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Nutrient Pollution: An Overview of Nutrient Reduction Approaches
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Good Afternoon Chairman Cardin, Ranking Member Sessions and Members of the Subcommittee on Water & Wildlife. I am pleased to appear before you today to discuss a topic of great concern to the National Wildlife Federation (NWF) and our 4 million members and supporters nationwide—nutrient pollution. As you know, excessive amounts of nutrients, namely nitrogen and phosphorus, threaten the environmental and economic viability of our nation's waters and the wildlife dependent upon them. Nutrient pollution is one of the most significant threats to waters all across the country. Excess nitrogen and phosphorus from sources such as sewage, animal manure, and fertilizer enter water bodies and have significant negative impacts on water quality. A 2009 report from a task group of senior state and EPA water quality and drinking water officials and managers found that half of U.S. streams have medium to high levels of nitrogen and phosphorus; 78 percent of assessed coastal waters exhibit eutrophication, nitrate drinking water violations have doubled in eight years; and algal blooms are steadily on the rise. Nutrient pollution also impacts almost all of our nation's Great Waters, both coastal and riverine ecosystems including the Chesapeake Bay, Great Lakes, Long Island Sound, Mississippi River, Ohio River, Puget Sound and the Gulf of Mexico. I am pleased that this subcommittee has asked for our thoughts regarding approaches to nutrient reduction in America's waters, but first, I'd like to take a moment to detail NWF's interest and work on this issue.

The National Wildlife Federation is the largest private, nonprofit conservation education and advocacy organization with 47 state and territorial affiliated organizations. Our staff,

members, partners and supporters in communities across the country are working to protect and restore wildlife habitat, confront global climate change and connect kids with nature. Our members are sportsmen, outdoor enthusiasts, nature lovers, and others who share a passionate concern for wildlife. And many of our constituents are fisherman, birders, swimmers and boaters, who witness the destructive impact of nutrient pollution each summer as they watch growing dead zones, declining fish stocks, and rivers and streams that have been overrun by algae that can cause sickness and impede many recreational activities.

Our regional offices throughout the country work with local and state governments to protect and restore local rivers, lakes and streams. We co-chair the Healing Our Waters Great Lakes Coalition, the Choose Clean Water Chesapeake Coalition, and the Coastal Louisiana Restoration Coalition. NWF is also a founding member and co-chair of the America's Great Waters Coalition, an alliance of national, regional, state and local organizations joined together to protect, preserve, and restore our nation's Great Waters. Each of these entities works in some capacity to reduce nutrient pollution because it is one of the most common and widespread pollution problems threatening America's aquatic ecosystems.

EPA's most recent National Aquatic Resource Surveys of aquatic health found that 67% of our streams are in poor or fair biological condition, and that of the stressors assessed, nitrogen and phosphorus are the most pervasive in the nation's wadeable streams and lakes. Approximately 50% of streams and more than 40% of lake acres have medium or high levels of nutrients. States have identified more than 15,000 waters nationwide that have been degraded by excess levels of nutrients to the point that they do not meet state water quality standards. This trend threatens some of our nation's most treasured waters. Some of these systems have become so impaired that they are required by the Clean Water Act to implement pollution diets known as Total Maximum Daily Loads. The impact of these ecosystem declines is devastating to wildlife and to those who depend on them. I'd like to illustrate that point by using two of our nation's most important aquatic ecosystems as examples – the Chesapeake Bay and the Great Lakes.

The Chesapeake Bay: A Declining Ecosystem

In the Chesapeake Bay, nutrient pollution is so pervasive that each summer the mainstem of the Bay experiences a dead zone that covers as much as one third of the Bay. Despite efforts to rein it in, it continues to grow. This summer, the Bay experienced an unusually large dead zone, which the Washington Post noted might be the largest in history.[1] These dead zones take many victims from across the tropic scale. The nutrient-related decline of submerged aquatic vegetation has eliminated essential habitat for many fish, shellfish, and other aquatic life. When healthy, this submerged vegetation serves as rich nursery ground, providing food and habitat for juvenile fish. Molting crabs hide from predators in the grass beds. Larger fish such as sea trout, drum, perch, pickerel, and bluefish patrol the grass beds in search of food. Many small and interesting creatures including pipefish, seahorses, mud crabs, spider crabs, and several kinds of shrimp and minnows inhabit the underwater grass beds.

