The Cryosphere Discuss., 8, 5015–5033, 2014
www.the-cryosphere-discuss.net/8/5015/2014/
doi:10.5194/tcd-8-5015-2014

The Cryosphere Discussions
Open Access

The organic carbon pool of permafrost regions on the Qinghai–Xizang (Tibetan) Plateau

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Received: 27 August 2014 – Accepted: 15 September 2014 – Published: 29 September 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Presently, Northern Circumpolar Soil Carbon Database was not involved permafrost organic carbon storage on the Qinghai–Xizang (Tibetan) Plateau (QXP). Here we reported a new estimation of soil organic carbon (SOC) pools of the permafrost regions on the QXP at different layers from the top 1 to 25 m depth using a total of 706 soil profiles. The SOC pools were estimated to be 15.29 Pg for the 0–1 m, 4.84 Pg for the 1–2 m, 3.89 Pg for the 2–3 m and 43.19 Pg for the layer of 3–25 m. The percentage (64.3 %) of SOC storage in deep layer (3–25 m) on the QXP was larger than that (38.8 %) in the northern circumpolar permafrost region. In total, permafrost region on the QXP contains approximately 67.2 Pg SOC, of which approximately 47.08 Pg (70.1 %) stores in perennially frozen soils and deposits. The present study suggested that the permafrost organic carbon pools of Northern Hemisphere should be updated from 1672 to 1739 Pg.

1 Introduction

Soil organic carbon (SOC) storage in permafrost regions has received worldwide attention under global warming scenarios, due to its direct contribution to the atmospheric greenhouse content (Ping et al., 2008a; Tarnocai et al., 2009; Zimov et al., 2009). Climate warming will thaw permafrost, releasing trapped carbon in permafrost affected soils into the atmosphere and further exacerbating global warming (Zimov et al., 2006; Schafer et al., 2011). Permafrost carbon has been potentially most significant carbon-climate feedbacks because of the size of carbon pools and intensity of climate forcing (Schuur et al., 2008; Mackelprang et al., 2012; Schneider von Deimling et al., 2012).

It has been estimated that permafrost regions of circum-Arctic areas contain approximately 1672 Pg of organic carbon, which includes 495.8 Pg for the 0–1 m, 1024 Pg for the 0–3 m and 648 Pg for deeper depth of 3–25 m (Tarnocai et al., 2009).The SOC of the permafrost regions in the Qinghai–Xizang (Tibetan) Plateau (QXP) may play an

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important role in global climate change (Li et al., 2008; Cheng and Wu, 2007), where permafrost area is approximately 1.35×10^6 km^2 (Ran et al., 2012). On the QXP, mean annual permafrost temperatures at 6.0 m depth have increased 0.12–0.67 °C from 1996 to 2006 (Wu and Zhang, 2008). The mean increasing rate of the active layer thickness is approximately 7.5 cm y^{-1} along the Qinghai–Tibetan Highway (Wu and Zhang, 2010). The thawing of permafrost with warming occurs, exposing organic carbon to microbial decomposition, which may initiate a positive permafrost carbon feedback (PCF) on climate (Schuur et al., 2008). Moreover, the strength and timing of the PCF was greatly dependent on the distribution of permafrost organic carbon. Thus, understanding of the storage and potential contribution of permafrost carbon to the atmosphere will be critical for better predicting future climate change. However, the present carbon storage in northern permafrost region does not include the SOC data on the QXP (Hugelius et al., 2013).

Recently, some studies have been conducted on SOC pools in the 0–1 m depth on the QXP (Wu et al., 2012; Wang et al., 2002, 2008; Ohtsuka et al., 2008; Yang et al., 2008, 2010; Liu et al., 2012; Dorfer et al., 2013). However, these results are all site specific and there is no SOC assessment in permafrost regions. There are about 706 soil profiles were excavated in the permafrost regions of the QXP, which make it possible to calculate the SOC pools in this region.

