Storage, patterns and controls of soil organic carbon in the Tibetan grasslands

YUANHE YANG*, JINGYUN FANG*, YANHONG TANG†, CHENGJUN JI*, CHENGYANG ZHENG*, JINSHENG HE* and BIAO ZHU‡

*Department of Ecology, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China, †National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8569, Japan, ‡Department of Environmental Studies, University of California, Santa Cruz, CA 95064, USA

Abstract

The soils of the Qinghai-Tibetan Plateau store a large amount of organic carbon, but the magnitude, spatial patterns and environmental controls of the storage are little investigated. In this study, using data of soil organic carbon (SOC) in 405 profiles collected from 135 sites across the plateau and a satellite-based dataset of enhanced vegetation index (EVI) during 2001–2004, we estimated storage and spatial patterns of SOC in the alpine grasslands. We also explored the relationships between SOC density (soil carbon storage per area) and climatic variables and soil texture. Our results indicated that SOC storage in the top 1 m in the alpine grasslands was estimated at 7.4 Pg C ($1 \, \mathrm{Pg} = 10^{15} \, \mathrm{g}$), with an average density of $6.5 \, \mathrm{kg \, m^{-2}}$. The density of SOC decreased from the southeastern to the northwestern areas, corresponding to the precipitation gradient. The SOC density increased significantly with soil moisture, clay and silt content, but weakly with mean annual temperature. These variables could together explain about 72% of total variation in SOC density, of which 54% was attributed to soil moisture, suggesting a key role of soil moisture in shaping spatial patterns of SOC density in the alpine grasslands.

Keywords: alpine grasslands, enhanced vegetation index, mean annual temperature, Qinghai-Tibetan Plateau, soil moisture, soil organic carbon, soil texture

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Introduction

Soil is the largest organic carbon (C) reservoir in the terrestrial biosphere, about two times larger than that of vegetation or the atmosphere (Schlesinger, 1997). Even a minor change in soil organic carbon (SOC) storage could result in a significant alteration in atmospheric CO_2 concentration (Johnston *et al.*, 2004; Bellamy *et al.*, 2005; Davidson & Janssens, 2006; Schipper *et al.*, 2007). Therefore, accurate estimation of SOC storage and its distribution is critical for predicting feedbacks of soil C to global environmental change (Post *et al.*, 1982; Jobbágy & Jackson, 2000; Callesen *et al.*, 2003; Wynn *et al.*, 2006).

The SOC storage in high-altitude ecosystems is of special interest because of the high C density (soil C storage per area) (Davidson & Janssens, 2006) and potential feedbacks to climate warming (Goulden *et al.*, 1998; Mack *et al.*, 2004; Zimov *et al.*, 2006). However, the storage and spatial patterns of SOC in high-altitude

ecosystems remain largely uncertain, due to insufficient field observations and large spatial heterogeneity (Jobbágy & Jackson, 2000; Garnett *et al.*, 2001; Liu *et al.*, 2006; Yang *et al.*, 2007). Furthermore, how environmental factors affect SOC storage and its distribution is also poorly understood for the cold regions (Hobbie *et al.*, 2000). Extensive field soil survey and appropriate scaling-up approaches are expected to improve assessments of SOC storage, particularly for these remote, high-altitude areas. A number of studies have showed that plant production is a major C input to soil in arid and semi-arid ecosystems (Jobbágy & Jackson, 2000; Austin, 2002; Epstein *et al.*, 2002) and a strong allometric relationship exists between above and belowground C (Enquist & Niklas, 2002). This suggests that the satellite data, which have been widely used to estimate vegetation biomass or production (e.g. Paruelo *et al.*, 1997; Myneni *et al.*, 2001; Fang *et al.*, 2003; Piao *et al.*, 2007), may be applicable for scaling site-level measurements to regional estimation of SOC storage.

