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Effect of fire on solute release from organic horizons under larch forest in Central Siberian permafrost terrain

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ABSTRACT

To evaluate the effects of forest fire and post-fire stand recovery on the organic layer chemistry and solute release within mound and trough microrelief elements (termed earth hummock microtopography) that mainly distribute permafrost affected area, we chose five fire plots (larch forests burned in 1951, 1981, 1990, 1994 and 2005) paired with adjacent control plots in mature larch forests in Central Siberian permafrost terrain. We determined total carbon, nitrogen and ash content in solid organic soils, and analyzed total carbon, nitrogen, bases and major anions in water extracts. There was a significant correlation between water-extracted organic carbon (WEOC) and total carbon (kg m^{-2}) in area basis, implying that the quantity of total carbon was a major factor in WEOC production. WEOC correlated negatively with pH, indicating strong control by organic horizons (organic solute leaching) on soil acidity and base cation dynamics. The sum of water extractable base cations was also correlated significantly to total carbon, indicating that cations can be released through organic matter decomposition. Organic horizons in troughs in burned plots released greater amounts of Ca, Mg and K than those in mounds, probably due to greater content of organic matter as a cation source. Anions including nitrate and phosphate and WEOC also accumulated in trough depressions, due probably to organic matter degradation. The contrasting distribution of solutes between mounds and troughs in burned plots seems to be controlled by organic horizon development via changes in microtopography after forest fires.

1. Introduction

The forest floor plays a significant role in boreal zone biogeochemical cycles, especially in the permafrost regions. Organic horizons developed under mosses serve as a large carbon sink, and have one order of magnitude greater organic carbon than in aboveground vegetation biomass (Prokushkin et al., 2006). Thick organic horizons also accumulate major nutrients such as N, P and S in organic form (Kaiser et al., 2001; Miyamoto and Hiura, 2008; Turner et al., 2004), making nutrients less accessible to higher plants. Dissolved organic carbon from the organic horizon constitutes ~10–25% of total annual C flux in the Siberian forest (Prokushkin et al., 2005), while dissolved organic nitrogen is likely the main form of N flux in boreal zone larch ecosystems. Thus organic horizons are major sources of solutes for microbial and/or plant nutrition produced during soil organic matter decomposition. Moreover solutes being released from surface organic horizons can be run off on the ground surface due to hampering vertical water infiltration by freezing mineral soils, especially in early spring, contributing to biological activity and productivity in the surrounding aquatic systems.

Thick organic horizons also play an important role as a heat insulator in summer from solar radiation, leading to cooler and hydromorphic soils with shallower active layers (Trumbore and Harden, 1997). Inversely, saturated frozen organic horizons in winter have higher thermal conductivity than dried ones in summer (Kujara et al., 2008), maintaining permafrost table higher position. However, once the organic horizons are removed, by forest fire in particular, the thermal regime in the active layer is changed drastically, resulting in a deepened active layer (Burn, 1998; Yoshikawa et al., 2002) probably causing subsidence (Kokelj et al., 2007), which is thermokarst (Jorgenson et al., 2006). Thawing ice in the active layer leads to degradation of the typical bowl-shaped permafrost table and thus flattens both the permafrost table and ground surface (Kokelj et al., 2007). During these microtopographic changes, soil minerals and organic materials can be redistributed within the mineral soil and/or spread across microrelief elements following cryoturbation processes. Hence potential release of nutrients and carbon from the organic horizons could be affected by topographical dynamics. Changes in nutrient and carbon release seem also to be influenced by fires, and tracking organic horizon change after fire is valuable for characterizing nutrient dynamics in permafrost terrain.

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In the Siberian larch (*Larix gemelinii Rupr.*) taiga, wildfires mainly burn organic matter accumulated on the ground surface due to low stand density and low inflammability of larch foliage (Hayasaka, 2004; Ito, 2005). Thus a forest fire can volatilize nutrients such as N, P, K, and S, with loss of Ca and Mg in particulate form as aerosols and fine ash mainly from organic horizons (Raison et al., 1985; Trabaud, 1994). This shifts the organic horizons from being sinks to sources of these elements, and consumption of organic horizons and changes in chemical composition by ground fires further lowers organic horizon potential to produce solutes (Murphy et al., 2006; Shibata et al., 2003).

Recently, fire frequency and burnt areas in Siberian forests have increased rapidly due mainly to anthropogenic activities (Fukuda, 2003; Kharuk et al., 2008). Thick organic horizons functioning as elemental sinks may be thinned due to the frequent fires. Therefore, it is necessary to evaluate various elemental dynamics in these ecosystems in relation to forest fires and stand recovery. Here, we address changes in properties of organic horizons developed in mature larch forests immediately after fire, and subsequent forest regeneration. Solutes release potential from the organic horizon samples were evaluated with respect to forest stand recovery further in connection with the development of earth hummock microtopography. The organic horizon sampling was conducted taking care of the hummock microtopography because ground fire that is a typical forest fire in Siberia differentiate burning of organic horizons depending on the hummock microrelief.

