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Changes in topsoil carbon stock in the Tibetan grasslands between the 1980s and 2004

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Abstract

Climate warming is likely inducing carbon loss from soils of northern ecosystems, but little evidence comes from large-scale observations. Here we used data from a repeated soil survey and remote sensing vegetation index to explore changes in soil organic carbon (SOC) stock on the Tibetan Plateau during the past two decades. Our results showed that SOC stock in the top 30 cm depth in alpine grasslands on the plateau amounted to 4.4 Pg C (1 Pg = 10^{15} g), with an overall average of 3.9 kg C m^{-2}. SOC changes during 1980s–2004 were estimated at -0.6 g C m^{-2} yr^{-1}, ranging from -36.5 to 35.8 g C m^{-2} yr^{-1} at 95% confidence, indicating that SOC stock in the Tibetan alpine grasslands remained relatively stable over the sampling periods. Our findings are nonconsistent with previous reports of loss of soil C in grassland ecosystems due to the accelerated decomposition with warming. In the case of the alpine grasslands on the Tibetan Plateau studied here, we speculate that increased rates of decomposition as soils warmed during the last two decades may have been compensated by increased soil C inputs due to increased grass productivity. These results suggest that soil C stock in terrestrial ecosystems may respond differently to climate change depending on ecosystem type, regional climate pattern, and intensity of human disturbance.

Keywords: alpine grasslands, normalized difference vegetation index, soil organic carbon, Tibetan Plateau

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Introduction

Terrestrial ecosystems in middle and high latitudes of the Northern Hemisphere have functioned as carbon (C) sinks for atmospheric carbon dioxide (CO_2) over the past 20 years (Schimel *et al*., 2001), but these sinks are largely dependent on the interactions between soils and climate system (Trumbore & Czimczik, 2008). If warming-induced C emissions from soils exceed vegetation growth, the ecosystems could become sources of atmospheric CO_2 (Davidson & Janssens, 2006). Numerous field experiments (e.g. Melillo *et al*., 2002; Feng *et al*., 2008), laboratory incubations (e.g. Fang *et al*., 2005; Conant *et al*., 2008), and modeling studies (e.g. Knorr *et al*., 2005; Ise *et al*., 2008) suggest that climate warming is likely to induce soil C loss from northern ecosystems, but little evidence comes from large-scale observations (e.g. Bellamy *et al*., 2005; Schipper *et al*., 2007).

Soils on the Tibetan Plateau, like those in high-latitude ecosystems, store a large amount of C because of the cold and relatively humid climate, and thus provide a unique opportunity for exploring the feedback between soil C and climate changes. However, little is known about soil organic carbon (SOC) dynamics in the Tibetan grasslands. Recently, Yang *et al*. (2008) demonstrated that the satellite dataset, which has been widely used to estimate vegetation biomass (e.g. Paruelo *et al*., 1997; Myneni *et al*., 2001), could be integrated with ground-based observations to estimate regional SOC stock because plant production is a major C input to soils in arid/semi-arid ecosystems (Austin, 2002; Epstein *et al*., 2002). Based on the satellite-based SOC estimation approach, this study aims at exploring SOC changes in the Tibetan grasslands by comparing current measurements with historical survey during the 1980s.

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Soil inventories, which systematically record information on soil types and their physical and chemical characteristics, are considered as the best ground-based observations for quantifying the size and spatial patterns of SOC stocks (e.g. Pan *et al*., 2003; Bellamy *et al*., 2005; Lettens *et al*., 2005; Yang *et al*., 2007). During the 1980s, China had implemented a soil survey project on the Tibetan Plateau (Xizang Land Management Bureau, 1994; Office of Agriculture Resource Layouting of Qinghai, 1997). To detect the changes in soil C stock on the plateau, we conducted four consecutive sampling campaigns during 2001–2004 and obtained 405 soil profiles from 135 sites across the plateau. We then used the integrated ground- and satellite-based approach to investigate changes in SOC stocks during the past two decades for the area-dominated alpine grasslands on the plateau.

