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Soil organic matter composition along altitudinal gradients in permafrost affected soils of the Subpolar Ural Mountains

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A B S T R A C T

Soil organic matter (SOM) in high-latitude soils is assumed to be highly vulnerable to climate changes. Relative little information exists from soils of mountain ecosystems which might respond differently to permafrost melt than in flat terrain due to a better drainage. In this study, we measured SOM composition of six typical soils along an altitudinal gradient of the remote Subpolar Urals, reaching from alpine tundra to the forest zone. The SOM characteristics was estimated by applying ^{13}C nuclear magnetic resonance (^{13}C NMR) spectroscopy, electron paramagnetic resonance (ESR), elemental analysis and amino acid composition of humic acid (HA) extracts from soils. Result showed that SOM stocks ranged between 8 and 13 kg C m^{-2} but reached up to 40 kg C m^{-2} in a Stagnic Podzol in the alpine tundra. In the mineral soil, ^{13}C NMR indicated that the contribution of alkyl-C was 60% in the forest and 50% in the tundra, while aromaticity was 5% in the tundra, but 19% in the forest. This shows that SOM of mineral soils in alpine tundra was more aliphatic but less aromatic than in the Podzols of the forested zone. In contrast to mineral soils, SOM characteristic in organic layers was very similar among all soil types despite different vegetation types. Consequently, we suggest that the large difference in SOM quality in the mineral soil between tundra and forest can primarily be attributed to abiotic soil conditions in the deeper soil with a stronger waterlogging and a lower permafrost depth in the tundra soils. The low status of oxidative SOM degradation in the mineral soil of the tundra is also an indication that SOM of tundra is highly vulnerable to an improved aeration associated with permafrost melt in drained mountain soils.

1. Introduction

Soils of high latitudes play an important role in the global carbon cycle. In the northern permafrost region, soils store about 40% of the global soil organic carbon on 17% of the area (Hiederer and Köchy, 2011; Jones et al., 2010; Tarnocai et al., 2009). Mountain soils with permafrost contain 66 Pg of soil organic carbon, which constitutes 4.5% of global pool (Bockheim and Munroe, 2014). These large carbon reserves are assumed to be highly vulnerable, because thawing of 'locked' carbon potentially releases large amounts of CO_2 and CH_4 to the atmosphere (Lal, 2005; Waldrop et al., 2010; Zimov et al., 2006). In addition, climate change scenarios predict a particular strong climate warming at high latitudes, strongly suggesting that permafrost melt will become reinforced potentially affecting world's climate in the near future (Harden et al., 2012).

Soil organic matter is a complex mixture of different organic substances. The chemical and functional properties of SOM are determined by the interaction of a number of factors such as the amount and chemical composition of plant detritus, the soil microbial community structure, microclimatic conditions and the mineralogical soil properties (Kögel-Knabner and Amelung, 2014; Schmidt et al., 2011). The chemical compounds contained within SOM differ in their bioavailability and in their affinity to the soil mineral phase (Kögel-Knabner and Amelung, 2014). Hence, the analysis of the chemical properties of soil organic matter helps to understand SOM vulnerability and to predict the responses of SOM to climate change (Xu et al., 2009). Soil humic acids (HAs) reflect the principle SOM properties and allow the assessment of SOM compounds involved in the biogeochemical cycle (Abe and Watanabe, 2004; Kholodov et al., 2011). One powerful approach to characterize SOM composition is nuclear magnetic resonance (^{13}C NMR), which quantifies the relative contribution of different chemical groups in humic substances (Kögel-Knabner, 2000). Based on NMR spectra, for instance, Sjögersten et al. (2003) showed that tundra soils of Scandes contained large fractions of labile SOM, suggesting that these soils may respond sensitive to climatic warming.

Most studies on permafrost soils have been conducted in the plains, primarily in North America (Dai et al., 2001; Gittel et al., 2014; Zimov et al., 2006). However, due to the overarching effect of anaerobicity upon permafrost melt (Harden et al., 2012; Waldrop et al., 2010), it seems likely that SOM cycling may respond fundamentally different to

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permafrost melt in mountains than in the plains because mountain soils are generally much better drained (Hagedorn et al., 2010). So far, mountains soils of the high Eurasian Arctic have hardly been studied except in the Scandes where permafrost is not widely spread (e.g. Sjögersten et al., 2003). In Russia, mountain soil studies have primarily focused on morphological and physicochemical soil properties (Dymov and Zhangurov, 2011; Firsova and Dedkov, 1983; Lesovaya et al., 2012; Semikolennykh et al., 2013; Vladychenskii, 1998). However, the few assessments of the carbon pools showed that mountain soils from mountain-tundra and mountain-forest belts contain high carbon stocks of 5 to 40 kg m^{-2} in the upper 50-cm soil layer (Pereverzev, 2011; Pereverzev and Alekseeva, 1980); partly exceeding the soil carbon stocks in Mid- and Northern Europe. In the South Ural Mountains, Kammer et al. (2009) have shown that although SOM pools remained almost constant with altitude and hence with climatic conditions, SOM composition strongly changed with thinner, more decomposable organic layers in the subalpine forest than in the tundra above.

Forest–tundra ecotones are a temperature sensitive vegetation boundary (Körner, 2012). Treeline advances and hence forest expansion have documented along the Ural mountain range and in other regions of Siberia (Devi et al., 2008; Hagedorn et al., 2014; Kirdyanov et al., 2012), very likely due to climatic warming and/or improved snow conditions. The climate change driven increase in forests will affect soil carbon cycling indirectly by changing microclimatic conditions and organic matter inputs into soil (Hagedorn et al., 2010; Kammer et al., 2009; Sjögersten-Turner et al., 2011). Hence, there is a complex interplay of climate change with other biotic and abiotic factors, which makes prediction on SOM cycling and characteristics difficult (Saenger et al., 2013; Zollinger et al., 2013).

