Soil Biology and Biochemistry 116 (2018) 224–236

Contents lists available at ScienceDirect

Soil Biology and Biochemistry

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

Climate warming impacts on soil organic carbon fractions and aggregate stability in a Tibetan alpine meadow

Song Guan[a], Na An[a], Ning Zong[b], Yongtao He[b], Peili Shi[b], Jinjing Zhang[a,*], Nianpeng He[b,c,d,**]

[a] Key Laboratory of Soil Resource Sustainable Utilization for Commodity Grain Bases of Jilin Province, College of Resource and Environmental Science, Jilin Agricultural University, Changchun 130118, China
[b] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Institute of Grassland Science, Northeast Normal University, Key Laboratory of Vegetation Ecology, Ministry of Education, Changchun 130024, China

ARTICLE INFO

Keywords:
Experimental warming
Soil organic carbon
Soil aggregates
Solid-state ^{13}C NMR
Alpine meadow
Tibetan Plateau

ABSTRACT

Alpine meadows in the Tibetan Plateau contain a large amount of soil organic carbon (SOC), which is highly vulnerable to climate change and has thus been a research priority for scientists in recent decades. However, how climate warming influences the composition and stability of SOC remains unclear. In this study, a warming experiment (2010–2015) using open-top chambers was established (with unwarmed control [CK], winter warming [WW], and year-round warming [YW]) to investigate the effects of warming on the contents of SOC and its fractions, chemical composition of SOC, and water stability of aggregates in an alpine meadow located at the Damxung Grassland Station in the northern Tibetan Plateau. Experimental warming had no apparent effect ($p > 0.05$) on SOC content (17.8 ± 1.96, 17.8 ± 1.13 and 17.8 ± 1.09 g kg^{-1} under CK, WW and YW, respectively) in the 0–20 cm soil layer. However, warming significantly ($p < 0.05$) increased soil water-soluble organic carbon (C) content by 46.2% and 69.2%under WW and YW, respectively, and affected SOC chemical composition with decreasing phenol C (by 2.6% under WW, $p > 0.05$; and 8.4% under YW, $p < 0.05$) and increasing carboxyl C (by 11.6% under WW, $p < 0.05$; and 5.0% under YW, $p > 0.05$). Warming decreased ($p > 0.05$) the proportions of macroaggregates (2–0.25 mm) and free microaggregates (0.25–0.053 mm), whereas warming significantly increased the proportion of non-aggregated silt- and clay-sized fractions (< 0.053 mm) by 41.0% and 55.7% under WW and YW, respectively. The variation in the aggregate size distribution resulted in the decline of the mean weight diameter and geometric mean diameter of water-stable aggregates by 5.1% ($p > 0.05$) and 8.5% ($p < 0.05$) under WW and by 8.5% and 6.6% (both $p < 0.05$) under YW, respectively. Of importance, the organic C content in free microaggregates, which provides greater physical protection to stabilize SOC, decreased by 10.9% ($p > 0.05$) under WW and by 22.4% ($p < 0.05$) under YW. The organic C contents of particulate organic matter and silt- and clay-sized fractions inside free microaggregates also significantly decreased under YW by 49.4% and 16.9%, respectively. However, the organic C content in non-aggregated silt- and clay-sized fractions significantly increased under WW and YW by 52.9% and 46.8%, respectively. The results suggest that short-term climate warming did not affect total SOC stocks, whereas it had a positive effect on WSOC, carboxyl C and non-aggregated silt- and clay-associated C and exhibited a negative effect on phenol C, free microaggregates-associated C and water stability of aggregates. These variables may act as sensitive indicators of climate warming in the Tibetan alpine meadows, which will in turn affect grassland ecosystem C fluxes in response to further climate change. The findings of the present study help improve our understanding of the responses of terrestrial ecosystem C cycling to future climate change.