Materials and methods

Study area

This study was conducted in the alpine grasslands (alpine steppe and meadow) on the Tibetan Plateau. The plateau is the highest and largest one on Earth, with a mean elevation of ~ 4000 m above sea level, and an area of $\sim 2.0 \times 10^6$ km^2, about 1.4 times the size of the Alaska and eight times the British Isles (Li & Zhou, 1998). Its climate is cold and relatively humid, with a mean annual temperature of 1.61 °C and annual precipitation of 413.6 mm, and has experienced a significant change over the past two decades: temperature rose at a rate of 0.05 °C yr^{-1} ($r^2 = 0.40$, $P = 0.001$) and precipitation also increased, although not significantly (+1.7 mm yr^{-1}; $r^2 = 0.12$, $P = 0.11$) (Yang, 2008). Its vegetation is dominated by alpine steppe and meadow, with a total cover of >60% (Chinese Academy of Sciences, 2001). The unique climate and vegetation types, together with a low intensity of human disturbance, make the plateau an ideal region for identifying the responses of natural ecosystems to climate change.

Original sampling

From 1980 to 1989 (with an average year of 1984), a comprehensive soil survey was undertaken on the Tibetan Plateau (Xizang Land Management Bureau, 1994; Office of Agriculture Resource Layouting of Qinghai, 1997). The survey provided comprehensive information on soil taxonomic classification, layer thickness, SOC concentration, bulk density, percentage of the fraction >2 mm, for 96 soil profiles from alpine grasslands (Yang *et al*., 2007). Because bulk density was not measured for some profiles, an empirical relationship between bulk density and SOC concentration was developed to estimate bulk density for those soil profiles using existing data [Eqn (1); Fig. 1a].

$$BD = 0.3 + 1.28\exp(-0.01724\,SOC)\ (r^2 = 0.66,\ P = 0.0001) \quad (1)$$

where *BD* and *SOC* represent bulk density (g cm^{-3}) and SOC (g kg^{-1}), respectively.

Soil resampling

To quantify the changes in soil C stock on the plateau, we conducted four consecutive sampling campaigns during the summers (July and August) of 2001–2004 and surveyed 405 soil profiles from 135 sites across the plateau (i.e. three soil profiles for each site) (Yang *et al*., 2008). For each soil profile, soil was sampled at depths of 0–10, 10–20, and 20–30 cm. Soil samples were taken to

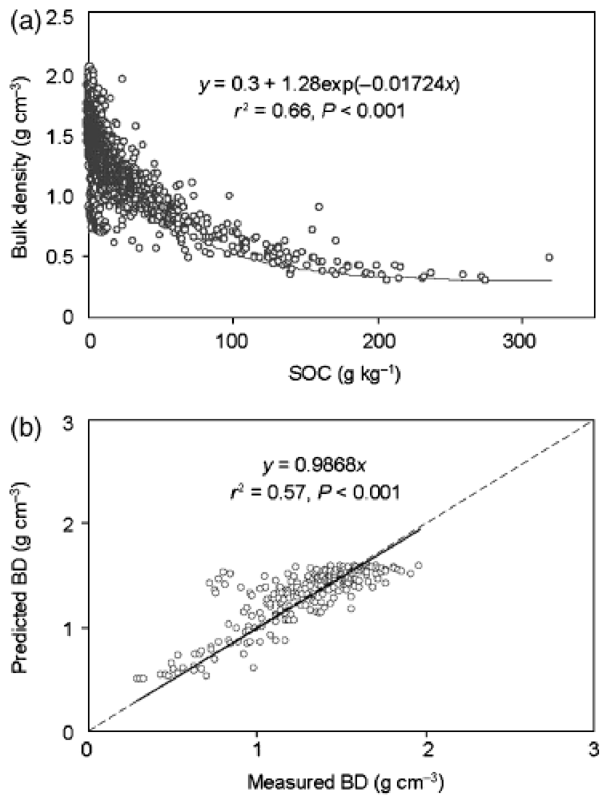

Fig. 1 Relationship between bulk density and soil organic carbon (a), and between predicted and measured bulk density (b) in the Tibetan grasslands. Data of bulk density and soil organic carbon are derived from actual measurements of 405 soil profiles surveyed during 2001–2004. To test the reliability of the empirical function between bulk density and soil organic carbon, 90% of data points are randomly extracted to develop the relationship between bulk density and soil organic carbon, and the remaining 10% are used to validate it. The dashed line shows that estimated bulk density is equal to measured value.

the laboratory, air-dried, weighed, and sieved through a 2 mm mesh. One sample was oven-dried at 105 °C to a constant mass for determining bulk density. The other was handpicked to remove plant residuals and then ground on a ball mill for C analysis. SOC concentration was measured with the same method as did for the 1980s' soil survey [Walkley-Black's method (Nelson & Sommers, 1982)]. For details about field investigation and laboratory analysis, see Yang *et al*. (2008).

