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Multi-proxy study of soil organic matter dynamics in permafrost peat deposits reveal vulnerability to climate change in the European Russian Arctic

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ABSTRACT

Soil organic carbon (SOC) in permafrost terrain is vulnerable to climate change. Perennially frozen peat deposits store large amounts of SOC, but we know little about its chemical composition and lability. We used plant macrofossil and biomarker analyses to reconstruct the Holocene paleovegetation and paleoenvironmental changes in two peat plateau profiles from the European Russian Arctic. Peat plateaus are the main stores of permafrost soil C in the region, but during most of the Holocene peats developed as permafrost-free rich fens with woody vegetation, sedges and mosses. Around 2200 cal BP, permafrost aggraded at the site resulting in frost heave and a drastic reduction in peat accumulation under the drier uplifted surface conditions. The permafrost dynamics (aggradation, frost-heave and thaw) ushered changes in plant assemblages and carbon accumulation, and consequently in the biomarker trends too.

Detailed biomarker analyses indicate abundant neutral lipids, which follow the general pattern: *n*-alkanols > sterols ≥ *n*-alkanes ≥ triterpenols. The lignin monomers are not as abundant as the lipids and increase with depth. The selected aliphatic and phenolic compounds are source specific, and they have different degrees of lability, which is useful for tracing the impact of permafrost dynamics (peat accumulation and/or decay associated with thawing). However, common interpretation of biomarker patterns, and perceived hydrological and climate changes, must be applied carefully in permafrost regions. The increased proportion (selective preservation) of *n*-alkanes and lignin is a robust indicator of cumulative decomposition trajectories, which is mirrored by functional compounds (e.g. *n*-alkanol, triterpenol, and sterol concentrations) showing opposite trends. The distribution of these compounds follows first order decay kinetics, and concurs with the downcore diagenetic changes. In particular, some of the biomarker ratios (e.g. stanol/sterol and higher plant alkane index) seem promising for tracing SOC decomposition despite changes in botanical imprint, and sites spanning across different soil types and locations. Carbon accumulation rate calculated at these sites varies from 18.1 to 31.1 gC m^{-2} yr^{-1}, and it's evident selective preservation, molecular complexity of organic compounds, and freezing conditions enhance the long-term stability of SOC. Further, our results suggest that permafrost dynamics strongly impact the more undecomposed SOC that could be rapidly remobilized through ongoing thermokarst expansion.

1. Introduction

Soils in northern high latitude regions store large amounts of organic carbon (C) because permafrost and anoxic conditions from water logging reduce decomposition rates (Davidson and Janssens, 2006). Recent estimates of these huge soil organic carbon (SOC) pools in the permafrost region are ~1024 PgC ($Pg = g \times 10^{15}$) in the upper 3 m, with an additional 241 PgC stored in the deltaic deposits and 407 PgC in deep (>3 m) Yedoma deposits (Tarnocai et al., 2009). Because of a warming Arctic climate, there is increased evidence of permafrost thaw (Romanovsky et al., 2010), which may enhance decomposition of SOC stored in soils, and shift them from being net carbon sinks to sources (White et al., 2002). In situ long-term studies have shown that soil warming and permafrost thaw lead to elevated rates of carbon respiration (Schuur et al., 2008, 2009; Dorrepaal et al., 2009). The magnitude and impact of remobilization of carbon pools on climate forcings therefore depend on the extent and rate of thaw in periglacial landscapes, as well as the potential lability of the thawed-out SOC.

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Regional inventories from discontinuous permafrost terrain in the European Russian Arctic have identified permafrost peatlands (particularly peat plateaus, which rise above the surrounding landscape due to high ground ice content) as especially sensitive to carbon remobilization because they hold large stocks of relatively undecomposed SOC (Hugelius and Kuhry, 2009; Hugelius et al., 2011, 2012). These peat plateaus store the largest amount of SOC in the area (≈65% of all landscape carbon), and are particularly vulnerable to remobilization through thermokarst formation (Hugelius and Kuhry, 2009; Hugelius et al., 2011, 2012). The area is currently experiencing permafrost warming and thaw (Oberman, 2008) and, hence, it is of great interest for assessing climate change impacts.

As part of an ongoing investigation at the Seida site (Fig. 1), we have previously characterized decomposition of bulk SOC at the landscape level (Hugelius et al., 2012). In this study, we describe molecular characteristics of SOC stored in the peat plateaus. We analyzed two ^{14}C-dated peat profiles for plant macrofossils and various geochemical proxies. Plant macrofossil analyses are used to ascertain the botanical origin of SOC, as well as to reconstruct Holocene peatland succession at the two investigated sites. To assess SOC lability, we use an array of geochemical analyses involving total organic carbon (TOC), C/N ratios, stable carbon isotopes, and specific biomarkers. The data provide information about the: 1) major components of SOC and their botanical origin, 2) proportion of chemically labile vs. potentially 'refractory' fractions, and 3) preservation of SOC affected by depth/age in relation to permafrost history and changes in the active layer depth. The selected aliphatic (*n*-alkanes, alkanols, sterols, and triterpenols) and phenolic compounds (lignin) and their ratios in particular are useful for tracing the impact of permafrost thawing on carbon storage despite changes in botanical composition. Moreover, the general pattern of peat accumulation overlain with local variations in botanical and geochemical composition, and regional permafrost history converge to explain the current vulnerability of SOC in this area that can be further extended to other permafrost regions in Eurasia and North America.

