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Holocene evolution of lakes in the forest-tundra biome of northern Manitoba, Canada

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A B S T R A C T

The late-Quaternary paleoenvironmental history of the western Hudson Bay region of Subarctic Canada is poorly constrained. Here, we present a regional overview of the post-glacial history of eight lakes which span the forest-tundra biome in northern Manitoba. We show that during the penultimate drainage phase of Lake Agassiz the lake water had an estimated pH of ~6.0, with abundant quillwort (*Isöetes* spp.) along the lakeshore and littoral zone and some floating green algae (*Botryococcus* spp. and *Pediastrum* sp.). Based on multiple sediment proxies, modern lake ontogeny in the region commenced at ~7500 cal yrs BP. Pioneering diatom communities were shaped by the turbid, higher alkalinity lake waters which were influenced by base cation weathering of the surrounding till following Lake Agassiz drainage. By ~7000 cal yrs BP, soil development and *Picea* spp. establish and the lakes began a slow trajectory of acidification over the remaining Holocene epoch. The natural acidification of the lakes in this region is slow, on the order of several millennia for one pH unit. Each of the study lakes exhibit relatively stable aquatic communities during the Holocene Thermal Maximum, suggesting this period is a poor analogue for modern climatic changes. During the Neoglacial, the beginning of the post-Little Ice Age period represents the most significant climatic event to impact the lakes of N. Manitoba. In the context of regional lake histories, the rate of diatom floristic change in the last 200–300 years is unprecedented, with the exception of post-glacial lake ontogeny in some of the lakes. For nearly the entire history of the lakes in this region, there is a strong linkage between landscape development and the aquatic ecosystems; however this relationship appears to become decoupled or less strong in the post-LIA period. Significant 20th century changes in the aquatic ecosystem cannot be explained wholly by changes in the terrestrial ecosystem, suggesting that future changes to the lakes of N. Manitoba will be strongly influenced by direct climatic effects to the lakes.

1. Introduction

The late-Quaternary paleoenvironmental history of the western Hudson Bay region of Subarctic Canada is poorly constrained. The region comprises the western Hudson Bay Lowlands and western Taiga Shield. This region has particular relevance to the discussion of climatic changes and attendant ecological shifts in terrestrial and aquatic ecosystems witnessed throughout the low and high Arctic (Kaufman, 2012 and references therein; Smol et al., 2005). The region is sensitive to both long-term climatic changes (Dyke, 2005; MacDonald et al., 1993) and short-term ecological changes often driven more directly by the surrounding topography and vegetation cover, than by climate alone (Payette and Delwaide, 2004). Future climate scenarios suggest this region will experience increased precipitation and warming (IPCC, 2007). Owing to the observed latitudinal amplification trend for Subarctic – Arctic regions (Moritz et al., 2002), it is likely future changes will be some of

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the largest on the North American continent (Holland and Bitz, 2003; Smol et al., 2005). Furthermore, the predicted climatic changes will likely impact the extent of sea ice in Hudson Bay, which will directly influence the local climate in the western Hudson Bay Region (Hochheim and Barber, 2014; Joly et al., 2011). Under future climate scenarios the significant carbon stores (peatlands) and discontinuous permafrost that characterize the Hudson Bay region are particularly relevant to perpetuating a CO_2 rich atmosphere with associated climatic feedbacks (Harden et al., 2012; Holmquist et al., 2014; Schuur et al., 2015).

The post-glacial evolution of lake ecosystems provides significant insights into how aquatic ecosystems respond directly to influences of climate (Wolfe, 2002) and indirectly to inputs from the surrounding landscape (Engstrom et al., 2000; Renberg, 1990). Early questions on the role that pedogenesis and the development of terrestrial ecosystems play in influencing the chemistry and ecology of lakes continue to be prevalent (Camill et al., 2012; Deevey, 1942; Perren et al., 2012). Detailed paleoecological studies of post-glacial lake acidification tend to describe a similar time-transgressive response, where the lake has a more alkaline pH than modern conditions, as the landscape is deglaciated and weathering of cations from glacial tills begins. As soils and the terrestrial ecosystem develop the tills are isolated and movement of base cations to the lake is reduced, while the contribution of organic acids from the landscape (both soils and vegetation) increases. This succession yields a water chemistry that is initially alkaline and nutrient-poor, followed by the progressive acidification of the lake with greater nutrient concentrations (Ford, 1990; Renberg, 1990; Whitehead et al., 1989). Often superimposed over the late-Holocene acidification trend is the influence of human activity (Renberg, 1990). The natural rate of acidification is commonly on the order of a decrease of one pH unit over a thousand years or more (Renberg, 1990; Whitehead et al., 1989), whereas anthropogenic acidification of poorly buffered lakes can be on the order of decades (Charles et al., 1987). The trends in lake evolution highlight the direct linkages between aquatic and terrestrial ecosystems that can be elucidated over millennial timescales and which are driven by the broad climatic and geographic attributes of a region.