National Oceanic and Atmospheric Administration (NOAA)-normalized difference vegetation index (NDVI) dataset

The remote sensing-derived NDVI, which measures the contrast between red and near-infrared reflection of solar radiation, can reflect vegetation cover and be used to monitor spatial and temporal variations of vegetation structural, phonological, and biophysical parameters (Slayback *et al*., 2003; Potter *et al*., 2007). The NDVI datasets used in this study were derived from the advanced very high resolution radiometer (AVHRR) on the NOAA and produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group, at a spatial resolution of $8 \times 8\,\mathrm{km}^2$ and 15 day interval, for the period of 1982–1989 and 2001–2004 (Zhou *et al*., 2001). The monthly NDVI were obtained using the maximum value composition (MVC) method (Holben, 1986). The growing season NDVI were calculated as the average of monthly NDVI from May to September, which were then aggregated to grid cells of $0.1 \times 0.1^\circ$ (Piao *et al*., 2003).

SOC estimation

Yang *et al*. (2008) developed a satellite-based approach to estimate SOC stock in the Tibetan grasslands. Specifically, they observed a positive correlation between SOC density (C stock per area) and aboveground biomass, and found that satellite-based vegetation index was closely associated with aboveground biomass; thus the relationship between SOC density and the satellite vegetation index could be derived. They further used the relationship to estimate SOC density and its distribution from the satellite dataset. Using the same approach, this study estimated SOC stock and its changes for the Tibetan grasslands.

SOC density in the top 30 cm was calculated for each soil profile using Eqn (2). We regressed SOC density against corresponding NDVI data [Eqns (3) and (4)], and used the relationships between SOC density and NDVI to estimate SOC density from satellite observations for each pixel and document spatial distribution of SOC density for the two periods (1980s and 2001–2004), respectively. We then calculated the difference between SOC density in the two periods for each pixel and obtained the distribution of the difference. Further, we digitized the vegetation map of the Tibetan Plateau at a scale of 1 : 1 000 000 (Chinese Academy of Sciences, 2001) and overlaid the map over the distribution of SOC density and its difference to obtain the sizes and their changes of SOC density for alpine steppe and alpine meadow.

$$SOCD = \sum_{i=1}^{n} T_i \times BD_i \times SOC_i \times (1 - C_i)/100 \quad (2)$$

$$SOCD = 20.201\,NDVI - 0.9206\,(r^2 = 0.51,\ P = 0.0005) \quad (3)$$

$$SOCD = 17.846\,NDVI + 0.0155\,(r^2 = 0.63,\ P = 0.0001) \quad (4)$$

where $SOCD$, T_i, BD_i, SOC_i, and C_i represent SOC density ($\mathrm{kg\,C\,m^{-2}}$), layer thickness (cm), bulk density ($\mathrm{g\,cm^{-3}}$), SOC ($\mathrm{g\,kg^{-1}}$), and percentage of the fraction >2 mm, respectively.

Finally, we calculated 95% confidence intervals of SOC density using Monte Carlo approach (e.g. Ogle *et al*., 2003; Vandenbygaart *et al*., 2004; Beilman *et al*., 2008). Specifically, we randomly extracted data of measured SOC density and corresponding NDVI value with bootstrapping techniques (Potvin & Roff, 1993), and then established the satellite-based SOC model to predict the regional SOC stock (Ogle *et al*., 2003; Vandenbygaart *et al*., 2004; Beilman *et al*., 2008). We conducted 10 000 model analyses and summarized model outputs for each run. From these 10 000 estimates, we obtained the 2.5% and 97.5% as a description of uncertainty (i.e. 95% confidence interval) (Ogle *et al*., 2003). All statistical analyses were conducted using software package R (R Development Core Team, 2007).

Results

SOC density showed large variations among different grassland types, with a higher value in alpine meadow than in alpine steppe (5.51 vs. $2.54\,\mathrm{kg\,C\,m^{-2}}$ for the 1980s and 5.48 vs. $2.54\,\mathrm{kg\,C\,m^{-2}}$ for the 2000s) (Table 1). In total, SOC stock in the upper 30 cm depth in alpine grasslands was estimated at 4.40 Pg C for the 1980s and 4.39 Pg C for 2001–2004, with an average density of $3.90\,\mathrm{kg\,C\,m^{-2}}$ for the former and $3.89\,\mathrm{kg\,C\,m^{-2}}$ for the latter, indicating that SOC stock in the Tibetan grasslands remained relatively stable over the past two decades. However, SOC changes in the Tibetan grasslands exhibited large spatial heterogeneity (Fig. 2a).