The Qinghai-Tibetan Plateau is the highest and largest plateau on the earth, with a mean elevation of $\sim 4000 \, \mathrm{m}$

Correspondence: Jingyun Fang, tel. +86 10 6276 5578, fax +86 10 6275 6560, e-mail: jyfang@urban.pku.edu.cn

and an area of $\sim 2.0 \times 10^6 \, \text{km}^2$, about 1.4 times the size of Alaska (Li & Zhou, 1998). The alpine grasslands (alpine steppe and alpine meadow) are the most dominant ecosystems on the plateau, occupying over 60% of the total area, with mean annual temperature (MAT) of 1.61 °C and annual precipitation of 413.6 mm (Li & Zhou, 1998). The unique climate and vegetation types, together with a low intensity of human disturbance, make the plateau an ideal region for investigating spatial patterns and environmental controls of SOC storage in high-altitude ecosystems. In this study, we conducted four field sampling campaigns during the summers (July and August) of 2001–2004 to measure SOC at the depth of 1 m for the alpine grasslands on the plateau. We then established the relationship between SOC density and satellite-based enhanced vegetation index (EVI) to estimate their storage and spatial distribution, and examined how environmental factors affect the spatial pattern of SOC density.

Materials and methods

Soil and biomass survey

In order to estimate storage and patterns of SOC in alpine grasslands, we sampled 405 soil profiles from 135 sites (i.e. three soil profiles at each site) on the Qinghai-Tibetan Plateau during the summers (July and August) of 2001–2004 (Fig. 1a). Because of bad weather and inaccessibility of traffic, the samplings were conducted along all the major roads which covered all major climate zones and grassland types across the plateau. At each sampling site, three soil pits were excavated to collect samples for analyses of physical and chemical properties. For each pit, soil samples were collected at depths of 0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm. Bulk density samples were obtained for each layer using a standard container with $100 \, \text{cm}^3$ in volume (50.46 mm in diameter and 50 mm in height) and weighed to the nearest 0.1 g. Soil moisture was measured gravimetrically after 24 h desiccation at 105 °C. Bulk density was calculated as the ratio of the oven-dry soil mass to the container volume. Soil samples for C analysis were air-dried, sieved (2 mm mesh), handpicked to remove fine roots, and then ground in a ball mill. SOC was measured using the wet oxidation method (Nelson & Sommers, 1982). Soil texture was determined by a particle size analyzer (Malvern Masterizer 2000, Malvern, Worcestershire, UK) after removal of organic matter and calcium carbonates. Additionally, all plants in five plots ($1 \times 1 \, \text{m}^2$) at
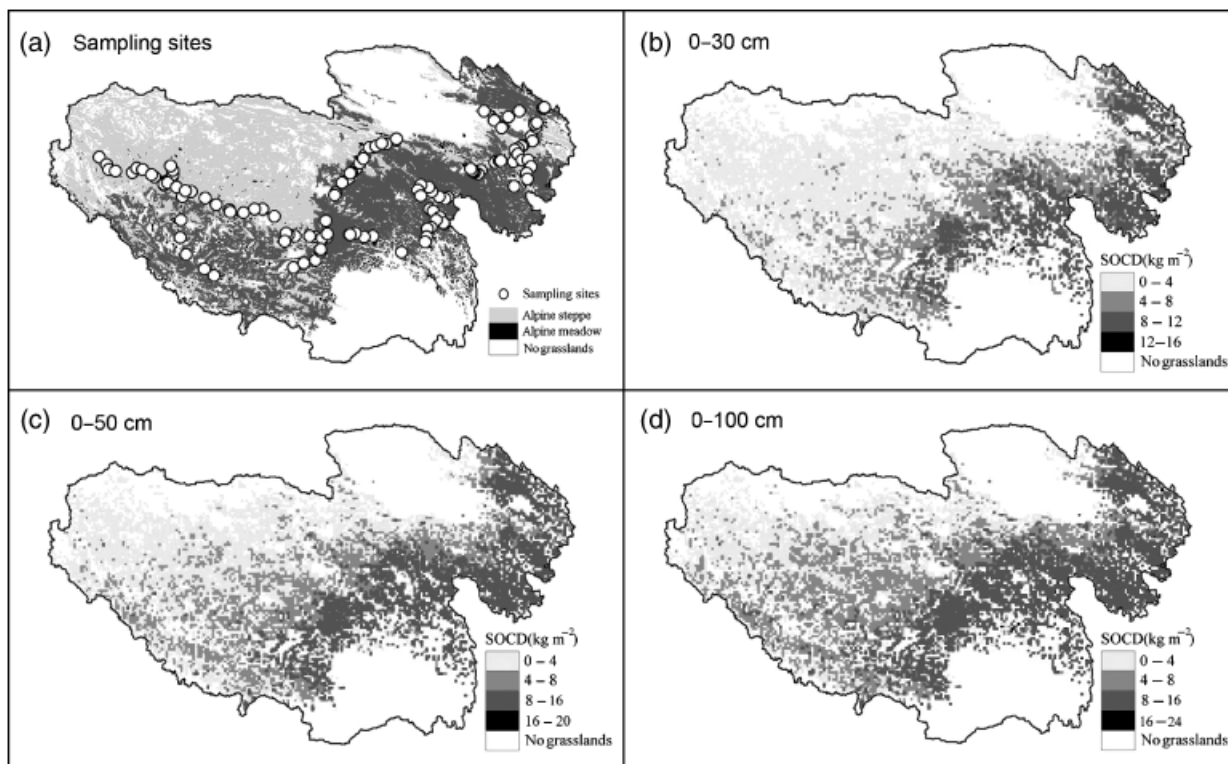
Fig. 1 Spatial distribution of (a) sampling sites and (b–d) soil organic carbon (SOC) density for different depths (30, 50, and 100 cm) in alpine grasslands on the Qinghai-Tibetan Plateau. A vegetation map of the plateau was obtained from China's vegetation atlas with a scale of 1 : 1 000 000 (Chinese Academy of Sciences, 2001), showing locations of 135 sites surveyed during 2001–2004. Spatial patterns of SOC density were estimated from MODIS–EVI data at a resolution of $0.1° \times 0.1°$.