Here, in our study, we assessed the pools and composition of SOM in high-latitude soils in one of the most remote and least studied mountain regions in Europe, the Subpolar Urals. We sampled soils from typical ecosystem types reaching from the alpine tundra above treeline on permafrost, the forest zone on drained soils on the slopes to mountain tundra on flat terraces with ice lenses. In these soils, we determined the concentration, chemical properties of total SOM and the structure of humic acids in soils. The major aim of this study was to determine how SOM composition and pools differ among typical soils of the Subpolar Urals in order to evaluate how vulnerable they might respond to expected climatic changes.

2. Materials and methods

2.1. Site description and soil sampling

The study was conducted in the Yugyd Va National Park in the northern part of the Subpolar Urals with untouched, natural, and undisturbed ecosystems (Patova, 2010). The study area is located on the Southern limit of perennial icy rocks in the European Subarctic region (Oberman, 1998). The Subpolar Urals are characterized by a strong continental climate with the site specific conditions depending on the local orographic features and the slope aspect. The mean annual temperature varies from −3 to −7 °C. The annual precipitation is 800–1000 mm, with the highest amounts falling in May–October (Taskaev, 1997). The parent materials are acidic rocks (quartzite–sericite schist, porphyric rhyolite) and moraine deposits.

We sampled soils along an altitudinal gradient on the Maldynyrd ridge (65°20′N, 60°40′E) reaching from 400 to 730 m a.s.l. (Fig. 1) and encompassing the following three typical vegetation zones: alpine tundra above 600 m a.s.l.; forest zone with *Larix sibirica* at an altitude of 500–580 m a.s.l.; and mountain tundra on permafrost icy rocks close to the soil surface on gentle slopes and flat terraces at 400–450 m a.s.l. close to the valley bottom. In each of the vegetation zones, we have sampled soils from two soil profiles according to soil horizons. Soil profile and vegetation cover photos are presented in Fig. 2. A short characterization of the study plots and a description and classification of soil according to the World Reference Base for Soil Resources (FAO, 2014) are provided in Table 1. More information on the vegetation and morphological characteristic can be found in Dymov et al. (2013). Soil sampling was carried out in 2011 by taking mixed samples from each horizon at five locations on an area of approximately 2 m^2. Soils were sampled down to the bedrock or to ice lenses which occurred at less than 50 cm depth. Bulk density of soils was determined by taking soil cores of 15 cm in diameter for organic horizons and 5 cm in diameter for mineral horizons. The bulk density values in gravelly horizons were determined according to Zaidel'man (2008). Stone and ice

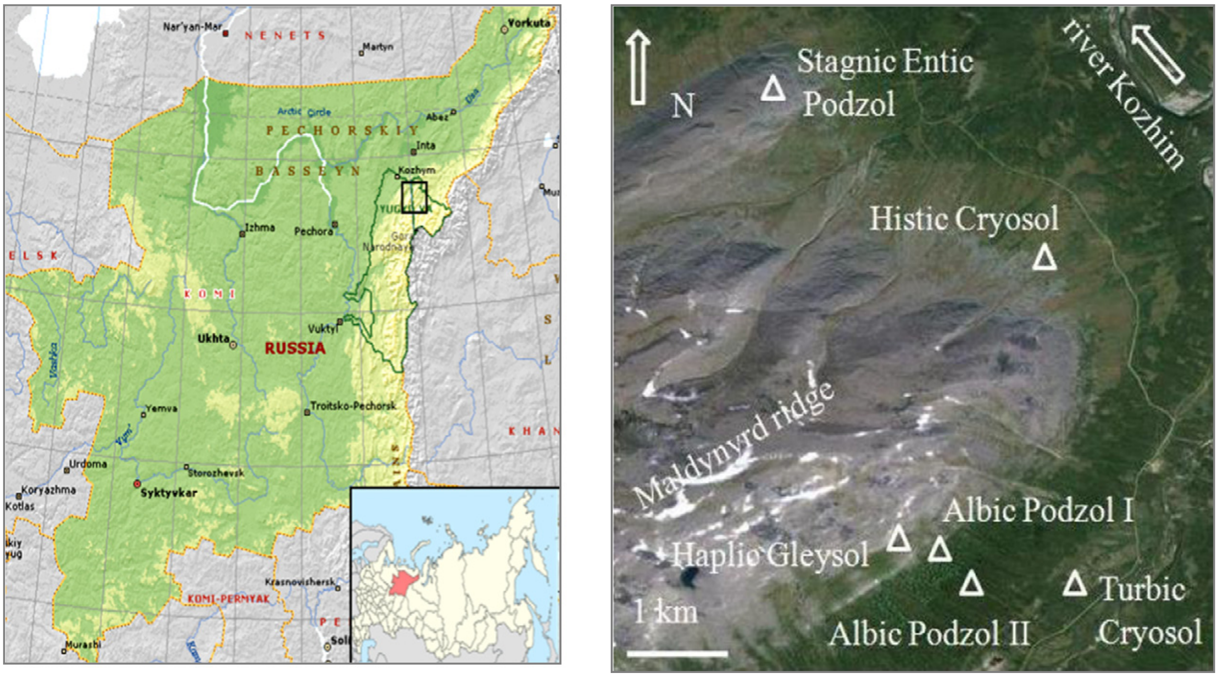

Fig. 1. Location of study sites on the Maldynyrd ridge (65°20′N, 60°40′E) in the northern part of the Subpolar Ural reaching from 400 to 730 m a.s.l.