REVIEW

Dreissenid Mussels Impact on Phosphorus Levels in the Laurentian Great Lakes

Miranda Steinmetz

Abstract

Great Lakes organisms depend on the essential nutrient phosphorus. However, excess phosphorus becomes a problem because it can cause increased algal growth. Recently, another emerging problem is the increase of dreissenid mussels, an aquatic invasive species. Dreissenid mussels have become a problem because they affect the food web. Dreissenid mussels also affect phosphorus levels by filtering, excreting, and biodepositing phosphorus. In general, both dreissenid mussels and phosphorus impact the productivity of the lakes. Policy makers and scientists should further study phosphorus levels and dreissenid mussels to better understand interactions of levels and mussels and how such interactions impact lake dynamics.

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Water quality
refers to the chemical, physical, biological, and radiological characteristics of water

Anthropogenic:
of, relating to, or resulting from the influence of human beings on nature

Eutrophication
the enrichment of an aquatic ecosystem from excessive nutrient loading such as phosphates and nitrates

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Introduction

The Laurentian Great Lakes account for 20% of the world’s total freshwater and over 80% of North America’s freshwater (Allan et al. 2013; Jetoo and Krantzberg 2014). The lakes are an important source of freshwater, but nutrient loading from human activity and the invasion of aquatic invasive species have degraded the **water quality**. Phosphorus is one of many nutrients loaded into the lakes. Phosphorus is naturally found in freshwater and is an essential element needed by organisms; however, in excess it can be a problem.

Phosphorus loading has been a known problem ever since **anthropogenic eutrophication** became evident in Lake Erie in the 1950s (EPA 2012). Much of the phosphorus input came from fertilizer use, atmospheric deposition, and detergents (Han et al. 2012). Another problem has since arisen, the invasion of dreissenid mussels in the late 1980s to early 1990s (Richerson 2013). Both phosphorus and dreissenid mussels continue to be nuisances to the water quality of the Great Lakes.In this review, I focus on the interaction between phosphorus levels and dreissenid mussels in the Great Lakes after I explain the role of phosphorus in aquatic ecosystems, the phosphorus cycle, and how dreissenids interact with the phosphorus cycle. Complex changes are occurring in the Great Lakes ecosystem due to the interaction of phosphorus and dreissenid mussels (Conroy et al. 2005; Nalepa and Schloesser 2014; Ozersky et al. 2015). I propose additional studies to better understand how dreissenid mussels interact with phosphorus loading to affect the Great Lakes, since this interaction is neither widely known, nor fully understood. These studies would also aid in the restoration of the Great Lakes, to return them to a more natural state.

History of the Great Lakes restoration

Humans have induced stress on the Great Lakes for over 400 years. Water quality and

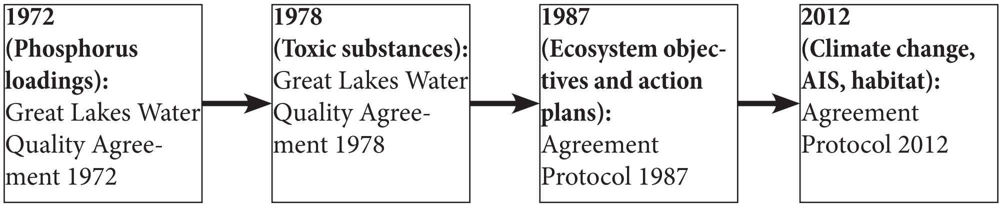

Figure 1. Great Lakes Water Quality Crucial Events. Timeline of the major agreements and protocols. Modified from (Jetoo and Krantzberg 2014).

habitat restoration was needed (Austin et al. 2007), so the Environmental Protection Agency (EPA) has helped by creating water quality agreements. Water quality agreements were created starting in the 1970s in response to harmful anthropogenic effects between the U.S. and Canada. Such anthropogenic factors include pollution, nutrient runoff, aquatic invasive species (AIS), climate change, and change in land use (Crain et al. 2008; Seilheimer et al. 2007). The first major agreement, the 1972 Great Lakes Water Quality Agreement (GLWQA) between the U.S. and Canada, happened in response to the poor condition of Lake Erie. The agreement mainly focused on phosphorus loading reduction and the restoration and enhancement of the water quality (Jetoo and Krantzberg 2014). In 1978, another GLWQA was created to address the challenge of persistent toxic substances. The Agreement Protocol of 1987 focused on ecosystem management through the incorporation of lake ecosystem plans and Remedial Action Plans (RAPs) (Jetoo and Krantzberg 2014). Another agreement protocol was created in 2012 which focused on climate change, aquatic invasive species, and habitat (Fig. 1). The protocols and agreements were created to restore and preserve the chemical, physical, and biological health of the Great Lakes (Jetoo and Krantzberg 2014).