each site were harvested to measure aboveground biomass (AGB). Biomass samples were oven-dried at 65 °C to a constant weight, and weighed to the nearest 0.1 g. AGB and SOC density for all 135 sites were listed in Appendix S1, together with their location and environmental variables.

MODIS–EVI and climate data

We obtained the moderate resolution imaging spectroradiometer (MODIS)–EVI data from the United States Geological Survey (USGS), with a spatial resolution at $500 \times 500 \, \text{m}^2$ for every 16-day interval, over the period of 2001–2004 (http://LPDAAC.usgs.gov). We then developed the monthly composites from the original EVI data using the Maximum Value Composition (MVC) method proposed by Holben (1986). The growing season's EVI data were the average of monthly EVI from May to September, which were then aggregated to grid cells of $0.1° \times 0.1°$ (Piao *et al.*, 2003).

MAT data at $0.1° \times 0.1°$ resolution were compiled from the climate database of Qinghai-Tibetan Plateau during 2001–2004. These data were spatially interpolated from the records of 43 climatic stations located above an elevation of 3000 m across the plateau (Piao *et al.*, 2003).

SOC estimation

We calculated SOC density for each soil profile using Eqn (1). We then established the site-level relationship between SOC density and MODIS–EVI for different depth intervals [Fig. 2c; Eqns (2)–(4) for 30, 50, and 100 cm, respectively].

$$\text{SOCD} = \sum_{i=1}^{n} T_i \times \text{BD}_i \times \text{SOC}_i \times \frac{(1 - C_i)}{100}, \qquad (1)$$

For 0-30 cm in depth: $\text{SOCD} = 26.515 \, \text{EVI} - 0.247$
$$(r^2 = 0.66, \ P < 0.001), \qquad (2)$$

For 0-50 cm in depth: $\text{SOCD} = 33.11 \, \text{EVI} - 0.319$
$$(r^2 = 0.60, \ P < 0.001), \qquad (3)$$

For 0-100 cm in depth: $\text{SOCD} = 40.589 \, \text{EVI} - 0.523$
$$(r^2 = 0.50, \ P < 0.001), \qquad (4)$$

where SOCD, T_i, BD_i, SOC_i, and C_i are SOC density (kg m^{-2}), soil thickness (cm), bulk density (g cm^{-3}), SOC (g kg^{-1}), and volume percentage of the fraction >2 mm at layer i, respectively.