Climatic changes during the late-Holocene in the northern hemisphere have elicited distinct changes in the aquatic communities of lakes (Hobbs et al., 2010a; Rühland et al., 2008; Smol et al., 2005). More recent work by Rühland et al. (2013, 2014) in the Hudson Bay Lowlands has also shown the sensitivity of aquatic communities to climatic changes since the 1990s in response to and in concert with changes in sea ice (Hochheim and Barber, 2014). The timing of shifts in lake aquatic communities is often attributed to global anthropogenic activity (climate warming and changes in atmospheric chemistry) and attendant changes in the lake thermal structure (Winder et al., 2009) and water chemistry (Charles et al., 1987; Wolfe et al., 2003). Paleoecological studies which seek to identify ecological responses to 20th century climatic drivers can be somewhat confounded by the Little Ice Age (LIA; a globally recognizable but asynchronous climatic period; Matthews and Briffa, 2005) terminating at the end of the 19th century (western Hudson Bay region; D'Arrigo and Jacoby, 1993). While this may represent a temporally inconvenient overlap of abiotic drivers, high-resolution (decadal to sub-decadal) analysis of sediment records are capable of deciphering distinct ecological responses (Hobbs et al., 2011). The interesting question when detailing the response to this most recent climatic period is whether it is unprecedented in the context of the Holocene? Objectively assessing this requires good geochronological data and attention to statistically comparable intervals of the lake's history.

Here we present a regional overview of the post-glacial history of eight lakes which span the boundary of the forest-tundra biome in N. Manitoba, north of the Hudson Bay Lowlands in the Taiga Shield ecozone. The goals of this study were to (1) document the aquatic – terrestrial linkages during the periods of lake ontogeny and Holocene development, (2) determine the role of regional climatic changes in structuring the long-term ecology of the lake, and (3) assess whether recent ecological changes are truly unprecedented in the context of the lake's history. We provide detailed multi-proxy data for algal communities (diatom sub-fossils and algal coenobia of *Pediastrum* sp. and *Botryococcus* spp.), aquatic plants (spores), and terrestrial succession (pollen); combined with sedimentological data a cohesive regional paleoenvironmental history is presented covering the remnants of glacial Lake Agassiz to present and spanning a region which has had no prior investigation.

2. Regional setting

The forest-tundra biome of North America traverses the Canadian Subarctic, extending from Alaska to Newfoundland (Payette et al., 2001). Our study region in northern Manitoba (Fig. 1) is situated entirely within this transitional zone and treeline runs through the region. The area north of treeline is dominated by low and high shrub tundra and is a mixture of lowland drainage areas rich in peat and uplands dominated by ridges, small hills and eskers with exposed till. The treeline region includes patchy stands of predominantly *Picea* and *Larix* with peatlands. This region is a highly connected hydrologic landscape, where approximately 21% of the region is covered by lakes and other bodies of water (Umbanhowar et al., 2015). The remaining area is dominated (46%) by lowland peat (variously tree-covered), 25% open upland tundra and 8% upland woodland or burn recovery (Umbanhowar et al., 2015). The study region is situated in the western Taiga Shield ecozone, north of the Hudson Bay Lowlands where peatlands make up 55–100% of the landscape (Holmquist et al., 2014). The study area is considered a zone of continuous permafrost with a few patches of discontinuous (50–90% coverage) permafrost (Natural Resources Canada, 1993). The surficial geology is characterized by a bouldery sandy diamicton of Precambrian crystalline rocks bordered by proximal glaciofluvial sand and gravel, where soils are largely undeveloped crysols (Matile and Keller, 2006). The bedrock consists of Paleoproterozoic intrusive hybrid granite as well as charnockite-mangerite and gneiss (Schledewitz and Lindal, 2002). Extensive areas of unvegetated bedrock and frost heaved and frost shattered bedrock blocks are exposed at the surface throughout the region.

Average seasonal temperatures in the region range from −25 to −30 °C (winter) and 10–15 °C (summer), and monthly precipitation ranges from 15 to 30 mm (winter) and 30–60 mm (summer) (Plummer et al., 2006). The climate in this region is a function of the position of the Arctic air mass, both in summer and winter (Bryson, 1966) and the movement of treeline in this region is in response to the southern boundary position of Arctic air (Ball, 1986). An additional factor in this area of the Subarctic is the possible influence of Hudson Bay on the local terrestrial climate (Hochheim and Barber, 2014; Rouse, 1991), where onshore winds can exert a cooling effect during the summer.

The lakes used in this study (Table 1) and those in a 44 lake survey (Umbanhowar et al., 2015) can be summarized as oligotrophic (total phosphorus median = 11.8 μg l^{-1}), P-limited (dissolved inorganic nitrogen (DIN): TP < 0.50) with moderate amounts of DOC (median 5.2 mg l^{-1}). The lakes (pH 4.9–7.0) and soils (pH 3.21–4.44) are both highly acidic but dissolved organic carbon (DOC) and pH are not significantly correlated with each other. Rather, base cations (particularly Ca^{+}) seem to play a more dominant role in predicting lake water pH (Umbanhowar et al., 2015). The mean elevation of the lakes is 264 m, with an elevational