Oligotrophic
waters that are usually cool, clear, and have low nutrient concentrations.

Mesotrophic
waters that have a moderate amount of dissolved nutrients

EPA monitoring and water quality assessment

To understand how phosphorus loading and dreissenid mussels affect the Great Lakes, one must be familiar with the current water quality status of the lakes. The Great Lakes are monitored through the EPA. Annually research teams collect information such as nutrient levels, water quality, temperature, dissolved oxygen levels, and biological information (EPA 2012).

Currently, the Great Lakes are meeting their trophic state goals and indices (Table 1). The three trophic indices that can be obtained are **oligotrophic**, **mesotrophic**, and eutrophic. Efforts to reduce total phosphorus concentrations have not been as effective in recent years due to increasing human populations which are putting greater stress on sewage treatment plants. There is also an increase in the number of vacation homes near the lakes which may lead to increased non-point sources of phosphorus loadings (EPA 2012). The different trophic states are indicative of their biological productivity. Lake Superior, the largest of the lakes, is oligotrophic and disturbed less by humans, whereas Lake Erie is much smaller and has a long history of issues with eutrophication and urbanization (EPA 2012).

The role of phosphorus in aquatic ecosystems

Phosphorus is an essential nutrient for organisms because it is needed in plant growth and metabolic reactions (Michigan 2012). Phosphorus is naturally found

Lake	Basin	Current Trophic State	Trophic State Goal
Superior	Entire	Oligotrophic	Oligotrophic
Huron	Entire	Oligotrophic	Oligotrophic
Michigan	Entire	Oligotrophic	Oligotrophic
Erie	Western	Oligomesotrophic	Oligomesotrophic
	Central	Oligomesotrophic	Oligomesotrophic
	Eastern	Oligotrophic	Oligotrophic
Ontario	Entire	Oligomesotrophic	Oligomesotrophic

Table 1. Trophic State Goals. Great Lakes' current trophic state and trophic state goals. Modified from (EPA 2012).

in low amounts in the Great Lakes (EPA 2012), and it usually functions as a growth limiting factor in aquatic plants. However, throughout time there have been issues with increasing total phosphorus (TP) in the lakes (EPA 2012). An increase of TP in natural systems can lead to increased algae blooms and increased growth of aquatic plants. Phosphorus is released in the lakes through a variety of sources such as runoff from agriculture, detergents, sewage treatment plants, and other point sources (Han et al. 2012; Hinderer and Murray 2011).

With European settlements came deforestation and drainage of wetlands to create farmland, which resulted in excessive

