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Seasonal variations in labile soil organic matter fractions in permafrost soils with different vegetation types in the central Qinghai–Tibet Plateau

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ABSTRACT

Labile soil organic matter (SOM) plays a crucial role in nutrient and carbon cycling, particularly in permafrost ecosystems. Understanding its variation is therefore very important. In the present study, we evaluated the seasonal patterns of labile SOM from April 2013 to March 2014 under alpine swamp meadow (ASM), meadow (AM), steppe (AS) and desert (AD) vegetation in permafrost regions of the China's Qinghai–Tibet Plateau. The fractions (0 to 10 cm depth) included dissolved organic carbon (DOC), light-fraction carbon (LFC) and nitrogen (LFN), and microbial biomass carbon (MBC) and nitrogen (MBN). These fractions showed dramatic seasonal patterns in ASM and AM soils, but were relatively stable in AD soil. Soil DOC concentrations in the ASM, AM, and AD soils increased from April to May 2013, then increased again from July to August 2013 and from February to March 2014. The LFC and LFN concentrations in all four vegetation types were higher from June to August 2013. The highest MBC and MBN concentrations in the ASM, AM, and AS soils all occurred in the summer and the ASM soil showed a second peak in October or November 2013. Seasonal changes in climatic factors, vegetation types, and permafrost features were great causes of labile SOM variations in this study. Throughout the entire sampling period, the ASM soil generally had the highest labile SOM, followed by the AM, AS, and AD soils; thus, the ASM soil is the best system conserving soil nutrient (especially labile fractions) and microbial activity. Correlation analysis indicated that these fractions were not related to soil moisture and temperature in AS or AD soils, but soil temperature and moisture were significantly related to MBC and MBN in AM soil and DOC in ASM soil. Thus, the response of the labile SOM fractions in this high-altitude permafrost soils to climate change depended strongly on vegetation types.

1. Introduction

Permafrost soils currently store more than twice of the amount of carbon (C) in the atmosphere (Ping et al., 2008; Tarnocai et al., 2009; Zimov et al., 2006), and recent climate warming is expected to accelerate the decomposition rate of soil organic matter (SOM) stored in permafrost soils (Zimov et al., 2006). Labile soil organic matter (SOM) fractions such as dissolved organic carbon (DOC), light-fraction carbon (LFC) and nitrogen (LFN), and the microbial biomass carbon (MBC) and nitrogen (MBN), were characterized by their fast turnover rates (Haynes, 2005), are especially important in the decomposition and mineralization processes of the permafrost ecosystems because they are the main source of C released from soil to the atmosphere, and their responses to climate change will be a very important factor determining the future soil C balance (Dutta et al., 2006; Neff and Hooper, 2002). Therefore, even minor changes in labile SOM components in response to changes in temperature, moisture, and the composition and availability of substrates can strongly influence C cycling between the atmosphere and the soil (Gregorich et al., 1994; Laik et al., 2009; Six et al., 2002). Studies in Alaska (Douglas et al., 2013; Petrone et al., 2006), Canada (Buckeridge et al., 2013; Edwards and Jefferies, 2013), and Russia (Prokushkin and Guggenberger, 2007) have shown that the labile SOM fractions in permafrost soils respond sensitively to variations in climatic conditions. For instance, soil temperature and moisture can control the soil MBC and MBN through their combined effects on substrate availability and the physical properties of the soil in high Arctic ecosystems (Bardgett et al., 2007; Christiansen et al., 2012). The seasonal variations in soil temperature and its effect on freezing and thawing of soil are primary drivers of variations in soil microbial biomass and nutrient levels in low Arctic sedge meadow soils in Canada (Edwards and Jefferies, 2013). In a field study of forest floor of a continuous-permafrost in Siberia, the temporal variability and spatial variability of soil DOC fluxes were well correlated with the seasonal and spatial variations in

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temperature and moisture under different slope aspects (Prokushkin et al., 2005). Accordingly, these observations suggest a close relationship between the labile SOM fractions and environmental factors, which, in turn respond to climatic changes.

In addition to potential shifts caused by changing climatic conditions, vegetation type affects the amounts of the labile SOM fractions and their responses to temperature and moisture dynamics in permafrost regions (Björk et al., 2008; Buckeridge and Jefferies, 2007; Edwards and Jefferies, 2013; Neff and Hooper, 2002). The labile SOM status depends strongly on the organic matter input (both quantity and chemical characteristics) by the vegetation. In addition, the vegetation type plays an important role by regulating soil temperature, moisture, and other soil physical and chemical properties that affect these fractions (Loya et al., 2004; Neff and Hooper, 2002). Bardgett et al. (2007) found that the relationship between soil MBN and soil temperature was determined by the soil water availability under different plant communities in a high-Arctic ecosystem. Buckeridge and Jefferies (2007) found that soil C availability and microbial activity were lower in degraded soils than vegetated soils. However, Björk et al. (2008) demonstrated that vegetation, snow cover dynamics and nitrogen (N) turnover showed minor importance to microbial community structure in alpine tundra soils. Thus, the significance of vegetation types needs to be documented in the context of climate change, especially in terms of how variations in vegetation types and associated environmental factors caused by climate change will affect the labile SOM fractions. Recently, work on the impacts of different vegetation types and of environmental conditions on labile SOM fractions has concentrated on the high Arctic (Bardgett et al., 2007; Christiansen et al., 2012), the low Arctic (Edwards and Jefferies, 2013; Kytöviita et al., 2011), and alpine ecosystems (Björk et al., 2008; Lipson et al., 1999). However, there is a lack of available information on whether similar variability occurs in other permafrost ecosystems, such as those found in the high-altitude permafrost ecosystems of the Qinghai–Tibet Plateau.

