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Asynchronous changes in trophic status of a lake and its watershed inferred from sedimentary diatoms of different habitats

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ABSTRACT

Paleolimnology is one important approach for setting realistic goals for restoration and management decisions for lakes. Two important assumptions for reconstructing total phosphorus in lakes using diatoms are: (1) phosphorus is the key limiting factor for diatom growth; (2) other factors (chemical, biologic, or physical activity) had not significantly affected the natural way the remains of diatoms were buried. Both other lines of evidence, which is evaluated by a form of causal criteria analysis–Eco Evidence, and evidence from Muskegon Lake itself, were analyzed to evaluate whether total phosphorus (TP) is the causal factor for diatom species composition change in Muskegon Lake. Both evidence supported the cause-effect linkage between TP and diatom species composition change. Interestingly, our data analysis on a long sediment core from Muskegon Lake showed benthic and planktonic diatoms responded to changes in phosphorus conditions at two spatial scales. When inferring TP based on species composition of all diatoms, relationships to geochemical proxies and land use were poor. However, when inferring TP using benthic and planktonic diatoms, benthic diatom inferred TP was related most to in-lake conditions and planktonic diatom inferred TP was related most to changes in the Muskegon River, upstream from the lake. Only benthic diatom inferred TP correlated well with geochemical proxies in the lake. With a 23 day residence time of water in Muskegon Lake, species composition of planktonic diatoms in the core was likely more regulated by exogenous (allochthonous) environmental factors and processes, Muskegon River, than benthic diatoms. Therefore, freshwater landscape and other landscape variables, such as water residence time, are as important as biological feature for understanding long term trophic status change for some lakes. Caution should be used when diatom assemblages are more influenced by other factors than in-lake condition.

1. Introduction

To establish pre-impact chemical and ecological conditions of lakes is of great importance for setting realistic goals for restoration and management decisions (Bennion & Battarbee, 2007). Diatom-based transfer functions provide one of the few methods for estimating past changes in lake-water total phosphorus (TP) concentrations, quantifying rates of lake eutrophication, and establishing goals for water-quality remediation, so they are widely used by scientists and lake managers to study lake eutrophication (Smol, 2008; Soranno et al., 2011). However, as with any models, diatom transfer functions will always produce a result. Therefore, it is important to evaluate how reliable the reconstructions are. Serious problems and limitations have been identified in reconstructing some environmental variables, such as temperature (Anderson, 2000; Battarbee et al., 2002) and nutrients (Whitmore, 1989; Fritz et al., 1993; Dixit et al., 1999; Arnett et al., 2012). Juggins (2013) nicely summarized problems in quantitative reconstruction in paleolimnology and gave his suggestions to avoid reconstructing variables that are acting as surrogates for other underlying factors. However, he did not provide a practical method to analyze the causal relationship between environmental variables and biota, one of his most important suggestions.

Causal analysis is challenging for environmental science study because usually we do not have data from before and after human alteration of landscapes, and many environmental factors covary. Evidence from the case itself plays an important role in the cause effect analysis. Meanwhile, multiple lines of evidence from field studies, experiments, and modeling of other papers are necessary to establish causality (Beyers, 1998; Norris et al., 2012). Eco Evidence, which was originally developed by epidemiologists in the 1960s (Weed, 1997; Tugwell and Haynes, 2006), provides a transparent and repeatable framework for assessing the evidence for and against causal

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relationships for environmental science study. The Eco Evidence method is an 8-step process in which the user conducts a systematic review of the evidence for one or more cause–effect hypotheses to assess the level of support for an overall question (Norris et al., 2012). In contrast to the longer narrative reviews more familiar to environmental scientists, Eco Evidence uses systematic review techniques to allow researchers to produce succinct reviews that test clearly stated hypotheses. In the present study, we used Eco Evidence to evaluate level of support of published papers on causal effect linkage between diatom species composition and environmental variables.

The reliability of a diatom inferred index is directly affected by the quality of diatom record, which is might be affected by many factors, such as loss via outflow, upstream contamination, resuspension and reworking of older sediment within lake basin, bioturbation within water column and diatom dissolution (Battarbee, 1986). All these factors might have negative effects on diatom reconstruction, which is based on diatom composition information. Up to now, the most serious concern on taphonomy and preservation of diatom, especially in saline and highly alkaline lakes, is over dissolution (Battarbee et al., 2001). Because valve walls are not silicified evenly and level of silicification for different diatom taxa is different, number of valves accumulation might be reduced and composition of the sediment assemblage might be biased (Ryves, 1994). However, factors like upstream contamination on the quality of fossil record have not been reported because of problems in estimating annual production in benthic habitats and problems of spatial variability of diatom accumulation rates in the sediments (Battarbee, 1978; Anderson, 1989).

Frey's (1988) review of paleolimnological literature emphasized that sediments and biological remains in them could come from multiple sources even within a lake, and that distinguishing these sources is important for determining the potential restoration targets and sources of stressors. In lakes with little external input, most of the sediments and proxies for historic condition likely originate within the lake. For habitats like estuaries, where rivers discharging to the estuary can be an important source of sediments, the primary sources of sediments deposited in the estuary could be the upstream river or estuary, depending upon relationships between the two (Cooper et al., 2004). Impoundments in rivers present another case where the upstream sources of sediments can be significant, but the relative importance of sediment proxies originating within the impoundment or upstream should vary with the relative size of the impoundment, size and discharge of the upstream river, and retention time in the impoundment (Reavie and Edlund 2010).