2. Materials and methods

2.1. Study area

The study area, in northern Central Siberia, is situated within the lower part of the Kochechum River watershed (64°N, 100°E), which is a branch of the Nizhnyaya Tunguska River, which is an eastern tributary of the Yenisei River. The watershed is on the Syverma plateau located in the Siberian Basaltic Province. Larch forests widely dominate the watershed. The permafrost-affected soils developed in the Siberian Basalt and are classified as Oxyaquic Cryosols or Gelic Cambisols according to the WRB classification system (FAO, 1998). Active layer thickness varies from shallow (several tens of cm) on north-facing slopes to deep (>1 m) on south-facing slopes. Beneath the soils, there is continuous permafrost of 200–300 m thickness (Pokrovsky et al., 2005). The permafrost table in this region prevents soil water percolation and drainage, keeping the soil moist. This hydromorphy, accompanied by low soil temperature, promotes organic horizon thickening to >10 cm. A thick mat of mosses (*Pleurozium schreberi Mitt.*, *Hylocomium splendens B.S.G.* and *Aulocomnium palustre Schwaegr.*) with a lichen component covers the organic horizons, and their necromass accompanied by larch litter contributes to the large accumulation of organic matter on the ground surface. During the last half century, forest fires have occurred repeatedly in the study area (~900 km^2) (1951, 1981, 1990, 1994 and 2005), enabling us to track changes in organic horizons with forest recovery. Changes in the hummock terrain during forest re-growth, which is a typical microtopography on the continuous permafrost, were also focused on concurrently as a factor influencing elemental dynamics in the organic horizons.

This area is characterized by a sharply continental climate, with a mean annual temperature of −9.1 °C, varying from −36 °C in January to 16.5 °C in July. Long-term average annual precipitation in this territory is 354 mm. One-third of precipitation originates from snowfall, and the remainder is concentrated in the short summer and autumn months between June and September.

2.2. Hummock microtopography

A specific topography termed "earth hummocks", is a typical microtopography in the study area as well as the rest of the permafrost-affected regions. The microrelief is characterized by mounds neighboring bowl-shaped depressions (Fig. 1), and is a specific feature of the earth hummocks that formed mainly by permafrost aggradation accompanying the freeze-thaw cycles of the active layer enabling to establish the bowl-shaped permafrost table (Kokelj et al., 2007; Mackay, 1980; Walker et al., 2008). The hummock relief was unique at each plot. The difference in ground surface level between a mound top and a trough bottom at each plot was determined by direct measurement. In troughs, frozen soil or ice sometimes exists just beneath an organic horizon, even in mid-summer. During the earth hummock formation process, soil solids are probably prone to subsidence into troughs due mainly to gravitational submergence (Mackay, 1980). Higher soil organic carbon content has been observed in the mineral soils under troughs than in adjacent soils (Sawada, 2006). The vertical distribution of minerals and organic components in permafrost-affected soils seems to depend on this typical microtopography.

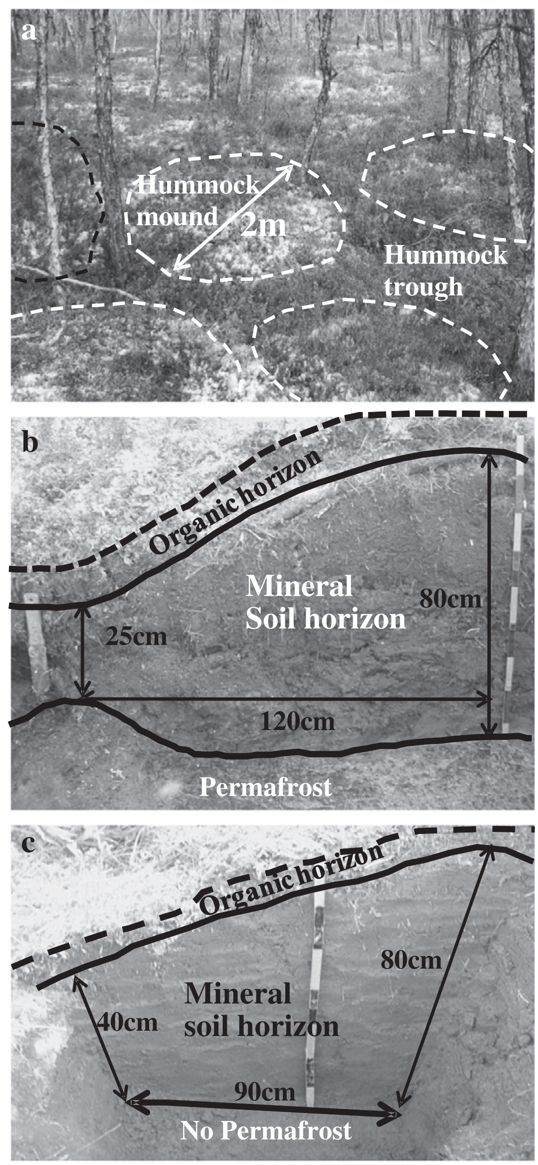

Fig. 1. (a) Ground surface of the hummock microtopography. Hummock mounds are indicated by dashed circles. (b) Soil profile in the 1994 control plot, showing the horizontal transition from hummock mound to hummock trough center, and vertical profile to the permafrost table. (c) Soil profile in the 1994 burned plot showing a hummock mound and hummock trough center to 80 cm depth.