We further estimated SOC density from EVI using the regression equation [Eqns (2)–(4)] for each pixel and obtained spatial distributions of SOC density for different depths of soil (Fig. 1b–d). Finally, we digitized the $1:1\,000\,000$ vegetation map of the Qinghai-Tibetan
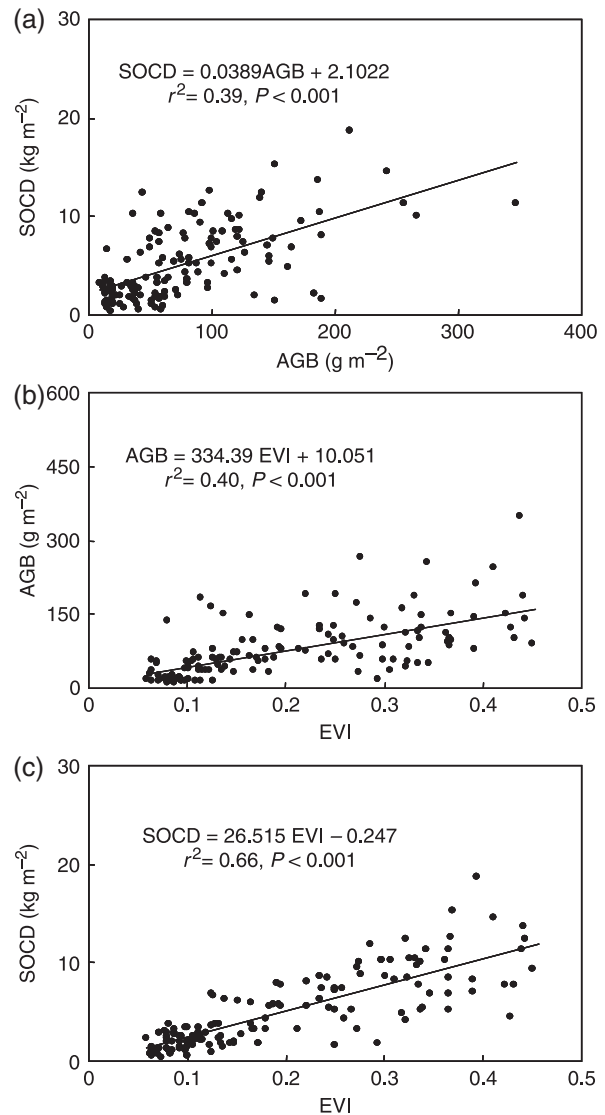

Fig. 2 Relationships between SOC density (SOCD) in the top 30 cm, aboveground biomass (AGB), and enhanced vegetation index (EVI) during 2001–2004: (a) SOCD vs. AGB, (b) AGB vs. EVI, (c) SOCD vs. EVI.

Plateau (Chinese Academy of Sciences, 2001) and overlapped the vegetation map over the spatial distribution of SOC density to obtain SOC density for alpine steppe and alpine meadow, respectively.

