Organic carbon pools in permafrost regions on the Qinghai-Xizang (Tibetan) Plateau

Cuicui Mu[1], Tingjun Zhang[1*], Xiaoqing Peng[1], Bin Cao[1], Xiankai Zhang[1], Bo Cao[1], Qingbai Wu[2], Guodong Cheng[2]

[1] College of Earth and Environmental Sciences, Lanzhou University, Lanzhou Gansu 730000, China

[2] State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou Gansu 730000, China

Correspondence to: Tingjun Zhang (tjzhang@lzu.edu.cn).

Abstract

The current Northern Circumpolar Soil Carbon Database did not include organic carbon storage in permafrost regions on the Qinghai-Xizang (Tibetan) Plateau (QXP). In this study, we reported a new estimation of soil organic carbon (SOC) pools in the permafrost regions on the QXP up to 25 m depth using a total of 190 soil profiles. The SOC pools were estimated to be 17.3±5.3 Pg for the 0~1 m depth, 10.6±2.7 Pg for the 1~2 m depth, 5.1±1.4 Pg for the 2~3 m depth and 127.2±37.3 Pg for the layer of 3~25 m depth. The percentage of SOC storage in deep layers (3~25 m) on the QXP (80%) was higher than that (39%) in the yedoma and thermokarst deposits in arctic regions. In total, permafrost regions on the QXP contain approximately 160±87 Pg SOC, of which approximately 132±77 Pg (83%) stores in perennially frozen soils and deposits. Total organic carbon pool in permafrost regions on the QXP was approximately 8.7% of that in northern circumpolar permafrost region. The present study demonstrates that the total organic carbon storage is about 1832 Pg in permafrost regions on northern hemisphere.

1. Introduction

Soil organic carbon (SOC) storage in permafrost regions has received worldwide attention due to its direct contribution to the atmospheric greenhouse gas contents (Ping et al., 2008a; Tarnocai et al., 2009; Zimov et al., 2009). Climate warming will thaw permafrost, which can cause previously frozen SOC become available for mineralization (Zimov et al., 2006). Permafrost has potentially the most significant carbon-climate feedbacks not only due to the intensity of climate forcing, but also the size of carbon pools in permafrost regions (Schuur et al., 2008; Mackelprang et al., 2012; Schneider von Deimling et al., 2012).

Recently, carbon stored in permafrost regions has created many concerns because of the implication on global carbon cycling (Ping et al., 2008; Burke et al., 2012; Zimov et al., 2006; Michaelson et al., 2013; Hugelius et al., 2013). 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 depth, 1024 Pg for the 0~3 m depth and 648 Pg for 3~25 m depth (Tarnocai et al., 2009). Based on newly available regional soil maps, the estimated storage of SOC in 0~3 m depth is estimated to 1035±150 Pg (Hugelius et al., 2014), about 1% higher than the previous estimate by Tarnocai et al. (2009). The thawing of permafrost would expose the frozen organic carbon to microbial decomposition, and thus may initiate a positive permafrost carbon feedback on climate (Schuur et al., 2008). The strength and timing of permafrost carbon feedback greatly depend on the distribution of SOC in permafrost regions. Therefore, understanding soil carbon storage in permafrost regions is critical for better predicting future climate change. However, the present knowledge of SOC pool in permafrost regions only limited to the circum-Arctic areas. Little is known about the SOC pools in the low-altitude permafrost regions.

The Qinghai-Xizang (Tibetan) Plateau (QXP) in China has the largest extent of permafrost in the low-middle latitudes of the world, with permafrost regions of about 1.35×10^{6} km^{2} and underlying ~67% of the QXP area (Ran et al., 2012). It has been suggested that SOC in permafrost regions on the QXP was very sensitive to global warming, due to the permafrost characteristics of high temperature (< –2.0℃), thin thickness (< 100 m) and unstable thermal states (Cheng and Wu, 2007; Li et al., 2008; Wu and Zhang, 2010). Mean annual permafrost temperatures at 6.0 m depth increased by a range of 0.12℃ to 0.67℃ from 1996 to 2006 (Wu and Zhang, 2008), and increased ~0.13℃ from 2002 to 2012 (Wu et al., 2015). Active layer thickness increased, on average, approximately ~4.26 cm y^{-1} along the Qinghai-Tibetan Highway from 2002 to 2012 (Wu et al., 2015). In addition, the carbon stored in permafrost area was labile and a great part of the carbon was mineralizable (Mu et al., 2014; Wu, et al., 2014).

Some studies have been conducted on SOC pools in 0~1 m depth on the QXP (Wang et al., 2002; 2008; Yang et al., 2008; 2010; Liu et al., 2012; Wu et al., 2012). It was estimated that total SOC for the top 0.7 m was about 30~40 Pg in the grassland of the plateau. The disagreement among the studies on the SOC pools was attributed to the limited sampling points and the quality of the SOC data gathered to date. Despite the importance of SOC in permafrost areas, there are still few reports to the SOC storage in permafrost regions of the QXP. So far, the current Northern Circumpolar Soil Carbon Database (Tarnocai et al., 2009) does not include the SOC in permafrost regions on the QXP (Tarnocai et al., 2009).

Perennially frozen soils are important earth system carbon pools because of their vulnerability to climate change (Koven et al., 2011). Some of the movement of SOC 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). It was reported that the total yedoma region contains 211+160/–153 Pg C in deep soil deposits (Strauss et al., 2013). Current studies have shown the importance of deep organic carbon in permafrost regions and its feedback with climate change (Hobbie et al., 2000; Davidson and Janssens, 2006; Schuur et al., 2009). Deep organic carbon can be more sensitive to temperature increasing compared with that in the active layer (Waldrop et al., 2010). Therefore, it is essential to study the distribution of organic carbon content in deep layers of permafrost regions.

