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Trends in *Mysis diluviana abundance* in the Great Lakes, 2006–2016

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ABSTRACT

With the large *Diporeia* declines in lakes Michigan, Huron, and Ontario, there is concern that a similar decline of *Mysis diluviana* related to oligotrophication and increased fish predation may occur. *Mysis* density and biomass were assessed from 2006 to 2016 using samples collected by the Great Lakes National Program Office's biomonitoring program in April and August in all five Great Lakes. Summer densities and biomasses were generally greater than spring values and both increased with bottom depth. There were no significant time trends during these 10–11 years in lakes Ontario, Michigan, or Huron, but there was a significant increase in Lake Superior. Density and biomass were highest in lakes Ontario and Superior, somewhat lower in Lake Michigan, and substantially lower in Lake Huron. A few *Mysis* were collected in eastern Lake Erie, indicating a small population in the deep basin of that lake. On average, mysids contributed 12–18% (spring-summer, Michigan), 18–14% (spring-summer, Superior), 30–13% (spring-summer, Ontario), and 3% (Huron) of the total open-water crustacean biomass. Size distributions consisted of two peaks, indicating a 2-year life cycle in all four of the deep lakes. *Mysis* were larger in Lake Ontario than in lakes Michigan, Superior, and Huron. Comparisons with available historic data indicated that mysid densities were higher in the 1960s–1990s (5 times higher in Huron, 2 times higher in Ontario, and around 40% higher in Michigan and Superior) than in 2006–2016.

Introduction

Mysis diluviana (formerly *relicta*; from here on referred to as *Mysis*) is an up to 25 mm long, glacial relict crustacean common to the Laurentian Great Lakes (Balcer et al., 1984). *Mysis* perform a diel vertical migration from the sediment surface to the thermocline (Beeton, 1960; Boscarino et al., 2009), and are important in the diet of both benthic and pelagic fish species (Wojcik et al., 1986; Crowder and Crawford, 1984; Isaac et al., 2012). *Mysis* are omnivorous, consuming diatoms, zooplankton, and amphipods (Grossnickle, 1982; Johannsson et al., 2001; O'Malley et al., 2017) and impact food webs both where they are native (Kitchell et al., 2000; Gal et al., 2006) and where they were introduced (Lasenby et al., 1986; Devlin et al., 2017). Hence, *Mysis* is a key species in the offshore food web of the deeper Laurentian Great Lakes and is therefore of considerable interest to fishery biologists, lake managers, ecosystem modelers, and other stakeholders and decision makers.

Invasion of non-indigenous species, especially the zebra and quagga mussels (*Dreissena polymorpha*, *D. rostriformis bugensis*), and efforts to reduce nutrient input into the Great Lakes by improving sewage treatment plants have led to oligotrophication in lakes Huron, Michigan, and Ontario (Madenjian et al., 2002; Mills et al., 2003; Evans et al., 2011). Both chlorophyll and silica dynamics suggest that primary production in lakes Michigan and Huron has declined in the last several years (Fahnenstiel et al., 2010; Mida et al., 2010). In Lake Huron, declines in algae, *Diporeia*, and zooplankton (Nalepa et al., 2007; Barbiero et al., 2012) since 2003 have contributed to decreased forage fish populations, especially alewife *Alosa pseudoharengus* (Riley et al., 2008), and also decreased abundance of salmonines. These declines in the lower food web have required reductions in stocking and resulted in the loss of an important recreational fishery (Michigan Dept. of Nat. Res., 2005). Similar changes are occurring in Lake Michigan, but lag behind those of Lake Huron (Fahnenstiel et al., 2010; Rodgers et al., 2014; Bunnell et al., 2014). Lake Ontario may also be experiencing these declines (Koops et al., 2015). Evidence from Lake Huron suggests these declines resulted in poorer feeding conditions for *Mysis* (Mida-Hinderer et al., 2012). At the same time, predation on *Mysis* may be increasing, representing a second cause of population declines. Movement of fish farther offshore may expose *Mysis* to additional predation (O'Gorman et al., 2000). Crashes in *Diporeia*, an alternative prey for fishes, have been followed by greater presence of *Mysis* in fish diets (Owens and Dittman, 2003; Stewart et al., 2009). In addition, *Mysis* may be competing with increasing numbers of *Bythotrephes* for zooplankton prey

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(Bunnell et al., 2011; Johannsson et al., 2011). With these changes, *Mysis* may be simultaneously exposed to additional predation by fish and lower growth rates due to reduced food supplies (Mida-Hinderer et al., 2012), both of which may lead to declining *Mysis* populations. Therefore, information on *Mysis* is critical for understanding recent Great Lakes food web responses to external drivers, such as invasive species and oligotrophication.

This paper describes the status of the *Mysis* populations in the Laurentian Great Lakes using data collected from 2006 through 2016 by the Environmental Protection Agency (EPA) Great Lakes National Program Office's (GLNPO) biological monitoring program. Our objectives were to (1) present the density and biomass of *Mysis* in all five Great Lakes, (2) test if there are significant time trends in each lake, (3) evaluate size structure as an indicator of *Mysis* growth rates, and (4) compare current findings with published historical data. Given recent changes in the lower food webs (Bunnell et al., 2014; Vanderploeg et al., 2002), we expected to see declines in *Mysis* populations from 2006 to 2016 in lakes as a result of continued oligotrophication (Huron and Michigan) and as a result of declining *Diporeia* populations (Huron, Michigan, and Ontario). Oligotrophication should lead to declining growth rates and population biomass as a result of lower algal and zooplankton production. The decline in *Diporeia* should lead to higher fish predation on *Mysis* as the remaining larger crustacean in these systems and therefore to lower *Mysis* populations. Because oligotrophication and declines in *Diporeia* have not occurred in Lake Superior, we did not expect similar declines of *Mysis* in that lake.