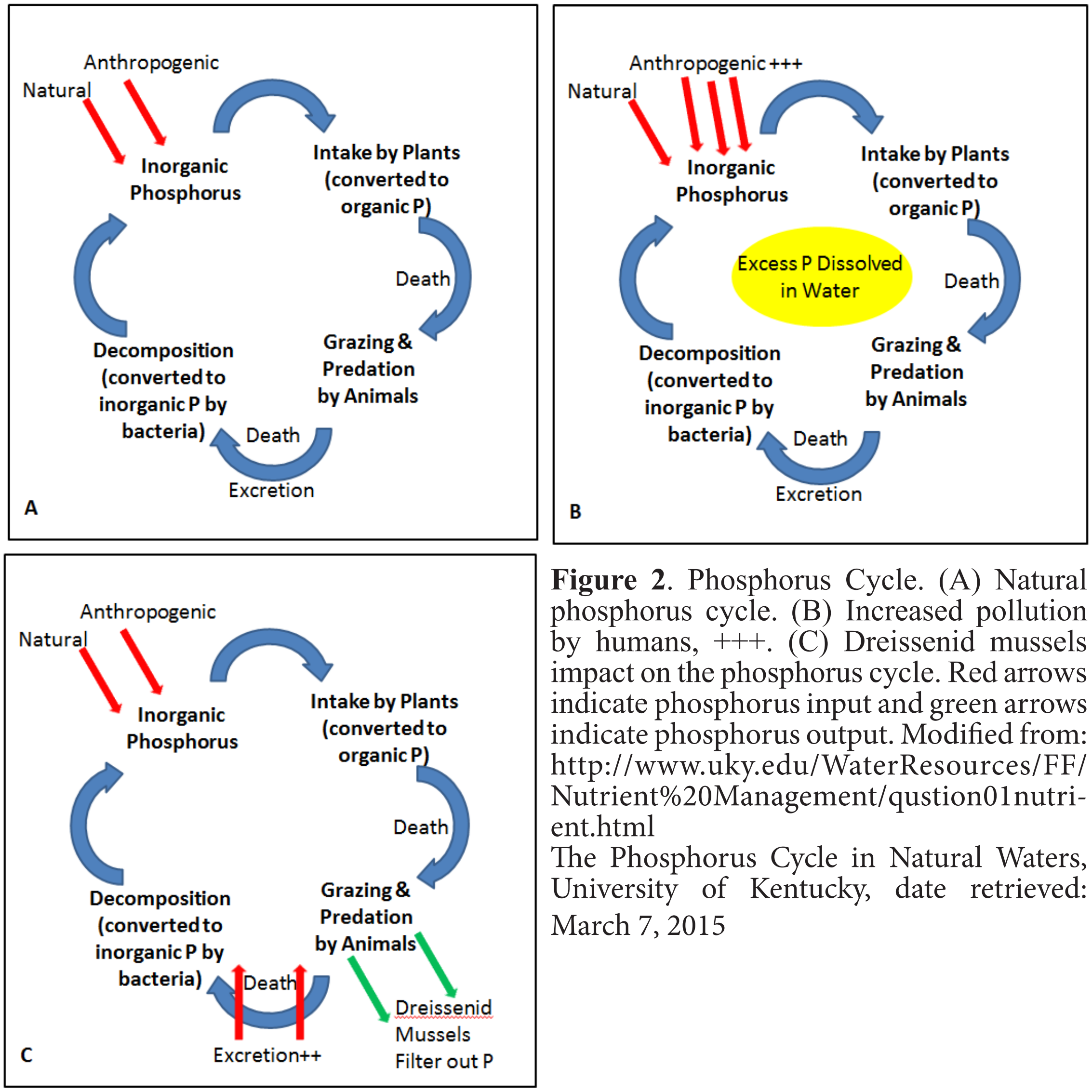

Figure 2. Phosphorus Cycle. (A) Natural phosphorus cycle. (B) Increased pollution by humans, +++. (C) Dreissenid mussels impact on the phosphorus cycle. Red arrows indicate phosphorus input and green arrows indicate phosphorus output. Modified from: http://www.uky.edu/WaterResources/FF/Nutrient%20Management/qustion01nutrient.html
The Phosphorus Cycle in Natural Waters, University of Kentucky, date retrieved: March 7, 2015

nutrient inputs and other pollution effects (EPA 2012). Phosphorus levels rose in the 1950s due to the use of phosphorus in detergents (Allinger and Reavie 2012). Two of the lakes that continue to have issues with high phosphorus levels are Lake Erie and Lake Ontario. Lake Erie in the early 1900s had TP levels at 15 to 25 µg/L and since the late 1990s TP has increased to 20 to 30 µg/L (Nicholls et al. 2001). The phosphorus levels in Lake Ontario almost mimic Lake Erie because Lake Erie contributes about 32% of its phosphorus into Lake Ontario (Dolan and Chapra 2012). Furthermore, phosphorus levels are higher in the lower lakes than in the upper lakes (Barbiero and Tuchman 2001). Each of the lakes has different target phosphorus loads, with each of the Great Lakes meeting their goals differently.

From 2003 to 2008 Dolan and Chapra (2012) found that Lake Superior's target load of 3400 MTA (metric tonnes per annum) was exceeded, partly due to high rainfall. Lake Huron exceeded its target load of 4360 MTA also due to high rainfall. Lake Erie's target load of 11,000 MTA has been exceeded 4 times, due to high rainfall and agricultural effects. Lake Michigan and Lake Ontario have target loads of 5600 MTA and 7000 MTA, respectively, which were never exceeded (Dolan and Chapra 2012).