Statistical analysis

Ordinary least squares (OLS) regression analyses were conducted to evaluate the relationships between SOC density and MAT, soil moisture, and soil texture. A general linear model (GLM) was used to assess integrative effects of MAT, soil moisture, and soil texture on the SOC spatial distribution. All analyses were performed using the software package R (R Development Core Team, 2005).
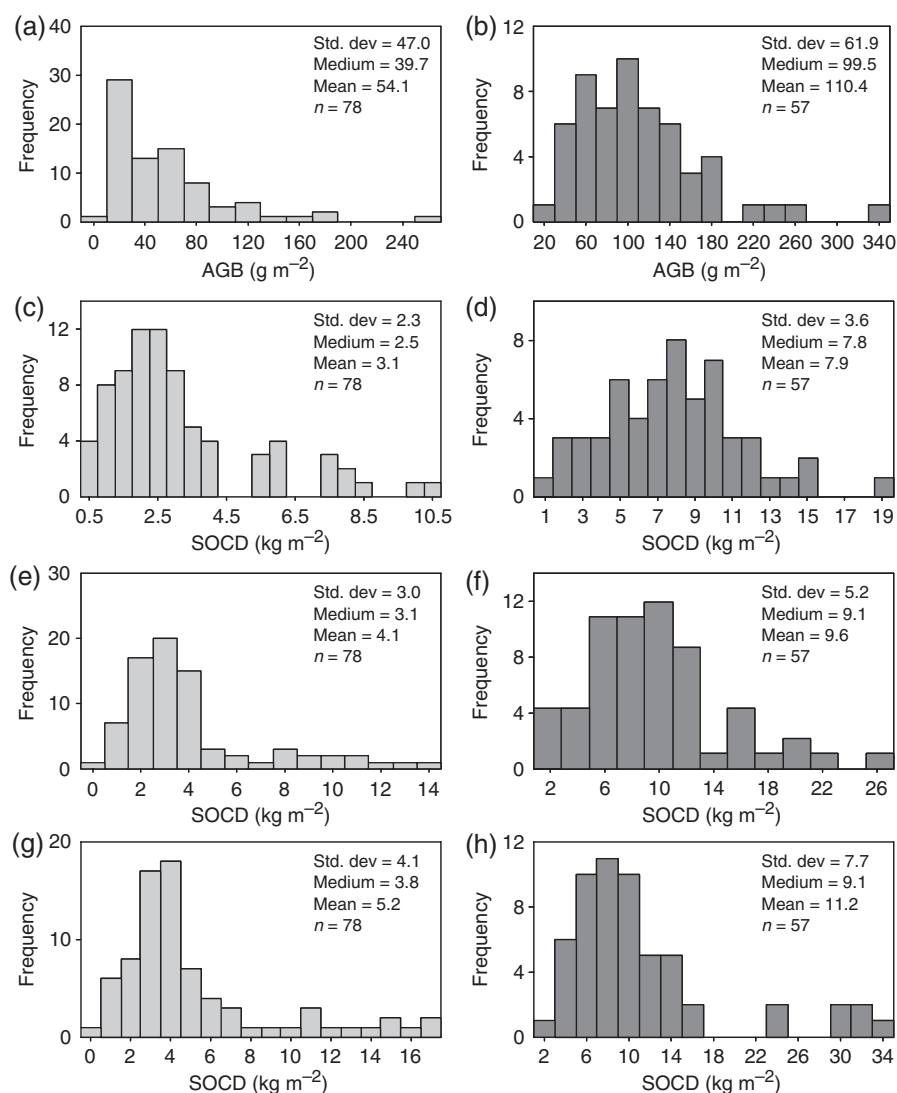
Fig. 3 Frequency distributions of aboveground biomass (AGB) and SOC density (SOCD) for different soil depths for alpine steppe (left, grey panels) and alpine meadow (right, black panels): (a–b) AGB, (c–d) SOCD for 0–30 cm, (e–f) SOCD for 0–50 cm, (g–h) SOCD for 0–100 cm.

Results

Storage and distribution of SOC

AGB varied markedly across 135 sampling sites (Fig. 3a and b). AGB for alpine steppe ranged from 9.8 to 267.4 g m^{-2}, while that for alpine meadow varied from 15.8 to 347.5 g m^{-2}. SOC density in alpine steppe and meadow also exhibited large variations, ranging 0.39–10.45 kg m^{-2} and 0.93–18.60 kg m^{-2} for 30 cm in depth, 0.39–13.59 kg m^{-2} and 1.26–25.83 kg m^{-2} for 50 cm, and 0.39–17.27 kg m^{-2} and 1.32–34.64 kg m^{-2} for 100 cm, respectively (Fig. 3c–h). Mean SOC density of all sites in alpine steppe and meadow for the three soil depths (30, 50, and 100 cm) were 3.1 and 7.9 kg m^{-2}, 4.1 and 9.6 kg m^{-2}, and 5.2 and 11.2 kg m^{-2}, respectively.

Spatially, SOC density decreased from the southeastern part to the northwestern areas (Fig. 1b–d).

AGB in alpine meadow (110.4 g m^{-2}) was larger than that in alpine steppe (54.1 g m^{-2}) (Table 1). Similarly, SOC density for the top 100 cm in alpine meadow (9.05 kg m^{-2}) was higher than that in alpine steppe (4.38 kg m^{-2}). Total SOC storage in 1 m in the alpine grasslands was estimated at 7.36 Pg C, with an overall average density of 6.52 kg m^{-2}. SOC in the upper 30 cm accounted for about 68% of total SOC in the 1 m top soil.

Effects of climatic variables and soil texture on SOC

SOC density in the top 30 cm showed a slight but significant increase with MAT ($r^2 = 0.10$, $P < 0.05$)

Table 1 Aboveground biomass (AGB) and soil organic carbon (SOC) storage for alpine steppe and meadow on the Qinghai-Tibetan Plateau

