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Impacts of surface soil organic content on the soil thermal dynamics of alpine meadows in permafrost regions: data from field observations

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ABSTRACT

The relationship between soil organic matter and soil temperature plays an important role in our understanding of the effect of climate change on the hydrological and carbon cycles in permafrost regions. Several studies have documented that the organic horizon thickness has profound buffering effects on soil temperature for both tundra and boreal forest ecosystems. In the present study, the alpine meadow ecosystem in the middle and low-latitude permafrost region of the Qinghai–Tibet Plateau (QTP) was selected to examine the impacts of surface soil organic matter on the thermal properties of deep soil. Based on the data obtained from more than 23 observation sites, the relationship between soil organic content and soil temperature dynamics in different seasons was determined. The findings indicate a strong positive exponential (in thawing period) and linear (in freezing period) relationship between surface soil organic content (SOC) and soil temperature dynamics in deep soil layers. The higher SOC at the surface soil layer is associated with a lower rate of soil temperature variation and a later onset time for the thaw–freeze transformation. In permafrost regions of the QTP, the greater lapse rate of soil temperature per 100 m of increased elevation resulted in more significant modification of the SOC and soil thermal relationship in alpine meadows than that in tundra and boreal ecosystems. The coupled soil organic matter, soil thermal and water relationships play an important role in the resilience of permafrost during climate changes.

1. Introduction

Permafrost plays an important role in regulating the vegetation distribution, soil carbon, and water cycle in high latitudes and in the Qinghai–Tibet Plateau (Tchebakova et al., 2009; Wang et al., 2004). Previous studies have shown that permafrost is influenced directly by changes in air temperature, vegetation cover and snow (Romanovsky et al., 2010; Wang et al., 2007; Zhang, et al., 2003) or indirectly through changes in hydrology or a wildfire disturbance that modifies the soil thermal regime (Jorgenson et al., 2010; Wang et al., 2012). Recent global warming has initiated permafrost degradation in Alaska (Osterkamp, 2007), Canada (Camill, 2005), Russia (Tchebakova et al., 2009) and Qinghai–Tibet Plateau (Wu and Zhang, 2008). Several modeling studies have projected that the permafrost degradation will be continual and widespread across the circumpolar region over the 21st century (Sazonova and Romanovsky, 2003; Lawrence et al., 2012). Consequently, changes in soil temperature alter the degradation and accumulation of soil carbon, habitats for vegetation and the surface water cycle (Schuur et al., 2008; Jorgenson et al., 2010). However, we still have an incomplete understanding of the complex interactions and feedbacks among air, vegetation, soil in active layer and permafrost (Jiang et al., 2012; Jorgenson et al., 2010; Shur and Jorgenson, 2007). To date, considerable uncertainties exist in the complex interaction of local factors (e.g., vegetation, soil properties, soil drainage, and topographical condition) that mediate the effects of air temperature on permafrost temperature (Jorgenson et al., 2010; Yi et al., 2009). Topography affects the vegetation distribution, soil texture, soil drainage, and soil temperature. Vegetation affects the soil texture, soil hydrothermal properties and water cycle (Wang et al., 2012). In turn, soil texture and hydrothermal properties have a particularly important effect on permafrost temperature and permafrost ecosystems (Jorgenson et al., 2010; Shur and Jorgenson, 2007).

The buffering effect of the low-conductivity surface organic matter on soil hydrothermal characteristics within an active layer is profound for both tundra and boreal forest sites in arctic regions (Jiang et al., 2012; Nicolsky et al., 2007). In black spruce forest, it was determined that the highest correlations occurred between minimum daily surface temperature in July and organic layer thickness. Average annual temperatures and average summer temperatures are inversely proportional to the thickness of the organic layer (Harden et al., 2006). O'Donnell et al. (2011) observed a negative exponential relationship between active layer depth (ALD) and organic horizon thickness (OHT). The sensitivity of soil organic matter (SOM) to air temperature change, in turn, resulted in