For the top layer, important factors controlling SOC pools are vegetation type and climate

(Jobbagy and Jackson, 2000). The vegetation type and climate conditions related closely to each other on the QXP (Wang et al., 2002). Thus it is possible to calculate the SOC pools at 0~2 m depth according to the area of vegetation type (Chinese Academy of Sciences, 2001) in the permafrost regions (LIGG/CAS, 1988). For deep layers, the geomorphology and lithological conditions play an important role in the distribution of SOC pools (Hugelius et al., 2013). Thus it is reasonable to estimate the SOC pools at 2~25 m depth according to the area of Quaternary geological stratigraphy in permafrost regions on the QXP.

The objective of this study is to assess the SOC pools in permafrost regions on the QXP, based on the published data and new field sampling through deep drilling from this study. The new estimation focuses on the permafrost regions and includes deeper layers, down to 25 m. SOC storages of the plateau were estimated using the published data of 190 soil profiles and 11 deep sampling sites from this study in combination with the vegetation map, permafrost map and geological stratigraphy map of the QXP (Figs. 1, 2, 3). The result would update current estimation of surface organic carbon pool and deep organic carbon storage in permafrost regions of the QXP, which can provide new insights in permafrost carbon on the global scale.

2. Materials and methods

2.1 Soil carbon database in previous reports

The soil carbon databases in 0~1 m depth were retrieved from the previous reports (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 from 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. The data of

Wu et al. (2012), Liu et al. (2012) and Mu et al. (2013) in the soil carbon database in 0~1 m depth were calculated separately, since their study regions of western QXP, Shulehe river basin (SLRB) and Heihe river basin (HHRB) belonged to the isolated permafrost zone and the climate conditions differed greatly with the continuous permafrost zones of the QXP. The total organic carbon pools in 0~1 m depth in permafrost regions on the QXP were calculated using 190 profile sites from published sources.

2.2 Field sampling

To calculate the deep carbon pools (2~25 m) in permafrost regions, 11 boreholes on the QXP were drilled from 2009 to 2013 (Fig. 1). Geographic location for the 11 boreholes, together with the active layer depth, sampling depth, vegetation type, geological stratigraphies, SOC contents, bulk density, water contents and soil texture are provided in the supplement materials.

The deep sampling sites were mainly located in three vegetation types of alpine meadow, alpine stepper and alpine desert (Fig. 2). Three sampling sites (KXL, HLH-1, HLH-2) were located in the vegetation type of alpine steppe. Another site (ZEH) was near to the *Zhouerhu Lake* in *Kekexili*, with soil formed from lacstrine deposits. It was typical alpine desert and perennially frozen, containing less amounts of organic carbon. Five sampling sites (KL150, KL300, KL450, WDL, XSH) were located in the vegetation type of alpine meadow. In addition, two sites in permafrost regions of the Heihe river basin (HHRB: Heihe-1, Heihe-2) with vegetation type of alpine meadow were rich in organic carbon with high soil water contents (Mu et al., 2013).

The deep sampling sites were mainly distributed in three geological stratigraphies: ZEH, WDL, XSH, Heihe-1 and Heihe-2 were in the Quaternary stratigraphy, KL150, KL300, KL450, HLH-1 and HLH-2 were in the Triassic stratigraphy, and KXL was in the Permian stratigraphy (Fig. 3).

2.3 Analytical methods

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 105℃ (for 48 h) and determining its mass.

2.4 Calculation of soil carbon pools

For the Stock of Soil Organic Carbon (SSOC, kg m^{-2}), it was calculated using the formula (1) (Dorfer et al., 2013):

$$SSOC = C \times BD \times T \times (1 - CF) \quad (1)$$

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 (wt%). Using this information, the SSOC was calculated for the 0~1m, 1~2 m, 2~3 m and 3~25 m depths, respectively. Then, SOC storage (Pg) was estimated by multiplying the SSOC at different depth by the distribution area.

For the organic carbon storage in 0~1 m depth, the reported SOC densities data of 190 sampling sites were collected through their distribution in permafrost regions (Fig. 1). The area of alpine meadow, alpine steppe and alpine desert in permafrost regions was calculated through overlaying the vegetation map over the QXP permafrost regions (Fig. 2). For the organic carbon storage in 1~2 m depth, the organic carbon densities of 11 boreholes were extrapolated to the located vegetation type area.

For the organic carbon storage in 2~3 m and 3~25 m depths, the area of permafrost regions in the Quaternary, Triassic and Permian stratigraphies on the QXP was calculated through overlaying the distribution of geological stratigraphies over the permafrost map (Fig. 3). The organic carbon pools of 2~3 m and 3~25 m depth were estimated through deep organic carbon densities multiplied by the area of geological stratigraphies. The three geological stratigraphies had thick sediments of about 25 m (Fang et al., 2002; 2003; Qiang et al., 2001). As for other geological stratigraphies, the poor soil development was reported and soil thickness was usually less than 3 m (Wu et al., 2012; Yang et al., 2008; Hu et al., 2014). Thus other stratigraphies were not considered in the estimation of deep organic carbon pool in the permafrost regions.

3. Results

3.1 Organic carbon pools in the 0~1 m depth

Based on the vegetation data on the QXP (Figs. 1, 2), the area of permafrost regions in the alpine meadow, alpine steppe and alpine desert are 0.302×10^6 km^2, 0.772×10^6 km^2 and 0.175×10^6 km^2 respectively, with a total area of approximately 1.249×10^6 km^2.