1. Introduction

Soil is the third largest reservoir of carbon (C), next to the lithosphere and the oceans, and stores approximately 1500 Gt in the top 1 m depth (Dlamini et al., 2016; Raheb et al., 2017), equivalent to almost twice the amount of C in the atmosphere and three times that in

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[*] Corresponding author.
[**] Corresponding author. Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

E-mail addresses: zhangjinjing@126.com (J. Zhang), henp@igsnrr.ac.cn (N. He).

http://dx.doi.org/10.1016/j.soilbio.2017.10.011
Received 20 January 2017; Received in revised form 15 September 2017; Accepted 13 October 2017

the terrestrial biomass (Dlamini et al., 2016). Even small changes in soil C stocks could have a vast impact on atmospheric CO_2 concentration (Muñoz-Rojas et al., 2013). As a consequence, the global average surface temperature has increased by 0.85 °C over the past 130 years (1880–2012) (IPCC, 2013). In China, the average surface temperature has increased by 1.40 °C during 1951–2007 (Ren et al., 2012). Elevated surface temperature can substantially impact global C budgets and produce positive or negative feedbacks to climate change (Wan et al., 2005). Therefore, understanding the response of soil organic carbon (SOC) stocks to warming is of critical importance to evaluate the feedbacks between terrestrial C cycle and climate change.

The extent to which climate warming influences SOC mainly depends on the stability of organic C in soil. Based on the decomposition degree and turnover rate (von Lützow et al., 2007), SOC can be chemically divided into labile or rapidly decomposed fractions [e.g., microbial biomass C (MBC), water-soluble organic C (WSOC), easily oxidizable organic C (EOC), particulate organic C (POC), and light fraction organic C (LFOC)] and resistant or slowly decomposed fractions [e.g., heavy fraction organic C (HFOC), humic acid C (HAC), fulvic acid C (FAC) and humin C (HUC)]. Both labile and resistant SOC fractions have been reported to act as potential indicators of climate change (Steinberg, 2003; Wang et al., 2016; Hu et al., 2017). Although the labile SOC fractions were assumed to be sensitive to climate warming (Song et al., 2012), some studies have found that the resistant SOC fractions had more sensitivity (Knorr et al., 2005) or similar responses to climate warming (Fang et al., 2005).

With respect to the stabilization mechanisms of SOC, it has been generally recognized that SOC could be protected against mineralization by incorporation into aggregates (physical protection), sorption onto clay (chemical protection), biochemical transformation into products that are resistant to microbial attack (biochemical protection), and translocation and storage in the subsoil (Six et al., 2002; Sarkhot et al., 2007). Although there have been some disputes (Fontaine et al., 2007; Dungait et al., 2012), physical protection within stable aggregates has been considered to be one of the major mechanisms of SOC stabilization (O'Brien and Jastrow, 2013; Smith et al., 2014; Chaplot and Cooper, 2015; Zhong et al., 2017). Soil aggregate-associated C has been used as an indicator for evaluating soil C sequestration (Six et al., 2000; Bronick and Lal, 2005). Specifically, hierarchically organized soil aggregates, a key feature of soil where organic matter is a major aggregate binding agent (Tisdall and Oades, 1982), play an essential role in the accumulation and stabilization of SOC by physically reducing the bioaccessibility (O'Brien and Jastrow, 2013; Zhao et al., 2017). In fact, soil aggregate stability is not only a key element of SOC stabilization but also can be used to predict SOC outputs from soils (Chaplot and Cooper, 2015). Chaplot and Cooper (2015) pointed to an increase of C losses by water erosion as soil aggregation decreased but an increase in gaseous emissions as soil aggregation improved. In addition, knowledge of SOC chemical composition is also important and could provide information for understanding the biochemical mechanism of the accumulation and stabilization of SOC at the molecular level (Six et al., 2002; Guo et al., 2016).

Grasslands cover approximately 40% of the world's land surface and store about 10% of the global SOC stock (Suttie et al., 2005). Grasslands are a key constituent of biogeochemical C cycle and can provide vital ecosystem services and goods (Dlamini et al., 2014). SOC in grassland ecosystems is not only critical for climate change but also yields important feedbacks to plant productivity and soil fertility (Dlamini et al., 2016). To date, some studies have examined the impact of climate change on SOC in grassland ecosystems. However, the results of previous studies have been contradictory. For example, warming had positive (Li et al., 2011), negative (Li et al., 2011; Wan et al., 2005), or no effects (Wang et al., 2014; Zhang et al., 2015) on SOC content. Likewise, warming could increase (Belay-Tedla et al., 2009; Zhang et al., 2015), decrease (Zhou et al., 2013), or have no obvious effect (Wang et al., 2014) on MBC content. The lack of consistent responses of SOC to warming is not surprising, given the complexity of key controlling factors for C cycling in different grassland ecosystems (Xu et al., 2012; Zhou et al., 2013). Therefore, more information is required to predict how climate change will affect SOC in grassland ecosystems in the future.

