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A paleolimnological assessment of human impacts on Lake Superior

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ABSTRACT

To understand environmental conditions in Lake Superior over the last two centuries, we conducted a paleolimnological study on two sediment cores collected in the eastern and western regions of the lake. We examined the diatom fossil assemblages, sedimentation rates, organic and trace metal accumulation rates, and GIS-reconstructed human land use stressors in order to evaluate lake history and the impacts of human activities. There is evidence that the diatom community reorganized due to nutrient enrichment beginning around the time of European settlement and significant agricultural development. Trace metal profiles tracked a period of mining and ore processing which temporarily increased trace metal loads to the lake in the mid- to late-20th century. In recent decades, more oligotrophic diatom species were favored, suggesting nutrient decreases associated with remedial activities. The diatom community is now dominated by the *Cyclotella comensis* complex, suggesting changes in the lake's physical and chemical processes associated with climate change. Similar long-term environmental trends were observed in both core locations, but the timing of some events differed, indicating localized effects such as nutrient enrichment. An understanding of Lake Superior's past responses to human activities can inform management decisions that account for influences within and outside the lake's catchment.

Introduction

Lake Superior is the largest freshwater lake in the world by surface area and the third largest by volume, storing 10% of the world's available fresh water (Kalff, 2003). The Lake Superior basin offers natural resources including fisheries, agriculture, shipping, tourism, and industry such as pulp and paper mills, timber logging, and mining (LakeNet, 2004; GLIN, 2012; Minnesota Sea Grant, 2012). Understanding the stressors on Lake Superior is necessary for management to preserve its ecology and economy.

Unlike the lower Great Lakes, which became eutrophic in the 20th century, Lake Superior has always been classified as oligotrophic (Dobiesz et al., 2010). Even so, monitoring over the last thirty years documented changes in Lake Superior. Spring lake nitrate concentrations increased five-fold over the last century, likely due to increased atmospheric deposition (Bennett, 1986; Sterner et al., 2007; Dobiesz et al., 2010). Open water surveys by the EPA Great Lakes National Program Office (GLNPO, 2010) indicated that phosphorus has been decreasing since 2000 (Gorman and Hoff, 2003). Based on models using monitoring data, total phosphorus (TP) loads to Lake Superior remain below the maximum levels set by the Great Lakes Water Quality Agreement (Dolan and Chapra, 2012). An increasing N:P ratio, characterized by high TN and low TP, is among the highest of the world's large lakes (Guildford and Hecky, 2000; Sterner et al., 2007). In addition, ionic concentrations (e.g. chloride) and turbidity in the water column have increased over the last few decades, with a marked jump in turbidity in 2004, the causes of which remain unclear (Gorman and Hoff, 2003; Urban, 2009; Osantowski et al., 2010).

Climate change is also impacting Lake Superior. Over the last century, the open water summer temperature increased 3.5 °C, a higher increase than that of ambient air temperature. During the same time, temporally averaged winter ice cover decreased 12–23% (Austin and Colman, 2008). Such changes in the temperature regime have affected the mixing regime of the lake. Over the last century, the stratified season increased from 145 days to 170 days, and begins earlier in spring (Austin and Colman, 2008). Over the last few decades, wind speed increased 5% per decade, creating a positive feedback loop with warming surface waters so that the water temperature is warming faster than the ambient air temperature (Desai et al., 2009).

Paleolimnological methods contribute understanding of a lake's long-term, holistic processes through the use of integrative data from physical and chemical information and microfossil assemblages (Reavie and Allinger, 2011). Diatom algae (division Bacillariophyta) provide a reliable ecological indicator because they are primary producers which respond rapidly to environmental change and remain in lake sediments as floristic fossils due to their siliceous cell walls (Vinebrooke, 1996; Hall and Smol, 1999). Diatoms respond to stressors like climate change (e.g. Gregory-Eaves et al., 1999), nutrient enrichment (e.g. Yurista and Kelly, 2007), and other effects that potentially result from anthropogenic activities. Changes in diatom assemblage

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composition can record impacts on water quality in the Great Lakes (Reavie et al., 2006).

Former paleolimnological investigations in Lake Superior yielded somewhat conflicting results. Support for human impacts on water quality is based on sediment core analyses from the eastern region of Lake Superior (collected in 1979) by Stoermer et al. (1985). Diatom assemblages shifted to *Aulacoseira* (previously identified as *Melosira*) *islandica* and *subarctica*, which are mesotrophic indicators that compete well during light limitation and winter circulation (Stoermer, 1993). The study concluded that the *Aulacoseira* taxa responded to human settlement effects between ca. 1850 and 1900, and further increased in response to nutrient loading beginning ca. 1950.

Research by Thayer et al. (1983a,b) identified challenges of using sedimentary diatoms in Lake Superior, notably unequal deposition in lake sediments and the potential for preferential dissolution of lightly silicified species. Thayer et al. (1983a) estimated that *Aulacoseira* increased before the *Ambrosia* pollen horizon (which signals initial landscape development) and therefore proposed that the inferred nutrient increase was not associated with settlement effects, unlike the findings of Stoermer et al. (1985). Instead, Thayer et al. (1983a) suggested that the increase in *Aulacoseira* taxa was due to changes in climate, specifically increasing temperature. Neither study benefitted from sediment dating technologies and other detailed analyses that can be performed today; so uncertainties remain in the timing and interpretation of the diatom trends.

No integrated paleolimnological study has been undertaken in decades, during some of Lake Superior's most dramatic changes. This study aims to update and refine the paleolimnological data to determine the timing of past changes and to gain a better understanding of modern changes seen in the monitoring data. In an effort to clarify apparent conflicts among past paleoecological data, we employed new indicators and research methods such as stratigraphic ^{210}Pb dating, trace metal analysis, detailed TP modeling based on modern species–environment relationships, and quantified human activities in the watershed acquired from historical records.

