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Impact of the Little Ice Age cooling and 20th century climate change on peatland vegetation dynamics in central and northern Alberta using a multi-proxy approach and high-resolution peat chronologies

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A B S T R A C T

Northern boreal peatlands are major terrestrial sinks of organic carbon and these ecosystems, which are highly sensitive to human activities and climate change, act as sensitive archives of past environmental change at various timescales. This study aims at understanding how the climate changes of the last 1000 years have affected peatland vegetation dynamics in the boreal region of Alberta in western Canada. Peat cores were collected from five bogs in the Fort McMurray region (56–57° N), at the southern limit of sporadic permafrost, and two in central Alberta (53° N and 55° N) outside the present-day limit of permafrost peatlands. The past changes in vegetation communities were reconstructed using detailed plant macrofossil analyses combined with high-resolution peat chronologies (^{14}C, atmospheric bomb-pulse ^{14}C, ^{210}Pb and cryptotephras). Peat humification proxies (C/N, H/C, bulk density) and records of pH and ash content were also used to improve the interpretation of climate-related vegetation changes. Our study shows important changes in peatland vegetation and physical and chemical peat properties during the Little Ice Age (LIA) cooling period mainly from around 1700 CE and the subsequent climate warming of the 20th century. In some bogs, the plant macrofossils have recorded periods of permafrost aggradation during the LIA with drier surface conditions, increased peat humification and high abundance of ericaceous shrubs and black spruce (*Picea mariana*). The subsequent permafrost thaw was characterized by a short-term shift towards wetter conditions (*Sphagnum* sect. *Cuspidata*) and a decline in *Picea mariana*. Finally, a shift to a dominance of *Sphagnum* sect. *Acutifolia* (mainly *Sphagnum fuscum*) occurred in all the bogs during the second half of the 20th century, indicating the establishment of dry ombrotrophic conditions under the recent warmer and drier climate conditions.

1. Introduction

Ombrotrophic peatlands, which receive water and nutrients exclusively from precipitation, cover more than 50% of the boreal regions of northern Alberta (Halsey et al., 1995a). These ecosystems are considered particularly sensitive to climate change (Charman et al., 2009; Booth, 2010) and act as archives of past climate change at various timescales (Mauquoy et al., 2002; Väliranta et al., 2007; Swindles et al., 2010). However, nonlinear response to external forcing, internal dynamics and feedback mechanisms in peatlands may complicate climate reconstructions from peat cores (Belyea, 2009; Swindles et al., 2012). In many peatland regions, the regional atmospheric moisture balance during the growing season is considered an important driver for vegetation dynamics (Charman et al., 2009), but vegetation may also be sensitive to other external forcing such as fires (Kuhry, 1994; Magnan et al., 2012) and various types of atmospheric inputs such as nitrogen deposition (Bubier et al., 2007).

In boreal and subarctic regions, permafrost development

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influences peatland hydrology and vegetation dynamics (Camill, 1999a). Upon freezing, the peatland surface is subjected to frost heaving, which results in an apparent drop in local water table relative to the surface and the establishment of xerophilous vegetation, while total peat decay may increase due to more time under aerobic conditions. Besides climate warming and vegetation dynamics, fires may also play a role in permafrost thaw when these are sufficiently severe to remove a part of the insulating *Sphagnum* cover, exposing the remaining section to increased thawing when air temperatures exceed 0 °C (Zoltai, 1993). Thawing permafrost may then collapse to create an internal lawn (*sensu* Vitt et al., 1994), characterized by wet and minerotrophic conditions, after which drier vegetation communities usually re-establish as peat continues to accumulate and the surface becomes drier. Past cycles of permafrost aggradation and degradation in the boreal peatlands of central and western Canada are typically characterized by a stratigraphic sequence of sylvic peat, representing the permafrost-affected level, overlain by *S. riparium*, *S. angustifolium* and finally *S. fuscum* (Zoltai, 1993; Vitt et al., 1994; Beilman et al., 2001). During the Holocene, both permafrost aggradation and thaw have affected local peatland vegetation and hydrology (Zoltai, 1993; Camill, 1999b; Beilman et al., 2001) as well as carbon accumulation dynamics in central and western boreal Canada (Vitt et al., 2000a; Camill et al., 2001, 2009).

Understanding the extent of the impact of past climate change on peatlands is essential for projecting future response of these ecosystems to climate change. The transitions associated with the onset of the Little Ice Age (LIA) and 20th century warming may be key for understanding the changes within peatland ecosystems under future climate warming. The boreal peatlands of central and western boreal Canada are expected to be particularly vulnerable to future climate change, because relict permafrost inherited from the LIA is currently in disequilibrium with climate conditions, suggesting that vegetation dynamics may likely shift in the nearby future (Turetsky et al., 2007).

