding is mainly related to the high input of organic substances in the farmland[8]. On the national scale in China, SOC loss induced by land-use pattern changes is most significant in arid and semi-arid districts without irrigation[9].

SOC at different soil depths responds differently to the changes in land-use pattern. Generally, SOC in deep soil layers is stable[10] and exhibits high carbon-sequestration potential[11]. Some of the soluble organic carbon in the surface soil transfers downward to the lower layers; hence, the response of organic carbon in deep soil layers to the changes in land-use pattern is relatively weak. Literature showed that land-use pattern is the most important factor influencing the SOC content in the 0-40 cm surface layer[6]. Some studies also demonstrated that land-use pattern mainly affects the SOC content at the 0-30 cm surface layer [12].

The Tibetan Plateau presents a mean altitude of approximately 4000 m above sea level, which is also regarded as the Third Pole of the Earth[13]. A large amount of SOC is stored in the Tibetan Plateau. This location experiences unique and complicated climate conditions and is hence considered a highly ecologically fragile zone[14] and an area sensitive to climate change. The fragile ecosystem is highly sensitive to global climate changes and human activities, thus resulting in irreversible ecological degradation and changes in soil materials. At present, human activities have significantly altered the land-use patterns, categories and coverage of vegetation in the Tibetan Plateau[15].

Grassland and farmland are the most important land-use patterns and the two major types of land-use change in Tibet. In particular, the increase in demand for food related to population growth in Tibet drives the alterations in regional land-use patterns, resulting in increased cultivated areas[16]. Most of these cultivated areas originate from the development and utilization of natural grassland[13]. Moreover, the grassland and farmland in Tibet show different degrees of degradation, thus causing the contents of SOC and nitrogen in grassland[17] and farmland to decrease. However, the changes in the contents of soil carbon and nitrogen in the extremely cold grassland and adjacent farmland in the Tibetan Plateau, as well as the distribution characteristics remain unclear. Moreover, the basic information on this topic is very weak. Thus, the storage and transformation of carbon and nitrogen in the Tibetan Plateau under different land-use patterns remain uncertain. Particularly, the soil in Tibet is characterized by poor texture, low basic nutrient content, and arctic–alpine and anoxic climate conditions. Considering these characteristics, the Tibetan soils present a low turn-around speed, and soil carbon patterns with low organic carbon and high organic residuals are generated. Under extreme climate conditions there are not conducive to the formation and turnover of soil organic matter, the mechanisms by which SOC and nitrogen in the ecosystem of Tibet respond to the changes in land-use pattern must be further investigated. This study will provide future scientific basis for the correct estimation and prediction of soil carbon and nitrogen loss during land-use pattern transformation in the Tibetan Plateau.

On the basis of extremely cold, arid climate conditions and extensive agricultural modifications, as well as the diverse effects of grassland and farmland on SOC and nitrogen, we formulated two hypotheses: (1) the contents of SOC and nitrogen are significantly influenced by land-use, and with increasing soil depth this effect will gradually decrease. (2) the input of agricultural organic substance can effectively increase the organic carbon content in deep soil layers. Accordingly, the objective of this research was to examine how the hypotheses work for different soils in Tibet.

2 Materials and methods

2.1 Study site

The study area is located in the southwest area of the Tibetan Plateau (Figure 1). This location corresponds to the main farming areas in Tibet, namely, the valleys of Yarlung Zangbo River, Lhasa River, and Nian-chu River. The study area lies at the north of the Himalayas and the south bank of Yarlung Zangbo River, with an average altitude of 4000 m above sea level. This area is characterized with cross valleys and centralized agriculture. Most of the valleys are around 2-5 km wide. Soil types mainly include mountain shrub steppe soil, alluvial soil, and meadow soil according Chinese soil taxonomic classification. The area also experiences a temperate semi-arid monsoon climate zone with arid climates and strong solar radiation, as well as clear dry and wet, cold and warm seasons. The mean length of the frost-free period is about 110 d annually, and the annual precipitation is approximately 290-430 mm. Potential evaporation is considerably higher (about 2249.6 mm) than precipitation. Rainfall is concentrated in June to September.