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changes in the soil organic matter distribution pattern, and the response of the soil organic layer to climate change is likely to depend not only on temperature and water conditions but also on complex interactions among soil properties, vegetation type and SOM chemistry (Fang et al., 2005; Paré and Bedard-Haughn, 2013). However, few studies have collectively examined the interaction of air, vegetation, and soil organic matter to provide insight regarding how these factors affect freeze-thawing processes and ecosystems in the permafrost. Our understanding of the relationship between soil organic matter (SOM) and soil temperature affects our predictions of the impact of climate change on permafrost, vegetation succession and soil-stored carbon (Fang et al., 2005; Lenton and Huntingford, 2003). Although simulations of how changes in organic matter horizons influence soil thermal and hydrological dynamics have been improved in several newer, large-scale ecosystem models, the interactions between soil temperature, soil moisture, soil organic matter and vegetation cover remain unclear and inadequately modeled (Jafarov et al., 2012; Yi et al., 2009). To understand these interactions better, it is necessary to conduct field observations in various topographies, climates, and ecosystems to gather more data and elucidate the mechanisms of these interactions.

Since the 1950s, the relationship between soil organic matter thickness and soil hydrothermal properties of the active layer has attracted considerable academic interest, but there are still no existing quantitative expressions that are useful for large-scale models, including land-surface models, ecosystem models and permafrost models (Garcı'a et al., 2007; Phil-Eze, 2010; Yu et al., 2009). The interactions among soil properties, soil organic matter, vegetation and soil hydrothermal dynamics are among the most important issues and challenges in soil and plant management and for the development of more accurate, large-scale ecosystem and land surface models. Introducing the quantitative expressions for relationships between the organic layer and soil hydrothermal dynamics might decrease current modeling bias. Therefore, the optimal additional organic layer(s) must be considered when developing numerical permafrost models and ecosystem models (Jafarov et al., 2012; Oleson et al., 2008; Yi et al., 2009), but these processes are poorly understood, particularly in permafrost regions (Schaefer et al., 2009; Yi et al., 2009). With climate warming, present continuous permafrost will turn into discontinuous permafrost, and vegetation change can develop sufficient upper organic layers to provide additional effects on soil freeze-thawing processes. For long-term climate change, understanding the relationship of the SOM and soil hydrothermal dynamics of active layer under different vegetation cover plays a critical role in the accurate prediction of the response of permafrost and alpine or cold ecosystems to climate changes (Fang et al., 2005; Jafarov et al., 2012; Yu et al., 2009).

The energy and water balance of the Qinghai–Tibet Plateau has an important influence on the Asian monsoon system, and thus is an important component of the energy and water cycles of the global climate (Wu and Zhang, 2008; Zhang et al., 2003). The permafrost region of the Qinghai–Tibet Plateau represents a distinct cryospheric environment at mid-latitudes, housing a number of typical alpine landscapes, including alpine meadows and alpine steppes, whose ecosystems and water cycles have clearly been adversely affected by global climate changes with air temperature rising from 0.4 to 0.6 °C in the last decade (Li and Wu 2005; Wang et al., 2007). Some early studies in this region have shown that there are close ties between permafrost and the extent of vegetation; indeed, permafrost degradation was found to significantly alter the vegetation (Li et al., 2013; Wang et al., 2007). It is important in understanding regional variations in water and energy cycling arising from global climate changes to understand the mechanisms behind the impacts of climate changes on alpine ecosystems in the permafrost region of QTP, and the laws governing variations in soil heat and associated soil water within the active layer of alpine ecosystems (Zhang et al., 2003). Thus, it is important to describe the interactions of air temperature, soil heat–water coupling, soil organic matter and alpine vegetation cover in the permafrost region. However, given the Qinghai–Tibet Plateau permafrost region's high sensitivity to climatic changes, the vegetation–soil–atmosphere water cycle and heating–cooling processes coupled thereto are quite complex. In addition, few studies have documented the effects of SOM changes on the relationship between soil moisture and temperature in the permafrost regions of the QTP (Wang et al., 2007; Zhang et al., 2005). In contrast to certain arctic regions where tundra and boreal forest have been the subjects of concern and study, few studies have examined alpine grassland (alpine meadows) in the permafrost region of the QTP to determine the effects of soil organic matter changes on the permafrost. In this study, we used extensive field data from the center of the QTP permafrost region to (1) investigate the responses of the soil thermal dynamics to changes in SOC in this mid-latitude permafrost region and (2) test the effect of SOC changes on the soil freeze–thaw processes of active layers in alpine meadows of the permafrost region.

