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The role of climate change in regulating Arctic permafrost peatland hydrological and vegetation change over the last millennium

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ABSTRACT

Climate warming has inevitable impacts on the vegetation and hydrological dynamics of high-latitude permafrost peatlands. These impacts in turn determine the role of these peatlands in the global biogeochemical cycle. Here, we used six active layer peat cores from four permafrost peatlands in Northeast European Russia and Finnish Lapland to investigate permafrost peatland dynamics over the last millennium. Testate amoeba and plant macrofossils were used as proxies for hydrological and vegetation changes. Our results show that during the Medieval Climate Anomaly (MCA), Russian sites experienced short-term permafrost thawing and this induced alternating dry-wet habitat changes eventually followed by desiccation. During the Little Ice Age (LIA) both sites generally supported dry-hummock habitats, at least partly driven by permafrost aggradation. However, proxy data suggest that occasionally, MCA habitat conditions were drier than during the LIA, implying that evapotranspiration may create important additional eco-hydrological feedback mechanisms under warm conditions. All sites showed a tendency towards dry conditions as inferred from both proxies starting either from *ca.* 100 years ago or in the past few decades after slight permafrost thawing, suggesting that recent warming has stimulated surface desiccation rather than deeper permafrost thawing. This study shows links between two important controls over hydrology and vegetation changes in high-latitude peatlands: direct temperature-induced surface layer response and deeper permafrost layer-related dynamics. These data provide important backgrounds for predictions of Arctic permafrost peatlands and related feedback mechanisms. Our results highlight the importance of increased evapotranspiration and thus provide an additional perspective to understanding of peatland-climate feedback mechanisms.

1. Introduction

High-latitude peatlands play a critical role in the global biogeochemical cycle, through which they also contribute to climate dynamics (Frolking and Roulet, 2007). Temperature and moisture balance are key factors modulating peat accumulation (Carroll and Crill, 1997; Davidson and Janssens, 2006; Ovenden, 1990). Global warming, especially amplified warming in high-latitude regions (IPCC, 2013), is expected to directly stimulate photosynthesis and net primary productivity (NPP) in high-latitude ecosystems because of increased growing season length (Charman et al., 2013). Thus, peat accumulation could accelerate too (Loisel and Yu, 2013). However, higher temperatures also increase peat decomposition rates through accelerated microbial activity (Dorrepaal et al., 2009; Ise et al., 2008), yet there is evidence from the past that during warm periods the increase in NPP exceeded the potential increase in decomposition (Charman et al., 2013). Climate scenario RCP8.5 for Arctic regions predicts that precipitation will increase more than 30% at the end of the twenty-first century (Collins et al., 2013), which could be beneficial for peat accumulation. However, increases in precipitation may be offset by increases in evapotranspiration under higher temperatures (Yu et al., 2009). Also, seasonal droughts may reduce NPP and increase decomposition (Yu et al., 2009). Moreover, habitat-specific plant functional types (PFTs) that characterise different peatlands (fens and bogs) have different NPP dynamics and the distribution of these communities can exert a control on peat accumulation patterns (Tuittila et al., 2012). While climate may directly affect plant productivity

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and decomposition, it may also have larger-scale impacts on the geographical distribution of peatland types (Väliranta et al., 2015).

Arctic permafrost peatlands are sensitive to climatic changes (Gałka et al., 2017a; Lamarre et al., 2012; Swindles et al., 2015a; Teltewskoi et al., 2016; Tremblay et al., 2014) and at the same time, Arctic permafrost peatlands affect local microclimate, hydrology, vegetation, peat and carbon accumulation and these non-climatic factors again influence the degradation and aggradation of permafrost (Zuidhoff and Kolstrup, 2000). Due to pronounced microtopography and persisting ice, eco-hydrological processes and therefore peat accumulation patterns in permafrost peatlands are complex (Oksanen, 2006; Oksanen et al., 2001), making the evaluation of climate change impacts on these environments challenging.

Northern Hemisphere mean annual temperature for the last 30- and 50-year periods is likely higher than any other 30- and 50-year periods during the past 800 years (Masson-Delmotte et al., 2013). Permafrost ground temperature monitoring studies have documented a rising trend over the last 20–30 years and observations suggest permafrost thaw in the southern margins of the permafrost area (Brown and Romanovsky, 2008; Johansson et al., 2011; Sannel et al., 2016). Even though these observations are not ubiquitous (Brown and Romanovsky, 2008), a widespread permafrost thaw can be expected as a consequence of global warming (Chadburn et al., 2017). It may be speculated that Arctic permafrost peatlands are on the edge of their climatological niche and have low potential to remain stable under future climate changes (Bosio et al., 2012). One presumption is that when permafrost thaws or if the active layer deepens considerably, permafrost areas become large CO_2 sources due to accelerated decomposition rates (Abbott et al., 2016; Koven et al., 2011; Schadel et al., 2016). It is suggested that these dynamics may be one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in the future (Schuur et al., 2008). However, because of the scarcity of information and data, disentangling the links between permafrost peatland vegetation, hydrology and climate, the future balance of NPP and decomposition processes in permafrost peatlands has remained uncertain. These coupled dynamics can be investigated by comparing palaeoecological data to documented climate epochs such as the Medieval Climate Anomaly (MCA) from *ca*. AD 950–1200, the Little Ice Age (LIA) from *ca*. AD 1400–1850, and recent warming since the late 19th century (e.g., Cook et al., 2004; Esper et al., 2002; Hanhijärvi et al., 2013; Wilson et al., 2016).