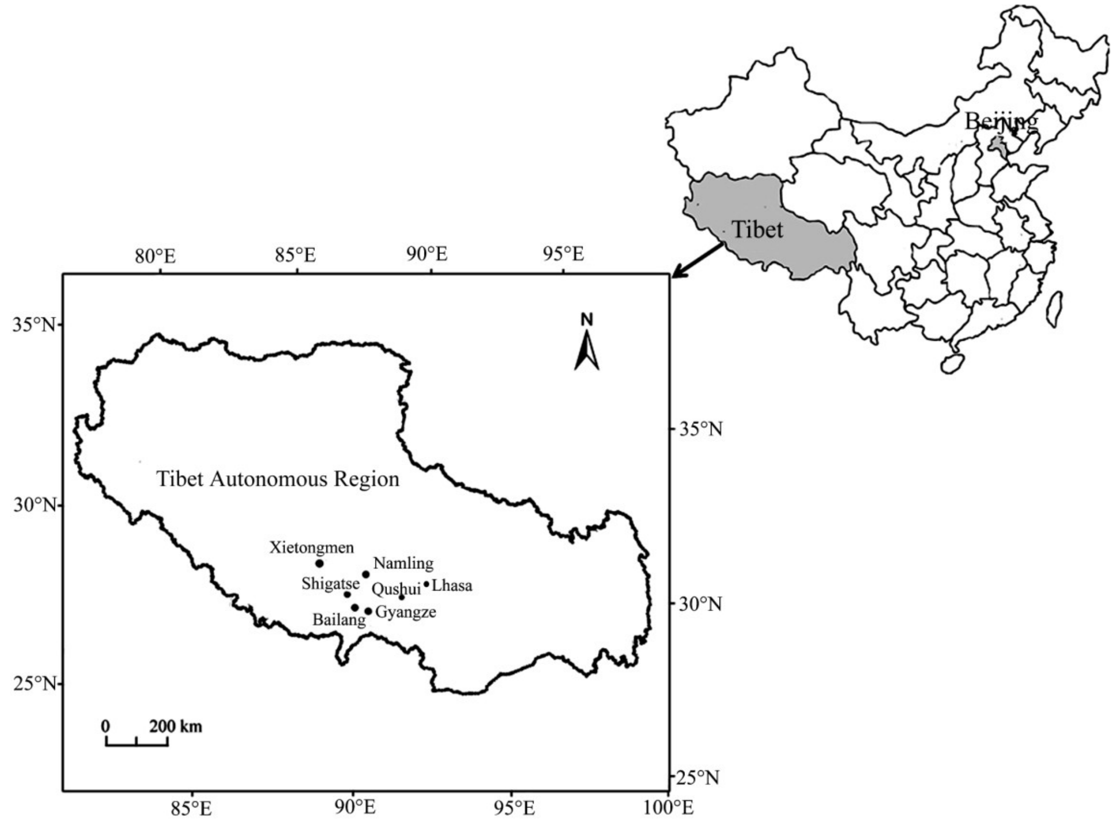


Figure 1 Location map of the study area

The planting system is one harvest a year in Tibet. The time from October to March of the following year is the land fallow period, whereas sowing begins in April. With single-crop types, cultivations focus on *Hordeum vulgare*, with an annual yield of 4.0 t/hm^2[18]. All plant roots are returned to the field. A small quantity of straw is also returned to the field, and a large quantity of straw is used as livestock feed. The soil is characterized by high sand/clay ratio, rich in gravel, high weathering rate, low accumulation of organic matter (SOC of 3.19-14.39 g/kg), and alkaline to strongly alkaline pH value of 8.1-9.0[19]. With increase in economic growth, the regional ecological environment becomes more fragile, and the effect of human activities on this fragile environment is significantly aggravated[20]. Hence, soil ecological degradation becomes increasingly severe.