Loss of submerged aquatic vegetation (SAV) has contributed to a substantial reduction in the once massive flocks of waterfowl that darkened the skies of Chesapeake winters. Populations of redhead ducks have declined markedly with the loss of SAV. Other species, such as the Canada goose, American widgeon, and canvasback, have had to change their feeding habits to include other sources of food.

The low oxygen conditions created by excess nutrients have severely impacted life in the Bay. Since 1960, there has been a substantial increase in the amount of Bay bottom with dangerously low levels of dissolved oxygen. Bottom-dwelling, or benthic organisms including worms, clams, oysters, crabs, and many smaller invertebrates are an essential link in the food web. With the decline of these benthic organisms, the entire Chesapeake ecosystem is altered. In fact, a recent study from the University of Maryland found that

[1] "Alarming Dead Zone Grows in the Chesapeake." Darryl Fears. Washington Post. Published July 24, 2011.

the Chesapeake ecosystem had been drastically altered by nutrient pollution over the last 100 years.[2]

As a result, the famous Rockfish fishery has been limited, crabs and oysters are hard to find and beach closures are an annual occurrence. These are just some of the direct impacts of nutrient pollution on aquatic ecosystems, in the Chesapeake and throughout the country. Unless strong action is taken immediately to curb nutrient pollution, this story will continue to repeat itself throughout the country.

Complicating Factors in the Great Lakes

In the Great Lakes, excess nutrients are also causing massive ecological changes. Today, NWF is issuing a report, *Feast and Famine in the Great Lakes: How Nutrients and Invasive Species Interact to Overwhelm Coasts and Starve Offshore Waters*. The report documents the widespread ecosystem breakdowns and the policies and practices needed to address them. (See Exhibit 1). As indicated in the report, excessive nutrients in nearshore waters – in particular phosphorus from both agricultural and point sources – have brought the Great Lakes to a crisis point:

- This summer Lake Erie experienced the worst toxic algal bloom in its recorded history – even worse than the 1960s, when Lake Erie was declared dead.
- Miles of Lake Erie beaches have been closed and algae extends many miles out into the lake with thicknesses of up to 2 feet. Photos of these algal blooms and a satellite photo of their extent are included in this testimony (Exhibit 2).
- Toxic and green algal blooms are common this summer in nearshore areas and embayments throughout the Great Lakes, including Saginaw Bay, Green Bay and the coasts of Lake Michigan.
- Lake Erie is experiencing blooms of mycrosystis, a toxic algae, which has been measured at levels 1,000 times higher than WHO guidelines for drinking water; this algae can cause sickness or even death in humans and animals.

[2] "Eutrophication of Chesapeake Bay: Historical Trends and Ecological Interactions." W. M. Kemp1 et al. Vol. 303: 1–29, 2005. Published November 21, 2005.

- We are seeing extensive blooms of the algae Cladophora along Lake Michigan's shores, which have interacted with invasive species to produce outbreaks of botulism poisoning that have killed fish and birds.
- Lake Erie has an anoxic zone where oxygen levels are too low for fish to live that seasonally extends thousands of square miles along the bottom of the lake.

This emerging nutrient crisis is already hurting people and wildlife and damaging the region's economy. NWF's Great Lakes office works closely with charter boat captains in the Great Lakes, particularly those in Lake Erie. Rick Unger, president of the Lake Erie Charter Boat Captains Association reports on terrible conditions on the lake. He says that the algae goes for miles along the beaches and extends miles into the open lake. In some places, the algae is two feet thick and looks like green mud. According to Captain Unger:

> "The algae is toxic. There are posted warnings: Don't drink the water. Don't touch it. Don't swim in it. People are getting sick out on the water. Captains have respiratory problems. The Ohio Department of Public Health is investigating."

In terms of Captain Unger's business, bookings are down; people don't want to go onto the water. Rebookings are nonexistent; once they've been out in the algae they don't want to go back. "When the algae moves in, the fish move out," reports Captain Unger. He says, "The costs of doing business are skyrocketing." He often has to go 10 miles further out to find fish, or 20 miles roundtrip. Gas costs $4.50 a gallon, his boat gets 1 mile per gallon, so that's an extra $90 (20 gallons) every trip.
Last year there were 800 charter boat captains in Lake Erie. This year, there are 700 – they lost 100 in a year. And by next year there will be a lot fewer. Captain Unger says there is no doubt that trend is because of the algae blooms. "There's miles and miles where the fish can't live," he says. "It's turning back into the 1960s, when it was called a dead lake."

