Geoderma 288 (2017) 166–174

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Changes of carbon stocks in alpine grassland soils from 2002 to 2011 on the Tibetan Plateau and their climatic causes

Litong Chen [a,*], Xin Jing [b], Dan F.B. Flynn [c], Yue Shi [b,d], Peter Kühn [e], Thomas Scholten [e], Jin-Sheng He [a,b]

[a] Key Laboratory of Adaptation and Evolution of Plateau Biota, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China
[b] Department of Ecology, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, 100871, China
[c] The Arnold Arboretum of Harvard University, 1300 Centre Street, Boston, MA, USA
[d] State Key Laboratory of Vegetation an Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China
[e] Department of Geosciences, Soil Science and Geomorphology, University of Tüebingen, Tüebingen 72079, Germany

ARTICLE INFO

Article history:
Received 21 May 2016
Received in revised form 28 October 2016
Accepted 10 November 2016
Available online 16 November 2016

Keywords:
Soil organic carbon (SOC)
SOC stocks
Repeated soil inventory
Alpine meadow
Alpine steppe
Tibetan Plateau

ABSTRACT

Based on field observations, remote sensing, and modeling, recent studies have reported inconsistent changes in soil organic carbon (SOC) stocks in grasslands of the Tibetan Plateau over the past few decades. However, direct evidence about the changes in SOC stocks in the plateau's grasslands coming from in situ, site-by-site, repeated surveys is rare. In this study, we carried out a repeated soil sampling to assess the changes in SOC stocks in the alpine grasslands across the Tibetan Plateau. Across all 41 sites in the alpine grasslands, SOC stocks exhibited a significant increase from 2002 to 2011 at an overall rate of 4.66 g C m^{-2} yr^{-1}. Mesic and low-temperature-limited alpine meadows showed an average carbon gain of 25.8 g C m^{-2} yr^{-1}, whereas the relatively dry alpine steppes exhibited a slight carbon loss of 11.9 g C m^{-2} yr^{-1}. Spatially, the changes in SOC stocks were significantly related to the original SOC stocks across alpine steppes, and soils with low carbon tended to gain carbon. Moreover, the changes in SOC stocks were also associated with March–April precipitation in alpine meadows, and with mean annual precipitation (MAP) in alpine steppes, with drier sites generally gaining carbon. Overall, the alpine grasslands of the Tibetan Plateau significantly accumulated SOC over this 10-year period, but many more site surveys are needed to comprehensively access the changes in SOC stocks across alpine grasslands on the plateau; and management strategies enhancing the ability of C sequestration should differ between alpine meadows and steppes due to their contrasting climate conditions.

1. Introduction

In terrestrial ecosystems, soils represent the largest stock of organic carbon (C), holding approximately 1500 Pg (10^{15} g) C (estimated at 0–100 cm depth), which is about twice the amount held in the atmosphere and thrice the amount contained in terrestrial vegetation (Kutsch et al., 2009). Even small changes in soil organic carbon (SOC) pools, caused by either climatic change or human activity and land use change may have a large impact on the global C cycle (Johnson et al., 2007; Don et al., 2009). Owing to the role they can play in mitigating or promoting the effects of elevated atmospheric CO_2 and associated global warming (Johnston et al., 2004), accurate assessments of SOC pools and their changes over time are of vital importance (Don et al., 2007). Accurate calculation of the dynamics of SOC stocks is also important for mechanistic understanding of the C cycle, and for assessing the feedbacks between SOC and climate change (Smith et al., 2012).

The Tibetan Plateau covers an area of an approximately 2.5×10^6 km^2 at an average altitude of 4000 m above sea level (a.s.l.), and can be regarded as the third pole (Qiu, 2008). Similar to the high-latitude tundra in the polar regions, approximately two-thirds of the total area of the high-altitude Tibetan Plateau was affected by permafrost (Zhao et al., 2000). This area contains a large amount of SOC, as estimated at 7.4–33.52 Pg in alpine grasslands (Wang et al., 2002; Wu et al., 2003; Yang et al., 2008), and its ecosystems are particularly sensitive to global warming (Yao et al., 1995; Liu and Chen, 2000; Zhang et al., 2013; Wang et al., 2014a; Zhang et al., 2016). The plateau has experienced a pronounced warming in recent decades (Liu and Chen, 2000; Chen et al., 2013), and this warming is predicted to continue in the 21st century (Chen et al., 2013). The high-altitude Tibetan Plateau therefore provides a very good opportunity to explore the feedback between SOC and climate change (Li et al., 2013; Li et al., 2014).