In this study we investigated past hydrological changes and associated variations in vegetation composition during the last millennium in four permafrost peatlands. We used two different proxies; testate amoebae (Amesbury et al., 2016; Charman et al., 2007; Swindles et al., 2015b) and plant macrofossils (Väliranta et al., 2007, 2012) to reconstruct past moisture conditions and vegetation history, which enabled cross validation of results and therefore more dependable data interpretation (Loisel and Garneau, 2010; Väliranta et al., 2012). Using ^{14}C and ^{210}Pb dating, we linked detected changes to known climate periods. Replicate records from the same peatland and/or close-by regions allowed us to evaluate whether detected changes were climate-driven and regional or forced by autogenic factors (Mathijssen, 2016, Mathijssen et al., 2017; Swindles et al., 2012). Our hypotheses were 1) that permafrost thawing triggered by warm climate conditions (e.g., MCA and recent warming), is reflected in proxy records as a change towards wetter plant communities and more hydrophilic testate amoeba assemblages, and that 2) permafrost aggradation under colder climate conditions such as LIA results in dry conditions through raising of the peat surface. Furthermore, we evaluate whether and how the peatland response to MCA warming differs from the on-going recent warming.

2. Study sites

Our four study sites are located in two regions: two sites (Indico and Seida) are located in the discontinuous permafrost zone of Russia whereas the other two (Kevo and Kilpisjärvi) are in the sporadic permafrost zone of the Finnish Lapland (Fig. 1 and Table 1).

Indico and Seida are located in the Arctic Northeast European Russian tundra. The peat plateaus in these two peatlands are elevated a few metres from the surrounding mineral soil and the vegetation is dominated by shrub-lichen-moss communities, such as *Betula nana*, *Rhododendron tomentosum*, *Empetrum nigrum*, *Sphagnum fuscum*, *Polytrichum strictum*, *S. lindbergii* and sedges *Eriophorum* spp. Compared to Seida, Indico presents extensive areas covered by lichens and mosses with a lower shrub layer. Large bare peat surfaces occur on both sites (Repo et al., 2009).

At the two sites in Finnish Lapland, Kevo and Kilpisjärvi, the peatlands are characterised by separate permafrost mounds a few metres high and surrounding wet flarks. The mound vegetation is dominated by dwarf shrubs, such as *Betula nana*, *Empetrum nigrum*, *Rubus chamaemorus* and bryophytes *Polytrichum strictum* and *Dicranum* spp. Different *Sphagnum* species such as *S. fuscum*, *S. balticum*, *S. majus* and *S. riparium* occur along a hydrological gradient from dry hummock to wet hollow and *Eriophorum* spp. are also present.

3. Materials and methods

3.1. Sampling

In total, six active layer peat cores (Table 1) were collected from dry habitats either from a raised peat plateau (Russia) or from a permafrost mount (Finland) using a Russian peat corer with a diameter of 5 cm. The coring locations were dominated by dwarf shrubs, such as *Ledum palustre*, *Empetrum nigrum*, *Betula nana*, *Vaccinium uliginosum* and *Rubus chamaemorus*; or dominated by *S. fuscum*. One of the surfaces was bare with only some lichens present. Some cracking features were detected on bare/lichen-covered surface and on the edges of permafrost mounts. These can be considered as natural permafrost peatland development and life-cycle features (Seppälä, 2006). Measured active layer thickness for the studied peatlands were between 20 and 50 cm. In Indico, three replicate peat cores (Ind1-3) were collected along a transect from the centre to the margins of the site to assess potential differences in sensitivity across the peatland surface. A single core was collected from each of the other sites. Individual cores were wrapped in plastic and transported to the laboratory in sealed PVC tubes and stored in a freezer. The cores were later defrosted and sub-sampled in 1-cm or 2-cm thick slices for further analyses. In some cases, analysis of both proxies from the same sample was not possible due to a lack of material. When this occurred, analysis was carried out using stratigraphically adjacent samples. In core ‘Sei’ from Seida the limited amount of material meant that only testate amoeba analysis was possible.

3.2. Chronology

Eighteen bulk peat samples were sent to the Finnish Museum of Natural History (LUOMUS, Helsinki, Finland) and the Poznan Radiocarbon Laboratory (Poznan, Poland) for accelerator mass spectrometry (AMS) ^{14}C dating (Table 1). Bulk peat samples were used because of high decomposition of some peat sections, which made picking out known macrofossils very difficult or impossible. Additionally, a recent study suggested that there is no significant difference between ages derived from bulk material and plant macrofossils in these settings (Holmquist et al., 2016). The