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Original Articles

Soil enzyme response to permafrost collapse in the Northern Qinghai-Tibetan Plateau

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ABSTRACT

Permafrost degradation can result in the formation of permafrost collapsed ground features, and thus greatly alter soil variables such as moisture, pH, soil carbon and nitrogen content, and the biogeochemical cycling of soil carbon. However, little is known about the biogeochemical processes in these features within mountainous-permafrost areas. We examined activities of six different soil enzymes (invertase, amylase, catalase, polyphenol oxidase, urease, and alkaline phosphatase) in three micro-topographical settings (i.e., collapsing, collapsed, and an unaffected control site) of a typical thermokarst feature on the northern Qinghai-Tibetan Plateau. Our results show soil moisture is substantially lower within the permafrost thaw-induced collapsed feature. In addition, soil organic carbon, light fraction organic carbon and total nitrogen in the upper 10 cm soil depth were lower in soils where permafrost was in the process of collapsing. Accordingly, soil enzyme activities varied considerably among the three settings, indicating biogeochemical processes have been altered by permafrost collapse. The invertase activities in collapsing soils were significantly lower than those of the control and collapsed soils for the upper 0–20 cm layer. Coefficient of variation values for amylase and polyphenol oxidase were 44.1% and 6.7%, respectively. For 0–10 cm soil depth, the catalase in collapsing soils were highest while the urease activities were lowest among the three settings. Statistical analysis demonstrated that light fraction carbon content, C:N ratios, and moisture were the most important predictors for enzyme activities. These results suggest that soil enzyme activities are good indicators for the decomposition of organic matter in permafrost collapse-affected areas.

1. Introduction

Permafrost, covering about one quarter of the land surface in the Northern Hemisphere (Zhang et al., 2008) and containing 1100–1500 Pg of organic carbon (Hugelius et al., 2014), is the largest terrestrial carbon pool. During the past decade, permafrost degradation has been detected widely both in high altitude and high latitude regions. The permafrost degradation can make the carbon preserved in the frozen soils more accessible to microbial decomposition, and also increases soil respiration rates in the active layer (Hicks Pries et al., 2015). Therefore, permafrost degradation can release large quantities of greenhouse gases from soils, which will likely magnify the climate warming and form a positive feedback loop (Dorrepaal et al., 2009; Schuur et al., 2008). It has been projected that about 10% of the permafrost carbon may enter into the atmosphere as greenhouse gases within this century (Schuur et al., 2015).

Thermokarst commonly occurs in ice-rich permafrost regions along with permafrost degradation since the melting of ground ice removes support of the ground surface (Balser et al., 2014; Burn and Lewkowicz, 1990; Jorgenson et al., 2006). Common thermokarst features observed in upland areas are thaw slumps, thermal erosion gullies and active layer detachments (Bowden et al., 2012; Gooseff et al., 2009; Krieger, 2012; Lewkowicz and Harris, 2005). Thermokarst features have been considered as one of the major sources of uncertainty in predicting ecosystem carbon balance in permafrost regions (Abbott et al., 2016).

The Qinghai-Tibetan Plateau (QTP) is the largest geomorphological

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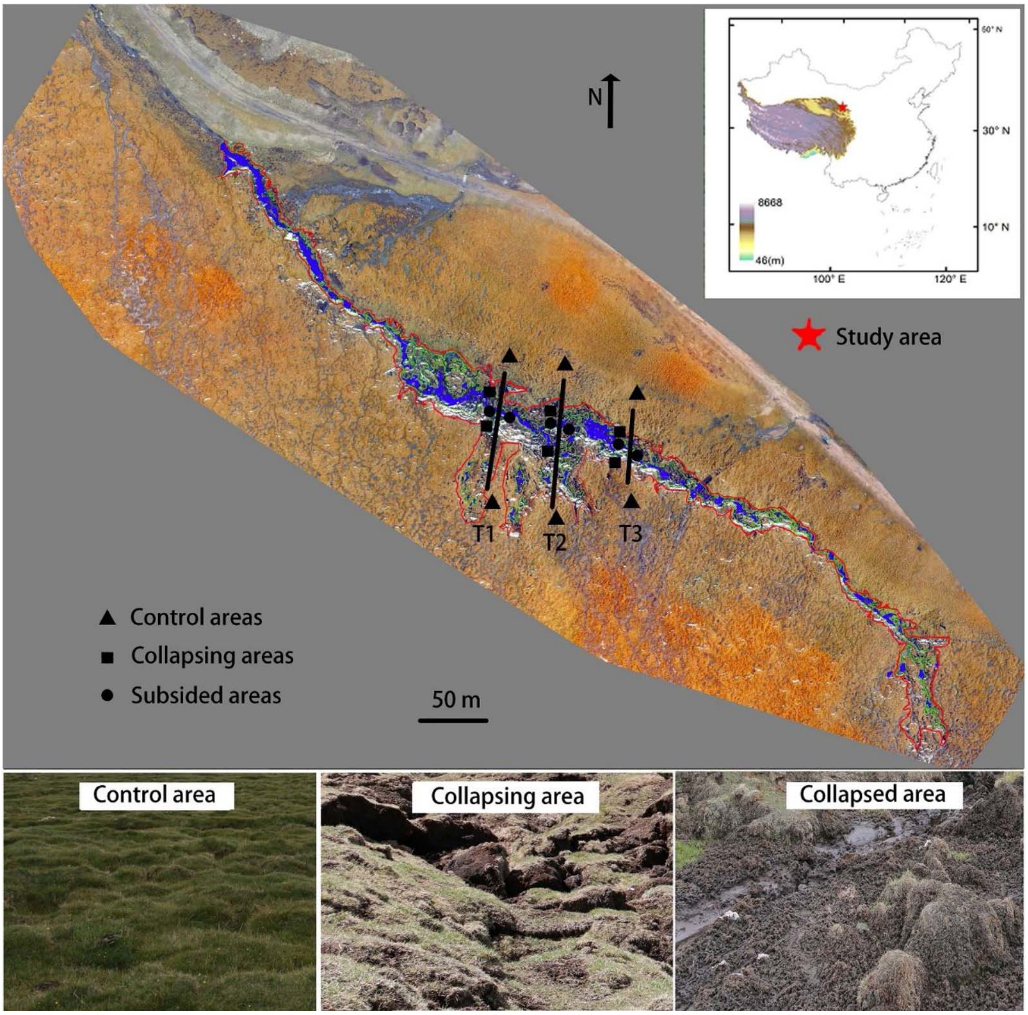