Recently, a number of studies have explored the SOC changes in the Tibetan Plateau's alpine grasslands. However, the results are conflicting. For instance, using a satellite-based approach, Yang et al. (2009) found that SOC stocks in the Tibetan Plateau's alpine grasslands had a slight decrease with a change rate of 0.6 g C m^{-2} yr^{-1} (−36.5 to 35.8 g C m^{-2} yr^{-1} at 95% confidence) between the 1980s and 2004.

* Corresponding author.
E-mail address: litong_chen@nwipb.cas.cn (L. Chen).

http://dx.doi.org/10.1016/j.geoderma.2016.11.016
0016-7061/

Based on soil data from the Second State Soil Survey of China (SSSSC), Xie et al. (2007) indicated that SOC in China's grasslands (including the Tibetan Plateau's alpine grasslands) declined by 3.56 Pg from the 1980s to 2000s. Fang et al. (2010) reviewed the dynamics of soil C stocks in China's grasslands over the past 20 years, and found that China's grasslands ecosystems were C neutral. By contrast, a process-based biogeochemical modeling study suggested that during the 20th century, soils in Tibetan Plateau's grasslands shifted from being a carbon source or neutral in the early part of the century to a carbon sink later. Furthermore, flux observations carried out over a short time period showed that soils in alpine meadows acted as a carbon sink of 120.9 g C m^{-2} yr^{-1} (ranging from 78.5 to 192.5 g C m^{-2} yr^{-1}) from 2002 to 2004 (Kato et al., 2006). Finally, a recent synthesis of flux measurements demonstrated that the alpine meadows on the eastern edge of the plateau were a strong carbon sink of 61.64 ± 34.51 g C m^{-2} yr^{-1} in the early 21st century (Yu et al., 2013). The large variability and inconsistency in SOC changes in alpine grasslands of the plateau observed among these above-mentioned studies can be partly attributed to the insufficient observations and/or the inconsistent methodologies. Consequently, direct measurements by repeated soil inventories are urgently needed to accurately assess the changes in SOC stocks across the Tibetan Plateau's alpine grasslands.

Generally, human disturbances (e.g. grazing) and climatic variables are considered as the two main factors affecting the C dynamics in grasslands all over the world. The effects of grazing on SOC stock and its changes in alpine grasslands on the Tibetan Plateau have therefore been well characterized in recent years (Dong et al., 2012; Su et al., 2015; Hu et al., 2016); however, there is little knowledge on how the climate change influences the changes in alpine grasslands' SOC stocks on this plateau. Currently, two hypotheses have been put forward to predict the potential dynamics of SOC stocks in the future changing environment (Garten, 2004). The first hypothesis, defined here as the temperature-loss hypothesis, predicts that since the decomposition of SOC is more sensitive to temperature change than net primary production (NPP) (Jenkinson et al., 1991; Cox et al., 2000; Davidson and Janssens, 2006), increasing temperature will result in a net loss of SOC. The second hypothesis, defined here as the nitrogen-gain hypothesis, predicts that due to the fertilization by nitrogen deposition, SOC stocks might gain more carbon than they lose in a nitrogen-rich and warming environment. Since the Tibetan Plateau is very sensitive to warming, we predicted that SOC stocks in mesic and low-temperature-limited alpine meadows would show a declining trend under the temperature-loss hypothesis and would show an increasing trend under the nitrogen-gain hypothesis. By contrast, in water-limited alpine steppes, SOC stocks would exhibit no changes or even decrease under the nitrogen-gain hypothesis since nitrogen deposition would have minor effects, whereas increased temperature would intensify soil aridity under water-limited condition.