For many sediment proxies of past conditions, distinguishing internal and external sources is difficult. Diatoms are a proxy for which internal and external sources could be distinguished if different types of diatoms are expected from different sources. For example, benthic and planktonic diatoms are used to distinguish within lake and upstream watershed sources of nutrients if one kind of diatom versus the other are expected from the lake or upstream source. In the present study, we firstly confirmed whether P is the key limiting factor for diatom assemblages change in Muskegon Lake; then, we reconstructed TP based on different types of diatoms and analyzed the sensitivity of reconstructed results based on different types of diatoms to lake conditions at different spatial scales; lastly, we analyzed why the sensitivity of reconstructed TP based on different types of diatoms to lake conditions at different spatial scales is different.

2. Materials and methods

2.1. Muskegon lake and Muskegon river watershed

Muskegon Lake is a dimictic drowned river mouth system along the west coast of Lake Michigan (Great Lakes, USA) in a watershed disturbed by human activity since the early 1800s (Fig. 1). The surface area of the lake is 16.91 km^2 with average length and width about 6 and 2.75 km, respectively. Its mean and maximum depths are 7 and 23 m, respectively. A large shoal is located on the north central side of the lake and extends almost half-way across the lake. Muskegon Lake is connected to Lake Michigan through a navigation channel. Approximately 95% of the water volume entering the lake is from Muskegon River, and the retention time of water in Muskegon Lake is estimated to be 23 days (Freedman et al., 1979).

The Muskegon River Watershed is 7,057 km^2. The Muskegon River is fed by groundwater in its headwaters in Higgins and Houghton Lakes. It travels 352 km from headwaters to mouth in Muskegon Lake. Water enters the river mostly via groundwater because of the shallow soils and highly permeable glacial tills of the watershed. The presettlement landscape of the Muskegon River Watershed (MRW) is estimated to be mostly forested (91%) with approximately 4% in open water, 2% in wetlands, and 3% in open fields (Pijanowski et al., 2007). Current estimates of wetland area are approximately 6% of the watershed, which likely better reflects wetland area presettlement. Some of the forested lands may have been forested wetlands in the presettlement land use characterization. Pre-settlement land cover was estimated with polygons downloaded from the Michigan Geographic Data Library. Land use and land cover from 1900 to 1978 were determined by backcast modeling by Pijanowski et al. (2005, 2006, 2007), as were interpolations of land use land cover from 1978 to 2006 and data from the National Land Cover Database. Presettlement were assumed to persist until 1837 when Muskegon Township was established (http://www.co.muskegon.mi.us/history_of_muskegon.htm). Land use and land cover estimates from presettlement to 1900 were calculated by linear interpolation from presettlement to 1900 backcast estimates by Pijanowski et al. (2005, 2006). Land use in 500 m buffer around Muskegon Lake was produced by Ray and Pijanowski (2010). Nutrient concentrations in the Muskegon River were measured during a monitoring project by the Muskegon River Watershed Partnership at 12 locations along the river in 2008. TN and TP averaged 0.64 mg TN/L and 0.03 mg TP/L.

2.2. Sediment core and sample analysis

A 149 cm gravity core was retrieved from a depositional basin of Muskegon Lake (43°14.042′N, 86°17.006′W) in 2006 (Fig. 1). The core was immediately sectioned on-shore after retrieval producing 0.5 cm increments for the first 8 cm and at 1 cm increments for the remainder of the core. Sediment samples were placed in cold-acid-washed polypropylene jars and stored on ice for return to the laboratory. Sediments for chemical analysis were freeze dried in the laboratory. Sediments for geochemical proxy analysis (Cr, Cu, Cd, Pb, Zn, Ca, P) were digested (Hewitt and Reynolds, 1990) by trace-metal grade HNO_3 (EPA Method 3051, USEPA, 2007) in a CEM-MDS-81D™ microwave. Samples were analyzed using a Micromass Platform™ inductively coupled, plasma, mass spectrometer with hexapole technology. Mercury in the sediments was quantified using a Lumex R-915 + 49 Zeeman corrected atomic absorption spectrometer with an R-915 pyrolyzer attachment (www.ohiolumex.com) (USEPA, 1998). Lead-210 and Cs-137 were measured by the Freshwater Institute in Winnipeg, Manitoba, Canada to determine sedimentation rates and sediment ages. Various models were explored to date sediment cores. There is no consensus as to which model is more appropriate in all cases (Oldfield and Appleby, 1984), and several factors were considered when choosing a model that included visual examination of the ^{210}Pb profile, profiles of ^{137}Cs activity and stable Pb concentration profiles (Yohn et al., 2002). The segmented constant flux constant sedimentation model (Golden et al., 1993) best described the excess ^{210}Pb in the core.

Vertical profiles of diatom community composition were examined in 38 samples collected from the core, including the 2 cm section, 4 cm section, and sections at 4 cm intervals (approximately) throughout the rest of the core. Diatom processing and taxonomical identification of the 149 cm core was performed by the algal ecology laboratory at