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Cladoceran assemblage changes across the Eastern United States as recorded in the sediments from the 2007 National Lakes Assessment, USA

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ABSTRACT

Cladoceran zooplankton subfossils have been widely applied as indicators of lake health and used to infer past environmental change. However, our understanding of how the environment controls the abundance and distribution of Cladocera, as recorded in lake sediments, is still developing; only a few large landscape studies have been conducted in temperate North American lakes. Here we examine cladoceran remains from across 72 lakes and through time by analysing sediments that were collected as part of the US Environmental Protection Agency 2007 National Lakes Assessment. Using both taxonomic and functional-trait approaches, we related both taxonomic and functional-trait subfossil cladoceran assemblages to a suite of biological, chemical, and physical variables of lake health by applying Redundancy Analyses and Multivariate Regression Trees. Primary gradients identified as predictors of the cladoceran assemblages were: calcium and pH, depth and measures associated with pelagic and littoral habitat, and climate. Notably, calcium was identified as the primary driver of the Bosminidae, with greater relative abundances of *Bosmina longirostris* at concentrations $\geq 3.99\ mg\ L^{-1}$, and with *Eubosmina* spp. associated with lower concentrations. Comparison of surface and pre-industrial sediments on a northern (temperate) lake subset suggested that the primary agents of change were localized, as we did not detect consistent directional shifts in Cladocera. In particular, the quality and complexity of the littoral habitat were associated with changes in key cladoceran groups through time. Overall, our study identified insightful relationships between cladoceran subfossil assemblages and environmental variables across spatial and temporal gradients, which are critical for refining the utility of Cladocera as ecological indicators in paleolimnological studies.

1. Introduction

The community composition of crustacean zooplankton has regularly been used as a proxy for assessing the health of freshwater aquatic ecosystems (Gannon and Stemberger, 1978; Xu et al., 2001). Zooplankton are a central component of aquatic ecosystems, occupying an intermediate trophic position and playing an important role in the transfer of nutrients from primary producers to higher trophic levels (Jeppesen et al., 2005; Vanni and Layne, 1997). Consequently, zooplankton are of great interest to managers and conservationists interested in protecting aquatic ecological health (e.g. Cairns et al., 1993; Mills and Schiavone, 1982; Simões et al., 2015).

One important group of freshwater crustacean zooplankton are the Cladocera, which leave remains that preserve in lake sediments and are frequently used in paleolimnological investigations to infer environmental change (Korhola and Rautio, 2001). Sediment records have been used to track cladoceran responses to a number of environmental and ecological factors and anthropogenic stressors such as acidification (Paterson, 1994), changes in lake-water calcium (Jeziorski et al., 2008; Shapiera et al., 2012), lake productivity (Hann et al., 1994; Korponai et al., 2011), planktivory pressure (Amsinck et al., 2005; Davidson et al., 2007) and climate (Lotter et al., 2000).

One of the most powerful tools used to improve our understanding of the factors that affect aquatic systems are large-scale surveys, which may be used to identify patterns across aquatic communities and match them to regional stressors and environmental gradients (e.g. Bos and Cumming, 2003; Hessen et al., 2006; Korosi and Smol, 2012a). While such surveys have been applied extensively in paleolimnology to assess regional drivers of diatom (e.g. Finkelstein et al., 2014; Winegardner et al., 2015) and chironomid (e.g. Fortin et al., 2015) assemblages, fewer large spatial studies have been conducted on subfossil Cladocera. In North America, sedimentary cladoceran surveys have focused on

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Nomenclature

Abbreviations

BsfcSand	Fractional presence of bottom substrate that is sand
Chl *a*	Water column chlorophyll *a* concentrations
CVRE	Cross validated relative error
Depth	Maximum observed depth
DOC	Dissolved organic carbon
FciAll	Total littoral fish cover
FDis	Functional dispersion
MRT	Multivariate regression tree
NLA	Environmental Protection Agency's National Lakes Assessment
PCA	Principal components analysis
RDA	Redundancy analysis
RVeg	Observed vs expected riparian cover complexity index
SLD	Shoreline development index
Stdev	Standard deviation
Temp	Annual mean temperature normals 1981-2010
US	United States of America