Methods

Mysis field collections

Mysis samples were collected during spring and summer, 2006–2016, at some of the standard stations established by the EPA for long-term monitoring of the open water of all five Great Lakes. During each survey, samples were collected first in Lake Michigan, then in lakes Huron, Erie, Ontario, and lastly in Lake Superior. Mysid samples were collected only when these stations were visited at night; thus, the stations sampled in a given lake varied among years and surveys. One additional Lake Erie station near Long Point (decimal degrees: 42.5331 N, 80.0243 W), depth = 55 m) was added to supplement sample size. Only results from stations deeper than 30 m were reported (Table 1). Spring cruises took place in April during isothermal conditions (end of March through first part of May depending on ice conditions, Table 1), and summer cruises took place in August when the water column was stratified.

All sampling was conducted aboard the R/V Lake Guardian by four research teams: 2006 (University of Wisconsin-Superior), 2007–2011 (University of Michigan), 2012 (GLNPO), and 2013–2016 (Cornell University). *Mysis* tows were performed at night, at least 1 h after sunset and no later than 1 h before sunrise. To prevent *Mysis* from avoiding the vessel, all external ship lights were turned off prior to arrival at a station, and technicians used only red flashlights on deck. *Mysis diluviana* cannot detect red light (Gal et al., 1999). Tows for 2006–2011 were performed using a 1- × 1-m square plankton net that extended 2 m to a cod end container with 250-μm mesh. The net's top two-thirds was made of Nitex, 1-mm bar mesh, and the bottom one-third of 250-μm Nitex. Tows for 2012–2016 were done with a 1-m, diameter, 2-m long, circular net with the top two thirds with 500-μm mesh net and the lower third and bucket with 250-μm mesh. The mouth of the net was lowered to 2–5 m above bottom, then raised to the surface at a speed of 0.5 m/s and washed down to ensure collection of any *Mysis* that were clinging to the net. The number of mysids caught in each net sample was adjusted for size of the net opening and calculated assuming 100% net efficiency. *Mysis* in samples were anesthetized immediately with carbonated water, and then preserved in 10% sugar-buffered, formaldehyde solution. Two replicate tows were performed in this way per station. Detailed description of the sampling procedure is given in GLNPO Standard Operating Procedure LG409, ver. 1 (2015, available from GLNPO).

Laboratory processing of Mysis

Preserved samples were processed in the laboratory by rinsing the samples using a 250-μm-mesh screen and then transferring the animals to Petri dishes or glass trays. Currently two mysid species are present in the Great Lakes (*Mysis diluviana* and *Hemimysis anomala*). *Mysis* is present in offshore samples, while *Hemimysis* is a shallow water species (Walsh et al., 2012). No *Hemimysis* individuals were found in the samples analyzed for this paper. Individual animals were counted, sexed, and measured to the nearest 0.1 mm, with standard length defined as the length from the tip of the rostrum to the end of the last abdominal segment. It is difficult to distinguish young *M. diluviana* males from females (Pothoven et al., 2004), therefore all mysids <11 mm were designated immature without further investigation of sexual characteristics. Adult males were identified based on their highly developed 4th pleopod, while gravid females were females with embryos in the marsupium. Remaining animals >11 mm, that were not obviously males or gravid females, were designated as females. During 2006 to 2011, all *Mysis* were measured (except two samples from 2008 with large numbers of mysids), while during 2012–2016, up to 100 random individuals were measured from each sample. Detailed description of the sampling procedure for 2012–2016 is given in GLNPO Standard Operating Procedure LG408, ver. 1 (2015). Analyses were done by technicians at University of Wisconsin-Superior (2006), University of Michigan (2007–2011), and Cornell University (2012–2016).

Measurements during 2006 were made with a micrometer eyepiece in the microscope, while during 2007, a Moticam 1000, 1.3 M pixel camera and Motic Images Plus 2.0 imaging software were deployed. During 2008–2011, individual *Mysis* were measured using a plastic metric ruler under a glass Petri dish after straightening the animals with forceps. Samples from 2012 to 2016 were measured on high-definition (16 M pixels) digital pictures using ImageJ (Schneider et al., 2012). Brood sizes were counted when present for all gravid females. Mysids smaller than 4 mm may have been released from the brood pouch during capture and were not counted by all three groups. Therefore, mysids <4 mm were not included in the density and biomass estimates. For abundance determinations, a few *Mysis* heads that were separated from bodies were counted as one individual and their lengths estimated based on size of the head and comparisons with intact animals. Density is reported in numbers per square meter assuming 100% efficiency of the net.

Biomass of *Mysis* was calculated using a length-weight equation from Johannsson (1995): $\ln(W) = -12.27 + 2.72 \ln(L)$, where W is dry weight in g and L is length in mm. This equation was derived for the standard length measure used here (tip of rostrum to end of abdomen/base of telson) even though the original reference states otherwise (see Rudstam et al., 2008). Biomass is reported as mg dry weight/m^2.

Laboratory processing of zooplankton

Zooplankton biomass was generated from zooplankton samples collected by the GLNPO zooplankton program and will be discussed in detail in future papers. Methods can be found in GLNPO Standard Operating Procedure 402 rev 12 (2017) and 404 rev 8 (2017).

Quality assurance

As quality assurance (QA), at least 10% of all *Mysis* samples were reanalyzed by a second analyst. In some cases small individuals were missed by the original analyst; these were added to the count. For 2012–2016, QA procedures (SOP LG408) required the differences between the two analysts' counts and length measurements to be <10%

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