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# Distribution characteristics and influencing factors of soil organic carbon in alpine ecosystems on the Tibetan Plateau transect, China

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**Abstract** The undisturbed regions along the Qinghai-Tibet Highway crossing the natural zones of montane desert, alpine meadow-steppe, and montane shrub-coniferous forest were chosen as the study areas. Soil samples were collected at 23 sites and the relations between the influencing factors and distribution of soil organic carbon (SOC) content were studied. The results indicated that the order of SOC content for the whole soil profile with different vegetations and in the horizontal direction was shown as below: forest > shrub > meadow > steppe > desert. All the SOC contents of the top 10 cm soil layers of forest, shrub and meadow vegetations, as well as that of the top 20 cm soil layers in steppe, in the vertical direction, were higher than those of corresponding lower soil layers. However, the SOC content in the desert soil was in accordance. The grey correlative analysis between the climatic factors and SOC content in the top soil show that precipitation was the dominant climatic factor affecting the distribution of SOC in the Tibetan Plateau transect. The influence of precipitation on the horizontal distribution of SOC decreased with the increase of precipitation in the horizontal direction. The vertical distribution of SOC along the soil profile was greatly affected by precipitation or the soil clay content in top soil layers, and was clearly influ-

enced by soil silt content or sand content in lower soil layers, as well. The influences of both soil bulk density and soil pH on the vertical distribution of SOC along the soil profile gradually declined. The plant biomass was the most important biotic factors affecting the distribution of the SOC.

**Keywords** Tibetan Plateau, China, transect, alpine ecosystem, soil organic carbon, influencing factors

## 1 Introduction

The largest carbon pool of the terrestrial ecosystem lies in the soil (Schlesinger, 1990), which is the most important component of the global carbon cycle. The SOC storage is 2/3 of that of the whole terrestrial ecosystem (Schlesinger, 1990), about 3 times of that in plants, and 2 times of that in the atmosphere (Post et al., 1982; 1990; Schlesinger, 1990; Wang et al., 2004). Terrestrial ecosystems in the northern hemisphere may play a vital role in the exact estimate of CO<sub>2</sub> uptake of the terrestrial ecosystem in the overall carbon budget (Kauppi et al., 1992; Ciais et al., 1995; Fan et al., 1998; Houghton et al., 1999; Fang et al., 2001; Wu et al., 2003). Recently, the studies indicate that the distribution pattern and turnover rate of SOC greatly influence the global carbon cycle (Batjes, 1996; Jobbágy et al., 2000, 2001). To clarify the distribution characteristics and influencing factors of SOC in the topsoil is helpful for us to improve our understanding of the mechanism of belowground carbon cycle and is also able to enhance the capacity of the soil carbon sink.

Most of the Tibetan Plateau is higher than 4000 meters above sealevel and its area is about 26.8% of the whole nation, which covers about 13 longitudes from east to west, and 31 latitudes from north to south (Li, 1987; Zhang et al., 2002). The plants and soil of the Tibetan Plateau are so sensitive to the climate changes, and therefore, the Tibetan Plateau is often called the “sensitivity area” in the study of global climate changes for its geo-

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graphic and climatic characteristics of high altitude and the lower temperature (Ma, 1960). The unique geographic environment of the Tibetan Plateau makes for the special status of the alpine ecosystems in the world, which provides us with a natural laboratory in studying the structure and function of the alpine ecosystems of different geographic and climatic conditions. In a word, the Tibetan Plateau is becoming the global hotspot in the fields of the geography and ecology.