Alterations to the natural phosphorus cycle

Humans and dreissenid mussels have impacted the phosphorus cycle. Humans have added excess phosphorus to the lakes, whereas the dreissenid mussels have added and removed some of the phosphorus (Fig.2). The transport of phosphorus from the natural and anthropogenic sources to the lakes is usually controlled by physical, chemical, and biological processes (Fig. 2A). When anthropogenic phosphorus inputs surpass the natural levels, there is excess dissolved phosphorus in the water (Fig. 2B). Once dreissenid mussels are introduced, they further alter the phosphorus cycle (Fig. 2C). Through filter feeding, dreissenid mussels can decrease the amount of phosphorus cycling; however, they can excrete a substantial amount of phosphorus, so there still can be an excess of dissolved phosphorus in the waters. Phosphorus cycle alteration can lead to ecological changes, which will be discussed in more detail later.

Negative effects of phosphorus

Alteration of the phosphorus cycle due to excess phosphorus can negatively impact the Great Lakes. It can lead to increased algal growth which prevents light from penetrating greater depths of the water (Nicholls et al. 2001). Algae decomposition causes decreased levels of dissolved oxygen which can create hypoxic/anoxic conditions, as seen in Lake Erie's "dead zone" (EPA 2012).

The agreements put forth to decrease TP have helped in the reduction of open lake eutrophication; however, problems still arise nearshore (LaBeau 2014). In the nearshore city of Toledo, Ohio, algal blooms likely caused high levels of the toxin microcystin in the waters during the first weekend of August 2014. As a result the city could not use the city water for any purpose (Welshans 2014). This incident shows the ongoing battle against phosphorus inputs to the lake.

Dreissenid mussel natural history

Both quagga (*Dreissena bugensis*) and zebra mussels (*Dreissena polymorpha*) are types of dreissenid mussels, which are aquatic invasive species. Zebra mussels were first seen in the U.S. in 1988 in Lake Erie, and quagga mussels were seen in 1989 (Nalepa and Schloesser 2014). Zebra mussels live in warm, eutrophic, shallow waters. Quagga mussels live in shallow warm waters and deep oligotrophic cold water

Sink
method of capture of a substance such that it cannot freely dissipate around in the lakes.

(Richerson 2013), and quaggas grow better than zebra mussels at low food concentrations (Hecky et al. 2004). Since 2004, quagga mussels have been slowly replacing the zebra mussels and are expanding into greater depths than the zebra mussels can live in (Evans et al. 2011). The mussels originated in Europe, and they most likely entered the Great Lakes in **ballast water** discharged from transoceanic ships (Richerson 2013).

Dreissenid mussels are becoming more prevalent in the Great Lakes, possibly because they are prolific breeders. A mature female can produce about one million eggs in one season, which can develop in a few days (Snyder et al. 1997). Dreissenid mussels are filter feeders that remove phytoplankton, zooplankton, and algae (Richerson 2013; Snyder et al. 1997). Dreissenid mussels can filter about one liter of water a day, per mature mussel (Snyder et al. 1997). The nutrients ingested are integrated into their body mass, excreted in a dissolved form, or released as feces or pseudofeces (Nalepa and Schloesser 2014).

Negative effects of dreissenid mussels

It is estimated that each year the U.S. loses about 11 to 16 million dollars in costs linked to dreissenid mussels (Higgins and Vander Zanden 2010), besides economic impacts, the mussels are affecting the ecology of the lakes. Dreissenid mussels are becoming more prevalent in the Great Lakes causing ecological and environmental problems which stress the lakes (Fig. 3). Dreissenid mussels' great filtering capacity

