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Biomonitoring using invasive species in a large Lake: *Dreissena* distribution maps hypoxic zones

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ABSTRACT

Due to cultural eutrophication and global climate change, an exponential increase in the number and extent of hypoxic zones in marine and freshwater ecosystems has been observed in the last few decades. Hypoxia, or low dissolved oxygen (DO) concentrations, can produce strong negative ecological impacts and, therefore, is a management concern. We measured biomass and densities of *Dreissena* in Lake Erie, as well as bottom DO in 2014 using 19 high frequency data loggers distributed throughout the central basin to validate a three-dimensional hydrodynamic-ecological lake model. We found that a deep, offshore hypoxic zone was formed by early August, restricting the *Dreissena* population to shallow areas of the central basin. Deeper than 20 m, where bottom hypoxia routinely develops, only young of the year mussels were found in small numbers, indicating restricted recruitment and survival of young *Dreissena*. We suggest that monitoring *Dreissena* distribution can be an effective tool for mapping the extent and frequency of hypoxia in freshwater. In addition, our results suggest that an anticipated decrease in the spatial extent of hypoxia resulting from nutrient management has the potential to increase the spatial extent of profundal habitat in the central basin available for *Dreissena* expansion.

Introduction

Hypoxia (bottom oxygen concentration <2 mg L^{-1}) and anoxia (bottom oxygen concentration <1 mg L^{-1}) are the manifestations of combined effects of two major processes, decomposition of elevated autochthonous and/or allochthonous production, and increased water column stability, and are commonly linked to cultural eutrophication and global climate change (Diaz, 2001; Diaz and Rosenberg, 2008; Scavia et al., 2014; Altieri and Gedan, 2015). Over the past few decades there has been an exponential increase in the number and areal extent of hypoxic zones observed in freshwater, marine, and coastal ecosystems that has resulted in strong negative impacts on aquatic communities including fish and benthic and planktonic invertebrates (Diaz and Rosenberg, 2008; Stramma et al., 2008; Turner et al., 2008; Vaquer-Sunyer and Duarte, 2008).

Many government efforts worldwide, including recently established U.S. and Canadian binational targets for reducing nutrient inputs to the Laurentian Great Lakes (GLWQA, 2012), are focused on the development of nutrient abatement strategies to reduce external nutrient loads to control eutrophication and hypoxia (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2008; Backer et al., 2010; GLWQA, 2012; Chesapeake Bay Watershed Agreement, 2014). Key to tracking success of these efforts will be the ability to monitor the ecosystem response to reduced nutrient loads, which includes monitoring the extent of Great Lakes hypoxic zones. Hypoxia is a widespread phenomenon in the Great Lakes that occurs seasonally in the bottom layer (hypolimnion) of some productive basins and embayments in lakes Michigan (e.g. Green Bay), Ontario (e.g. Hamilton Harbor) and in Lake Erie (central basin) (Dermott et al., 2007; Scavia et al., 2014; Hamidi et al., 2015). These zones are dynamic in time and space and are affected by physical processes including mesoscale meteorological forcing events (Bocaniov and Scavia, 2016). The hypoxic zone can extend into nearshore zones during upwelling events, shrink or even disappear during severe storms, and then become re-established later, making the spatial and temporal extent of hypoxia difficult to quantify via hypoxia monitoring surveys currently conducted every three weeks by U.S. Environmental Protection Agency Great Lakes National Program Office (U.S. EPA GLNPO). Alternatively, the deployment of stationary oxygen loggers may increase our temporal coverage but misrepresent the

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spatial extent of the basin-wide hypoxic zone and hypolimnion thickness. Therefore, resource managers need alternative methods of monitoring that are able to provide more sensitive and time-integrated measures of hypoxia, especially its spatial extent. One such time-integrated method to monitor low oxygen events is biological monitoring. This method is based on the assumption that changes in water quality are accompanied by the changes in certain species sensitive to the environmental condition of interest (e.g. dissolved oxygen concentration, Merritt et al., 2008; Wiederholm, 1980). Benthic organisms, especially sessile species that live more than one year, are most vulnerable to hypoxia, thus the presence of robust benthic communities containing sensitive species indicates acceptable oxygen conditions and can be used to monitor progress toward ecosystem restoration (Mandaville, 2002; Merritt et al., 2008). In the Laurentian Great Lakes, benthic communities are now dominated by invasive zebra (*Dreissena polymorpha*) and quagga (*Dreissena rostriformis bugensis*) mussels (Watkins et al., 2007; Nalepa et al., 2010; Karatayev et al., 2014). Both dreissenid species are known to be sensitive to low oxygen (reviewed in McMahon and Bogan, 2001; Karatayev et al., 2007) and have a long life span, usually >3 years (reviewed in Karatayev et al., 2006), which suggests that their presence can be used to assess past habitat conditions that were unfavorable for their survival. Here, we investigated interactions between hypoxia and invasive mussels at a system-wide scale in Lake Erie where hypoxia is a key issue for water resource management.

In Lake Erie, bottom hypoxia regularly occurs in the central basin (Vanderploeg et al., 2009; Kraus et al., 2015; Bocaniov and Scavia, 2016) and occasionally in the western basin (Ackerman et al., 2001; Bridgeman et al., 2006). The central basin has always experienced seasonal hypoxic conditions (Beeton, 1961; Delorme, 1982), but the extent of hypoxia substantially increased during the cultural eutrophication of the 1950s–1960s. After the implementation of phosphorus reduction programs in the 1970s the extent of the hypoxic zone shrank (Makarewicz and Bertram, 1991; Bertram, 1993), but it then rebounded in the late 1990s and 2000s to previously reported levels (Scavia et al., 2014), driven by increases in dissolved reactive phosphorus (Richards et al., 2010; Scavia et al., 2014) and climate change (Michalak et al., 2013). As a result, a large portion (up to 10,000 km^2) of the central basin now becomes severely hypoxic during August and September and remains hypoxic until fall overturn (Vanderploeg et al., 2009; Kraus et al., 2015; Bocaniov and Scavia, 2016).