Table 1 Description of sampling areas

Sample region	Longitude and latitude	Elevation /m	Soil type	Soil texture
Gyangze	28°55′ N 89°39′ E	4088	Subalpine steppe soil	Sandy loam
Bailang	29°09′ N 89°13′ E	3886	Subalpine steppe soil	Sandy loam
Xietongmen	29°19′ N 88°22′ E	3893	Subalpine steppe soil	Loam sand
Shigatse	29°21′ N 88°50′ E	3842	Subalpine steppe soil	Sandy loam
Namling	29°61′ N 89°06′ E	3835	Subalpine steppe soil	Sandy loam
Qushui	29°22′ N 90°51′ E	3594	Yellow brown soil	Sandy clay

2.2 Collection and determination of soil samples

In April 2014, we selected a field in contiguous areas of more than 2 hm^2, with a centralized farmland and reclamation period of more than 50 a (Figure 1) as study area. Considering the different regional farmland areas, we selected two sample areas from Bailang and Gyangze. One sample area was selected in another area. A total of eight sample areas were established (Table 1). Three sampling points were then randomly selected from each sample area and designated as replicates for each study area. Overall, 48 sampling points were chosen. From each sampling, soil samples were collected from the 0-5, 5-10, 10-20, 20-30, 30-40 and 40-50 cm layers. These samples were placed in bag and stored at 4°C in the laboratory for later use. The natural grassland adjacent each studied farmland was also selected as the comparison in each sampling area. The vegetation in the grassland was sparse, with *Stipa* Linn as the dominant vegetation, and with coverage of 30%-40%. After removing the roots, stones and other non-soil constituents, a portion of fresh soil sample was obtained using the method of quartering for determinations of the contents of NN and AN in the soil. Another portion of the soil was air dry and screened through a 0.25 mm mesh for soil TN and organic carbon content determination. Semi-micro Kjeldahl method was used to determine the TN[21]. NN and AN were extracted using 2 mol/L KCl and determined with a continuous flow analyzer (AA3HR, German SEAL). Ten gram of moisture soil was weighed and shaken in 2 mol/L KCl solution (50 mL) for 1 h and then filtered. The contents of NN and AN, as well as of soil moisture content, were determined. SOC content was determined using the potassium dichromate oxidation method. Soil samples (0.5 g) were weighed accurately, to which 5 mL of 1 N $K_2Cr_2O_7$ and 5 mL of H_2SO_4 were added. The suspension were thoroughly shaking and boiled at 170-180°C for 5 min. Afterward, 0.2 mol/L $FeSO_4$ standard solution was used to titrate the soil suspension. The amount of consumed $FeSO_4$ was obtained to determine the amount of organic carbon that reacted with $K_2Cr_2O_7$.

2.3 Data processing

The differences in nitrogen contents in different soil layers between the grassland and farmland were analyzed by one-way analysis of variance (ANOVA) and LSD method with SPSS 20.0 (IBM, USA) statistical analysis software. Maps were constructed using Origin 9.0 (Originlab Corporation, USA). Data were expressed as means ± standard deviations.

Data variability was evaluated through the coefficient of variation (CV) as Equation (1),

$$CV = \text{Standard deviation (SD)} / \text{mean value} \times 100\% \quad (1)$$

The means of SOC and TN in 0-50 cm layer were calculated using Equation (2),

$$C = \frac{\sum C_i h_i}{H} \quad (2)$$

where, c is mean values of SOC or TN (g/kg); C_i is SOC or TN concentration in layer i (g/kg); h_i is a soil layer depth (cm) in layer i; H is soil profile total depth (cm).