Table 1 Stocks and changes of SOC for alpine grasslands on the Tibetan Plateau during 1980s–2004

Grassland type	Area (10^4 km^2)	SOC stock (1980–1989)		SOC stock (2001–2004)		Changes in SOC (1980s–2004)	
		Density (kg C m^{-2})	Storage (Pg C)	Density (kg C m^{-2})	Storage (Pg C)	Rate (g C m^{-2} yr^{-1})	Total C (Tg yr^{-1})
Alpine steppe	61.08	2.54 (1.87, 3.21)	1.55 (1.14, 1.96)	2.54 (2.18, 2.90)	1.55 (1.33, 1.77)	0 (−42.8, 43.4)	0 (−26.2, 26.5)
Alpine meadow	51.74	5.51 (5.03, 5.99)	2.85 (2.60, 3.10)	5.48 (5.08, 5.91)	2.84 (2.63, 3.06)	−1.67 (−37.4, 36.1)	−0.86 (−19.4, 18.7)
Total	112.82	3.90 (3.38, 4.44)	4.40 (3.81, 5.01)	3.89 (3.57, 4.22)	4.39 (4.03, 4.76)	−0.56 (−36.5, 35.8)	−0.63 (−41.2, 40.3)

Values in parenthesis denote 95% confidence intervals estimated using Monte Carlo approach with 10 000 interactions.
SOC, soil organic carbon.

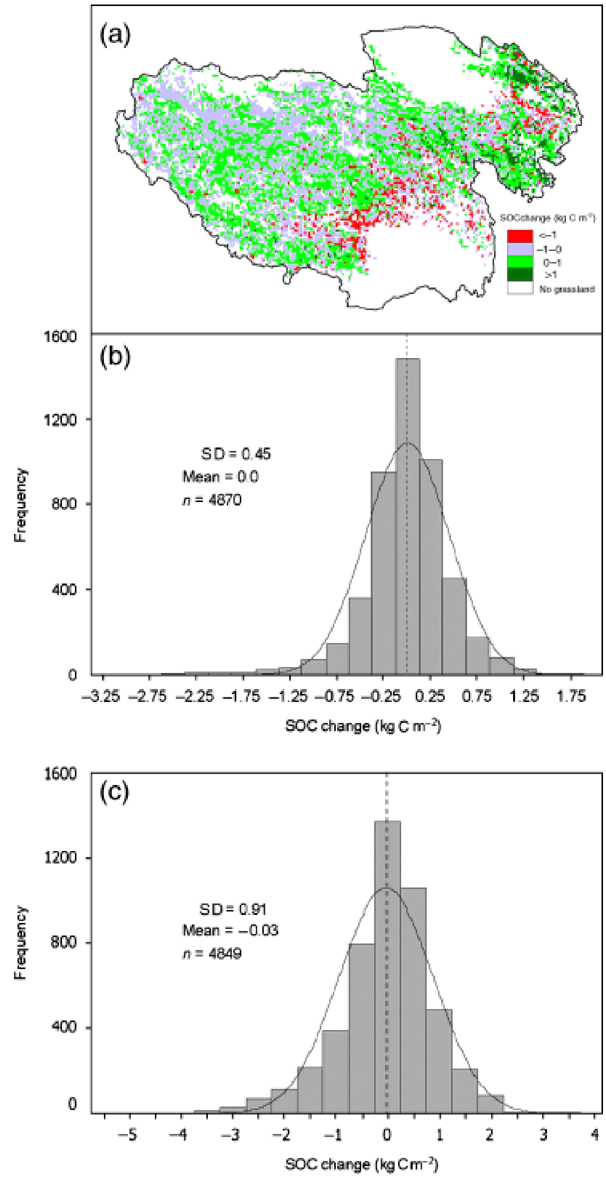

Fig. 2 Soil organic carbon (SOC) changes in the Tibetan grasslands over the last two decades at a resolution of $0.1 \times 0.1°$ (a), and their frequency distributions for alpine steppe (b) and alpine meadow (c).