Organic carbon storage of the permafrost regions in the 0~1 m depth on the QXP was approximately 17.3±5.3 Pg, of which approximately 11.3±4.0 Pg (65%) in the alpine meadow, 5.3±2.8 Pg (31%) in the alpine steppe, and 0.7±0.3 Pg (4%) in the alpine desert, respectively (Table 1). There were great variations in SOC contents among the sites under alpine meadow area. SOC store in the HHRB (39.0±17.5 kg m^{-2}) was much higher than that of most sites in the predominately continuous permafrost zone on the QXP. In contrast, the SOC stores showed little variation over the sites in the alpine steppe and alpine desert areas, with the ranges of 6.9±3.6 kg m^{-2} and 3.9±1.5 kg m^{-2}, respectively.

3.2 Distribution of deep organic carbon

According to the distribution of sampling sites at the geological stratigraphies, for the Quaternary stratigraphy, average SOC contents at 2~3 m and 3~25 m depths were 0.8±0.6% and 0.8±0.7%. For the Triassic stratigraphy, average SOC contents at 2~3 m and 3~25 m depths were 1.1±0.3% and 1.2±0.6%. For the Permian stratigraphy, average SOC contents at 2~3 m and 3~25 m depths were 1.5±0.4% and 1.1±0.3%. As for the permafrost regions in HHRB, the SOC contents (Heihe-1, Heihe-2) were higher than those of predominately continuous permafrost zone on the QXP, with a range of 5.1±3.7% and 2.7±2.4% to depth of 19 m. SOC contents decreased with depth in most deep boreholes, while SOC contents in deeper layers were higher than those in the top layer at the XSH, KL150 and KL300 (Fig. 4).

With the deep soil data, a relationship between SOC contents (SOC%) and soil depth (h) in deep soils of permafrost regions can be characterized by a power function (2) (Fig. 4):

$$SOC\% = 14.11h^{-1.20} \ (R^2 = 0.68,\ p < 0.01,\ n = 362) \qquad (2)$$

3.3 Deep organic carbon pools

Based on the Quaternary stratigraphies data in permafrost regions of the QXP (Fig. 3), the area of permafrost regions in the Quaternary, Triassic and Permian stratigraphies are 0.194×10^6 km^2, 0.238×10^6 km^2 and 0.135×10^6 km^2 respectively, with a total area of approximately 0.567×10^6 km^2, about 45% of permafrost regions on the QXP.

Organic carbon storages in permafrost regions on the QXP were approximately 10.6±2.7 Pg in the 1~2 m depth, 5.1±1.4 Pg in the 2~3 m depth and 127.2±37.3 Pg in deep depth of 3~25 m (Table 2). In total, it contains approximately 160±87 Pg of organic carbon at depth of 25 m in permafrost regions on the QXP.

Active layer thickness on the QXP varies from 0.8 to 4.6 m, and in most regions, active layer thickness was about 2 m (Cheng and Wu, 2007; Wu and Zhang, 2008; Zhao et al., 2010; Wu et al., 2012). Thus we consider the upper 2 m as the active layer. According to this depth, the organic carbon storage in permafrost layers of 132±77 Pg was approximately five times of that (28±6 Pg) in the active layer.

SOC storages in Quaternary, Triassic and Permian stratigraphies were 31±17 Pg, 69±53 Pg and 32±20 Pg at depth of 2~25 m, respectively. More than a half of organic carbon is stored in permafrost layers which belonged to the Triassic stratigraphy.

4. Discussions

Our estimates indicate that organic carbon storage in permafrost regions in the 0~1 m depth on the QXP was approximately 17.3±5.3 Pg. However, previous soil carbon pools on the alpine grasslands of the whole QXP was estimated to be 33.5 Pg of 0~0.75 m (Wang et al., 2002), and 10.5 Pg of 0~0.30 m (Yang et al., 2010). The difference, in large part, between our new estimate and previous reports can be explained as follows: i) Area of vegetation types in permafrost regions was recalculated. The area of permafrost regions of about 1.249×10^6 km^2 was smaller than that of Wang et al. (2002) (1.63×10^6 km^2) and Yang et al. (2010) (1.26×10^6 km^2). ii) Carbon density data of sampling sites located in permafrost regions was collected. The integration of carbon data from the results of recent publications (Ohtsuka et al., 2008; Dorfer et al., 2013; Wu et al., 2012) and our field data resulted in a higher carbon density than those of previous reports (Wang et al., 2002; Yang et al., 2010). iii) The regions of SLRB and HHRB were not considered in previous SOC pool estimate. The organic carbon storages of 0.43±0.11 Pg in SLRB and 0.25±0.11 Pg in HHRB were added in the present study.

It is worth to mention that there were wide variations in organic carbon contents in permafrost regions 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). A possible explanation is the spatial heterogeneity of SOC contents in permafrost regions of the QXP. In addition, the different analytical methods may also contribute to the differences of carbon contents (Table 1). It has been demonstrated that if taking the dry combustion method as standard, the recovery of organic carbon was 99% for wet combustion and 77% for Walkley-Black (Kalembasa and Jenkinson, 1973; Nelson and Sommers, 1996).

The SOC stocks at 0~1 m depth (17.3 kg m^{-2}) in the alpine meadow on the QXP is higher than that in subarctic alpine permafrost (0.9 kg m^{-2}) (Fuchs et al., 2014), and similar with that of the lowland and hilly upland soils in North American Arctic region (55.1 kg m^{-2}, 40.6 kg m^{-2}) (Ping et al., 2008a). It implies that SOC of the alpine meadow in permafrost regions has a large proportion in permafrost carbon pools. The SOC contents at 0~1 m depth (3.9 ± 1.5 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). These results suggest that the SOC stocks are closely related to the vegetation type in the permafrost regions.