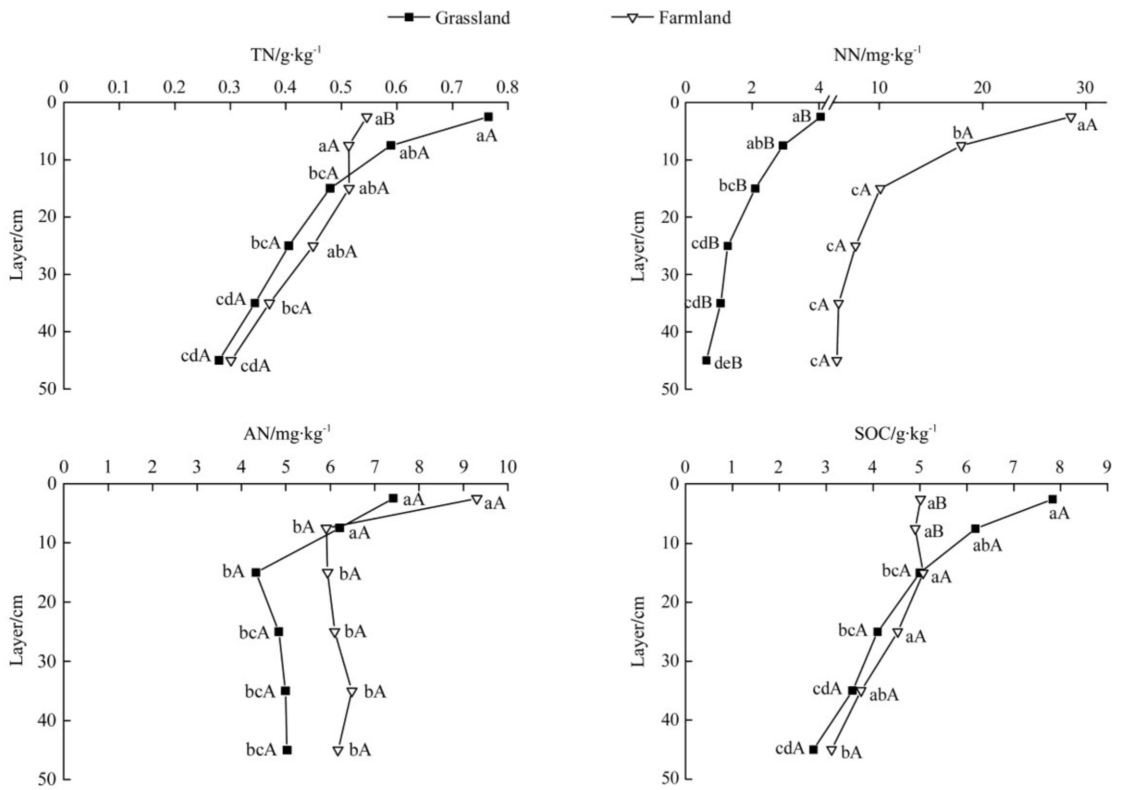
3 Results and analysis

3.1 TN concentration

The TN contents in the farmland and grassland both decreased with soil depth (Figure 2). The TN contents in the 0-5 cm and 40-50 cm layers of the farmland were (0.55±0.21) and (0.30±0.11) g/kg, respectively, corresponding to a reduction of 45.45%. The TN CV in the 0-50 cm layer was 21.30%. However, the variability of the TN content in the 0-30 cm layer decreased at 8.03%. The differences in TN content among the 0-5, 5-10, 10-20, and 20-30 cm layers were not significant (p>0.05). Conversely, the differences in TN content between the 0-5 and 5-10 cm layers and between the 30-40 and 40- 50 cm layers were significant (p<0.05).

The TN content in the 0-5 cm layer of grassland was (0.76±0.49) g/kg, which was significantly higher than those of the other soil layers except for that in the 5-10 cm layer. The TN content was 63.16% lower in the 40-50 cm layer than that of the 0-5 cm layer. The TN CV in all layers was 37.15%.

The pattern of difference in TN content between the soils of the two kinds of ecosystems is presented as follows. At the 0-10 cm layer, the TN content was greater in the grassland than in the farmland, whereas the opposite was true in the layers deeper than 10 cm. At the 0-5 cm layer, the TN content in the grassland was significantly greater than that in the farmland (p<0.01) but the difference between two soils was not significant in the 5-10 cm layer.



Note: Different small letters indicate significant differences among the depth at the 0.05 level, different capital letter indicate significant difference at the same layer between grassland and farmland at the 0.05 level.

Figure 2 Soil TN, NN, AN and SOC concentration of different depths

3.2 NN concentration

The NN concentration in the farmland and grassland both decreased with increasing soil depth (Figure 2). The NN contents in the 0-5 and 40-50 cm layers of the farmland were (28.56±27.23) and (5.90±5.97) mg/kg, respectively, corresponding to a reduction by 79.34%. This decline was much larger than that in the TN content. The CV value of the NN content among layers was 70.47%. However, the difference in NN between the depths of 0-5 and 5-10 cm was not significant. The nitrogen contents of these two layers were significantly different from the 10-20 cm layer. Additionally, the differences among the 10-20, 20-30, 30-40, and 40-50 cm layers were not significant. These observations indicated that the farmland NN content was mainly centralized in the 0-10 cm surface layer.

In the 0-50 cm soil profile, the vertical variability of the NN content in the grassland was significantly lower than that in the farmland. In the 0-5 cm surface layer, the NN content was (4.05±2.50) mg/kg, which was significantly higher than those in all other layers except for that in the 5-10 cm layer. The NN content decreased with increasing soil depth. In the 40-50 cm layer, the NN content was (0.63 ± 0.56) mg/ kg.