Recently, most studies on the Tibetan Plateau only cover the study of the estimate of the carbon storage (Wang et al., 2002), the emission of the greenhouse gas (Liu et al., 2001; Pei et al., 2003), the turnover of the soil organic matter (SOM) (Wang et al., 2005) and the nitrogen cycle (Cao et al., 1999; Zhang and Cao, 1999; Xu et al., 2003). However, at present, the scientists seldom touch the distribution characteristics and influencing factors of SOM in different natural zones. The natural zone is a national region of the similar vegetation and soil types (Zheng et al., 1979; Zheng, 1996) and different natural zones differ greatly in their vegetation, soil and climate (Zheng et al., 1979; Zheng, 1996). The SOM distribution in the different natural zones is diverse because the plants and soil there have encountered a long-term adaptation to the local climate, which can be indicated clearly by the SOC distribution. In this paper, we try to compare the distribution characteristics of SOC in different natural zones and explore the influencing factors that control the distribution as well as their relations. This could be beneficial to the further study of regional carbon cycle on the Tibetan Plateau.

## 2 Materials and methods

### 2.1 General situation of the study transect

The undisturbed regions along the Qinghai-Tibet Highway, crossing four natural zones of montane desert, alpine meadow-steppe, montane shrub-steppe and montane shrub-coniferous forest, were chosen as our study transect. In the transect, according to the actual location of the sampling sites and its vegetations, at the same time, considering the variabilities of the temperature and humidity of the transect and the continuity of study area, we united the four natural zones of the transect into three natural zones: (I) montane desert zone (Temperate zone of the plateau) (Zheng et al., 1979; Zheng, 1996); (II) alpine meadow-steppe zone (sub-frigid zone of the plateau) (Zheng et al., 1979; Zheng, 1996); (III) montane shrub-coniferous forest zone (Temperate zone of the plateau) (Zheng et al., 1979; Zheng, 1996). In the transect, the mean annual temperature varies from  $-2.8^{\circ}\text{C}$  to  $-3.1^{\circ}\text{C}$  and the mean annual precipitation varies from the 15–200 mm of the montane desert zone in the northern part, to the 500–1000 mm of the montane shrub-coniferous forest zone in the southern

part of the transect. The hydrothermal conditions in the inner part of the Tibetan Plateau are highly diverse, so the distributions of vegetation differ greatly in a relatively larger scale. The continuous and patch distribution is the distinct characteristic for the vegetation on the Tibetan Plateau. The sample sites mostly lie in five vegetations: the desert, steppe, meadow, shrub and forest. According to the continuity of the vegetation and their hydrothermal conditions, we assign the vegetations in the transect into different natural zones: the desert in the northern part of the transect is the montane desert zone, the steppe and meadow in the middle of the transect is the alpine meadow-steppe zone, the shrub and forest in the southern part of the transect is the montane shrub-coniferous forest zone. The soil order is Frigid calcic soil, Felty soil, Dark felty soil, Castanozems, Frigid desert soil, Gray-brown desert soil and Brown earth, respectively (Liu et al., 1992).

### 2.2 Sampling

From July to August in 2004, we collected 312 soil samples at 23 different sample sites along the Qinghai-Tibet Highway. We crossed the following cities along the Qinghai-Tibet Highway in sequence: Wulan, Dachaidan, Germu, Wudaoliang, Naqu, Lhasa and Linzhi, with three replicates for each sample point. The soils on the Tibetan Plateau are young and have not fully developed, so the soil horizon is thin and the soil genetic horizon often disappeared (Liu et al., 1992). In this study, the soils were sampled by using the regular sampling method. The following procedure was followed: sampling at the layers of 0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–80 cm and 80–100 cm, with the deepest sampling depth at 100 cm for the parent material horizon. Finally, we accurately measured the location and the altitude of the sampling sites.

### 2.3 Gathering of meteorological data

As there are few weather stations on the Tibetan Plateau, and the sampling sites often lack weather stations nearby, all the data of temperature and precipitation needed in the transect were collected from the thirty year mean output by Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994). Fitting results by the Chinese researchers indicate that this model is reliable (Zhu et al., 2003).

### 2.4 Sample analysis and data processing

The SOC was measured by oxidation of potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) (Lu, 1999), the soil mechanical component by Laser Particle Size Analyzer (Mastersizer-2000), the soil pH by acidometer (Lu, 1999) and the soil bulk density by cutting ring method (Lu, 1999).

