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The post-glacial history of northern Lake of the Woods: A multi-proxy perspective on climate variability and lake ontogeny

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ABSTRACT

Lake of the Woods (LOW) is a large, morphologically and hydrologically complex lake of international importance, located in the provinces of Ontario and Manitoba and the state of Minnesota. A high-resolution sedimentary sequence retrieved near Kenora, Ontario, and spanning at least the past ~11,000 cal yr BP (calibrated years before present), was analysed for multiple environmental proxies with an emphasis on diatom assemblage composition and spectrally-inferred chlorophyll *a*. These biological proxies indicate that northern LOW was relatively nutrient-rich soon after its isolation from glacial Lake Agassiz ~10,000 cal yr BP. The post-glacial hydrological and environmental history of LOW was found to be controlled by both climate and isostatic rebound. During the low water phase of the mid-Holocene dry and warm period, abrupt and synchronous shifts across all proxies suggest that the northern basin had a relatively deep and well-mixed water column that experienced increases in nutrients and whole-lake algal production. This differs from recent limnological changes associated with warming since the late-1970s, where primary production increased concurrently with large shifts in diatoms indicative of increased thermal stability, but with little change in nutrients. The millennial-scale context of this study provides evidence that climate has long played an important role in algal dynamics in LOW, with implications for lake management strategies concerning recent increases in nuisance algal blooms on LOW.

Introduction

The Lake of the Woods (LOW) is a large remnant of glacial Lake Agassiz, the largest lake in North America during the last glacial retreat, that covered much of the LOW basin from about 12,000 to 10,000 cal yr BP (Yang and Teller, 2005). The developmental history, areal extent and volume of glacial Lake Agassiz has been linked to its proximity to the margin of the Laurentide Ice Sheet (LIS), the elevation and location of its overflow channels, and to differential isostatic rebound (e.g. Teller and Leverington, 2004). In the Lake of the Woods region of Ontario, Manitoba, and Minnesota, the fluctuating level of Lake Agassiz controlled the level of water across the LOW basin during its early stages. Initially, after the LIS had retreated from the region, water depths exceeded the confining margins of the LOW basin, and water covered a vast area south of the ice sheet. When the level of Lake Agassiz declined, waters eventually became confined by the topography surrounding the LOW basin, and the depth and extent of LOW was controlled mainly by climate and the effects of differential isostatic rebound (Teller, 1987; Teller and Leverington, 2004; Yang and Teller, 2005; Teller et al., 2018).

Today LOW is a large, hydrologically and morphologically complex freshwater system, the majority of which is located in Ontario (Canada) but straddling the boundary of the province of Manitoba and the state of Minnesota (U.S.A.) (Fig. 1). The southern region of LOW (e.g. Big Traverse Bay, which is largely located in Minnesota) is a shallow basin that is relatively uniform in depth, is well-mixed and is mesotrophic to eutrophic (Anderson et al., 2017). The northern region of LOW is distinctly different in that it is hydrologically and morphologically heterogeneous with numerous deep sub-basins and bays that thermally stratify, over 14,000 islands, and is generally less productive (Pla et al., 2005). The LOW region is adjacent to two ecotonal boundaries – the deciduous forest-boreal forest ecotone and the prairie-forest ecotone – making this a particularly sensitive area for tracking the limnological effects of past changes in climate (Frelich and Reich, 2010). This region of northwestern Ontario has reported some of the highest rates of temperature increases in North America since the mid-twentieth century (Schindler, 1997; Chiotti and Lavender, 2008) with increases in average annual temperature of 1.4 °C, which are projected to further increase by 1.5 to 2.5 times over the next 25 to 50 years (McKenney et al., 2010), particularly during the winter (Chiotti and Lavender, 2008; McDermid

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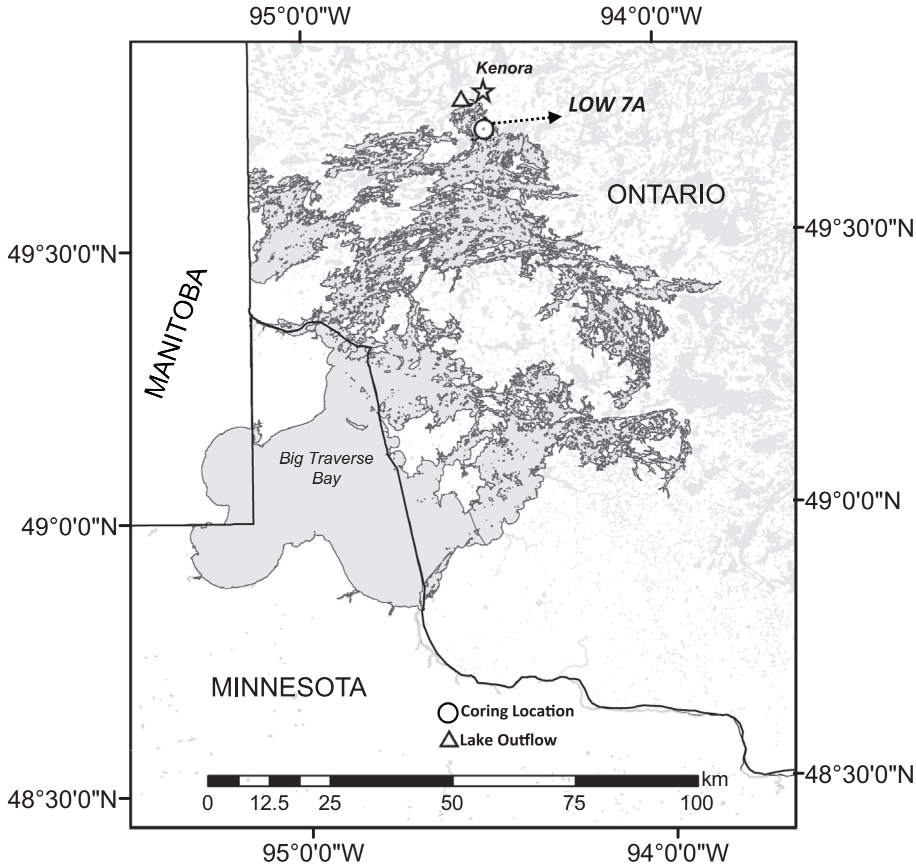