In the 0-50 cm layer, the NN content was higher in the farmland than in the grassland. The differences among all soil layers were significant (p<0.01). The difference also decreased with increasing depth. The NN content in the 0-5 cm layer of farmland was 45.08 mg/kg, which was higher than that in the grassland. This content lowered to 5.16 mg/kg in the 40-50 cm layer.

3.3 AN concentration

The AN contents in the farmland and grassland decreased with increasing soil depth at surface 0-20 cm. By contrast, the AN contents gradually increased from 20 cm and deeper, but these differences were not significant. The AN content in the 0-5 cm layer of the grassland was (7.42±4.61) mg/kg, which was then reduced by 41.64% to (4.33±3.19) mg/kg in the 10-20 cm layer. Furthermore, the AN content increased to (5.03±2.88) mg/kg in the 40-50 cm layer, thereby increasing 13.92% compared to the content of the 10-20 cm layer. The CV of AN along the vertical profile was 20.79%.

The soil AN content along the vertical profile of the farmland exhibited a similar variability as the grassland, with a CV of 19.74%. The soil AN contents of the 0-5 and 10-20 cm layers were (9.30±4.87) and (5.94±2.85) mg/kg, respectively, which then increased to (6.17±3.13) mg/kg in the 40-50 cm layer. Generally, the AN contents in all the layers were higher in the farmland than in the grassland, but this discrepancy was not significant (p>0.05).

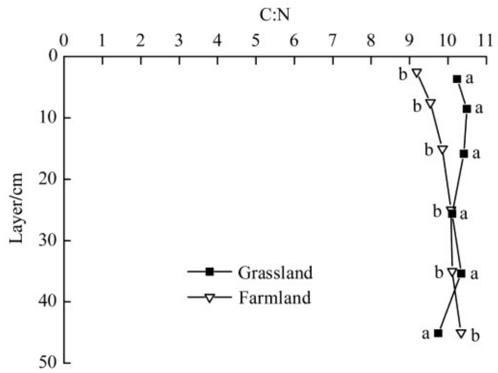
3.4 SOC concentration

The SOC content decreased with increase in soil depth. The SOC contents at the 0-5 and 40-50 cm grassland layers were (7.83±5.28) and (2.73±0.94) g/kg, respectively, corresponding to a 65.13% reduction. The SOC content at the 0-5 cm depth was significantly different from those in all the layers except at 5-10 cm. The variability of the SOC in the vertical profile of the grassland was larger than that in the farmland, with CVs of 38.07% and 18.10%, respectively. The SOC content in the farmland also decreased with increasing depth. However, the differences in this parameter among the layers deeper than 40 cm were not significant. The SOC content at 40-50 cm was significantly lower than those in all the layers at 0-30 cm depth. Moreover, the observations also showed that in the grassland, the roots and vegetation litters mainly affected the carbon cycling in the surface soil. These plant materials became an important carbon source in the surface soil; hence, the SOC content in the surface soil was significantly greater than those in the deeper layers.

The SOC content in the 0-10 cm layer was higher in the grassland than in the farmland. The average contents of organic carbon in farmland and grassland were (7.01±4.46) and (4.96±1.78) g/kg, respectively. Moreover, the SOC contents in the 0-5 cm surface layer of the two soil types were significantly different (p<0.01). At soil layers deeper than 10 cm, the SOC content was greater in the farmland than in the grassland. The average organic carbon contents were (4.11±1.53) and (3.84±2.15) g/kg.

3.5 Soil C:N ratio

The difference in soil C:N ratio between the same layers of grassland and farmland soils was not significant (Figure 3). But soil C:N ratio did not exhibit significant change with soil depth, the soil C:N ratio increased with increasing depth in the farmland, from 9.18±0.41 at 0-5 cm to 10.34±2.12 at 40-50 cm. With increasing depth, the SOC exhibited smaller variability than soil nitrogen. In the grassland, the soil C:N ratio presented an decreasing trend with increasing soil depth, from 10.24±1.15 at 0-5 cm to 9.75±1.64 at 40-50 cm. However, the differences among all the layers were not significant. In particular, the SOC and TN contents in all the layers of grassland maintained a relatively consistent variation.