Perennially frozen soils are important earth system carbon pools because of their vulnerability to climate change (Koven et al., 2011). SOC in deep layer is usually earlier deposits and has been kept frozen, which has higher microbial decomposability (Waldrop et al., 2010). Some of the movement of soil organic carbon from surface to few meter depth is accomplished through cryoturbation (Bockheim et al., 1998), which is caused by cracking due to soil freeze–thaw cycles and by soil hydrothermal gradients (Ping et al., 2008b). Current studies have shown the importance of deep permafrost organic carbon and its feedback with climate change (Hobbie et al., 2000; Davidson and Janssens, 2006; Schuur et al., 2009). The deep permafrost organic carbon was more sensitive to temperature increasing compared with that in the active layer (Waldrop et al., 2010). The total Yedoma region contains 211 + 160/ − 153 Gt C in deep soil deposits (Strauss et al., 2013). Despite its importance, the distribution of permafrost organic carbon in the 0–25 m depth on the QXP has been largely unknown.

The objective of this article is to assess the SOC pool on the QXP, based on the published data and some new field sampling from this study. Unlike those from previous assessment of SOC on the QXP, the new estimation focuses on the permafrost regions and includes deeper layers, down to 25 m. The result might update new estimation of surface organic carbon mass and deep permafrost carbon storage, which can provide new insights in permafrost carbon on the QXP.

2 Materials and methods

2.1 Soil carbon database on the QXP

Permafrost regions in China are mainly on the QXP (LIGG/CAS, 1988), which occupied approximately 1.35×10^6 km^2 of the QXP area (Ran et al., 2012). It has been pointed out that the vegetation communities have great impacts on SOC distribution (Jobbagy and Jackson, 2002; Wu et al., 2012). Therefore, it is essential to calculate the SOC pool according to vegetation types. Based on the China vegetation data (Chinese Academy of Sciences, 2001) (Fig. 1), the permafrost regions in the alpine meadow, alpine steppe and alpine desert are 0.53×10^6 km^2, 0.72×10^6 km^2 and 0.092×10^6 km^2, respectively (Yang et al., 2010).

The soil carbon databases in the 0–1 m depth were based on the previous reports (Wang et al., 2002; Yang et al., 2010; Liu et al., 2012; Wu et al., 2012; Dorfer et al., 2013; Mu et al., 2013) (Table 1). We integrated the databases form Wang et al. (2002), Yang et al. (2010), Dorfer et al. (2013) and Ohtsuka et al. (2008) because these studies were all performed in the middle and eastern part of the QXP. Moreover, we complemented the data of Wu et al. (2012), Liu et al. (2012) and Mu et al. (2013) in the soil carbon databases in the 0–1 m depth, because their study regions of western QXP, Shulehe River Basin (SLRB) and Heihe River Basin (HHRB) were not involved in the estimation of organic carbon storage on the QXP in previous reports. The total permafrost carbon pool on the QXP was built up using 706 profile sites.

2.2 Deep permafrost carbon

In addition to the soil carbon in the 0–1 m depth, we also reported deep permafrost carbon pools (0–25 m) by 11 sites on the QXP by field machine-drill from 2009 to 2013 (Fig. 1). Five sites near the Qinghai Tibetan Highway were located in the Kaixinling Basin (KXL), Honglianghe Valley (HLH-1, HLH-2), Xiushuihe Valley (XSH) and Wudaoliang Basin (WDL), respectively. The elevation ranged from 4525 to 4779 m. Soil types were mainly Quaternary alluvial sand, silt and silty clay, under where were Tertiary mudstone and sandstone (Luo et al., 2012). Ice-rich permafrost was found at some areas in this region (Lin et al., 2010). Three sampling sites (KL150, KL300, KL450) were located in the Kunlun Mountains with the ecosystem of alpine meadow. Another site (ZEH) was near to the Zhouerhu Lake in Kekexili, with soil type as lake deposits. It was typical alpine desert and perennially frozen, contain less amounts of organic carbon and ice. In addition, the two deep permafrost sites in the Heihe River Basin (Heihe-1, Heihe-2) were the alpine meadow and rich in organic carbon with high soil water contents (Mu et al., 2013).