Fig. 1. Location of the sediment core (LOW 7A) sampling site on Lake of the Woods near Kenora, Ontario, Canada.

et al., 2015). In addition to increasing air temperatures, summers in northwestern Ontario are projected to become drier over the next ~50 years (McDermid et al., 2015), and will likely be punctuated by extreme precipitation events.

Over the past few decades, lake users have raised concerns that there has been an increase in the intensity and frequency of algal blooms on LOW that may be indicative of a deterioration in lake water quality (Chen et al., 2009; DeSellas et al., 2009; Clark and Sellers, 2014), in spite of substantial reductions in external nutrient loading from the Rainy River since the 1970s (Hargan et al., 2011). However, historical reports suggest that algal blooms have been a part of the history of the southern basins of LOW for at least the past ~200 years (Robertson and McCracken, 2003; McElroy and Riggs, unpublished data; Anderson et al., 2017). A warmer and drier climate can potentially exacerbate water quality concerns such as cultural eutrophication (Adrian et al., 1995; Smol, 2010), enhance the release of phosphorus from lake sediments (Edlund et al., 2017; James, 2017; Reavie et al., 2017), and, together with a longer open water season, extend the period for whole-lake primary production (Michelutti et al., 2010; Paterson et al., 2017) and for algal bloom formation (Jeppesen et al., 2007; Paerl and Huisman, 2008).

Paleolimnological studies exploring the effects of climate change on water quality more often focus on a lake's recent history (e.g. past two centuries) than on longer-term Holocene-scale trends (Smol and Cumming, 2000; Moos et al., 2009). For example, diatom-based paleolimnological records tracking changes over the past ~150 years from the Ontario portion of the LOW indicate that lake water total phosphorus concentrations declined over the past few decades (Rühland et al., 2010) and, with the exception of a few oligotrophic bays, most studied portions of northern LOW are currently mesotrophic (Pla et al., 2005). In addition, recent warming, an increase in the ice-free period, and indirect changes in nutrient cycling were found to be the main driver of algal assemblage composition (Rühland et al., 2010; Hyatt et al., 2011) and overall increases in whole-lake primary production (Paterson et al., 2017). These previous paleolimnological studies focused on the past ~150 years, and thus provided insights into baseline (reference) conditions and the limnological effects of recent anthropogenic disturbances.

The detailed diatom and chlorophyll *a* record from a northern location in LOW, which we present here was part of a broader assessment of LOW post-glacial history detailed by Teller et al. (2018) spanning >11,000 years. Their study focused primarily on sedimentological, mineralogical, and stratigraphic analyses, and included a study of ostracodes from six cores across this large, complex system. Based predominantly on sedimentological characteristics, Teller et al. (2018) provided evidence that differential isostatic rebound resulted in substantial hydrological differences in LOW that were superimposed on the region's response to the dry and warm Hypsithermal period, with the deeper, more isostatically depressed northern regions remaining relatively deep whereas the shallower southern basins likely dried up completely. This conclusion supports interpretations about changes in lake extent and depth in LOW based on the isostatic modeling of Yang and Teller (2005). Whilst a cursory summary of diatom changes was presented in Teller et al. (2018), here we provide a detailed examination of a suite of environmental proxies (focusing on diatoms and sedimentary chlorophyll *a*) preserved in a dated sediment core retrieved in the northernmost region of LOW near the city of Kenora, Ontario. We focus on the effects that large-scale changes in post-glacial climate from the time of glacial Lake Agassiz to modern-day LOW have had on aquatic biota, primary production, trophic status, and physical lake properties (e.g. water column mixing and thermal stratification). Building on previous algal-based paleolimnological work on LOW that focused on the past ~150 years (Rühland et al., 2010; Hyatt et al., 2011;