The soil attribute data below the 30-cm soil layers weighed by soil depth were united as one value and indi-

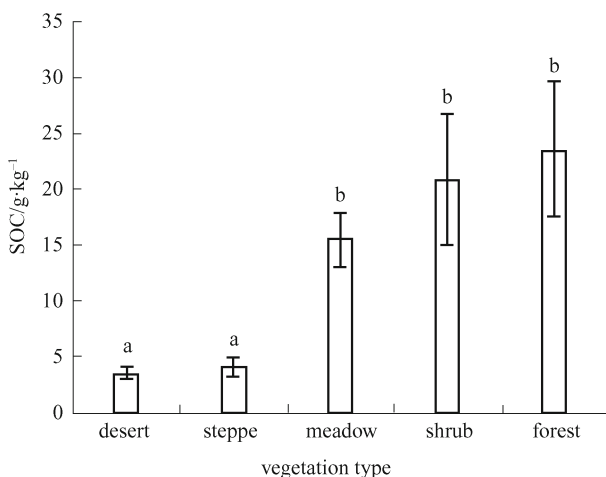
cated by soil attribute data of >30 cm. Data were analyzed and the figures were done by Excel. We also did the grey correlation degree analysis. The grey correlation degree index can reflect the influence degree of different factors to some studied parameters and it also can filter out the most important factors to some parameters (Xu, 2002). The one-way ANOVA and the bivariate correlation analysis were done by SPSS.

### 3 Results and discussion

#### 3.1 SOC distribution on the Tibetan Plateau transect

##### 3.1.1 Horizontal SOC distribution in different vegetations on the Tibetan Plateau transect

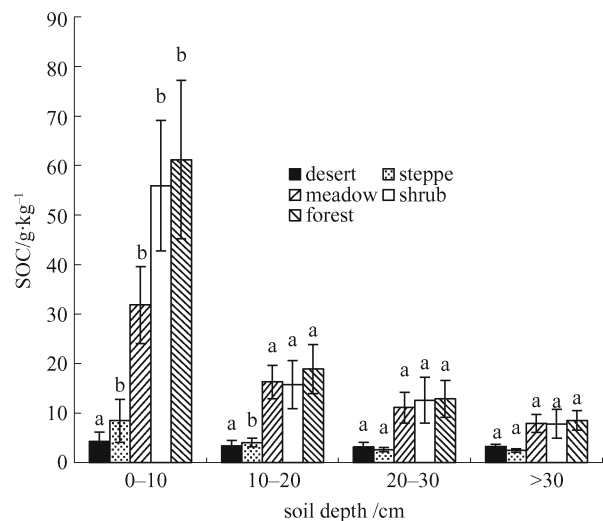
The distribution of SOC content in the whole soil profile varied greatly in different vegetations on the Tibetan Plateau (Fig. 1). The SOC content of the desert was  $3.5 \text{ g}\cdot\text{kg}^{-1}$  and it was  $4 \text{ g}\cdot\text{kg}^{-1}$  for the steppe. They had no significant differences. However, the SOC contents of the meadow, shrub and forest were significantly higher than that of desert and they had no significant differences between them (Fig. 1). As a whole, the SOC content south of the transect was higher than that of northern part. The SOC content of the whole soil profile in different vegetations was as follows: forest > shrub > meadow > steppe > desert. This indicated that the SOC contents were mainly controlled by plant productivity and the mineralization degree of the SOM as they had been intensively affected by the hydrothermal conditions (Paul, 1984; Lal et al., 1995). The hydrothermal conditions were improved from north to south of the transect, which is helpful to the growth of plants and it can promote the SOC content of the soil.



**Fig. 1** SOC distribution in different vegetation types on the Tibetan Plateau transect  
Note: The same letter indicates no significant differences.