To test our hypotheses, we analyzed changes in SOC stocks in alpine grasslands across the Tibetan Plateau during the past decade from 2002 to 2011. During the summer of 2011, we sampled 205 soil profiles from 41 sites selected from the 2002–2003 soil inventory (Yang et al., 2008). We addressed the following three questions. (i) To what extend have SOC stocks in the Tibetan Plateau's alpine grasslands changed over this 10-year period? (ii) Have the changes in SOC stocks in alpine meadows and steppes exhibited consistent responses? (iii) Since climatic variables widely affect the potentials for C sequestration in ecosystems, at the spatial scale, how do climatic factors affect the changes of SOC stocks in alpine meadows and steppes?

2. Materials and methods

2.1. Study area

Our study was conducted in the alpine grasslands on the Tibetan Plateau, which has experienced substantial climate change during the past decade. Mean annual temperature (MAT) has significantly increased at a rate of 0.087 °C yr^{-1}, whereas mean annual precipitation (MAP) varied only slightly (Fig. S1). The alpine meadows and alpine steppes are two major vegetation types on the plateau, with covering >60% of the plateau's total surface which corresponds to an area of 1.6×10^8 ha and comprises 40% of the national Chinese grassland area (Wu, 1980). Alpine meadows is the most widely distributed vegetation type on the plateau (Zhou, 2001) occurring at elevations ranging from 3200 to 5200 m a.s.l. (Kato et al., 2004). The dominant plant species found in alpine meadows are *Kobresia pygmaea*, *Kobresia humilis*, *Polygonum gentiana*, and *Saussurea* sp. Alpine steppes vegetation consists mainly of *Stipa purpurea*, *Stipa subsessiliflora* and *Carex moorcroffiana* (Chang, 1981). The soil types in alpine meadows and steppes are felty and cold calcic soils, respectively (Xiong and Li, 1987); these are defined as cambisols based on the World Reference Base for soil resources (WRB) (Shi et al., 2010).

2.2. Original sampling

In order to quantify the storage and patterns of SOC in alpine grasslands, four consecutive sampling campaigns were conducted by Peking University, China, during the summer (July and August) of 2001–2004 (in most cases in 2002/03). Four hundred five soil profiles from 135 sites across the Tibetan Plateau were surveyed (i.e. three soil profiles at each site) (Yang et al., 2008). For each soil profile, the soil pit was excavated to collect soil samples at depth increments of 0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm. Soil samples were taken to the laboratory, air-dried, weighed, and sieved through a 2 mm mesh, and then these samples were handpicked to remove plant residuals and then ground on a ball mill for SOC analysis by the Walkley-Black's method (Nelson and Sommers, 1982). Bulk density samples were obtained for each layer using a standard container with 100 cm^3 in volume (50.46 mm in diameter and 50 mm in height) and weighed to the nearest 0.1 g, and then were oven-dried at 105 °C to a constant mass to determine its determining bulk density. For details about the field investigation and laboratory analysis, see Yang et al. (2008).

2.3. Resampling

To detect changes in SOC stocks (top 30 cm) in grasslands of the Tibetan Plateau, we carried out a resampling of soil profiles during the summer of 2011 (July and August), surveying 205 profiles from 41 sites (i.e. five profiles at each site) randomly selected from the 2002/03 sampling campaigns according to the original longitude and latitude as well as original sampling profile of each site (Fig. 1, Table S1). Of the 41 sites, 18 were alpine meadows and 23 were alpine steppes. Following the almost same procedure as in the original sampling, soil samples were collected by hand with a steel core (5 cm in inner diameter) in four soil increments (0–5, 5–10, 10–20, 20–30 cm) at each profile in each site. Three to eight cores were mixed as a replicate in each soil increments (Chen et al., 2015). Soil samples were air-dried, sieved through a 2 mm mesh, handpicked to remove plant detritus, and then ground into a fine powder. SOC content was measured by the Walkley-Black's method (Nelson and Sommers, 1982). Five replicates of bulk density sample at each site were obtained for each layer using a standard container of 100 cm^3 in volume, and thus it was calculated as the ratio of the oven-dried (105 °C) soil mass to the container volume.

2.4. SOC calculation and climate data

We only concerned the SOC changes in top 30 cm, SOC density (C stock per land area) in the top 30 cm therefore was calculated with Eq. (1).

$$SOCD = \sum_{i=1}^{n} T_i \times BD_i \times SOC_i \times \frac{1-\frac{C_i}{100}}{100} \tag{1}$$