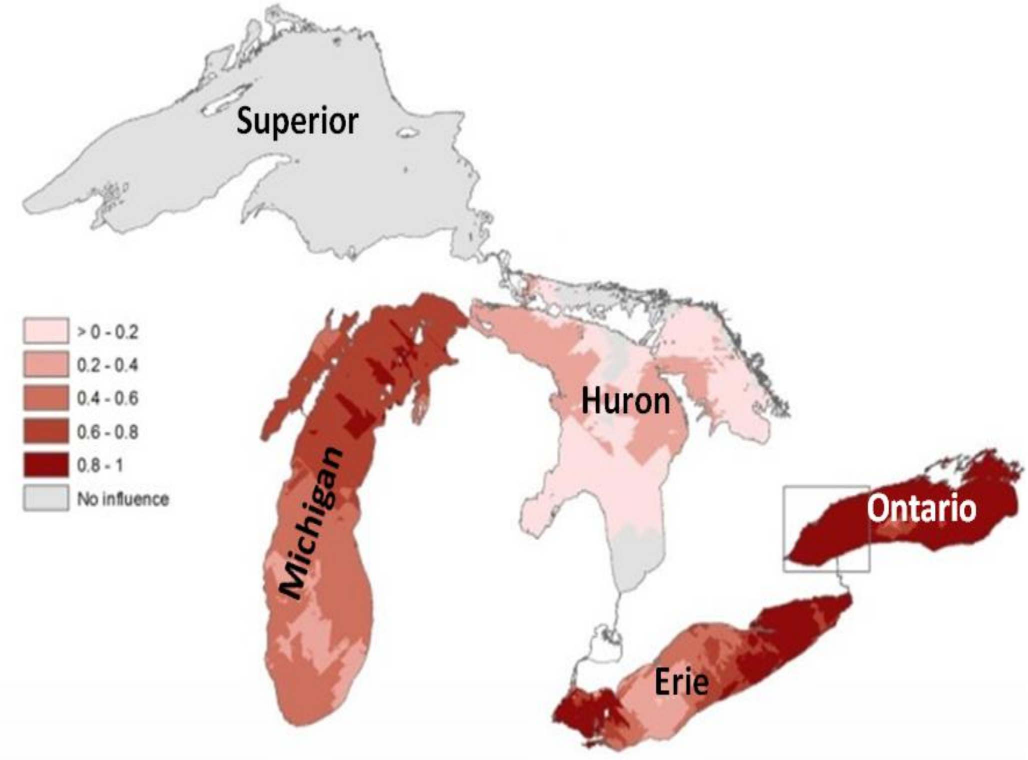

Figure 3. Dreissenid mussels as a stressor. Map of what areas of the Great Lakes are impacted most by the mussels. Higher stressed areas are indicated with a darker red color. Modified from: http://www.greatlakesmapping.org/great_lake_stressors/2/zebra-and-quagga-mussels Spatial distribution of zebra and quagga mussels as a stressor in the Laurentian Great Lakes, GLEAM, date retrieved: February 11, 2015.

can negatively impact the ecosystem because removing phytoplankton decreases the food source for zooplankton, which feeds small fish. Those smaller fish feed larger predators, so there is a cascade effect on the food web (Hinderer and Murray 2011 and Richerson 2013). Hinderer and Murray (2011) found that Lake Huron prey fish have decreased by 95%. *Diporeia,* a prey fish has declined over the years in the Great Lakes possibly due to the feeding of zebra and quagga mussels, and the transport of pathogens linked to their waste (Evans et al. 2011).

Another negative impact is the accumulation of toxins in the tissues and shells of the dreissenid mussels. After feeding the undesirable matter, pseudofeces, are ejected out and can accumulate on the shells of other dreissenid mussels and native mussels. Accumulation of pseudofeces on other mussels is bad because those waste particles are decomposed, oxygen levels decrease, the pH becomes more acidic, and toxic byproducts of ammonia and hydrogen sulfide are produced (Snyder et al. 1997). Dreissenid mussels can accumulate toxins in their tissues to levels 300,000 times greater than environmental levels, which are released when the mussels decompose. Also, dreissenid mussels attach and cover native mussels, causing the native mussels to be stressed (Snyder et al. 1997).

The invasion of dreissenid mussels has increased growth of nuisance algae. A study was done that surveyed homeowners and business owners along the coast of Lake Ontario and the western St. Lawrence River, regarding the change in water clarity and algae in response to the mussels' invasion. The results indicated that homeowners and business owners realized that nuisance algae have increased (Limburg et al. 2010). More microcystin, a nuisance algae, was found more frequently after dreissenid invasion and did not change after implemented phosphorus controls in Lake Ontario.