##### 3.1.2 The vertical SOC distribution in different vegetations on the Tibetan Plateau transect

The vegetations were under different environmental conditions, which would lead to different distribution characteristics of SOC content in the topsoils (Jobbágy et al., 2001). The SOC contents of different soil layers in the desert had no significant differences (Fig. 2). The SOC content in the top 0–10 cm soil layer was  $4.2 \text{ g}\cdot\text{kg}^{-1}$  and that of below the 30 cm soil layer was  $3.2 \text{ g}\cdot\text{kg}^{-1}$ , which indicated the SOC content from topsoil to the parental material horizon varied slightly. The SOC contents of different soil layers in the steppe had significant differences. The SOC contents of the 0–10 cm and 10–20 cm soil layers were both above  $4 \text{ g}\cdot\text{kg}^{-1}$ , while those of 20–30 cm and >30 cm soil layers both obviously decreased. They were only 30.6% and 28.8% of the SOC content in the 0–10 cm soil layer. Compared with the desert and steppe vegetations, the SOC contents of 0–10 cm soil layers in meadow, shrub and forest vegetations increased significantly, and the SOC contents in the top 0–10 cm soil layer were obviously higher than those below 10 cm soil layers (Fig. 2). The SOC content had a significant and positive correlation with the aboveground plant productivity, due to the fact that more litters recycled back to the topsoil.



**Fig. 2** SOC distribution of different soil horizons in certain vegetation types on the Tibetan Plateau transect  
Note: The same letter indicates no significant differences.

#### 3.2 Relation between SOC distribution and influencing factors on the Tibetan Plateau transect

##### 3.2.1 Relation between SOC distribution and climatic factors on the Tibetan Plateau transect

The topsoil was directly connected to the outer environment, which was very sensitive to climate changes. Here, we filtered out the relatively more important climatic

factors controlling the SOM distribution by using the grey correlation degree analysis between the climatic factors and the SOC contents in 0–30 cm soil layer. The acquired results indicated both of the temperature and precipitation were the important factors influencing the SOM distribution (Post et al., 1982; Jobbágy et al., 2001). In our study, we found that on the transect, precipitation was the dominant climatic factor controlling the SOC distribution in the upper soil, and temperature came second (Table 1). The highest altitude, lower temperature in a year, and lower variability of the annual temperature were the main unique climatic characteristics on the Tibetan Plateau (Ma, 1960; Institute of Botany, the Chinese Academy of Sciences, 1988). In the inner part of the Tibetan Plateau, the temperature slightly differed in different natural zones. But as a whole, the lower temperature in all the years has been the intrinsic climate characteristic of the alpine ecosystems on the Tibetan Plateau. The temperature didn't vary significantly in different natural zones any more than precipitation. Compared with temperature, the precipitation varied significantly in different natural zones (Ma, 1960; Institute of Botany, the Chinese Academy of Sciences, 1988; Liu et al., 1992; Gao et al., 1995), and so the precipitation had become the most significant climatic factor influencing the SOC distribution pattern by controlling the distribution and growth of plants and indirectly controlling the SOM distribution. At a large scale, the distribution pattern of vegetation on the Tibetan Plateau was coincident with that of precipitation (Ma, 1960; Institute of Botany, the Chinese Academy of Sciences, 1988) and this once more explained the importance of precipitation on the Tibetan Plateau. The following analysis was all based on the correlative analysis between the precipitation and SOC contents.

**Table 1** Grey correlation degree analysis between climatic factors and SOC content in the top 30 cm soil layers

GCDI	PGS	NPGS	PJ	MAP	TGS	NTGS	TJ	MAT
SOC	0.932	0.926	0.92	0.91	0.886	0.882	0.879	0.584
order	1	2	3	4	5	6	7	8

Note: GCDI represents grey correlation degree index; PGS represents precipitation in growing season; NPGS represents precipitation in non-growing season; PJ represents precipitation in July; MAP represents mean annual precipitation; TGS represents temperature in growing season; NTGS represents temperature in the non-growing season; TJ represents temperature in July and MAT represents mean annual temperature. Sample size was 106.

In different natural zones the precipitation and the SOC contents had significant correlations (Table 2). From the following distribution sequence of natural zones: from montane desert zone in the north of transect to the alpine meadow-steppe zone in the middle of transect, and to the montane shrub-coniferous forest zone in the south of transect, the distribution pattern of moisture varied from arid, semi-arid, semi-humid and to humid, at the same time, the correlation between the precipitation and SOC

contents gradually decreased. This indicated that the degree of influence of precipitation on the SOC contents decreased as the hydrological conditions improved. It was reflected in the horizontal distribution of SOC that the limitation of precipitation on the plant distribution and growth decreased as the increase of precipitation.