2.3 Analytical methods

The SOC densities reported in the previous studies were employed to calculate the SOC pools in the top 1 m layer. The SOC data of the 11 drilling holes were used for the calculation of SOC pools of the layers below 1 m. For SOC analyses, the homogenized samples were quantified by dry combustion on a Vario EL elemental analyzer (Elemental, Hanau, Germany). During measurement, 0.5 g dry soil samples were pretreated by HCl (10 mL 1 mol L^{-1}) for 24 h to remove carbonate (Sheldrick, 1984). Bulk density was determined by measuring the volume (length, width, height) of a section of frozen core, and then drying the segment at 60 °C (for 48 h) and determining its mass.

2.4 Calculation of soil carbon pools

For the organic carbon storage in the 0–1 m depth, we multiplied the comprehensive and complementary organic carbon contents by the areas of alpine meadow, alpine steppe and alpine desert, respectively.

For the Stock of Soil Organic Carbon (SSOC, kg m^{-2}), it was calculated using the formula Eq. (1):

$$\mathrm{SSOC} = C \cdot \mathrm{BD} \cdot T \cdot (1 - \mathrm{CF}) \tag{1}$$

where C was the organic carbon content (wt%), BD was the bulk density (g cm^{-3}), T was the soil layer thickness and CF was the coarse fragments and/or ice content (wt%). Using this information, the SSOC was calculated for the 1–2, 2–3 and 3–25 m depth, respectively. Then, soil organic carbon storage (Pg) was estimated by multiplying the SSOC at different depth by the soil area with different vegetation type.

3 Results

3.1 Organic carbon pools in the 0–1 m depth

On the QXP, organic carbon storage of the permafrost regions in the 0–1 m depth was approximately 15.29 Pg, of which approximately 9.45 Pg (61.8 %) in the alpine meadow, 5.44 Pg (35.6 %) in the alpine steppe and 0.40 Pg (2.6 %) in the alpine desert, respectively (Table 1). There was much variation in SOC contents over alpine meadow area. SOC contents in the Heihe River Basin (HHRB) (58.5 kg m^{-2}) and Shulehe River Basin (SLRB) (8.7 kg m^{-2}) were far from the range of the most QXP (10.4–29.5 kg m^{-2}). Moreover, there was less variation in SOC contents over alpine steppe and alpine desert area, with the ranges of 3.72–9.24 and 3.07–4.39 kg m^{-2}, respectively. The study area in Wu et al. (2012) was estimated approximately to be 0.045×10^6 km^2 (Fig. 1) and the organic carbon storage was 0.36 Pg.

3.2 Distribution of deep permafrost organic carbon

Average SOC contents in deep permafrost soils near the Qinghai Tibetan Highway were approximately 2.34, 1.17, 1.14, 1.21 and 2.83 % at the KXL, HLH-1, HLH-2, XSH and WDL, respectively (Fig. 2). SOC contents decreased with depth at the KXL, HLH-1 and HLH-2. While SOC contents in deeper depth were higher than those in the top layer at the XSH, WDL and KL300. Average SOC contents in the Kunlun Mountains (KL150, KL300, KL450) ranged from 1.01–2.01 %. SOC content in the Zhuoerhu Lake (ZEH) had a lower value of 0.13 % over alpine desert area. In addition, permafrost organic carbon contents in the Heihe River Basin (Heihe-1, Heihe-2) were higher than those on the most QXP, with average values of 3.2–6.7 % in the depth of 6 cm (Mu et al., 2013).