SOC decreases with the depth on the QXP (Fig. 4), which is in good agreement with those reported in circum-Arctic regions (Strauss et al., 2013; Zimov et al., 2006). This could be explained by the dynamics of Quaternary deposit and SOC formation in permafrost regions (Strauss et al., 2013). However, the organic carbon contents of deep layers in some sites (XSH, KL150 and KL300) were higher than those in the top layers (Fig. 4), which may be caused by the cryoturbation and sediment burying process (Ping et al., 2010), and Quaternary deposits following the uplift of Tibetan Plateau (Li et al., 1994; 2014). Overall, SOC decreases exponentially with depth (equation 1) in permafrost regions on the QXP, which is in agreement with results from other regions (Don et al., 2007). Certainly, more efforts are still needed in studying the distribution of deep organic carbon density in permafrost regions.

In the present study, it is the first time to study the deep organic carbon in permafrost regions, and quantify the carbon storage below 1.0 m depth on the QXP. The mean SOC content of 11 boreholes in permafrost regions on the QXP (2.5 wt%) was similar with that in the yedoma deposites (3.0 wt%) (Strauss et al., 2013), and that of lowland steppe-tundra soils in Siberia and Alaska (2.6 wt%) (Zimov et al., 2006). Since it has been pointed out that yedoma deposits contain a large amount of organic carbon, it would be reasonable to infer that deep soil carbon in permafrost regions on the QXP may also have a great contribution to carbon pools. Our estimations indicate that the soils on the QXP contains 33.0±13.2 Pg of organic carbon in the top 3.0 m of soils, with an additional 127.2±37.3 Pg C distributed in deep layers (3~25 m) of the Quaternary, Triassic and Permian stratigraphies in permafrost regions. In northern circumpolar permafrost region, 1024 Pg of organic carbon was in the 0~3 m depth and 648 Pg (39%) of carbon was stored in deep layers of yedoma and deltaic deposits (Tarnocai et al., 2009). The percentage of SOC storage in deep layers (3~25 m) on the QXP (80%) is much higher than that (39%) in the yedoma and thermokarst deposits in Siberia and Alaska. This could be explained as that the paleoenvironment of the QXP was wet and warm, or lacustrine sediment in most regions (Zhang et al., 2003; Lu et al., 2014), which always links to the well formation of soil organic matter (Kato et al., 2004; Piao et al., 2006; Chen et al., 1990).

In total, there is approximately 160±87 Pg of organic carbon stored at 0~25 m depth in permafrost regions on the QXP, which would update the total carbon pools to 1832 Pg in permafrost regions of northern hemisphere. The total carbon pools on the QXP permafrost regions account for approximately 8.7% of the total carbon pools in permafrost regions in northern hemisphere. Since the permafrost region on the QXP was about 6% of northern permafrost area (Ran et al., 2012), it could be seen that SOC in permafrost regions on the QXP should be paid more attention in the future studies.

5. Conclusions

(1) According to the organic carbon data in previous analysis and field exploration of deep boreholes in permafrost regions, the organic carbon storages in permafrost regions on the QXP were estimated to approximately 17.3±5.3 Pg in the 0~1 m, 10.6±2.7 Pg in the 1~2 m, 5.1±1.4 Pg in the 2~3 m and 127.2±37.3 Pg in deep depth of 3~25 m.

(2) The percentage of SOC storage in deep layers (3~25 m) of permafrost regions on the QXP was 80%, which was higher than that in the yedoma and thermokarst deposits in Siberia and Alaska.

(3) In total, organic carbon pools in permafrost regions on the QXP are approximately 160±87 Pg, of which 132±76 Pg occurs in permafrost layers. The total carbon pools in permafrost regions in northern hemisphere are now updated to 1832 Pg.

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References

Bockheim, J. B., Walker, D. A., Everett, L. R., Nelson, F. E., and Shikolmanov, N. I.: Soils and cryoturbation in moist nonacidic and acidic tundra in the Kuparuk river basin arctic Alaska, USA, Arct. Alp. Res., 30, 166–174, 1998.

Burke, E. J., Hartley, I. P., and Jones, C. D.: Uncertainties in the global temperature change caused by carbon release from permafrost thawing, The Cryosphere, 6(5), 1063–1076, 2012.

Editorial Board of Vegetation Map of China, Chinese Academy of Sciences, Vegetation Atlas of China (1:1 000 000), Beijing: Science Press, 2001.

Chen, K. Z., Bowler, J. M., and Kelts, K.: Palaeoclimate evolution within the Qinghai-Xizang (Tibet) plateau in the last 40000 years, Quaternary Sciences, 1, 22–30, 1990.

Cheng, G. D., and Wu, T. H.: Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau, Journal of Geophysical Research, 112, F02S03, DOI: 10.1029/2006JF000631, 2007.

Davidson, E. A., and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature, 440, 165–173, 2006.

Dorfer, C., Kuhn, P., Baumann, F., He, J. S., and Scholten, T.: Soil Organic Carbon Pools and Stocks in Permafrost-Affected Soils on the Tibetan Plateau, PLoS ONE, 8(2), e57024, doi:10.1371/journal.pone.0057024, 2013.

Don, A., Schumacher J., Scherer-Lorenzen, M., Scholten, T., and Schulze, E.D.: Spatial and vertical variation of soil carbon at two grassland sites — Implications for measuring soil carbon stocks, Geoderma, 141, 272–282, 2007.

Fang, X. M., Lu, L. Q., Mason, J. A., Yang, S. L., An, Z. S., Li, J. J., and Guo, Z. L.: Pedogenic response to millennial summer monsoon enhancements on the Tibetan Plateau, Quaternary International, 106–107, 79–88, 2003.