51.1% of total pixels in alpine steppe and 53.3% in alpine meadow showed an increase, whereas the remaining 48.9% and 46.7% decreased (Figs. 2b and c).

Discussion

SOC estimates and uncertainty analysis

Topsoil C density in the Tibetan grasslands (3.9 kg C m^{-2}) is lower than that of China's uncultivated soils (5.0 kg C m^{-2}), but higher than that of cultivated soils in China (3.5 kg C m^{-2}) (Song *et al*., 2005). Overall, SOC density in the Tibetan grasslands is comparable with an average level in China's soils (3.9 vs. 3.7 kg C m^{-2}) (Yang *et al*., 2007). Moreover, SOC stock (4.4 Pg C) in the Tibetan grasslands accounts for 13.3% of China's total SOC stock in the top 30 cm (32.9 Pg C) (Yang *et al*., 2007), implying its important role in national terrestrial ecosystem C cycling (Fang *et al*., 1996).

The satellite-based SOC assessment can reduce the uncertainties derived from the large soil heterogeneity, but some uncertainties still exist because of the following reasons. First, although soil profiles were sampled across all the major grassland types on the plateau, the regressed relationships for generating spatial patterns of SOC stock could cause a potential uncertainty because most soil profiles were taken from the mid-latitude areas of the plateau (Yang *et al*., 2008). Second, although the remote sensing vegetation index could explain large proportion of variances in SOC density, the remaining residuals probably introduced some errors into the regional estimation (Yang *et al*., 2008). Third, bulk density for those soil profiles which lacked it was estimated from SOC concentration. These error sources suggest that more ground-based observations are required to improve our understanding on size and changes of SOC stock in the Tibetan grasslands.

In order to document these uncertainties, we evaluated our estimates from the following aspects. First, we quantified the uncertainties of our satellite-based SOC estimation using Monte Carlo approach. The results showed that SOC changes in the Tibetan alpine grasslands ranged from -36.5 to $35.8\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ at 95% confidence (Table 1), supporting our conclusion that SOC stock in alpine grasslands did not experience significant change during the past two decades. Second, to test the reliability of satellite-based estimates, we randomly extracted 75% of sampling sites to establish the relationship between SOC density and NDVI, and then used the relationship and corresponding NDVI to estimate SOC density for the remaining sites. The results indicated that predicted SOC density was well consistent with measured value, with a slope of 1.07 and 1.02 for the relationships during the period of 1980–1989 and 2001–2004 ($r^2 = 0.52$, $P < 0.001$; $r^2 = 0.55$, $P < 0.001$) (Figs. 3a and b). This demonstrates that the satellite-based approach is suitable for estimating regional SOC stock and its change.

Third, it is a common approach to estimate bulk density from SOC concentration for those soil profiles which lack it, although this may produce some errors (e.g. Bellamy *et al*., 2005; Xie *et al*., 2007; Yang *et al*., 2007). In order to evaluate such uncertainties, we randomly extracted 90% of soil samples to redevelop the equation between bulk density and SOC concentration

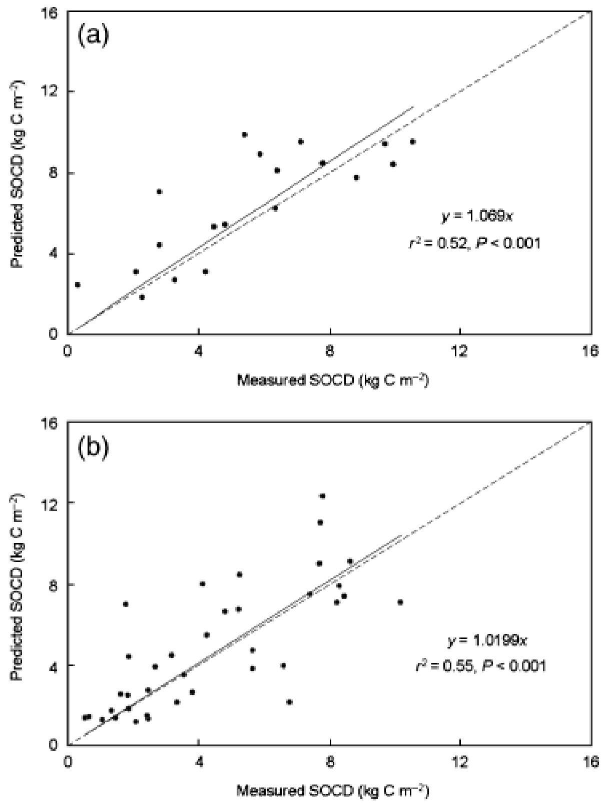

Fig. 3 Comparison between predicted and measured soil organic carbon (SOC) density in the Tibetan grasslands for the period of 1980–1989 (a) and 2001–2004 (b). In this analysis, 75% of data points are randomly extracted to develop the relationship between SOC density and normalized difference vegetation index, and the remaining 25% are used to validate it. The dashed line shows that estimated SOC density is equal to measured value.