Based on the deep permafrost soil data on the QXP, a relationship between soil organic carbon contents (SOC%) and soil depth (h) in deep permafrost soils can be characterized by a power function (2) (Fig. 2):

$$\mathrm{SOC\%} = 16.307 h^{-1.164} \quad (R^2 = 0.65, p < 0.001, n = 261) \tag{2}$$

3.3 Deep permafrost organic carbon pools

Permafrost organic carbon storages on the QXP were approximately 15.29 Pg in the 0–1 m depth, 4.84 Pg in the 1–2 m, 3.89 Pg in the 2–3 m and 43.19 Pg in deep depth of 3–25 m (Table 2). The organic carbon storage in the 0–1 m depth was approximately twice that in the 1–3 m depth. In total, it contains approximately 67.2 Pg of permafrost organic carbon on the QXP, of which 47.08 Pg (70.1 %) stores in permafrost layers.

The active layer thickness of the QXP varies from 0.8–4.6 m, and in most regions, the active layer thickness was about 2 m (Wu et al., 2012; Wu and Zhang, 2008). Therefore, we consider the upper 2 m as the active layer. According to this depth, the organic carbon storage in deep permafrost was approximately twice that in the active layer.

SOC storages in the alpine meadow, alpine steppe and alpine desert were 32.39 Pg, 38.79 and 0.82 Pg, of which 17.73 Pg (54.7 %), 29.64 Pg (76.4 %) and 0.32 Pg (39.0 %) stored in permafrost layers, respectively. Among the three vegetation types, more organic carbon is stored in deep permafrost in the alpine steppe.

4 Discussion

Our estimates indicate that permafrost organic carbon storage in the 0–1 m depth on the QXP was approximately 15.29 Pg. However, previous soil carbon pools on the alpine grasslands of the whole QXP was estimated to be 9.88 Pg (Wang et al., 2002), and 10.54 Pg (Yang et al., 2010). The difference, in large part, between our new estimation and previous estimation is because that we add the regions which were not considered in the previous SOC pool estimation. The study area of the western QXP, Shulehe River Basin and Heihe River Basin were considered as independent regions to be calculated. There is much variation in permafrost organic carbon contents on the QXP in previous reports (Wang et al., 2002; Yang et al., 2010; Liu et al., 2012; Wu et al., 2012; Dorfer et al.,2013; Ohtsuka et al., 2008; Mu et al., 2013). Thus, it is difficult to draw a definite conclusion about the SOC pools in the permafrost regions of the QXP due to the spatial heterogeneity. In the present study, we integrated all the published data and estimated that the SOC pool of the top 1 m was higher than that of previous reports. This result highlighted the importance of SOC in the permafrost regions of QXP.

It is the first time to study the deep permafrost organic carbon on the QXP. Our estimation recognized and quantified the significant carbon below the 1 m depth. The 11 deep permafrost sites can represent the vegetation types of alpine meadow, alpine steppe and alpine desert. The mean SOC content of the 11 drilling holes on the QXP (1.14–6.7 wt%) was similar with that (3.0 wt%) in the yedoma deposites (Strauss et al.,

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2013), and that (~ 2.6 wt%) of lowland steppe-tundra soils in Siberia and Alaska (Zimov et al., 2006). The SOC content (8.7–29.05 kg m^{-2}) in the alpine meadow on the most QXP was higher than that (0.9 ± 0.2 kg m^{-2}) of Tarfala Valley, Northern Sweden (Fuchs et al., 2014), and lower than that (55.1 kg m^{-2}, 40.6 kg m^{-2}) in lowland and hilly upland soils in North American Arctic region (Ping et al., 2008a). The SOC content (58.5 kg m^{-2}) in the Heihe River Basin on the QXP was similar with that in North American Arctic region and that (53–57 kg m^{-2}) in the White Hills, the Arctic Coastal Plain and Arctic Foothills of northern Alaska (Bockheim et al., 2007). The SOC content (3.07–4.39 kg m^{-2}) in the alpine desert on the QXP was similar with that (3.4 kg m^{-2}, 3.8 kg m^{-2}) in rubbleland and mountain soils in North American Arctic region (Ping et al., 2008a). In total, the highest mean SOC content on the QXP was lower than that (32.2–69.6 kg m^{-2}) in organic soils and cryoturbated permafrost-affected mineral soils in the northern permafrost region (Tarnocai et al., 2009).