Fang, X. M., Lu, L. Q., Yang, S. L., Li, J. J., An, Z. S., Jiang, P.A., and Chen, X.L.: Loess in Kunlun Mountains and its implications on desert development and Tibetan Plateau uplift in west China, Science in China, 45, 291–298, 2002.

Fuchs, M., Kuhry, P., and Hugelius, G.: Low soil organic carbon storage in a subarctic alpine permafrost environment, The Cryosphere Discuss, 8, 3493–3524, 2014.

Hobbie, S. E., Schimel, J. P., Trumbore, S. E., and Randerson, I. R.: Controls over carbon storage and turnover in high-latitude soils, Glob. Change Biol., 6, 196–210, 2000.

Hu, G. L., Fang, H. B., Liu, G. M., Zhao, L., Wu, T. H., Li, R., and Wu, X. D.: Soil carbon and nitrogen in the active layers of the permafrost regions in the Three Rivers' Headstream, Environ. Earth. Sci, 72, 5113–5122, 2014.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D. K.: The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, Earth Syst. Sci. Data, 5, 3–13, 2013.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C. L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, 2014.

Jobbagy, E. G., and Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation, Ecological Applications, 10(2), 423–436, 2000.

Kalembasa, S. J., and Jenkinson, D. D.: A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil, Journal of the Science of Food and Agriculture, 24, 1085–1090, 1973.

Kato, T., Tang, Y., and Gu, S.: Carbon dioxide exchange between the atmosphere and an alpine meadow ecosystem on the Qinghai–Tibetan Plateau, China, Agric For Meteorol, 124, 121–34, 2004.

Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, P. Natl. Acad. Sci. USA, 108, 14769–14774, 2011.

Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Map of Snow, Ice and Frozen Ground in China (1:4,000,000). Cartographic Publishing House: Beijing, China (in Chinese), 1988.

Li, J. J., Zhang, Q. S., and Li, B. Y.: Main processes of geomorphology in China in the past fifteen years, Acta Geographical Sinica, 49, 642–648, 1997.

Li, J. J., Fang, X. M., Song, C. H., Pan, B. T., Ma, Y. Z., Yan, M. D.: Late Miocene–Quaternary rapid stepwise uplift of the NE Tibetan Plateau and its effects on climatic and environmental changes, Quaternary Research, 81, 400–423, 2014.

Li, X., Cheng, G. D., Jin, H. J., Kang, E. S., Che, T., Jin, R., Wu, L. Z., Nan, Z. T., Wang, J., and

Shen, Y. P.: Cryospheric Change in China, Global and Planetary Change, 62(3–4), 210–218, 2008.

Liu, W. J., Chen S. Y., Qin, X., Baumann, F., Scholten, T., Zhou, Z. Y., Sun, W. J., Zhang, T. Z., Ren, J. W., and Qin, D. H.: Storage, patterns, and control of soil organic carbon and nitrogen in the northeastern margin of the Qinghai–Tibetan Plateau, Environ. Res. Lett., 7, 1–12, 2012.

Lu, H. Y. and Guo, Z. T.: Evolution of the monsoon and dry climate in East Asia during late Cenozoic: A review, Science China Earth Science, 57, 70–79, 2014.

MacDougall, A. H., Avis, C. A., and Weaver, A. J.: Significant contribution to climate warming from the permafrost carbon feedback, *Nat. Geosci*., 5(10), 719–721, doi:10.1038/ngeo1573, 2012.

Michaelson, G. J., Ping, C. L., Clark, M.: Soil pedon carbon and nitrogen data for Alaska: An analysis and update, Open Journal of Soil Science, 3, 132–142, 2013.

Mu, C. C., Zhang, T. J., Wu, Q. B., Zhang, X. K., Cao, B., Wang, Q. F., Peng, X. Q., and Cheng, G. D.: Stable carbon isotopes as indicators for permafrost carbon vulnerability in upper reach of Heihe River basin, northwestern China, Quaternary International, 321, 71–77: 2014.

Mu, C. C., Zhang, T. J., Cao, B., Wan, X. D., Peng, X. Q., and Cheng, G. D.: Study of the organic carbon storage in the active layer of the permafrost over the Eboling Mountain in the upper reaches of the Heihe River in the Eastern Qilian Mountains, Journal of Glaciology and Geocryology, 35(1), 1–9, 2013.

Nelson, D. E., and Sommers, L. E.: Total carbon, organic carbon, and organic matter, Methods of soil analysis, Part 3 - chemical methods, 961–1010, 1996.

Ohtsuka, T., Hirota, M., Zhang, X., Shimono, A., Senga, Y., Du, M., Yonemura, S., Kawashima, S., and Tang, Y.: Soil organic carbon pools in alpine to nival zones along an altitudinal gradient (4400–5300 m) on the Tibetan Plateau, Polar Science, 2, 277–285, 2008.

Ping, C. L., Michaelson, G. J., Jorgenson, T., Kimble, J. M., Epstein, H., Romanovsky, V. E., and Walker, D. A.: High stocks of soil organic carbon in the North American arctic region, Nature Geosci., 1, 615–619, 2008a.

Ping, C. L., Michaelson, G. J., Kimble, J. M., Romanovsky, V. E., Shur, Y. L., Swanson, D. K., and Walker, D. A.: Cryogenesis and soil formation along a bioclimate gradient in Arctic North America, J. Geophys. Res., 113, G03S12, doi:10.1029/2008JG000744, 2008b.

Piao, S. L., Fang, J. Y., and He, J. S.: Variations in vegetation net primary production in the Qinghai–Xizang Plateau, China, from 1982 to 1999, Clim Chang, 74, 253–67, 2006.