With respect to other grassland ecosystems, alpine grassland ecosystem is more sensitive to climatic change (Zhang et al., 2016). The Tibetan Plateau, a typical alpine ecosystem dominated by alpine grasslands, is the highest (a mean elevation of 4000 m above sea level) and largest (an area of 2.5×10^6 km^2) plateau on earth (Wang, 2016). It is estimated that the Tibetan Plateau contains 30–40 Gt of SOC, which accounts for more than 20% of the SOC storage in China and 2–3% of the global soil C stocks (Shang et al., 2016). Previous studies have demonstrated that the Tibetan Plateau has been subjected to distinct warming in recent decades (Guo and Wang, 2011; Wei and Fang, 2013). The magnitude of warming on the Tibetan Plateau is approximately 0.32 °C greater than that of the global average and that of other regions in China (Liu and Chen, 2000; Ren et al., 2012). It has been predicted that the average surface temperature on the Tibetan Plateau will be 2 °C higher than the global average by 2050 (Thompson et al., 2000). Therefore, how SOC responds to climate warming in the Tibetan alpine grassland ecosystem has become a research priority in recent decades.

Alpine meadow, which accounts for over 40% of the Tibetan Plateau area (Fan et al., 2011), is considered particularly sensitive to climate warming (Jiang et al., 2016). In previous studies, some researchers have explored the effects of experimental warming on SOC content (Li et al., 2011; Wang et al., 2014; Yu et al., 2014; Zhang et al., 2015) in alpine meadows on the Tibetan Plateau. Moreover, some researchers have also examined the impacts of experimental warming on labile SOC fractions (MBC, WSOC) contents (Luo et al., 2009; Rui et al., 2011; Wang et al., 2014; Yu et al., 2014; Zhang et al., 2015). As in other grassland ecosystems, uncertainty remains about how experimental warming affects SOC and its fractions contents in the Tibetan alpine meadow ecosystem. To the best of our knowledge, no studies have explored how experimental warming impacts SOC chemical composition and soil structure stability in the Tibetan alpine meadow. This study conducted warming experiment using open-top chambers (OTCs) to investigate how climate warming affects SOC and its fractions contents, SOC chemical composition, and soil aggregate stability in a Tibetan alpine meadow. The specific objectives of this study were to evaluate: (1) warming impacts on the quantity and quality of SOC with respect to labile and resistant SOC fractions and SOC chemical composition and (2) warming influences on hierarchically organized soil aggregates and their stability. A previous study in this OTCs experiment showed that aboveground biomass significantly decreased during short-term (2 years) warming (Zong et al., 2013). Given that the input of aboveground litter to soil is a major process that regulats the quantity and quality of SOC (Zech et al., 1997; Xu et al., 2013; Cao et al., 2016; Li et al., 2017) and the stability of soil aggregates (Bronick and Lal, 2005; Cao et al., 2016; Li et al., 2017), we hypothesized that SOC and aggregate stability would change because of variation of the balance between C inputs by litter and C losses from mineralization and erosion.

2. Materials and methods

2.1. Study site, experimental design, and soil sampling

Field warming experiments were conducted in a fenced alpine meadow located at the Damxung Grassland Station, Tibetan Plateau (30°51′N, 91°05′E, 4333 m above sea level) (Fig. 1). The mean annual temperature is 1.3 °C, and the mean annual precipitation is 476.8 mm. The growing season extends from May to September, and the freezing period extends from October to next April. The soil is classified as Cambosol (Chinese Soil Taxonomy) or Inceptisol (USDA Soil Taxonomy), with a pH of 6.95 and containing 67.0% sand, 18.2% silt, 14.7% clay, 11.3 g kg^{-1} of organic C, and 1.20 g kg^{-1} of total N in the