There is an exponential decreasing trend of the SOC along with the depth in the drilling holes. This was in agreement of those reported in circum-Arctic regions (Strauss et al., 2013; Zimov et al., 2006), which could be explained by the SOC formation dynamics in the permafrost regions. However, in the XSH, WDL and KL300, it was found that the organic carbon contents in some deep layers were higher than those in the top layer (Fig. 2), which may caused by the cryoturbation and sediment burying process (Ping et al., 2010).

Our estimates indicate that the soils on the QXP contains 24.02 Pg of organic carbon in the surface 0–3 m, with an additional 43.19 Pg (64.3 %) of carbon locked in deep layers (3–25 m) of the alpine steppe (27.76 Pg), alpine meadow (15.43 Pg) and alpine desert (0.23 Pg) in permafrost. In northern circumpolar permafrost region, 1024 Pg of organic carbon in the 0–3 m depth and 648 Pg (38.8 %) of carbon were stored in deep layers of yedoma and deltaic deposits (Tarnocai et al., 2009). Strauss et al. (2013) showed that there was 83 + 61/ – 57 Gt C for Yedoma deposits and 128 + 99/ – 96 Gt C for thermokarst deposits. It shows that the percentage (64.3 %) of SOC storage in deep layer (3–25 m) on the QXP was larger than that (38.8 %) in the northern circumpolar permafrost region. This could be explained as that the paleoclimate of the QXP was warm (Zhang et al., 2003; Lu et al., 2014), which always links to the well development of vegetation (Kato et al., 2004; Piao et al., 2006). It has been well known that the vegetation cover is favorable to soil organic carbon formation (Chen et al., 1990).

In total, there is approximately 67.2 Pg of organic carbon stored in the active layer and permafrost on the QXP, which is smaller than that in Canada (111.9 Pg) and North America (114.5 Pg) (Tarnocai et al., 2009). The proportion of carbon storage in perennially frozen soils and deposits (47.08 Pg, 70.1 %) on the QXP was lower than that (1466 Pg, 88 %) in northern circumpolar permafrost region. This 67.2 Pg of organic carbon would account for approximately 4.1 % of northern permafrost carbon pools (1672 Pg), while the permafrost region on the QXP was about 6 % of northern permafrost area. As a consequence, permafrost organic carbon storage on the QXP was relatively low, which may relate to the higher temperature of the permafrost and the thicker active layer than those of circum-Arctic regions (Wu and Zhang, 2008). The carbon budget balance in alpine permafrost regions on the QXP can still need future study.

5 Conclusions

According to the organic carbon data in previous analysis and field exploration of deep permafrost, we calculated that permafrost organic carbon storages on the QXP were approximately 15.29 Pg in the 0–1 m, 4.84 Pg in the 1–2 m, 3.89 Pg in the 2–3 m and 43.19 Pg in deep depth of 3–25 m. The estimation for the top 1 m layer was larger than that reported for this region in previous analyses.

A relationship between soil organic carbon contents and soil depth in deep permafrost can be characterized by a power function. The percentage (64.3 %) of SOC storage in deep layer (3–25 m) on the QXP was larger than that (38.8 %) in the northern circumpolar permafrost region. In total, it contained approximately 67.2 Pg SOC, of which 47.08 Pg (70.1 %) occurs in permafrost layers, which were below 2 m. It contained approximately 24.02 Pg SOC in the surface 0–3 m depth, with an additional 43.19 Pg carbon locked in deep layers (3–25 m) of alpine steppe (27.76 Pg), alpine meadow (15.43 Pg) and alpine desert (0.23 Pg). The northern permafrost carbon pools, which were estimated to 1672 Pg in previous study, should be 1739.2 Pg if the 67.2 Pg was taken accounted into consideration, and this 67.2 Pg SOC would account for approximately 3.9 % of northern permafrost carbon pools (1739.2 Pg).