Qiang, X. K., Li, Z. X., Powell, C. McA., and Zheng, H. B.: Magnetostratigraphic record of the Late Miocene onset of the East Asian monsoon, and Pliocene uplift of northern Tibet, Earth and Planetary Science Letters, 187, 83–93, 2001.

Ran, Y. H., Li, X., Cheng, G. D., Zhang, T. J., Wu, Q. B., Jin, H. J., and Jin, R.: Distribution of Permafrost in China: An Overview of Existing Permafrost Maps, Permafrost and Periglacial Processes, 23, 322–333, 2012.

Schneider von Deimling, T., Meinshausen, M., Levermann, A., Huber, V., Frieler, K., Lawrence, D. M., and Brovkin, V.: Estimating the near-surface permafrost-carbon feedback on global warming, Biogeosciences, 9(2), 649–665, doi:10.5194/bg-9-649-2012, 2012.

Schuur, E. A. G., Vogel, J. G., Crummer, K. Lee, G., H., Sickman, J. O., and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556–559, 2009.

Sheldrick, B. H.: Analytical Methods Manual, 212 pp., Land Resour. Res. Inst., Res. Branch, Agric. Can., Ottawa, 1984.

Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzschuh, U., and Hubberten, H. W.: The deep permafrost carbon pool of the yedoma region in Siberia and Alaska, Geophys. Res. Lett., 40, 6165–6170, doi:10.1002/2013GL058088, 2013.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem. Cycles, 23, GB2023, doi:10.1029/2008GB003327, 2009.

Wang, G. X., Qian, J., Cheng, G. D., and Lai, Y. M.: Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication, The Science of the Total Environment, 291, 207–217, 2002.

Waldrop, M. P., Wickland, K. P., White, R., Berhe, A. A., Harden, J. W., and Romanovsky, V. E.: Molecular investigations into a globally important carbon pool: permafrost-protected carbon in Alaskan soils, Global Change Biology, doi: 10.1111/j.1365-2486.2009.02141.x, 2010.

Wang, G., Li, Y., Wang, Y., and Wu, Q.: Effects of permafrost thawing on vegetation and soil carbon losses on the Qinghai-Tibet Plateau, China, Geoderma, 143, 143–152, 2008.

Wu, X. D., Zhao, L., Fang, H. B., Yue, G. Y., Chen, J., Pang, Q. Q., Wang, Z. W., and Ding, Y. J.: Soil Organic Carbon and Its Relationship to Vegetation Communities and Soil Properties in Permafrost of Middle-western Qinghai-Tibet Plateau, Permafrost and Periglacial Process, 23, 162–169, 2012.

Wu, X. D., Fang, H. B., Zhao, L., Wu, T. H., Li, R., Ren, Z. W., Pang, Q. Q., and Ding, Y. J.: Mineralization and Fractions Changes in Soil Organic Matter in Soils of Permafrost Region in

Qinghai-Tibet Plateau, Permafrost and Periglacial Processes, DOI:10.1002/ppp.1796, 2014.

Wu, Q., Hou, Y., Yun, H., Liu, Y. Changes in active-layer thickness and near-surface permafrost between 2002 and 2012 in alpine ecosystems, Qinghai–Xizang (Tibet) Plateau, China. Global and Planetary Change, 124, 149–155, 2015.

Wu, Q. B., and Zhang, T. J.: Changes in active layer thickness over the Qinghai-Tibetan Plateau from 1995 to 2007, Journal of Geophysical Research, 115, D09107, doi:10.1029/2009JD012974, 2010.

Wu, Q. B., and Zhang, T. J.: Recent permafrost warming on the Qinghai-Tibetan Plateau, Journal of Geophysical Research, 113, D13108, doi:10.1029/2007JD009539, 2008.

Yang, Y. H., Fang, J. Y., Tang, Y. H., Ji, C. J., Zheng, C. Y., He, J. S., and Zhu, B.: Storage, patterns and controls of soil organic carbon in the Tibetan grasslands, Global Change Biology, 14, 1592–1599, 2008.

Yang, M., Nelson, F. E., Shiklomanov, N. I., Guo, D., and Wan, G.: Permafrost degradation and its environmental effects on the Tibetan Plateau: A review of recent research, Earth-Science Reviews, 103 (1–2), 31–44, 2010.

Zimov, N. S., Zimov, S. A., Zimova, A. E., Zimova, G. M., Chuprynin, V. I., and Chapin III, F. S.: Carbon storage in permafrost and soils of the mammoth tundra-steppe biome: Role in the global carbon budget, Geophys. Res. Lett., 36, L02502, doi:10.1029/2008GL036332, 2009.

Zimov, S. A., Schuur, E. A. G., and Chapin, F. S.: Permafrost and the global carbon budget, Science, 312, 1612–3, 2006.

Zhang, Q. B., Cheng, G. D., Yao, T. D., Kang, X. C., and Huang, J. G.: A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau, Geophysical Research

Letter, 30, doi:10.1029/2003GL017425, 2003.

Zhao, L., Wu, Q. B., Marchenko, S. S., Sharkhuu, N.: Thermal state of permafrost and active layer in Central Asia during the international polar year, Permafrost and Periglacial Processes, 21(2), 198–207, 2010.

Supplement

Dataset of the geographic location for 11 boreholes on the Qinghai-Xizang (Tibetan) Plateau, together with the active layer depth, sampling depth, vegetation type, geological stratigraphies, soil organic carbon (SOC) contents, bulk density, water contents and soil texture.