Grassland type	Area (10^4 km^2)	AGB (g m^{-2})	SOC density (kg m^{-2})			SOC storage (Pg)		
			30 cm	50 cm	100 cm	30 cm	50 cm	100 cm
Alpine steppe	61.08	54.1	2.94	3.67	4.38	1.80	2.24	2.68
Alpine meadow	51.74	110.4	6.17	7.51	9.05	3.19	3.89	4.68
Total	112.82	79.9	4.42	5.43	6.52	4.99	6.13	7.36
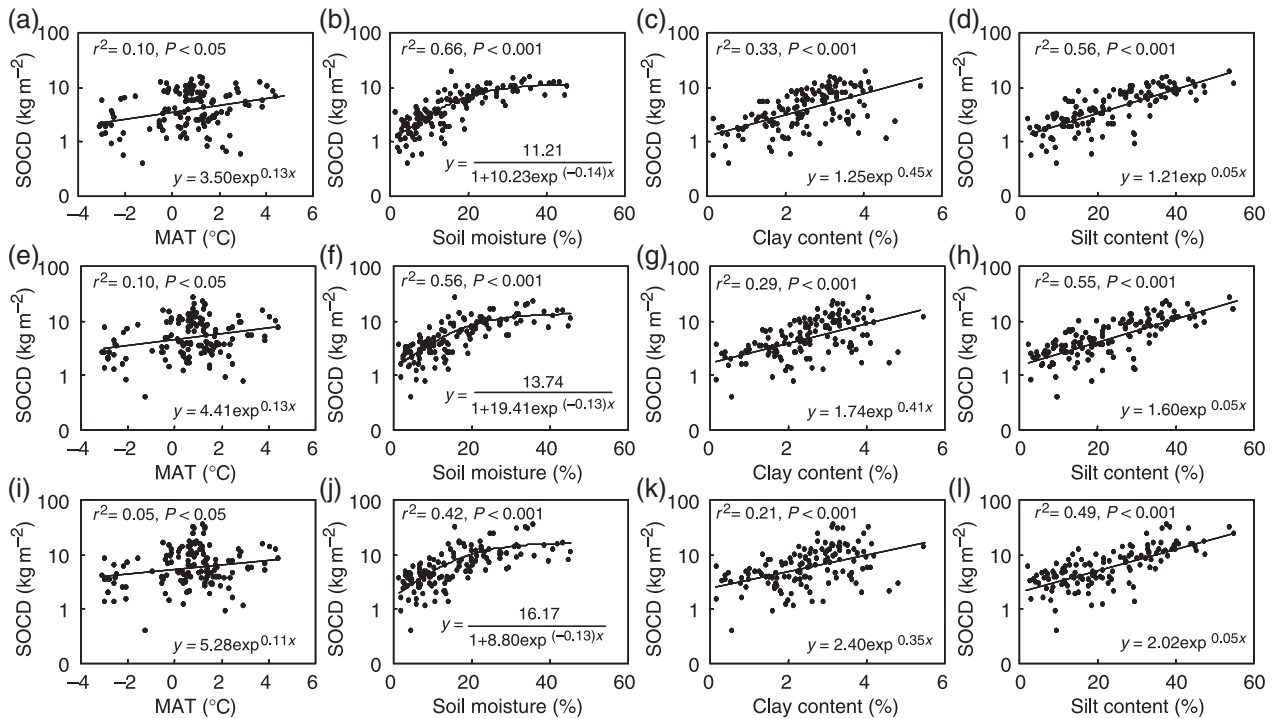
Fig. 4 Relationships between SOC density (SOCD) and environmental factors for different depths in alpine grasslands on the Qinghai-Tibetan Plateau: (a–d) 0–30 cm, (e–h) 0–50 cm, (i–l) 0–100 cm.

(Fig. 4a). SOC density also increased with an increase in soil moisture up to ~30%, and then leveled off (Fig. 4b). The relationship between SOC density and soil moisture was well characterized by a logistic function of $SOCD = 11.21/[1 + 10.23 \exp^{(-0.14 \times moisture)}]$ ($r^2 = 0.66$, $P < 0.001$). In addition, SOC density was positively correlated with both clay and silt content ($r^2 = 0.33$, $P < 0.001$ for clay content; $r^2 = 0.56$, $P < 0.001$ for silt content) (Fig. 4c and d). Similar relationships between SOC density and environmental factors were also observed for other soil depths (50 and 100 cm) (Fig. 4e–l).