Acknowledgements. This work was supported by the Global Change Research Program of China (grant 2010CB951402), National Natural Science Foundation of China (grants 91025013, 91325202), the Key Program of the Chinese Academy of Sciences (grant KZCX2-XB3-03), and the National Key Scientific Research Project (grant 2013CBA01802), and was completed at Lanzhou University and the State Key Laboratory of Frozen Soil Engineering, and the Cold and Arid Regions Environmental and Engineering Research Institute

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Table 1. Organic Carbon Pools in the 0–1 m depth with ecosystem type on the QXP.

Ecosystem	Reference	Region	Site data (n)	Area ($\times 10^6$ km^2)	SOC content (kg m^{-2})	SOC storage (Pg)
Alpine meadow	Yang et al. (2010)	QXP	204	0.53	12.72 ± 0.93	8.93
	Wang et al. (2002)	QXP	~ 124		29.05	
	Ohtsuka et al. (2008)	QXP	1		13.7	
	Dorfer et al. (2013)	QXP	2		10.4	
	Mu et al. (2013)	HHRB	11	0.0065	58.5 ± 3.4	0.40
	Liu et al. (2012)	SLRB	42	0.013	8.70 ± 1.19	0.12
Alpine steppe	Yang et al. (2010)	QXP	234	0.68	5.17 ± 0.49	4.95
	Wang et al. (2002)	QXP	~ 124		8.96	
	Wu et al. (2012)	Western QXP	52	0.045	7.73 ± 3.18, 3.72 ± 1.31	0.36
	Liu et al. (2012)	SLRB	~ 42	0.013	9.24 ± 1.11	0.13
Alpine Desert	Wang et al. (2002)	QXP	~ 124	0.092	3.07	0.40
	Wu et al. (2012)	Western QXP	25		3.28 ± 1.52	
	Liu et al. (2012)	SLRB	~ 42		4.39 ± 0.71	

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Table 2. Permafrost organic carbon storage to the depth of 25 m on the QXP.

Soil depth (m)	Alpine meadow SOC ($kg\,m^{-2}$)	SOC storage (Pg) QXP	SOC storage (Pg) HHRB	Alpine steppe SOC ($kg\,m^{-2}$)	SOC storage (Pg)	Alpine desert SOC ($kg\,m^{-2}$)	SOC storage (Pg)	Total (Pg)
Active layer								
0–1	7.51–61.9	9.45	0.40	2.41–10.9	5.44	1.76–5.1	0.40	15.29
1–2	3.3 ± 0.4	2.0	0.16	3.4 ± 0.4	2.67	1.7 ± 0.1	0.17	4.84
Total (Pg)		14.66			9.15		0.50	20.13
Permafrost								
2–3	3.4 ± 0.2	1.92	0.40	2.4 ± 0.2	1.88	0.8 ± 0.2	0.092	3.89
3–25	27.4 ± 1.0	15.2	0.23	35.0 ± 3.4	27.76	2.4 ± 0.1	0.23	43.19
Total (Pg)		17.73			29.64		0.32	47.08