Table captions

Table 1 Organic carbon pools in the 0~1 m depth with different vegetation type on the QXP

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

Figure captions

Figure 1 Location of sampling sites on the QXP, shown on the background of QXP permafrost distribution (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 Location of sampling sites on the QXP, shown on the background of QXP vegetation atlas at a scale of 1:400 0000 (Chinese Academy of Sciences, 2001) (Sampling sites were same with those shown on the background of permafrost distribution)

Figure 3 Location of sampling sites on the QXP, shown on the background of QXP Quaternary geological map (Sampling sites were same with those shown on the background of permafrost distribution).

Figure 4 Distributions of soil organic carbon contents in deep soils in permafrost regions on the QXP.

Table 1 Organic carbon pools in the 0~1 m depth with different vegetation type on the QXP

Vegetation types	References	Analytical methods	Study area	Site data (n)	Area ($\times 10^6$ km^2)	SOC stock ($kg\ m^{-2}$)	SOC storage (Pg)
Alpine meadow	Yang et al., (2010)	Wet oxidation	QXP	22	0.224	9.3 ±3.9	10.7 ±3.8
	Ohtsuka et al., (2008)	Heat combusion	QXP	1		13.7	
	Dorfer et al., (2013)	Heat combusion	QXP	2		10.4	
	Mu et al., (2013)	Heat combusion	HHRB	11	0.0065	39.0 ±17.5	0.3 ±0.1
	Liu et al., (2012)	Wet oxidation	SLRB	~42	0.013	8.7 ±1.2	0.1 ±0.02
Alpine steppe	Yang et al., (2010)	Wet oxidation	QXP	33	0.772	3.7 ±2.0	5.3 ±2.8
	Wu et al,, (2012)	Wet oxidation	Western QXP	52		7.7 ±3.2	
	Liu et al., (2012)	Wet oxidation	SLRB	~42		9.2 ±1.1	
Alpine desert	Wu et al., (2012)	Wet oxidation	Western QXP	25	0.175	3.3 ±1.5	0.7 ±0.3
	Liu et al., (2012)	Wet oxidation	SLRB	~42		4.4 ±0.7	

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

Vegetation types	**Alpine meadow**			**Alpine steppe**		**Alpine desert**		
Soil depth (m)	SOC (kg m^{-2})	SOC storage (Pg)		SOC (kg m^{-2})	SOC storage (Pg)	SOC (kg m^{-2})	SOC storage (Pg)	Total (Pg)
		QTP	HHRB					
0~1 m	~	11.0±3.9	0.3±0.1	6.9±3.6	5.3±2.8	3.8±1.5	0.7±0.3	17.3±5.3
1~2 m	16.7±4.7	4.9±1.4	0.2±0.1	6.5 ±2.2	5.0±1.7	3.0±1.3	0.5±0.2	10.6±2.7
Total (Pg)		16.4±5.2			10.3±2.7		1.2±0.3	27.9±6.2
Geological stratigraphies	**Quaternary**			**Triassic**		**Permian**		
Soil depth (m)	SOC (kg m^{-2})	SOC storage (Pg)		SOC (kg m^{-2})	SOC storage (Pg)	SOC (kg m^{-2})	SOC storage (Pg)	Total (Pg)
		QTP	HHRB					
2~3 m	9.8±8.4	1.9±1.6	0.1±0.06	9.6±4.5	2.3±1.1	5.6±0.9	0.8±0.1	5.1±1.4
3~25 m	134.9±115.3	26.2±22.4	2.3±1.4	281.9±191.7	67.1±45.6	234.2±86.0	31.6±11.6	127.2±37.3
Total (Pg)		30.5±16.6			69.4±52.8		32.4±20.2	132.3±76.8