Fig. 1. Location of the study area and the three sampling different settings. The red line denotes the permafrost collapse-affected area. The blue areas outlined in green are collapsed areas (collapsed and without vegetative cover). The rest of the area within the red line are drape patches (collapsed with intact vegetation). The control areas were approximately 10–15 m outside of the red lines (> 5 m from the boundary where ground surface showed subsidence or deformation). T1, T2, and T3 are the transects along the gully where the samples were collected. The bottom image shows the three different settings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unit of the Eurasian continent and is the largest low-latitude permafrost region in the world. The permafrost area on the QTP is about 1.06×10^6 Km^2 (Zou et al., 2016), containing about 160 Pg organic carbon in the upper 25 m of soil (Mu et al., 2015). The permafrost on the QTP is very sensitive to climate warming because it is considered as "warm" permafrost and the ground temperature is near the freezing point (Wu and Zhang, 2010; Zhao et al., 2010). Multiple thermokarst features have been detected on the QTP (Niu et al., 2012). However, our understanding of biogeochemical processes associated with those features is very limited.

Soil enzymes are the primary mediators of soil biological processes, including organic matter degradation, mineralization and nutrient recycling (Sinsabaugh et al., 2014; Sinsabaugh, 2010). Soil enzymes are produced by both plants and soil microorganisms, and they catalyze important transformations in nutrient cycles, including those of carbon, nitrogen, and phosphorus (Wallenstein et al., 2009). Numerous soil microenvironments and properties influence *in situ* soil enzyme activities, such as temperature, moisture, substrate quality and availability (Allison and Jastrow, 2006; Hernández and Hobbie, 2010; Sinsabaugh et al., 2014; Wallenstein et al., 2009), pH (Rousk et al., 2010), redox status (DeAngelis et al., 2010), soil texture (Marx et al., 2005) and mineralogy (Heckman et al., 2009). To minimize the resource expenditure, the enzyme activities are usually at levels which can maintain the demand for particular resources (Allison et al., 2007). Therefore, the specific extracellular enzyme activity could provide insight into the intensity of biochemical processes of the substrate which is catalyzed by the enzyme (Burns et al., 2013).

The activities of enzymes play key roles in the biochemical functioning of soils (Song et al., 2013; Yan and Quan, 2013). The assessment of the hydrolases activities can provide information on the status of key reactions that participate in the rate limiting steps of the decomposition of organic matter and the transformation of nutrients in soils (Nannipieri et al., 2002). Soil enzyme activities are sensitive indicators of stress on ecosystems and potentially could serve as robust measures of health and sustainability of soil ecosystems (Dick, 1994). Based on the great heterogeneities in soil moisture and temperature, soil carbon and nitrogen in permafrost collapse-affected areas (Mu et al., 2016; Pizano et al., 2014), we hypothesize that soil enzyme activities will have different patterns among the three settings (control, collapsing and collapsed), and be a good indicator of change in biogeochemical processes. To test these hypotheses, six soil enzymes involved in the C, N, and P cycles were examined to gain an understanding of the soil biogeochemistry in permafrost collapse-affected areas. Our specific objectives were to (i) examine the soil physio-chemical variable, soil organic carbon (SOC) and total nitrogen content in permafrost collapse-affected areas (ii) assess the soil enzyme activities in the different micro-topographies; (iii) analyze the use of enzyme activity as an indicator of change of soil variables (including soil pH, moisture, soil carbon and nitrogen) in this area. The results provide insights into the impact of the thermokarst processes on the carbon cycle, which is an area of great uncertainty.