This nutrient crisis in the Great Lakes is exacerbated by invasive mussels. Quagga and zebra mussels, now numbering in the trillions in Lake Michigan alone and widespread throughout the Great Lakes, have caused a major ecosystem shift: their efficient filtering

capabilities are sequestering much of the nutrients already in or entering lake waters and redirecting them to nearshore and deep bottom waters, reducing availability to other organisms. This phenomenon is encouraging explosive algal blooms in the nearshore while at the same time forming a nutrient desert in offshore waters, contributing to declines in fish populations. For example, Lake Huron has endured a 95% decline in fish biomass in offshore waters of Lake Huron in 15 years and we've seen and 80 percent decline in "primary production" – organisms in the water column that feed fish – in Lake Michigan in the last 25 years (since mid-1980s). In addition, the populations of the tiny freshwater shrimp, Diporiea, that is the base of the Great lakes food web, , have declined in Lake Michigan by 94% in 10 years and in Lake Huron by 57% in 3 years. This is unprecedented: algal blooms caused by excess nutrients and fish population crashes caused by too few nutrients, all happening in the same ecosystem.

Today's *Feast and Famine* report from National Wildlife Federation makes a number of policy recommendations that are included in the policy section of this testimony. I would like to highlight three overarching principles here. First, management actions based on whole-lake objectives alone (or alternatively, focusing on one part of the ecosystem, such as offshore waters) are unlikely to be successful. Controls and management strategies need to take into account the different conditions of nearshore and offshore areas. As part of an overarching lake- or ecosystem-wide management approach, we need to refine management and policy at smaller levels (e.g., sub-basin or watershed) as appropriate. Second, while implementation of policies specific to nutrients and invasive species is critical, we need to explore policies that can address both stresses in an integrated way. For example, if research indicates that an invasive species may be limited in part by nutrients, reductions in nutrient loads could slow its growth and spread while reducing risks of harmful algae blooms. Finally, further nutrient reductions, particularly in targeted watersheds, are essential. Today in the Great Lakes, new nutrient loadings will in many cases continue to feed harmful algal blooms or invasive species, rather than contribute to the growth of desirable fish species.

The Great Lakes and Chesapeake are just two examples of the severity of the nation's nutrient pollution problems. As Captain Unger reports, those problems are causing economic as well as ecological damage. Spending a pleasurable day on the water usually involves at least some expense for travel, equipment and supplies. When multiplied by America's nearly 40 million anglers, their dollars employ millions of people in industries ranging from fishing tackle manufacturing to travel and hospitality to boat manufacturing. Since anglers are found in every state, their expenditures have a significant effect on state and local economies as well.

While many people recognize the recreational and economic benefits of fishing, its significant conservation benefits often go unnoticed. For each fishing-tackle purchase and each gallon of boating fuel consumed, a portion of the money is returned to state fish and wildlife agencies for conservation efforts. America's success in restoring many species of fish and wildlife and protecting natural habitat can largely be credited to the billions of dollars generated by sportsmen and women.

The American Sportfishing Association reports that 45 million anglers generate $45 billion every year in retail sales.[3] A portion of this money goes to licensing and other fees, which are the primary source for improving fish habitat, public access and environmental education.

Sportfishing, and the powerful economic effects it creates, would not be possible without fish. Those same fish would not exist without suitable habitat, which makes clean and healthy rivers, lakes and coastal waters essential to the bottom line. For this reason, NWF urges this committee to do all it can to reduce nutrient pollution in our nation's waters.

<u>Looking Forward and Reducing Nutrient Pollution.</u>

[3] "Sport Fishing in America: An Economic Engine and Conservation Powerhouse." American Sportfishing Association. Revised Edition, January 2008.

Understanding the impact of nutrients on our nation's waters, NWF believes that the federal government has taken some key steps towards remedying this problem and that several others must be considered.