Dreissenid mussels have changed phytoplankton biomass (Nicholls and Carney 2011). However, phytoplankton biomass changes were greater in phosphorus load production in comparison to the mussel invasion (Nicholls and Carney 2011). As quagga mussels are replacing zebra mussels, the fraction of the water column cleared is exceeding the phytoplankton growth, as seen in Lake Michigan (Vanderploeg et al. 2010). Dreissenid mussels change productivity patterns, favoring benthic algae and toxic cyanobacteria (Nalepa and Schloesser 2014).

Dreissenid mussel interaction with phosphorus cycling

Both dreissenid mussels and phosphorus loading affect the phosphorus cycle. Dreissenid mussels alter the phosphorus cycle by filtering phosphorus in, and excreting phosphorus. The mussels' impact the phosphorus cycle based on several factors: stratification, body of water, water depth, the season, and differences between quagga and zebra mussels.

Seasonal lake **stratification** can also influence how much the phosphorus cycle is altered by dreissenid mussels. When looking at temperate lakes, similar to the Great Lakes, dreissenid mussels can slightly decrease phosphorus levels in stratified lakes (Higgins et al. 2011). A study on Lake Simcoe, a temperate lake, in ice-free seasons, post dreissenid invasion, from 1996 to 2008 didn't see a relationship between dreissenid mussels and total phosphorus levels (Young et al. 2011). If there was an expected relationship, where the dreissenid mussels increased phosphorus levels, then the predicted value of phosphorus in the lake would have been greater than what was actually measured (Young et al. 2011). However, in the majority of cases dreissenid mussels excrete more phosphorus than the amount of phosphorus filtered (Zhang et al. 2011).

One factor that influences how much the phosphorus cycle is altered is whether or not the body of water is a lake or river. In habitats across the U.S. and Eurasia, Higgins and Vander Zanden (2010) found that dreissenid mussels removed large amounts of phosphorus in the 4 lakes of their study but not the 2 river habitats studied.

Depending upon lake depth, dreissenid mussels may increase or decrease phosphorus levels in the water. In deep waters, an average of 25 m deep, dreissenid mussels have been shown to decrease the amounts of phosphorus, increasing water clarity through nutrient remineralization (Zhang et al. 2011). However, in waters that are not deep the dreissenid mussels provide an increase in phosphorus by the remineralization of fecal and pseudofeces, as well as direct excretion (Hecky et al. 2004). The remineralization of phosphorus shortens the phosphorus turnover time (Conroy et al. 2005).

Dreissenid mussels' filtration capacity can change dissolved and particulate nutrient concentrations in temperate lakes (Cha et al. 2013). The two species of dreissenid mussels have different filtering capacities which can determine the amount of phosphorus excreted. The study by Conroy et al. (2005) revealed that zebra mussels excrete higher levels of phosphorus than quagga mussels. The results indicated that quagga mussels have a higher metabolic efficiency, allowing them to retain phosphorus better (Conroy et al. 2005). The dreissenid mussels' ability to retain large amounts of carbon and nutrients in their tissues and shells may be a substantial **sink** for phosphorus (Nalepa 2014; Ozersky et al. 2015).

Changes have been seen in the Great Lakes algae biomass due to the invasion of the dreissenid mussels. In the early to mid-1980s in Lake Erie, it was found that phytoplankton communities have changed despite constant phosphorus loads (Conroy et al. 2005). An increase in cyanobacteria in the study indicated that the probable cause was the invasion of dreissenid mussels. Dreissenid mussels' activity has been found to boost benthic plant growth in coastal marine habitats, and it is hypothesized that similar activity would be seen in the Great Lakes (Hecky et al. 2004). Conroy et al. (2005) found that increasing phytoplankton blooms in western Lake Erie could be attributed to an increase in nutrient flux from the two mussels.

One interpretation is that increased urbanization near the water, the more phosphorus is excreted by dreissenid mussels. Urban areas create more phosphorus runoff so more phosphorus is available for dreissenid mussels to filter and excrete. The data from the Ozersky et al. (2009) study on the almost completely urbanized area of Lake Ontario's northwestern shore is consistent with this interpretation. They found that the mussels were capable of excreting more phosphorus than what is needed for *Cladophora glomerata*. Their data also suggested that annually, dreissenid mussels could be recycling and supplying about 32,340 kg of bioavailable phosphorus. In addition they noted that such excreted phosphorus by the dreissenid mussels would supply more total phosphorus than the watershed sources (Ozersky et al. 2009). Variability in dreissenid mussels' excretion, biodeposition, and nutrient content in the lakes may be due to differences in seasons and depths.