**Table 2** Correlative analysis between precipitation and SOC in different natural zones

precipitation factor	montane desert zone <sup>1</sup>	alpine meadow-steppe zone <sup>2</sup>	montane shrub-coniferous forest zone <sup>3</sup>
MAP	0.668**	0.471**	0.391*
PGS	0.667**	0.462**	0.356*
NPGS	0.66**	0.488**	0.189
PJ	0.66**	0.455**	0.069

Note: \* and \*\* stand for  $P < 0.05$  and  $P < 0.01$ , respectively; superscripts 1, 2, 3 indicate sample size of 17, 47 and 42, respectively. The meaning of the abbreviations is the same as in Table 1.

Many studies had shown that the SOM distribution was mainly controlled by the climatic factors in the top soils, while it was mainly controlled by the non-climatic factors in the deeper soil depth (Jobbágy et al., 2000, 2001). In this paper we also gained the same conclusion. The correlation decreased between the precipitation factors and SOC contents as the soil depth increased (Table 3). Compared with the upper 30 cm soil depth, the correlation (0.776) between the precipitation in the non-growing season and the SOC content rose in the below 30 cm soil depth. This may have been due to the precipitation in the non-growing season related to the latent water source of the below-ground frozen soils. Before the coming of the rainy season on the Tibetan Plateau, the latent water quantities provided by the frozen soil in the deeper soil layers was the main water source and limiting factor for the growing of aboveground vegetation in the early growing season (Gao et al., 1995; Jobbágy et al., 2000).

**Table 3** Correlative analysis between precipitation and SOC in different soil layers

precipitation factors	0–10 cm	10–20 cm	20–30 cm	>30 cm
MAP	0.696**	0.694**	0.636**	0.626**
PGS	0.658**	0.641**	0.621**	0.564**
NPGS	0.67**	0.62**	0.555**	0.776**
PJ	0.581*	0.567**	0.543**	0.265

Note: \* and \*\* represent  $P < 0.05$  and  $P < 0.01$ , respectively; sample size  $n = 23$  in each of upper 30 cm soil layers; sample size  $n = 37$  in >30 cm soil layer; the meaning of the abbreviations is the same as in Table 1.

### 3.2.2 The influence of edaphic factors on the SOC distribution on the Tibetan Plateau transect

The distribution of the SOC content was also controlled by the edaphic factors (Huang, 2000). The edaphic factors

could affect plant growth, the living space and activity of microorganisms, and the turnover rate of SOM, all of this would indirectly control the SOC distribution. In different natural zones, the correlation between the edaphic factors and the SOC content differs significantly (Table 4). In the alpine meadow-steppe zone and the montane shrub-coniferous forest zone, the SOC contents had a significant and positive correlation with the soil clay content, while in the montane desert zone, the SOC content had no significant correlation with soil clay content because the desert soil was mainly composed of soil sand (Gao et al., 1985). In all the three natural zones, the soil silt content was positively correlated with the SOC content (Table 4) and the soil sand content was negatively correlated with the SOC content. All the facts explained that the soil clay and soil silt contents were helpful in fixing the SOC and the soil sand content was harmful to the SOC sequestration (Balesdent et al., 1998). The soil bulk density and soil pH were both negatively correlated with the SOC content in the transect (Table 4). The lower soil pH often restrained the activity and quantity of soil microorganism and then led to a higher SOC sequestration (Huang, 2000).

