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Review

Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia

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ABSTRACT

Relieving phosphorus loading is a key management tool for controlling Lake Erie eutrophication. During the 1960s and 1970s, increased phosphorus inputs degraded water quality and reduced central basin hypolimnetic oxygen levels which, in turn, eliminated thermal habitat vital to cold-water organisms and contributed to the extirpation of important benthic macroinvertebrate prey species for fishes. In response to load reductions initiated in 1972, Lake Erie responded quickly with reduced water-column phosphorus concentrations, phytoplankton biomass, and bottom-water hypoxia (dissolved oxygen <2 mg/l). Since the mid-1990s, cyanobacteria blooms increased and extensive hypoxia and benthic algae returned. We synthesize recent research leading to guidance for addressing this re-eutrophication, with particular emphasis on central basin hypoxia. We document recent trends in key eutrophication-related properties, assess their likely ecological impacts, and develop load response curves to guide revised hypoxia-based loading targets called for in the 2012 Great Lakes Water Quality Agreement. Reducing central basin hypoxic area to levels observed in the early 1990s (ca. 2000 km^2) requires cutting total phosphorus loads by 46% from the 2003–2011 average or reducing dissolved reactive phosphorus loads by 78% from the 2005–2011 average. Reductions to these levels are also protective of fish habitat. We provide potential approaches for achieving those new loading targets, and suggest that recent load reduction recommendations focused on western basin cyanobacteria blooms may not be sufficient to reduce central basin hypoxia to 2000 km^2.

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Introduction

Several anthropogenic stressors have impacted Lake Erie since European settlement. However, phosphorus (P) loading has been particularly influential (Ludsin et al., 2001). During the 1960s and 1970s, increased P inputs degraded water quality and reduced hypolimnetic oxygen levels (Bertram, 1993; Makarewicz and Bertram, 1991; Rosa and Burns, 1987). Reduced oxygen, in turn, eliminated thermal habitat vital to cold-water organisms in the central basin (CB) (Hartman, 1972; Laws, 1981; Leach and Nepszy, 1976; Ludsin et al., 2001) and contributed to the local extirpation of important benthic macroinvertebrates and declines of several fish species (Britt, 1955; Carr and Hiltunen, 1965; Ludsin et al., 2001). This development and control of freshwater eutrophication by phosphorus loads is ubiquitous and well documented (e.g., Schindler, 2006, 2012; Smith and Schindler, 2009).

In response, P abatement programs were initiated in 1972 as part of the Great Lakes Water Quality Agreement (GLWQA) (DePinto et al., 1986a). Lake Erie responded relatively quickly, as indicated by measurable decreases in total phosphorus (TP) loads (Dolan, 1993), water-column TP concentrations (DePinto et al., 1986a; Ludsin et al., 2001), phytoplankton biomass (especially cyanobacteria; Bertram, 1993; Makarewicz et al., 1989), and bottom-water hypoxia (dissolved oxygen <2 mg/l) (Bertram, 1993; Charlton et al., 1993; Makarewicz and Bertram, 1991), as well as by recovery of several ecologically and economically important fishes (Ludsin et al., 2001). Although P abatement was primarily responsible for improving water quality through the mid-1980s, zebra (*Dreissena polymorpha*) and quagga (*D. rostriformis bugensis*) mussel invasions during the late 1980s and early 1990s, respectively, likely magnified these changes (Holland et al., 1995; MacIsaac et al., 1992; Nicholls and Hopkins, 1993) and might have contributed to the recovery of some benthic macroinvertebrate taxa (Botts et al., 1996; Pillsbury et al., 2002; Ricciardi et al., 1997). Since the mid-1990s, however, Lake Erie appears to be returning to a more eutrophic state (EPA, 2010; Murphy et al., 2003), as indicated by increases in cyanobacteria (e.g., *Microcystis* spp., *Lyngbya wollei*; Bridgeman et al., 2012; Michalak et al., 2013; Stumpf et al., 2012), the resurgence of extensive benthic algae growth (particularly *Cladophora* in the eastern basin) (Depew et al., 2011; Higgins et al., 2008; Stewart and Lowe, 2008), and the return of extensive CB hypoxia (Burns et al., 2005; Hawley et al., 2006; Rucinski et al., 2010; Zhou et al., 2013).

In 2005, EcoFore-Lake Erie – a multi-year, multi-institutional project supported by the National Oceanic and Atmospheric Administration – began with the goal of developing a suite of management-directed models useful for exploring causes of changes in P loading, their impacts on CB hypoxia, and how these changes might influence Lake Erie's highly valued recreational and commercial fisheries. The EcoFore-Lake Erie project focused on CB hypoxia because of uncertainty about the mechanisms underlying its return to levels commensurate with the height of eutrophication during the mid-20th century (Hawley et al., 2006) and because of its great potential to harm Lake Erie's valued fisheries (sensu Ludsin et al., 2001).

Herein, we provide a synthesis of the results from those efforts, as well as work undertaken through other related projects, leading to science-based guidance for addressing the re-eutrophication of Lake Erie and in particular, CB hypoxia. In the following sections, we document recent trends in key eutrophication-related properties and assess their likely ecological impacts. We develop P load response curves to guide revision of hypoxia-based loading targets, consistent with the 2012 Great Lakes Water Quality Agreement (GLWQA, IJC 2013), and provide potential approaches for achieving the revised loading targets.

Phosphorus loading trends

Total phosphorus loading

Total P loading into Lake Erie has changed dramatically through time, with temporal trends driven in large part by implementing P abatement programs as part of the GLWQA and inter-annual differences responding to variable meteorology (Dolan, 1993). Following initial implementation of nutrient abatement programs beginning in 1972, TP inputs declined precipitously, reaching the GLWQA target loading level of 11,000 MTA during the 1980s (Fig. 1; see Dolan and Chapra, 2012 for methods). Since then, loading has remained below the