2. Material and methods

2.1. Site description and data collection

The observation sites used in this study were constructed in the Tanggula Mountain and Fenghuo Mountain regions, which are located in the central regions of the Qinghai–Tibet Plateau (Fenghuo Mountain: 92°50′–93°30′ E, 34°40′–34°48′ N; Tanggula Mountain: 33°02′ N, 92°00′ E) (Fig. 1). The two mountains are the typical permafrost regions that have alpine meadows and swamps as the dominant types of vegetation. The observation sites were in alpine meadow with elevations ranging from 4610 to 5323 m. The region has a continental alpine cold and dry climate with mean annual temperature and mean annual precipitation of −4.8 °C and 424.7 mm, respectively. In total, there were 23 sites, among which seven were in alpine wet meadows, and 16 were in ordinary alpine dry meadows (Fig. 1). The dominant plant species are sedges *Kobresia pygmaea* (C. B. Clarke) and *Kobresia humilis* (C.A. Meyex Trauvt.) Serg (Zhou, 2001). Light livestock grazing pressure was found in the study sites prior to the experimental setup (Yang et al., 2012), and fences were used in the study site to prevent yak grazing.

The soil types in the study region are primarily classified as Mattic-Gelic Cambisols (alpine meadow soil) in Chinese taxonomy (NSSO, 1998) or as Cambisols in FAO/UNESCO taxonomy. The depth of the active layer of the soil ranged from 1.9 to 2.1 m in the alpine wet meadow and from 1.95 to 2.5 m in the alpine meadow (Wu and Liu, 2004). At each site, we randomly selected five points to collect soil samples from the top 20 cm. The soil samples were then dried and mixed to determine the properties of the soil in the laboratory. The bulk densities of the soils and the soil organic matter contents (SOM) were determined simultaneously, and the mean values were calculated for each site. Soil organic carbon (SOC) was determined by using a Carlo Erba NA1500 (Lakewood, NJ, USA) elemental analyzer. To remove inorganic carbon, all samples were acid treated with sulfurous acid (6% H_2SO_3) prior to analysis (O'Donnell et al., 2011; Skjemstad and Baldock, 2008). The physical characteristics of the soil profiles for the different vegetation covers are listed in Table 1.

Fig. 1 shows the field observation sites distributed in the Fenghuo Mountain area, where 19 sites were located in both wet alpine meadow and dry meadow. Only 4 sites located in the Tanggula Mountain area (not shown in Fig. 1). In 14 sites (including 4 sites in the Tanggula Mountain area and 10 sites in the Fenghuo Mountain area), the soil moisture and temperature at depths of 0.05, 0.20, 0.30, 0.40, 0.80, 1.0, and 1.20 m were measured by temperature (Vaisala HMP45AC, Finland) and moisture (CS616, Campbell, USA) sensors with Data logger (CR1000, Campbell, USA). At other 9 sites, the soil moisture and temperature at depths of 0.05, 0.10, 0.20, 0.30, 0.40, 0.80, 1.20 and 1.60 m were measured. Both soil moisture and temperature were monitored simultaneously at 30 min intervals from April to November, and at 2-h intervals from December to March. Two micro-meteorological stations