Unfortunately, it remains difficult to reconstruct permafrost history in peatlands because there is no unique plant assemblage related to permafrost. However, the process of permafrost aggradation and thaw is often associated with changes in peat properties such as bulk density and C/N ratio that may be preserved in peat sequences (Treat et al., 2016; Jones et al., 2017). The analysis of plant macrofossils combined with peat physical and chemical properties is the most promising approach to improve detection of past permafrost in peatlands.

The boreal regions of west-central Canada have been subjected to periods of climate variations during the last millennium, including the Medieval Climate Anomaly (MCA; ~1100–1200 CE) and the Little Ice Age (LIA; ~1530–1890 CE) (Luckman et al., 1997; Edwards et al., 2008). The MCA has been recorded across boreal central Canada in pollen records with a ~1 °C July temperature and positive precipitation anomalies around 950 CE (Viau and Gajewski, 2009). Warm intervals, comparable to 20th century values, were reconstructed for the first half of the 11th century from tree-ring records in the Canadian Rockies (Luckman and Wilson, 2005). In western Canada, climate shifted from warm winters and moist summer conditions during the MCA (~1100–1250 CE) to cool winters and dry summers during the LIA associated with more frequent intrusions of dry Arctic air masses and decadal-scale cold shifts ~2 °C colder than today (Luckman and Wilson, 2005; Edwards et al., 2008). The LIA was one of the coldest periods of the Holocene over many parts of the Northern Hemisphere (Bradley and Jones, 1993; Mann et al., 2009). Although hydroclimatic conditions fluctuated in western Canada during the LIA (Wolfe et al., 2005; St. George et al., 2009; Lapp et al., 2013), dry and cool conditions dominated from the early 1500s until the late 1800s (Edwards et al., 2008). Particularly cold and very dry atmospheric conditions were recorded during the 18th century in the Peace-Athabasca Delta region in northern Alberta (Wolfe et al., 2005). The LIA was followed by a warming trend at the end of the 19th century (Luckman and Wilson, 2005; Wolfe et al., 2005) and particularly warm conditions established during the second half of the 20th century (Wolfe et al., 2005; Sinnatamby et al., 2009) with a trend towards particularly dry conditions over the last few decades (Sauchyn et al., 2015).

Overall, the exact timing of the LIA cooling phases and related permafrost development in peatlands remains largely unknown in boreal and subarctic Canada, partly due to the lack of detailed peat chronologies for the last ~500 years. Permafrost developed in many bogs of northern Alberta at some point during the LIA (16th to 19th century), preceding a widespread thaw during the 20th century (Vitt et al., 2000b). In eastern Canada, the LIA was also associated with permafrost development in subarctic bogs (Lamarre et al., 2012), a slowdown in peat (carbon) accumulation in boreal bogs (Garneau et al., 2014) and an expansion of pools in northern boreal poor fens (van Bellen et al., 2013; Arlen-Pouliot and Payette, 2015). During the same period, temperate bogs in Europe showed an increase in surface wetness associated with cold and wet climate conditions (Mauquoy et al., 2002) and lower rates of peat accumulation as a result of decreasing vegetation productivity (De Vleeschouwer et al., 2009), similar to reconstructions from semi-continental, low boreal Alaska, where cooler conditions and shifts in seasonal precipitation contributed to a change in peatland vegetation (Jones et al., 2014). Globally, the response of peatlands to the LIA climatic conditions was variable and highly dependent on the initial climatic setting and particular local conditions, such as the dominant vegetation at the onset of cooling.

This study is part of a larger multi-proxy project that aims to evaluate the impact of industrial development of the Athabasca bituminous sands on the atmospheric deposition of trace metals and organic contaminants by comparing recent anthropogenic deposition to pre-industrial conditions (Shotyk et al., 2014, 2016; 2017; Zhang et al., 2016). The main objective of the present study is to understand the response of peatland vegetation to the LIA cooling and subsequent climate change in central and northern Alberta. We also aim to detect past permafrost events in peat sequences and reconstruct with precision the timing of its formation and thaw. In order to achieve these goals, we have reconstructed vegetation dynamics along with physical and chemical peat properties on seven peat cores that registered up to 2600 years of organic matter accumulation using high-resolution dating methods, including ^{14}C, bomb-pulse ^{14}C dating, ^{210}Pb and cryptotephras.

The dating approach used in this study is essential to develop robust chronologies in the uppermost recent peat layers. Radiocarbon dating, which is one of the main methods applied to peat sequences, is of limited value for sediments accumulated between 1650 CE and 1950 CE (Charman and Garnett, 2005). The chronology of recent peat layers often only rely on ^{14}C dating of single or few samples for the past ~500 years, resulting in large age uncertainties during this period of major climate fluctuations including the LIA. The combination of ^{14}C dates (pre- and post-bomb) with other chronometers (^{210}Pb and cryptotephras) to produce a single age-depth model, reduces the chronological uncertainties inherent to each method (Davies et al., 2016). This approach may allow reconstructing the timing and duration of permafrost development in peatlands with much higher temporal precision (e.g. decadal scale) during the LIA and linking recent vegetation changes to instrumentally documented climate change.