Note: Different small letters indicate significant differences among the depth at the 0.05 level.

Figure 3 Soil C:N ratio of different layers of grassland and farmland

3.6 Differences in soil carbon and nitrogen contents among different sample areas

The differences in total organic carbon and TN contents in the 0-50 cm layers from different sample areas are listed in Table 2. Considerable differences in soil carbon and nitrogen contents among different sample areas were revealed. For instance, carbon and nitrogen contents were higher in the sample areas of Bailang and Qushui but lower in Namling and Xietongmen. In the grassland, Qushui was found to exhibit the highest TN content among the sample grassland areas. The differences among sample plots except for that in Bailang were significant (P<0.05). Xietongmen was found to exhibit the lowest TN content at only 0.16 g/kg. In the farmland, the TN content in Qushui was significantly the highest among those of all the grassland sample plots. The spatial variability of the TN content in the farmland was lower than that in the natural grassland, with CVs of 34.73% and 56.98%, respectively. In the grassland, the

SOC content was the highest in Bailang, which did not differ significantly with that of Qushui. By contrast, the differences among the other four sample areas were significant. The organic carbon contents of the farmland samples were the highest in Qushui and Bailang and the lowest in Xietongmeng. The differences among these contents in Shigatse, Namling, and Gyangze were not significant. The differences in SOC contents among the different sample farmland areas were less than those among the different sample grassland areas. The coefficient of spatial variation was 30.73%, and the CV of the organic carbon content in the grassland was 52.60%. The coefficient of spatial variation indicated that the soil carbon and nitrogen contents presented a smaller spatial variation in the farmland than in the grassland.

Table 2 SOC and TN concentration of different sampling plots

	Land-use	Bailang	Xietongmen	Shigatse	Qushui	Namling	Gyangze
TN /g·kg^{-1}	Grassland	0.63ab	0.16d	0.22d	0.72a	0.26d	0.44c
	Farmland	0.51b	0.19e	0.44c	0.62a	0.35d	0.41c
SOC /g·kg^{-1}	Grassland	6.95a	2.26b	2.42b	6.70a	2.48b	4.03b
	Farmland	5.35a	2.51c	4.07b	5.81a	3.26bc	3.62b

Note: Different letters indicate significant differences among the different sampling areas at the 0.05 level.

4 Discussion

4.1 Changes in soil nitrogen concentrations

The variations of soil nitrogen contents in the farmland and adjacent grassland show similar trends as SOC. In particular, the soil nitrogen content is greater in the grassland than in the farmland in the 0-10 cm layer, whereas the reverse pattern is exhibited by the layers below 10 cm. This finding may be explained by the centralized distribution of the grassland plant root system in the 0-10 cm surface layer. Plant roots promote the accumulation and upward migration of nitrogen in the soil. Soil fertilization in the farmland is mainly achieved with inorganic nitrogenous fertilizers. Under rainfall infiltration, downward leaching of nitrogen promotes the accumulation of nitrogen in the deeper layers, thus increasing the TN content in depth of the farmland (below 10 cm) with respect to that of the grassland soils.

Soil nitrogen mineralization and exogenous nitrogen input are important factors affecting the distribution characteristics of soil mineralized nitrogen content. In our study, we found that the soil mineralized nitrogen content in all layers of the farmland soil is significantly higher than that of grassland soil. This finding may be partially explained by the different soil temperatures and moistures in the two land-use patterns causing the differences in nitrogen mineralization. The results may also be ascribed to the application of nitrogenous fertilizers in the farmland, which increases the mineralized nitrogen content. Nitrogen mineralization is an important means to generate mineralized nitrogen. This phenomenon is mainly affected by temperature, moisture, and the interaction between these two parameters. Arid[22] and alpine-cold[23] environmental conditions restrict soil nitrogen mineralization. Our research area covers an alpine-cold, arid region with low basic soil nitrogen content. Therefore, the nitrogen content, which can be mineralized and lost, is very limited. However, field irrigation in the farmland increases soil moisture with respect to that in grassland for a long period, thus providing suitable conditions for nitrogen mineralization[24]. Cultivation disturbance increases soil aeration and results in nitrogen mineralization. Some studies showed that the nitrogen mineralization rates in soils with cultivation disturbance are about twice of those in soils without cultivation disturbance[25]. The application of chemical nitrogen fertilizer does not only directly increase soil mineralized nitrogen content but also generates an excitation effect on the original soil nitrogen content for promoting nitrogen mineralization in soil[26]. Therefore, our study revealed that soil mineralized nitrogen content in the farmland is much higher than that in the grassland. The ratio of soil mineralized nitrogen to TN in the grassland is significantly lower than that in the farmland. The ratio of soil inorganic nitrogen to TN in the 0-50 cm layer is 1.76% in the grassland and 4.23% in the farmland, the latter of which is 2.4 times that of the former.