A GLM suggested that environmental variables (MAT, soil moisture, clay content, and silt content) explained 72.1% of the overall variation of SOC density

in the top 30 cm (Table 2). The best-fit model of the GLM analysis could be expressed as Eqn (5).

$$\log(SOCD_{30}) = 0.015 \times MAT + 0.034 \times Moisture \\ + 0.051 \times Clay + 0.013 \times Silt \\ - 0.005 \times Moisture \times Clay - 0.001 \\ \times Moisture \times Silt - 0.135. \quad (5)$$

Of the variables examined, soil moisture explained the largest proportion (~53.5%) of the SOC variation. Soil texture explained about 9.6% of the variation, and interactions of soil moisture with clay and silt content could further explain another 2.2%.

Table 2 Summary of the results obtained from a general linear model (GLM), showing the integrative effects of mean annual temperature (MAT), soil moisture, and soil texture on soil organic carbon (SOC) density in the top 30 cm

Source	df	Parameters	SE	MS	SS (%)
MAT	1	0.015	0.011	1.15***	6.71
Moisture	1	0.034	0.006	9.16***	53.54
Clay	1	0.051	0.043	0.47***	2.78
Silt	1	0.013	0.005	1.16***	6.81
Moisture × Clay	1	−0.005	0.003	0.38***	2.24
Moisture × Silt	1	−0.001	0.000	0.01	0.01
Residuals	128			0.04	27.91

$***P < 0.001$.

df, degree of freedom; SE, standard errors; MS, mean squares; SS, proportion of variances explained by the variable.

SOC density was $\log_{10}$-transformed before analysis.

The parameters of the best-fit GLM model and their standard errors (SE) were also presented.

Discussion

Satellite-derived SOC estimates

In the present study, we used satellite data to estimate SOC storage in the alpine grasslands, which may reduce the uncertainties resulted from soil spatial heterogeneity. We first examined the relationship between SOC density and AGB using the measurements from 135 sites across the study region. A significant and positive linear relationship ($r^2 = 0.39$, $P < 0.001$; Fig. 2a) between the two variables suggests that C inputs to soil through plant production largely determine SOC density in the alpine grasslands (e.g. Burke et al., 1989; Austin, 2002; Epstein et al., 2002; Wynn et al., 2006). Then, we found that the growing season's EVI derived from MODIS dataset was closely correlated with AGB in the alpine grasslands ($r^2 = 0.40$, $P < 0.001$; Fig. 2b). Further, our results indicated that SOC density was strongly correlated with EVI ($r^2 = 0.66$, $P < 0.001$; Fig. 2c), which provided a base for the satellite-derived SOC estimation in this study. Although we successfully estimated SOC density for the alpine grasslands using EVI data, we must emphasize that the approach could only be applicable for the ecosystems in which plant production determines the spatial distribution of SOC, and that it should be cautious when applying this approach to other regions.

Wu et al. (2003) estimated China's total SOC storage using data from the second national soil survey. In their analysis, SOC density for the alpine meadow and steppe was estimated at 9.47 and 7.48 kg m^{-2}, respectively, which were higher than ours in this study (9.05

and 4.38 kg m^{-2}). The differences were possibly due to very limited number of soil profiles from the Tibetan Plateau in the national soil survey used by Wu et al. (2003). Although soil profiles used in our study were more intensive than those in the previous estimates, some uncertainties still existed in our estimate. Firstly, the established relationships for generating spatial patterns of SOC storage could have a potential uncertainty because most soil profiles were surveyed from the mid-latitude areas of the plateau due to the adverse weather condition and inaccessibility. Secondly, although MODIS–EVI could predict about 70% variances of SOC density, remaining residuals probably introduced some uncertainties into the regional estimation.

Relationship between SOC density and temperature

Temperature is an important variable affecting SOC density (Schimel et al., 1994; Jobbágy & Jackson, 2000; Callesen et al., 2003). SOC density decreases with increasing temperature as a result of accelerated decomposition (Burke et al., 1989; Schimel et al., 1994; Jobbágy & Jackson, 2000). Our data indicate that SOC density in the alpine grasslands increases significantly with temperature, in accordance with an exponential function of MAT. Although this finding conflicts with the global trend (Schimel et al., 1994), it is consistent with studies from the high-latitude regions (e.g. Callesen et al., 2003). According to our data, a 1 °C increase in MAT could lead to a 13.9% increase in SOC density on the plateau, compared with a 3.3% decrease in SOC density at the global scale (Schimel et al., 1994).