The return of severe hypoxia in the central basin of Lake Erie has had strong impacts on the spatial distribution and migration of a number of aquatic organisms including fish, zooplankton, and phytoplankton communities (Vanderploeg et al., 2009; Scavia et al., 2014; Kraus et al., 2015). Less information is available on the effect of hypoxia on benthos in the central basin, although evidence suggests hypoxia limits the distribution of *Dreissena*, especially in deep stratified areas (Patterson et al., 2005; Karatayev et al., 2014). However, it is unknown to what degree the populations of *Dreissena* spp. in a large lake can be affected by hypolimnetic hypoxia and to what extent mussel distribution reflects the spatial extent of the hypoxic zone.

In contrast to the deeper central basin, the shallow western basin rarely stratifies and historically (before 1960s) was not hypoxic, as it supported extremely large populations of mayflies *Hexagenia*, which are intolerant to low oxygen (Shelford and Boesel, 1942; Britt, 1955). Similarly to the central basin, cultural eutrophication resulted in significant large-scale depletion of dissolved oxygen in the western basin, causing a reduction of *Hexagenia* almost to the point of extirpation in the 1960s (Beeton, 1961; Carr and Hiltunen, 1965). Water quality improvements by the mid-1980s, coupled with the introduction of dreissenids in the basin, temporarily halted eutrophication (Makarewicz and Bertram, 1991; Leach, 1993) and subsequently brought about the restoration of *Hexagenia* to pre-extirpation levels by 1999 (Schloesser et al., 2000). Since the reappearance of eutrophication, however, *Hexagenia* have suffered occasional recruitment failures, most likely due to episodes of severe oxygen depletion following temporary thermal stratification (Ackerman et al., 2001; Bridgeman et al., 2006).

Regular extended periods of hypoxia in the central basin and occasional episodes of hypoxic conditions in the western basin should have a strong impact on *Dreissena* spp. population dynamics, making these species useful indicators of the near bottom hypoxic conditions. We hypothesized that: 1) mussel density will be lowest at sites with more frequent hypoxia, reflecting impaired recruitment and higher mortality; and 2) mussels in areas with hypoxia will be smaller, reflecting a younger local population comprised only of recent recruits. To test these hypotheses and the ability of using *Dreissena* spp. abundance to map hypoxic zone extent we: 1) measured bottom dissolved oxygen using data loggers distributed throughout the central basin to validate a three-dimensional hydrodynamic-ecological model simulating dissolved oxygen distribution; 2) carried out a lake-wide survey of *Dreissena* spp. in Lake Erie in 2014; 3) used a three-dimensional coupled hydrodynamic-ecological lake model calibrated and validated for Lake Erie in previous applications to simulate the spatial extent of hypoxia and the amount of days with hypoxia at each site sampled during 2014 survey; and 4) compared predicted values with the spatial distribution, abundance and size structure of *Dreissena*.

Materials and methods

Study area and hypoxia description

Lake Erie is divided into three basins: the shallow western basin (average depth 7.4 m), the intermediate central basin (18.3 m), and the deepest eastern basin (average depth 24.4 m) (Bolsenga and Herdendorf, 1993) (Fig. 1a). The western basin is the most productive and turbid due to large inputs of nutrients and suspended sediments (Mortimer, 1987; Barbiero and Tuchman, 2004). Although the western basin stratifies only intermittently during the summer, it may periodically experience short-term episodes of severe hypoxia (Ackerman et al., 2001; Bridgeman et al., 2006). In contrast to the central basin, which requires several months to become hypoxic, the near bottom water in the western basin may rapidly become hypoxic following periods of calm weather and development of brief episodes of stable temporal stratification (Bridgeman et al., 2006). However, these hypoxic events are short-lived and the basin will turn-over, re oxygenating the bottom layer during the next wind event. The central basin is deeper and has a large offshore area that typically stratifies during the summer. The basin receives nutrients and sediments from the western basin and is susceptible to sediment resuspension and seasonal hypoxia (Delorme, 1982; Mortimer, 1987; Scavia et al., 2014; Bocaniov and Scavia, 2016; Bocaniov et al., 2016). Finally, the eastern basin is the least eutrophic, develops stable stratification during summer with a large thick hypolimnion that never goes hypoxic, and has the lowest inputs of suspended solids and nutrients (Kemp et al., 1977; Mortimer, 1987).

Dreissena sampling protocol

As part of the Lake Erie Cooperative Science and Monitoring Initiative field year (CSMI, Richardson et al., 2012), the distribution, density, wet biomass, and length-frequency distribution of *Dreissena* spp. were measured in Lake Erie at 107 sites (Fig. 1b). Offshore sites were sampled aboard the U.S. EPA R/V *Lake Guardian* using a regular PONAR grab sampler (sampling area 0.052 m^2), while nearshore sites (<10 m depth) were sampled aboard Buffalo State R/V *John J. Freidoff* using a petite Ponar grab sampler (sampling area 0.023 m^{-2}). Sites were stratified based on depth zones and lake basins. Samples from rock/bedrock at 5 and 10 m depths in the eastern basin were collected by SCUBA divers (0.25 m^2 quadrat). A total of 294 Ponar dredge samples and 27 quadrat samples were collected in July and August of 2014.