In our study, we found that soil mineralized nitrogen decreases with increasing depth. The decline of soil mineralized nitrogen in the natural grassland is significantly lower than that in the farmland. This finding is mainly related to the nitrogen mineralization rates in different soil layers and the migration of nitrogen in the vertical profile. Chen[27] revealed that soil nitrogen mineralization rate significantly decreases with increasing soil depths. In the 0-60 cm soil profile, soil nitrogen exhibits an increased mineralization rate with cultivation disturbance[25]. Therefore, soil mineralized nitrogen content in the vertical profile shows a declining trend. This declining trend is also more significant in the 0-20 cm layer of farmland. With increasing soil depths, the influence of soil disturbance decreases, and mineralized nitrogen content exhibits reduced variability.

For mineralized nitrogen, AN content accounts for a major proportion in the grassland, whereas NN mainly constitutes the nitrogen in the farmland. The ratio of AN to the TN in all the layers is greater in the farmland than in the grassland, but the difference is not significant. The relative contents of soil AN and NN are mainly related to nitrifying bacterial activity in the soil. Soil ammonia-oxidizing bacteria were more abundant and have a higher nitrification rates in the topsoil[28], thus, the 0-5 cm layer exhibits the highest accumulation of soil NN in the farmland. With increasing depth, the ventilation worsens and soil nitrogen nitrification weakens, thus facilitating the accumulation of AN. As such, our study demonstrated an increasing trend for soil AN and a decreasing trend for NN in the farmland and grassland with increasing soil depth.

4.2 Changes in SOC concentrations

Vegetation type significantly influences the vertical distribution of SOC[29]. In this research, the vertical distribution of SOC content in the farmland and grassland is reported to decline with increasing soil depth, especially in the grassland. This finding is consistent with the results of other investigations on the grasslands of the Tibetan Plateau[30]. The variability of vertical distribution of SOC is smaller in the farmland than in the grassland. This observation is consistent with that found by Shi[31] regarding the Lhasa River Valley. The trend may be related to the residual decomposition of the crop root system in soil and cultivation disturbance, resulting in some compensation in SOC content with increased depths. Grasslands without disturbance are affected by surface litter and roots. Hence, the SOC in this soil type is mainly distributed in the surface layer with a centralized distribution of roots. Furthermore, the source of SOC in the lower layer is very limited.

The root system of agricultural crops is an important factor affecting the vertical distribution of SOC[29]. This contribution to SOC exceeds those of the aboveground, and it has more opportunity for physic-chemical interactions with soil particles, often with stronger stability[32]. Swedish research shows that the influence of the root system of agricultural crops on farmland organic carbon content is 2.3 times higher than that of the aboveground residue[33]. Moreover, the contribution of the root system to the organic substance is more difficult to degrade than that of the aboveground. The root system of the agricultural crops remains in the soil, with higher biomass than those in the grassland. This occurrence exerts an important effect on its contribution to the SOC. The plant root system in the alpine-cold grassland is mainly distributed in the 0-30 cm surface layer, whereas 73% of this root system is distributed across the 0-20 cm layer[34]. Therefore, SOC in the grassland is mainly distributed in the 0-20 cm soil layer. However, the root system of the agricultural crops reaches more deeply than the grassland, generally reaching up to 60-70 cm. With the higher biomass of the root system per unit area, the contribution of the root system of the agricultural crops to the SOC in the lower layer is higher than that in the grassland. In the current study, we found that the SOC content in the layers below 10 cm is higher in the farmland than in the grassland. In particular, the SOC in the farmland is mainly stored in the deeper soil layers. This result is consistent with the findings of Albaladejo[6], indicating that the conversion from grassland to farmland in the alpine areas in Tibet mainly results in the loss of SOC from the surface. However, this occurrence facilitates the accumulation of SOC in the lower layers. The scientific management of agricultural soil in alpine-cold areas can promote the accumulation of SOC in the deeper layers to a certain degree. This strategy can also partially offset the loss of SOC from the surface, which is caused by cultivation. SOC in the grassland is primarily centralized in the 0-10 cm surface layer. Similar finding is also reported by other scholars who studied the grasslands of Tibetan Plateau. Numerous studies showed that the SOC in the natural grasslands of the Tibetan Plateau is mainly centralized in the 0-10 cm layer[29] or 0-20 cm layer[35], with an exponential decline with increasing depths[36]. With further depths, the relationship between SOC content and environmental factors is weakened; the SOC content of the deep soil layer is primarily affected by the downward input of surface carbon[37].