Methods

Sediment core sampling

We selected coring sites based on known sedimentation patterns in Lake Superior (Sergei Katsev, personal communication). In the field, an echo sounder targeted areas with known high sedimentation rates. Two sites were sampled, one from the eastern trenches (8 April 2010, Research Vessel *Lake Guardian*, Lat. 47.188°, Long. −85.116°) and one off the coast of Isle Royale (10 June 2010, Research Vessel *Blue Heron*, Lat. 47.973°, Long. −88.466°) (Fig. 1). The eastern site, northwest of Whitefish Point, used GPS coordinates to correspond with a historical core collected in 1979 (Stoermer et al., 1985). The sediment was collected at a depth of 213 m using an Ocean Instruments model 750 box corer (30 cm × 30 cm × 90 cm), from which two 6.5-cm internal diameter cylindrical cores were sub-sampled. Two cores from the western location were collected at a depth of 234 m with an Ocean Instruments model MC-400 multi-corer (9.4 cm diameter). The surface sediment in the western core was stabilized using Zorbitrol polymer gel to minimize disturbance prior to extrusion (Tomkins et al., 2008). For each location, one core was extruded at 0.25-cm intervals for the first 20 cm, then at 0.5 cm from 20 to 30 cm, and 1 cm intervals to the bottom of the core.

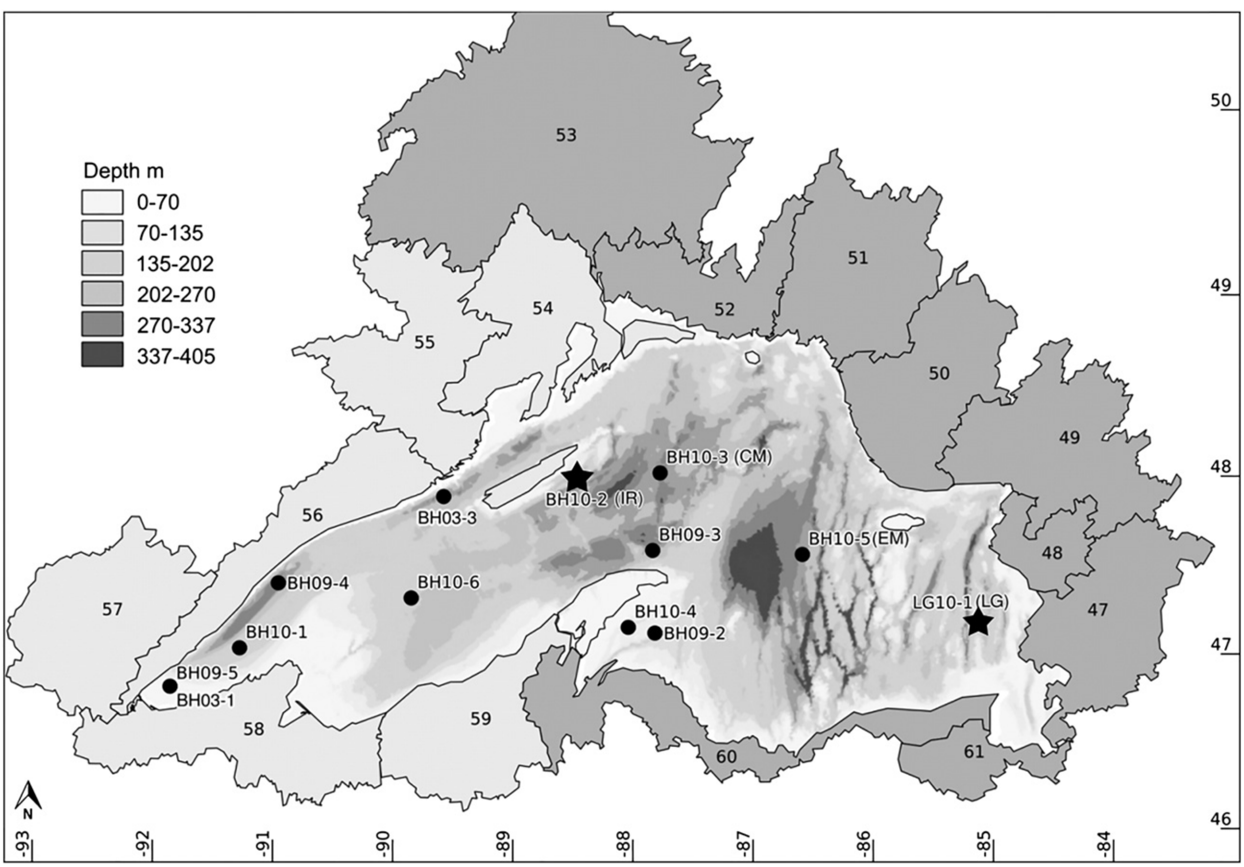

Fig. 1. Lake Superior bathymetric map with surrounding watershed. The X and Y axes are latitude and longitude. Increasing lake depth is indicated by darker shading. Stars represent coring sites used in this study (LG10-1 (LG) = eastern core and BH10-2 (IR) = western core); circles are other cores sampled in the last decade. Although only two cores were studied here, additional core identifications are provided to harmonize with other studies and future publication as they appear. Surrounding watershed boundaries are indicated using arbitrary identification numbers used in the stressor database. Watersheds draining to the eastern side of the lake, represented by the eastern core (LG), are shaded dark; watersheds draining to the western half of the lake, represented by the western core (IR), are shaded light.