2. Study area

Peat profiles were collected July–August 2008 from a peat plateau–thermokarst complex located near the village of Seida, west of the Ural Mountains (Fig. 1). The mean annual temperature and precipitation are −6.1 °C and 538 mm (Vorkuta climate station, 75 km northeast of Seida, period 1961–1990), respectively. The area is underlain by undulating glaciofluvial sandy loam of uncertain age (Oberman and Mazhitova, 2003), and was last glaciated during the Late Saalian (160–140 ka).

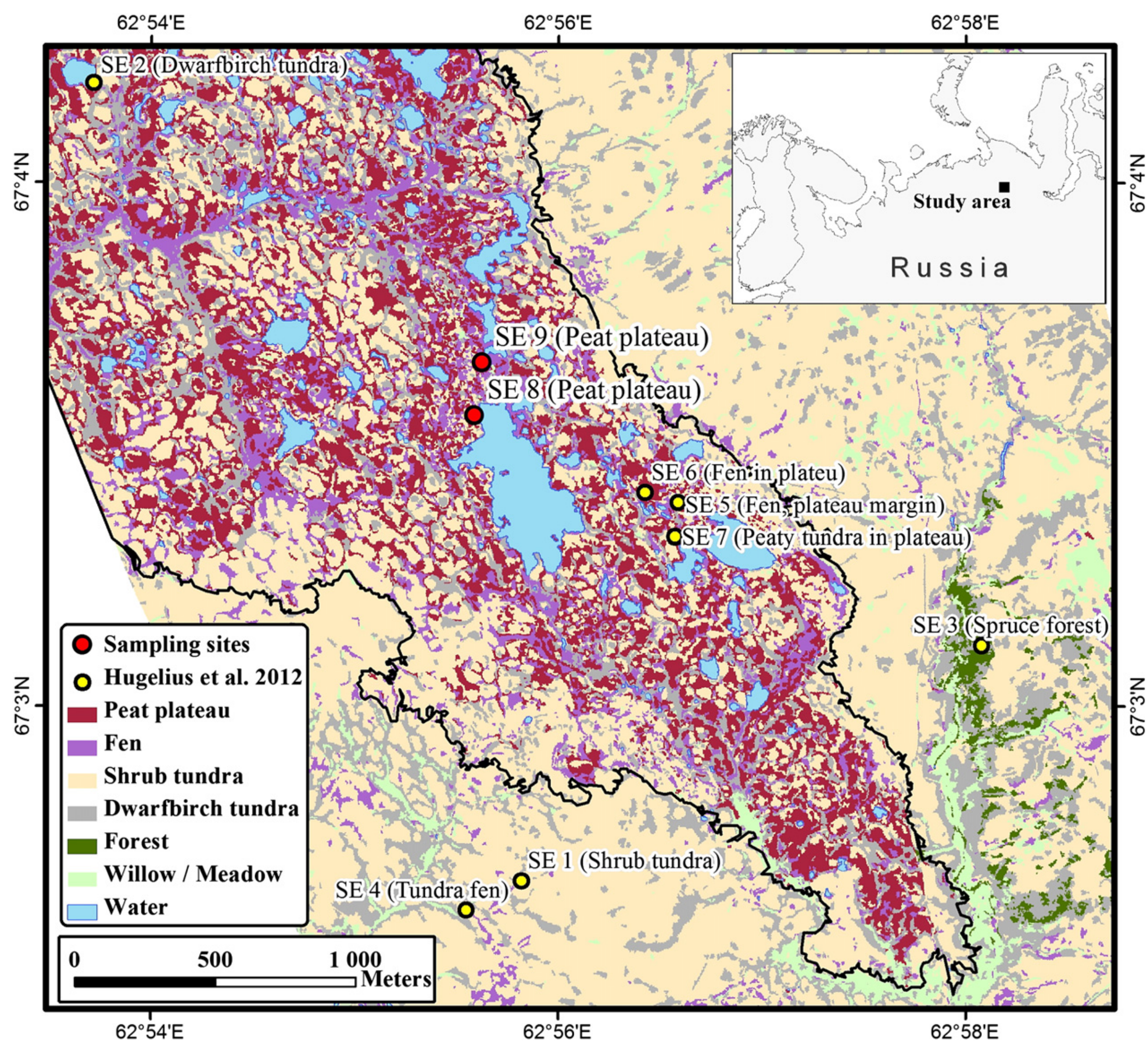

Fig. 1. Sampling locations (SE9 and SE8) and land cover pattern in Seida northern European Russian Arctic (from Hugelius et al., 2012). Molecular characteristics have been detailed for only these two sites, the focus of this study.