Along with the influences of regional temperature and rainfall, the effect of land-use pattern in alpine-cold and arid ecological regions on SOC content is mainly reflected in the 0-10 cm surface layer. After a change from farmland to grassland, SOC contents in the 0-5 cm and 5-10 cm layers are reduced by 35.96% and 20.76%, respectively. Albaladejo et al.[6] reported that the land-use pattern in the semi-arid Mediterranean climate zone in Spain is the dominant factor affecting SOC content in the 0-40 cm layer. In particular, the effect of land-use pattern on SOC is more severe than those found in our study. This discrepancy may be ascribed to the fact that the soil at 0-10 cm depth is affected more easily by external environmental conditions under the alpine-cold, arid ecological environment than that in the semi-arid climate, causing SOC to undergo mineralized degradation. This finding may also be explained by the relatively poor sensitivity of SOC to environmental factors in deep soil.

4.3 Soil C:N ratio

Soil C:N ratio is an important factor influencing the variations in soil carbon and nitrogen[38], and it is closely related to land-use pattern and management measures. In the present study, the soil C:N ratio of the grassland does not differ significantly with increasing soil depth. These findings are consistent with those of Yang et al.[34] on the grasslands of Qinghai–Tibet Plateau. The soil C:N ratio of the farmland increases with increasing soil depth. This trend may be attributed to the effect of nitrogen application to the surface soil in farmlands, resulting in high nitrogen contents in the surface soil, which gradually decrease with increasing depth. The soil C:N ratios in the farmland and grassland approximately 10.00, which is significantly lower than the mean value obtained (20.39±13.09) from the alpine-cold grassland in the Qinghai–Tibet Plateau but closer to that of the *Stipa purpurea* + sand binder grassland[39] and the national scale mean value of China (11.9)[40]. With different land-use patterns, soil C:N ratio is relatively stable. Nonetheless, the difference in soil C:N ratio between the farmland and grassland did not reach significant level.

4.4 Spatial variation of soil C, N concentrations in different plots

In Tibet, soil types, climatic conditions and land-use patterns are highly complicated. These factors determine the degree of spatial heterogeneity of SOC[39,41] and nitrogen[42] contents across different soil layers. This notion is consistent with our study results, that is, the SOC and TN contents in the different sample areas exhibit high spatial variation (moderate spatial variation, CV: 30%-57%). In our study, the spatial variation of the TN and organic nitrogen contents is smaller in the farmland than in the grassland. Under anthropogenic influence, the differences in soil carbon and nitrogen contents in all regions are lower than those under natural grassland. This regional difference will severely affect the accuracy of SOC and TN estimations and might be a challenge to large-scale research on soil carbon, nitrogen content, and spatial variability.

5 Conclusions

The following conclusions were obtained from the results of this study:

1) In the alpine-cold, arid ecosystem of Tibet, the transformation from grassland to farmland significantly affects the SOC and nitrogen contents in the 0-10 cm surface layer. This effect is generally observed in relatively shallow layers. Additionally, the deeper layers of soil also exhibit a clear response to cultivation disturbance.

2) Both the SOC and TN in the farmland and grassland showed higher spatial heterogeneity in the vertical distribution at the 0-20 cm layer than at the layers below 20 cm.

3) The farmland management maybe improvement SOC content in the layers below 10 cm. This factor

compensates for the loss of soil carbon from the surface, which is caused by cultivation.

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