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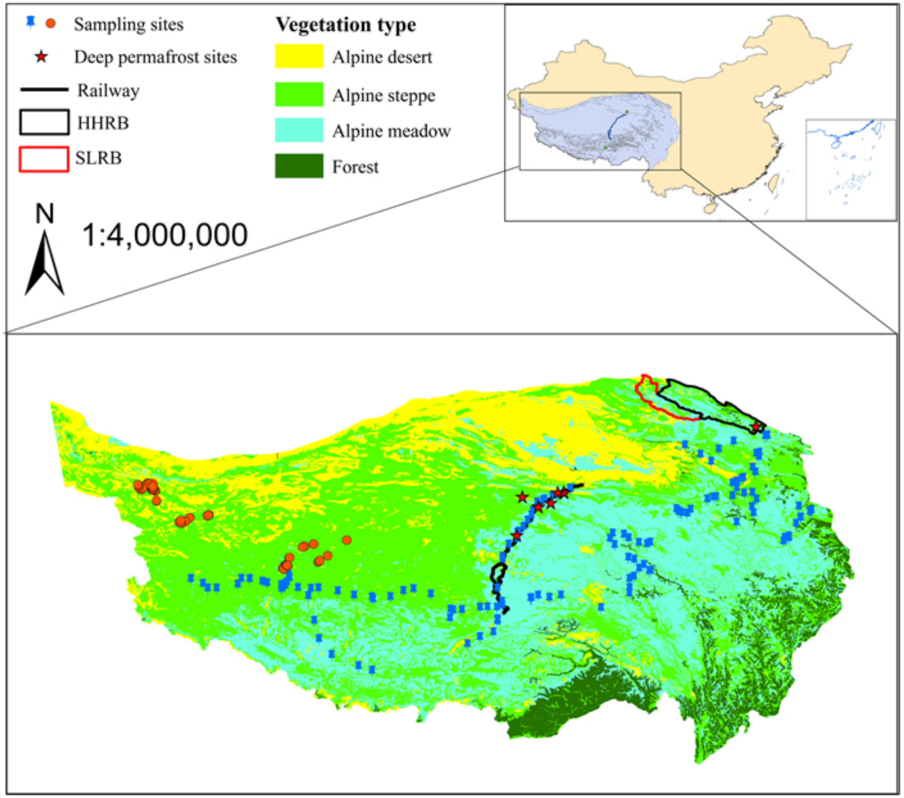

Figure 1. Location of sampling sites on the QXP, shown on the background of QXP vegetation atlas at a scale of 1 : 4 000 000 (Chinese Academy of Sciences, 2001). Blue points were sampling sites in Yang et al. (2010); orange points were in Wu et al. (2012); red box was Shule River Basin (SLRB) in Liu et al. (2012); black box was Heihe River Basin (HHRB) in Mu et al. (2013).

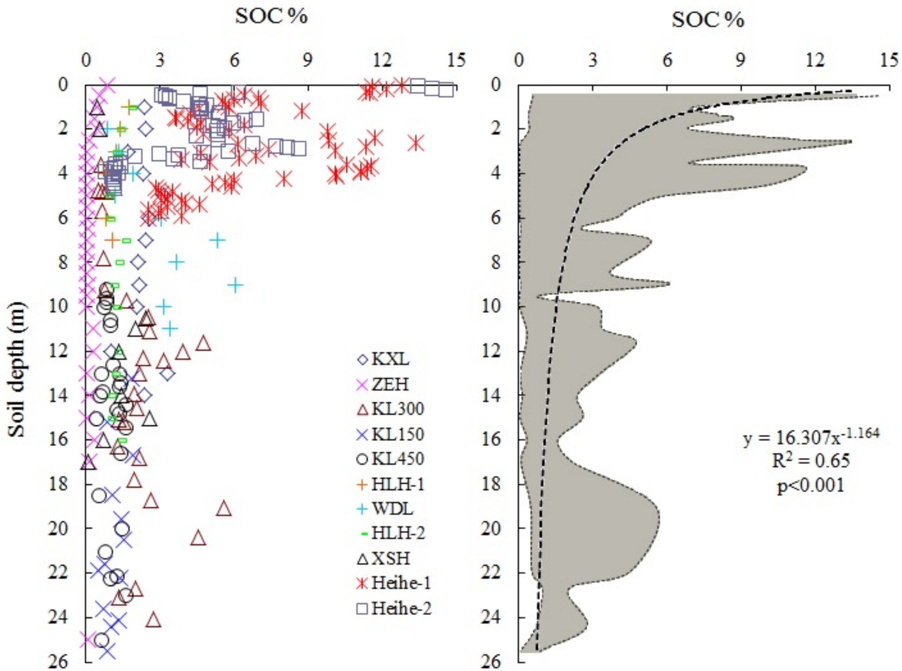

Figure 2. Distributions of soil organic carbon contents in deep permafrost soils on the QXP. The gray area showed the maximum and minimum values of the SOC content.

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