and used the remaining 10% to validate it. We found that the predicted bulk density was closely correlated with measured value with a slope of 0.99 ($r^2 = 0.57$, $P < 0.001$) (Fig. 1b). This documents that the empirical function is satisfied with the estimation of regional SOC stock.

Fourth, land use change may induce potential fluctuations in SOC stock (Guo & Gifford, 2002). However, Tibetan Plateau does not experience significant land use change during the past two decades (Liu *et al*., 2005a, b). The area of alpine grasslands on the plateau was reported to a slight decrease by 525 km^2 during 1990–2000 (Liu *et al*., 2005b), which only accounts for about 0.5% of the total grassland area on the plateau. Therefore, land use change could not exert a significant effect on SOC stock in the Tibetan grasslands.

In addition, the changeover of satellite sensors (NOAA 7, 9, 11, and 14) in time-series NDVI datasets (Zhou *et al*., 2001) may induce some uncertainties into

SOC estimation. However, GIMMS group had conducted sensor calibration including a sensor degradation correction and intersatellite calibration, to remove the effects of satellite transitions on NDVI data quality (Los, 1998; Zhou *et al*., 2001). Slayback *et al*. (2003) demonstrated that GIMMS-NDVI changed smoothly across satellite transitions after sensor calibration, suggesting that sensor transition will not significantly affect satellite-based SOC estimation.

SOC change over the past two decades

SOC stock in the Tibetan grasslands did not change significantly over the past two decades, which is distinctly different from recent observations in European grasslands (e.g. Bellamy *et al*., 2005; Lettens *et al*., 2005; Schipper *et al*., 2007). For example, Bellamy *et al*. (2005) reported that soil C was lost across England and Wales between 1978 and 2003 at a mean rate of $31.4\,g\,C\,m^{-2}\,yr^{-1}$. By contrast, Lettens *et al*. (2005) observed that grassland soils in Belgium functioned as C sink over the last several decades. The decrease in SOC stock in grasslands of England and Wales may be associated with global warming, declined animal manure, changes in agricultural practice, and land use change (Smith *et al*., 2007; Hopkins *et al*., 2009), whereas the increase in SOC stock in grasslands of Belgium may be attributed to increased application of organic amendments (Lettens *et al*., 2005). The stable soil C stock in the Tibetan grasslands is presumably driven by the dynamic balance between C inputs from plant production and outputs through microbial decomposition (Davidson & Janssens, 2006). During the past two decades, extended growing season and enhanced plant growth induced by climate warming have contributed to a significant increase in net primary production in the Tibetan grasslands (Piao *et al*., 2006), resulting in a possible increase of organic C inputs to soil. Meanwhile, soil C will be susceptible to decomposition under warmer conditions (Melillo *et al*., 2002; Fang *et al*., 2005; Conant *et al*., 2008; Feng *et al*., 2008). As a consequence, the loss of C associated with soil respiration may offset the increase in plant production, leading to an unchanged SOC stock.

Our findings have important implications. The Tibetan Plateau is the highest and largest one in the world, where there are less residents and rather low intensity of human disturbances. Over the past several decades, its climate has experienced a significant warming and slight increase in precipitation (Yang, 2008). SOC changes on the plateau can be an indicator of the interactions between natural ecosystems and climate systems and a lesson for us to better understand how ecosystem processes respond to climatic dynamics. Our results document that topsoil C stock in the Tibetan grasslands did not change significantly over the past 20 years, which conflict with the decrease of soil C reported in European grasslands (e.g. Bellamy *et al*., 2005; Schipper *et al*., 2007). This finding emphasizes that terrestrial ecosystems may respond differently to climate change depending on ecosystem type, regional climate pattern, and intensity of human disturbance. These factors should be incorporated into a modeling of soil C responses to climate changes.

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