**Table 4** Correlative analysis between edaphic factors and SOC content in different natural zones

edaphic factors	montane desert zone <sup>1</sup>	alpine meadow-steppe zone <sup>2</sup>	montane shrub-coniferous forest zone <sup>3</sup>
clay	0.100	0.568**	0.494**
silt	0.777**	0.322*	0.449**
sand	-0.748**	-0.343*	-0.465**
soil bulk density	-0.52*	-0.368**	-0.743**
pH	-0.686**	-0.496**	-0.393**

Note: \* and \*\* represent  $P < 0.05$  and  $P < 0.01$ , respectively; the meaning of superscripts 1, 2, 3 is the same as in Table 2.

The influence of the edaphic factors on the distribution of the SOC was obviously diverse by analyzing the correlation between the edaphic factors and the SOC content in different soil layers (Table 5). The SOC content had a positive correlation with the soil clay content in the upper 20 cm soil depth, while it had a positive correlation with the soil silt content and a negative correlation with the soil sand content in the lower 20 cm soil depth. The results indicated that the different size-fractions of the soil had different functions in fixing the SOM at different soil depth.

**Table 5** Correlative analysis between edaphic factors and SOC content in different soil layers

soil layer/cm	clay	silt	sand	bulk density	pH
0–10	0.483*	0.289	-0.286	-0.852**	-0.79**
10–20	0.68**	0.328	-0.334	-0.646**	-0.741**
20–30	0.456*	0.475*	-0.517*	-0.58**	-0.714**
>30	0.08	0.290*	-0.283*	-0.49**	-0.706**

Note: \* and \*\* represent  $P < 0.05$  and  $P < 0.01$ , respectively

### 3.2.3 The influence of other factors on the SOC distribution on the Tibetan Plateau transect

The SOC content was jointly controlled by the carbon input and carbon output in soil (Thompson et al., 1996; Wang et al., 2004), and it would be affected by the differences in the growth pattern of the plant and the composition of litters. The aboveground biomass of vegetation on the Tibetan Plateau differed greatly, the pattern of aboveground biomass was as follows: forest > shrub > meadow > steppe > desert (Luo et al., 1999, 2002a, 2002b), which was in accordance with the horizontal distribution pattern of SOC content along the transect (Fig. 1). The highest aboveground biomass ( $150.29 \text{ mg}\cdot\text{hm}^{-2}$ ) of forest vegetation led to an ample supply of SOM in the forest soil and so the SOC content in forest soil was the highest among all the vegetations. The lowest aboveground biomass ( $2.01 \text{ mg}\cdot\text{hm}^{-2}$ ) in the desert vegetation means the lowest SOC content of desert soil. Most of the roots lived in the 0–30 cm soil layers (Luo et al., 1999) and significant and positive correlations were found on the transect between the plant biomass and SOC content ( $y = 0.69\ln x - 0.28$ ,  $R^2 = 0.49$ ,  $P < 0.01$ ,  $n = 10$ ;  $y$ : SOC content ( $\text{g}\cdot\text{kg}^{-1}$ ),  $x$ : plant biomass ( $\text{mg}\cdot\text{hm}^{-2}$ )), which also reflected the contribution of the plant biomass to the belowground SOM.

## 4 Conclusions

In the horizontal direction on the Tibetan Plateau transect, the distribution of SOC contents in different vegetations can be seen as below: forest > shrub > meadow > steppe > desert. In the vertical direction, all the SOC contents of the top 10 cm soil layers in the vegetations of the forest, shrub and meadow, as well as that of the top 20 cm soil layers in the steppe, were higher than that of the corresponding lower soil layers. However, the SOC content in desert was in accordance with different soil layers.

The grey correlation degree analysis indicated that the precipitation was the dominant climatic factor affecting the distribution of SOC on the Tibetan Plateau transect. The influence of the precipitation on the horizontal distribution of SOC decreased with the increase of precipitation in the horizontal direction and the vertical distribution of SOC along soil profile was also greatly affected by precipitation.

The vertical distribution of SOC along the soil profile was greatly affected by the soil clay content in the upper part of soil. Besides, it could be clearly influenced by the soil silt content or the sand content in the lower part of soil. The influences of both the soil bulk density and soil pH on the vertical distribution of SOC along the soil profile declined gradually. The plant biomass was the most important biotic factors affecting the distribution of SOC.

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