Abbreviations of Functional Groups

P_pred	Pelagic predators
P_herb	Pelagic herbivores
L_pred	Littoral predators
L_para	Littoral parasites
L_vrsm	Littoral herbivores associated with vegetation, rock, sand, and mud substrate
L_vrs	Littoral herbivores associated with vegetation, rock, and sand substrate
L_vrm	Littoral herbivores associated with vegetation, rock, and mud substrate
L_vsm	Littoral herbivores associated with vegetation, sand, and mud substrate
L_vm	Littoral herbivores associated with vegetation and mud substrate
L_v	Littoral herbivores associated with vegetation substrate
L_rsm	Littoral herbivores associated with rock, sand, and mud substrate
L_rs	Littoral herbivores associated with rock and sand substrate
L_rm	Littoral herbivores associated with rock and mud substrate
L_m	Littoral herbivores associated with mud substrate

boreal or northern environments in Canada (Armstrong and Kurek, 2018; Bos and Cumming, 2003; DeSellas et al., 2008; Jeziorski et al., 2015, 2012; Korosi et al., 2008; Korosi and Smol, 2012a; Kurek et al., 2011; Sweetman et al., 2008; Sweetman and Rühland, 2010; Thienpont et al., 2015) and Alaska (Sweetman and Smol, 2006a). Across the conterminous United States, very few sedimentary cladoceran surveys have been performed, with only one regional survey, to our knowledge, of littoral Chydoridae from Minnesota and North Dakota (Synerholm, 1979). Our goal is to redress this gap and provide new information about the diversity and distribution of subfossil cladoceran assemblages across broad geographic scales from a suite of lakes extending along a north-south gradient across the Eastern United States.

The National Lakes Assessment (NLA) is an extensive sampling program coordinated by the US Environmental Protection Agency of over 1000 lakes (both natural and man-made reservoirs) across the continental United States, providing a rich dataset to explore the drivers of ecological structure and functioning of aquatic ecosystems. The sampling program in 2007 collected information on a suite of biological, recreational, chemical and physical variables of lake health using standardized protocols (USEPA, 2007). The NLA also collected top-bottom sediment core samples, representing modern (top) and, ideally, pre-industrial (bottom) periods (the period of time captured by the bottom sediment depends upon the length of the core and sedimentation rate). Using the NLA sediments, we had the opportunity to explore both spatial and temporal changes in the subfossil cladoceran assemblages for an understudied region, and identify how these ecological indicators were distributed along environmental gradients.

Broadly, our objectives for this study were to identify the drivers and dynamics of cladoceran subfossil assemblages across a large latitudinal gradient. We first developed a large-scale survey from lakes across the eastern portion of the United States to identify the most parsimonious set of variables explaining the greatest variation in the subfossil Cladocera assemblages preserved in surface sediments. Patterns of cladoceran assemblages and diversity were assessed using both taxonomic and functional trait approaches. We then used modern and pre-industrial sediments from a subset of lakes from the

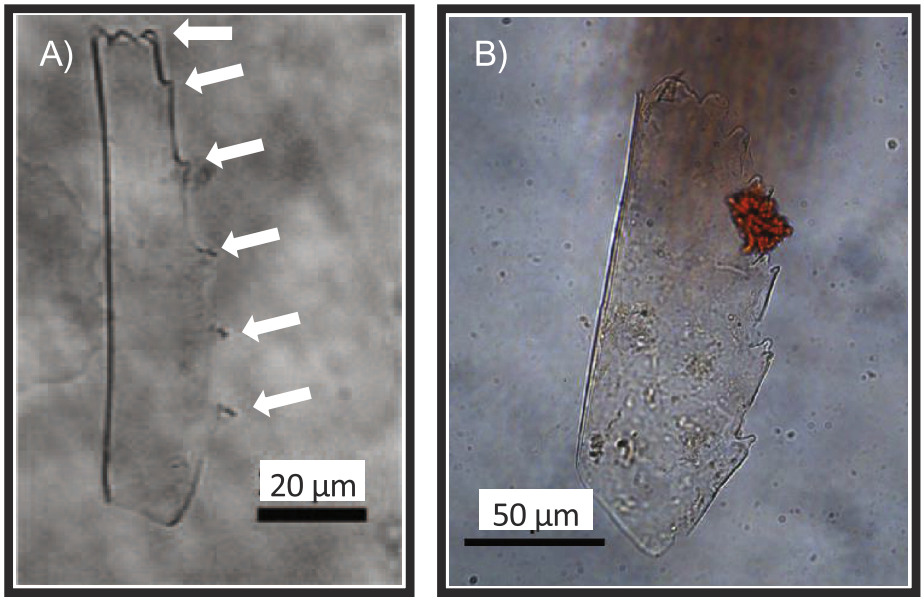

Fig. 1. Distribution of NLA 2007 sites sampled for sedimentary Cladocera across the Eastern United States. The marker shape indicates if the site was included in the top-bottom analyses (circle) or solely part of the spatial survey of surface (top) sediments. The marker fill denotes whether the lake is a natural lake (black fill) or a constructed reservoir (hollow). Data is from the 2007 USEPA National Lakes Assessment database (https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2007-results).