Increased SOC could be caused either by increasing plant production or by decreasing soil decomposition (Jobbágy & Jackson, 2000; Davidson & Janssens, 2006). In the alpine grasslands on the plateau, temperature is a limiting factor for vegetation growth and thus higher temperature may stimulate vegetation productivity (Piao et al., 2006). The resulting increase in C inputs may override the temperature-induced rising in soil decomposition rate, and consequently SOC density tends to increase. This suggests that biophysical processes which control SOC accumulation in cold regions (such as in the alpine grasslands on the Qinghai-Tibetan Plateau) may differ from those in other regions (Hobbie et al., 2000).

Relationship between SOC density and soil moisture

In general, precipitation could stimulate plant production and thus contribute to the accumulation of SOC in a water-limiting area (Jobbágy & Jackson, 2000; Callesen et al., 2003; Wynn et al., 2006). In our study, a significant logistic relationship ($r^2 = 0.66$, $P < 0.001$; Fig. 4b) is

found between SOC density and soil moisture. This suggests that SOC density increases with soil moisture content up to ~30%, and then approaches a constant. According to the relationship (Fig. 4b), SOC density exhibits a maximum increase rate at approximately 16.6% of soil moisture, and reaches a maximum value of 11.2 kg m^{-2}. The slight change in SOC density under moist soil conditions (>30% of soil moisture) is likely because other growth-limiting factors may constrain SOC density in the alpine grasslands, such as temperature and nitrogen availability (Kato *et al.*, 2006; Zhao *et al.*, 2006). A similar relationship between SOC density and soil moisture has also been observed in temperate regions, such as in the Great Plains of the United States (Burke *et al.*, 1989) and Australia (Wynn *et al.*, 2006), implying that water availability may be a powerful variable for predicting SOC density across broad biogeographic regions.

Effect of soil texture on SOC density

Soil texture significantly influences SOC storage at the local scale (Brady & Weil, 2004; Wynn *et al.*, 2006), mainly by two ways. Firstly, increasing clay and silt content reduces microbial decomposition through stabilizing SOC and decreasing C leaching and thus leads to an accumulation of SOC (Schimel *et al.*, 1994; Torn *et al.*, 1997; Jobbágy & Jackson, 2000; Wynn *et al.*, 2006). Secondly, increasing clay and silt content stimulates plant production via increasing water holding capacity and thus increases C inputs to soil (Schimel & Parton, 1986; Burke *et al.*, 1989; Schimel *et al.*, 1994). In this study, soil texture alone explained 9.6% of the spatial variance in SOC density. Moreover, it co-affects soil C stock together with soil moisture. The interaction of these two variables accounted for 2.2% of the total variation. A similar result was also reported in other studies (e.g. Burke *et al.*, 1989).

Conclusions

Storage, spatial patterns, and environmental controls of SOC in alpine grasslands on the Qinghai-Tibetan Plateau were investigated using data from regional soil survey during 2001–2004 and concurrent datasets of EVI. To our knowledge, this is the first satellite-based approach for estimating the magnitude and spatial distribution of SOC storage and the first to report the unique relationships between SOC density and environmental factors for alpine grasslands on the plateau. Total SOC storage in alpine grasslands was estimated at 7.4 Pg, about 1/10 of that (69.1 Pg) in China (Yang *et al.*, 2007). Spatially, SOC density showed a southeast-to-northwest distribution: decreasing from southeastern

to the northwestern part of the plateau. SOC density in alpine grasslands significantly increased with soil moisture, clay content, and silt content, which was consistent with observations from temperate regions. In contrast with the global trend, SOC density in alpine grasslands increased weakly with MAT, possibly due to an indirect effect of increasing plant production. Overall, these environmental variables could together explain about 72% of total variation in SOC, of which 54% was attributed to soil moisture, suggesting a key role of soil moisture in shaping spatial distributions of SOC density in the alpine grasslands.

Acknowledgements

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Supplementary material

The following material is available for this article online:

Appendix S1. Data set of aboveground biomass (AGB) and soil organic carbon (SOC) density in different depths of 30, 50, and 100 cm for alpine grasslands on the Qinghai-Tibetan Plateau, together with location (longitude, latitude and altitude), mean annual temperature (MAT), annual precipitation (AP), soil moisture, clay content, silt content, and grassland type of each site. Grassland type: AS, alpine steppe; AM, alpine meadow.

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