Figure 1

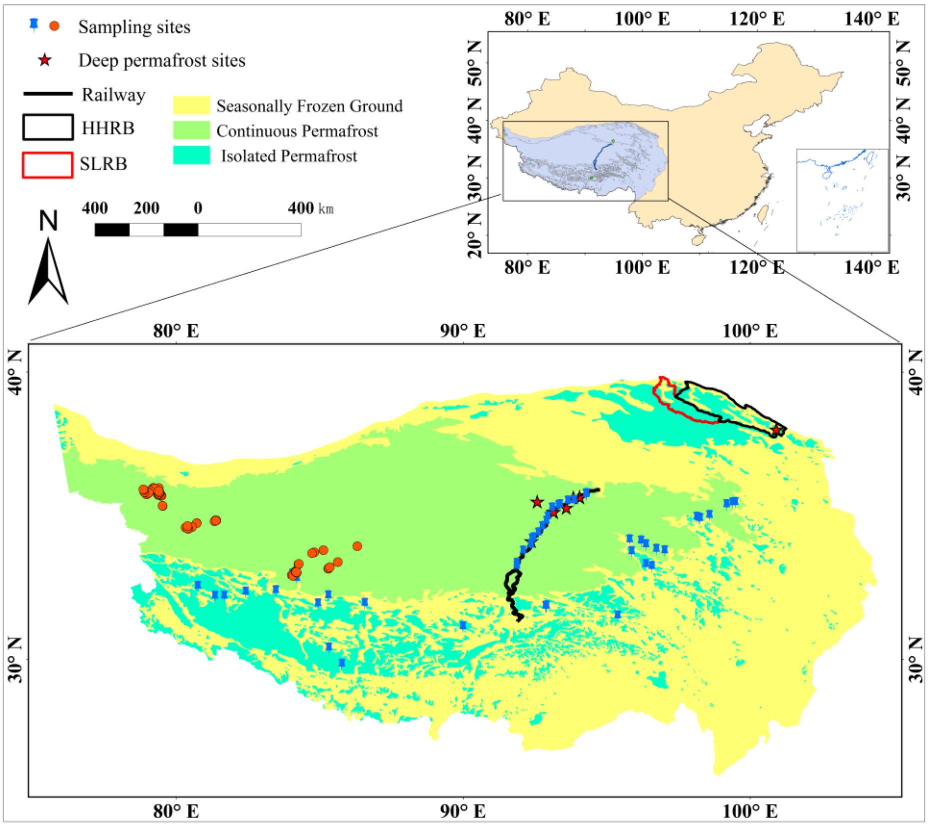

Figure 2

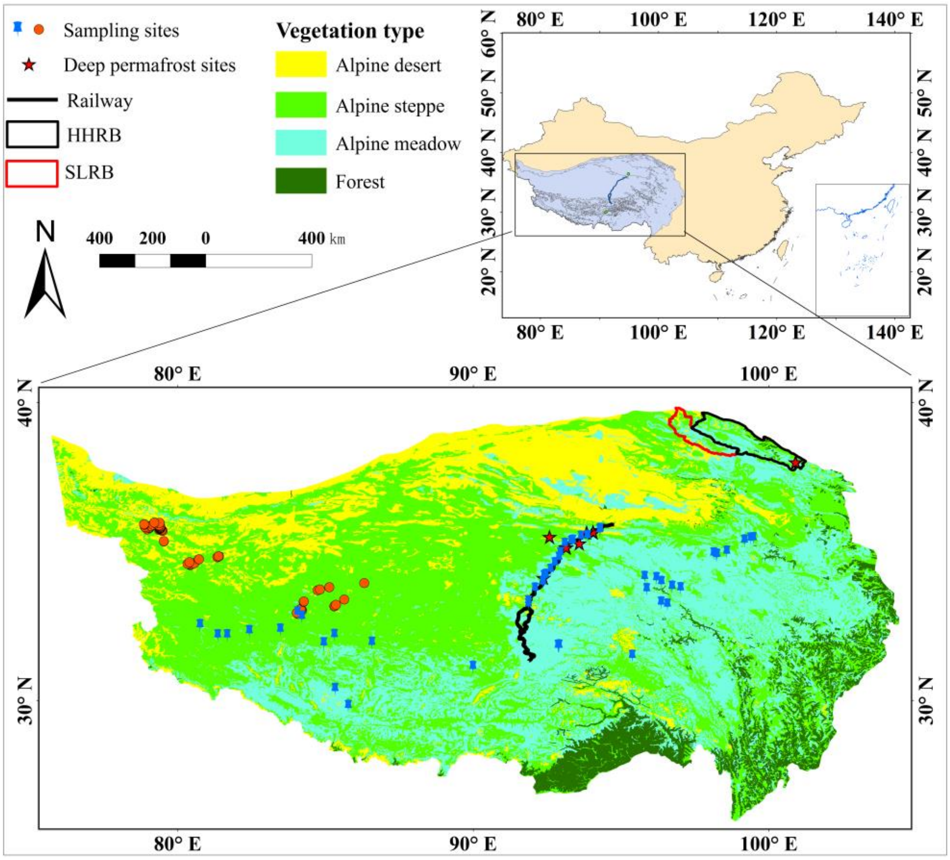

Figure 3

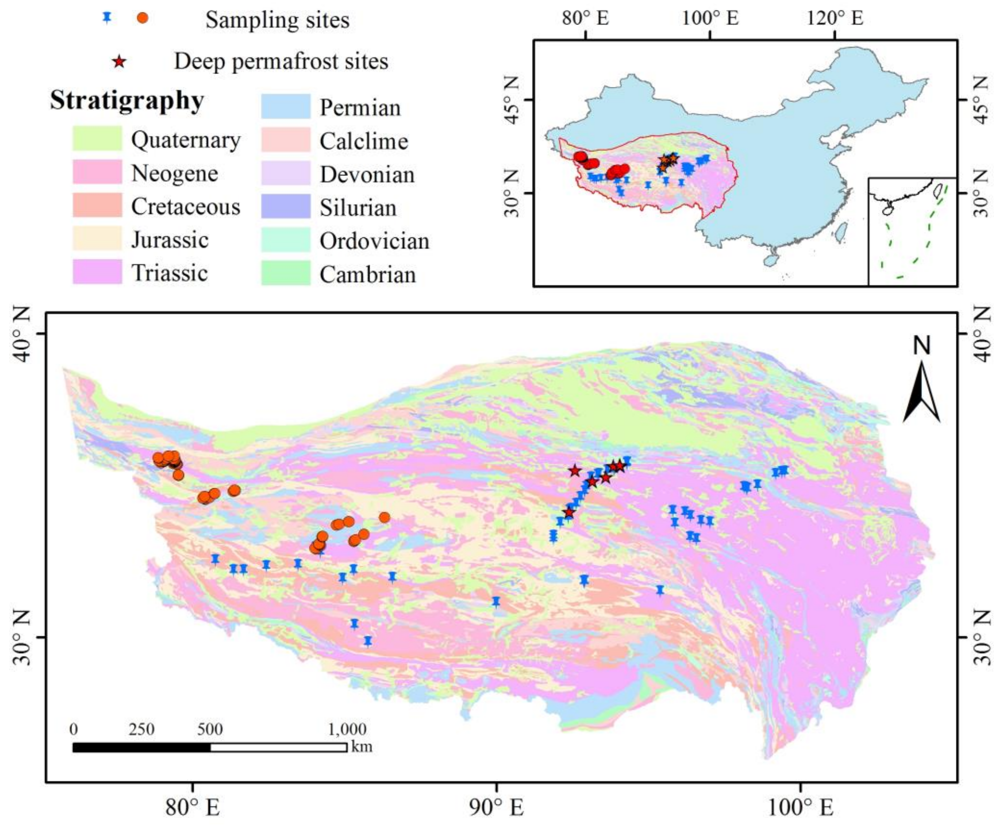

Figure 4