The Qinghai–Tibet Plateau, with an average altitude of 4000 m a.s.l., represents the largest and highest mid- to low-latitude permafrost region; 54.3% of its total area is underlain by permafrost (Cheng, 2005; Zhao et al., 2010). The soil organic carbon storages found in the Qinghai–Tibet Plateau comprise 30–40 $\times$ 10^9 t, which accounts for more than 20% of the soil organic carbon storage in China and 2–3% of the global soil carbon pool (Wu et al., 2012). Over the past few decades, a clear warming trend and widespread permafrost degradation have been observed in the Qinghai–Tibet Plateau (Zhang et al., 2008), which was characterized by the increased mean annual ground temperature, increased depths of the seasonal thawed active soil layer and reduced thickness of permafrost (Cheng and Wu, 2007; Li et al., 2012). Permafrost degradation has resulted in changes in the soil energy and moisture balances as well as the plant productivity and diversity (Cheng and Wu, 2007; Wang et al., 2014; Yang et al., 2010). Further, permafrost degradation on the Qinghai–Tibet Plateau will affect C exchanges between the atmosphere and the soil (Yang et al., 2010), and the extent of this impact is strongly depended on the vegetation type, soil properties, soil hydrothermal regimes, and SOM composition (Baumann et al., 2009; Ping et al., 2014). Therefore, knowing the dynamics of soil organic carbon of the Qinghai–Tibet Plateau is very important. To date, several studies have been dedicated to total soil organic carbon stocks of the permafrost soils in the Qinghai–Tibet Plateau in the context of climate change and have concluded that the distribution of total soil organic carbon stock was largely determined by vegetation communities and soil moisture content (Baumann et al., 2009; Wu et al., 2012). However, a comprehensive understanding of the seasonal variations of labile SOM fractions and their responses to changing climate (i.e., temperature and moisture) and substrate availability (i.e., plant inputs) is still largely unknown.

This uncertainty hampers our ability to predict the responses of labile SOM fractions to the changing climate and substrate availability. Therefore, the objectives of the present study were (1) to characterize the seasonal variations in dissolved organic carbon (DOC), light-fraction carbon (LFC) and nitrogen (LFN), and microbial biomass carbon (MBC) and nitrogen (MBN) in the permafrost-affected soils under different vegetation types; and (2) to clarify the contributions of relevant climatic parameters to the observed responses of substrate availability and labile SOM fractions in these regions of the central Qinghai–Tibet Plateau.

2. Materials and methods

2.1. Site description

The study was conducted from April 2013 to March 2014 (11 months total) between Xidatan and the Beiluhe (34°50′–35°43′ N,92°56′–94°08′E) along the central Qinghai–Tibet highway in China's Qinghai Province (Fig. 1), where the altitude ranges from 4538 to 4753 m a.s.l. The region has a typical continental alpine cold and dry climate with a mean annual precipitation ranges from 290.9 to 393.0 mm, of which more than 70% falls during summer (from June to August). The mean annual air temperature ranges from −6.0 °C to −3.8 °C (Wang et al., 2001; Yang et al., 2004; Yue et al., 2013; Zhao et al., 2006). The study area is underlain by continuous permafrost, with an active layer developing during the thawing period to a maximum depth of 1.5 to 2.5 m, depending on the vegetation and soil types (Yue et al., 2013; Zhao et al., 2006).

We studied four typical vegetation types in the study area: (1) alpine swamp meadow (ASM), which is located in the Beiluhe1 area and is dominated by *Kobresia tibetica*, *Kobresia humilis*, and *Kobresia pygmaea*; (2) alpine meadow (AM), which is located in the Xidatan area and is dominated by *K. pygmaea* and *Androsace tapete*; (3) alpine steppe (AS), which is located in the Beiluhe2 area and is dominated by *Carex moorcroftii* and *Leontopodium nanum*; and (4) alpine desert (AD), which is located in the Kunlun Pass and is dominated by *Littledalea racemosa* and *Poa annua*. Vegetation cover was the highest in ASM, followed by AM and AS and the lowest in AD. The distance between the ASM and AS sites (both in the Beiluhe area) was about 3 km.

2.2. Soil environmental monitoring

Across the entire sampling period (from April 2013 to March 2014), air temperatures at 2 m above the ground and soil temperatures at a depth of 10 cm in the soil from four vegetation types were monitored at 30-min intervals using a CR3000 datalogger (Campbell Scientific, Logan, Utah, USA). Type K thermocouples were used along with reference temperature thermistors on the datalogger to measure air and soil temperatures at a monitoring station about 10 m distance from each experimental site. Soil volumetric water content was monitored using Hydra-Probes (Stevens Water Monitoring Systems Ltd., Portland, Oregon, USA) at a depth of 10 cm in the soil. Air temperatures at the ASM and AS sites were obtained from the databases of the Beiluhe Long-term Observation and Research Station on Frozen Soil Engineering and Environment in Qinghai–Tibet Plateau, Chinese Academy of Sciences. Air temperatures at the AM and AD sites, soil temperatures and soil volumetric water contents for all four vegetation types were obtained from the databases of the Cryosphere Research Station on the Qinghai–Xizang (Tibet) Plateau, Chinese Academy of Sciences. Fig. 2 summarizes the meteorological data.

2.3. Soil sampling and laboratory analyses

We established three 5 m × 5 m plots for each vegetation type for soil sampling. The plots were separated by a distance of at least 3 m to reduce the effects of interactions between plots. Soils were sampled once per month in two days at 0 to 10 cm depth between April and December 2013 and from February to March 2014. Because the soil was totally frozen during January 2014, which made it difficult to collect soil samples, we did not obtain soil samples in this month. In each plot, 8