Interaction between dreissenid mussels and phosphorus levels in the Great Lakes

One might assume that dreissenid mussels' great filtering capacity would decrease phosphorus levels in the Great Lakes; however, this is not entirely true since dreissenid mussels also excrete phosphorus. Lake Michigan, Lake Erie, and Lake Ontario studies found that dreissenid mussels excreted a major source of the dissolved phosphorus into the water (Nalepa and Schloesser 2014; Ozersky et al. 2009).

In Lake Simcoe it was found that excretion, biodeposition, and nutrient content in the lakes and mussels varies depending on the season and depth (Hecky et al. 2004; Ozersky et al. 2015), which should be similar to the Great Lakes. In Lake Erie, it was found that dreissenids can provide sources of available phosphorus without an increase in phosphorus loading, which might be a reason for the reemergence of eutrophication near the shores (Hecky et al. 2004). If dreissenid mussels are in abundance on already previously stressed lakes, like Lake Erie, similar results of increasing phosphorus levels may occur.

Dreissenid mussels' tissues and shells may be a substantial sink for phosphorus (Nalepa 2014; Ozersky et al. 2015). As seen in Lake Erie dreissenid mussels added to the remineralization of phosphorus which in turn shortens the phosphorus turnover times (Conroy et al. 2005). Another study from 1997 to 1999 in Lake Erie showed that an increase in dreissenid mussel body size from 10 mm to 15 mm or increasing the mussel density by 10-fold increases the population's phosphorus excretion more than expected (Zhang et al. 2011). They also found that dreissenids consumed less phosphorus than what they excreted. In addition they indicated that in shallow waters where frequent mixing occurs, phosphorus concentrated in the bottom waters can be mixed up. However, in deep waters the nutrient remineralization of mussels can increase the water clarity (Zhang et al. 2011). Studies done in other lakes showed that the mussels decreased levels of phosphorus (Higgins and Vander Zanden 2010; Higgins et al. 2011; Young et al. 2011). Overall, dreissenid mussels seemed to be a major source of recycled bioavailable phosphorus. Human urbanization on lake shores has increased TP levels which the mussels exacerbate; however, people are taking steps to combat these changing environmental factors.

Mitigation and restoration

Political responses to the increasing problem of the mussels began to emerge in 1990 in both Canada and the U.S. As more funding became available more research has gone into studying dreissenid mussels. Currently, the government is monitoring dreissenid mussels and is trying to contain them (Nalepa and Schloesser 2014). Containment methods consist of depriving the mussels of oxygen, thermal treatment, exposure and desiccation, radiation, manual scraping, high pressure jetting, and removable substrates (Richerson 2013). In general, The Great Lakes Regional Collaboration (GLRC) Strategy has the goals of enhancing the coastal health, treating areas of concern, reducing non-point contamination sources, reducing toxic pollutants, preserving habitats, enhance conservation, address aquatic invasive species, development of a system of indicators, and sustainable development (Allan et al. 2013; Austin et al. 2007). Some of the economic benefits of such restoration would be an estimated $50 billion in long term benefits, and about $30 to $50 billion in short term benefits. However, the initial investment of this strategy is $26 billion (Austin et al. 2007). For long term financial and environmental benefits there will need to be ongoing dreissenid mussel monitoring.

Conclusions and future directions

Humans have impacted ecosystems in a variety of ways; however the cumulative interactive effect of dreissenid mussels and phosphorus not widely known, or fully understood. It is known that dreissenids mussels are important in processing nutrients where the mussels are abundant (Nalepa and Schloesser 2014). In addition it is known that both dreissenid mussels and phosphorus impact the productivity of the lakes. As quagga mussels gradually start to increase in numbers, studies will be needed to look at those changing dynamics. Additionally more studies must be done to better describe the interactions between phosphorus input and the invasion of dreissenid mussels in regard to affecting the Laurentian Great Lakes.

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Author Biography

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