EPA acknowledged the national extent of the nutrient problem, when it issued its 1998 "National Strategy for the Development of Regional Nutrient Criteria." The report reflected an understanding that numeric nutrient criteria can be an effective way to prevent nutrient pollution and to help states comply with the Clean Water Act. EPA encouraged every state to develop numeric nutrient criteria to protect waters from this source of pollution and to help them meet water quality standards under the Clean Water Act. In 2008, an EPA status report found that 19 states have adopted numeric nutrient standards for some or all of their lakes and reservoirs, and 14 states have adopted numeric nutrient standards for some or all of their lakes and streams. We believe that numeric nutrient criteria is the most logical way to ensure ecosystem health in a site specific manner, and urge EPA and Congress to continue to work to ensure that every impaired stream segment, river and lake has a numeric nutrient goal to help restore the ecosystem.

To that end, we applaud the specific EPA actions in Florida and the Chesapeake Bay to promulgate and implement numeric nutrient criteria and we recognize the national significance of these initiatives. A recent article in the Environmental Law Reporter summed this up best, stating, "The CWA, with multiple paths to its destination, is reinventing itself once more. Enacted in modern form in 1972, the next quarter century saw EPA focused on the development of technology standards for industrial and municipal point sources. In the mid-1990s, prodded forward by a stream of citizen suits, the Agency started to address nonpoint sources of pollution through water quality standards and the TMDL program. This movement stalled from 2000-2009 and the current revival raises the question of whether EPA can finally make nonpoint and ambient-based controls effective. The answers are being tested in two venues where the problems are among the most acute and their solutions the most resisted: the Chesapeake

Bay and Florida. *As go the Chesapeake and the Sunshine State, so will go the future of clean water for years to come.*[4]"

The success of EPA's initiative to work with the state of Florida to reduce nutrient pollution may foretell the fate of future generations. If this initiative is further delayed, it could stymie similar efforts throughout the country and ensure the permanent decline of our nation's aquatic ecosystems. If EPA cannot effectively limit nutrients in Florida, a state dependent on recreation and tourism, where the algal blooms are so pervasive that they can be seen from the shores of most rivers and lakes, what chance do other ecosystems have?

In the interest of the Everglades, water quality throughout the state of Florida and all of the waters impaired by nutrients throughout the country, we urge the committee to recognize the importance and necessity of the promulgation of numeric nutrient criteria, in Florida and wherever else nutrient pollution threatens rivers, lakes and streams. We urge you to support the EPA as it works to ensure that all Americans enjoy healthy and pollution free waters.

In addition, NWF recommends that:

- Restoration funding such as the Great Lakes Restoration Initiative, EPA's Chesapeake Bay Program, the Long Island Sound Study and other restoration and pollution reduction programs must be increased and used to intensively target these damaged eutrophic areas with targeted funding to help farmers improve conservation practices and identify the precise vectors and mechanisms that are causing the algal blooms. EPA and other agencies should support an integrated suite of activities, not isolated actions.
- Funding to stop combined sewer overflows and raw sewage overflows is essential. Although not the primary source of nutrient pollution overall, in many

[4] Houck, Oliver A. "The Clean Water Act Returns (Again): Part I, TMDLs and the Chesapeake Bay." Environmental Law Reporter. March, 2011.

places these large wastewater treatment plants have huge and lasting effects, impacts that will get worse as storms continue to worsen. For this reason we urge reauthorization and maximum funding for the Clean Water State Revolving Fund.

- EPA must do a better job of developing and approving nutrient standards that match the conditions of different waterways and different segments of waterways. A one-size-fits all approach will only cause further damage. A single state-wide nutrient standard will not work; and in many cases, neither will a lakewide nutrient standard. We urge Congress to do all it can to assist states and EPA in promulgating and implementing site specific nutrient reduction targets.
- Farm Bill programs are essential. Most producers will not take their land out of production for essential buffer strips or wetlands if it substantially hurts their bottom line. We need financial incentives to at least cushion the blow. Funding for the conservation title of the Farm Bill is essential. We urge Congress to expand conservation funding in the next Farm Bill and to ensure that these mandatory funds are not capped annually by the Appropriations Committee.
- There needs to be more research. Many of the practices that once reduced nutrient loadings are not working any more, or at least are not working in the same way. For example, no till farming has had strong benefits in reducing sediment transport and runoff. However, in places such as the Lake Erie watershed, we are now seeing less uptake of fertilizers in the soil and higher amounts of soluble reactive phosphorus, a much more damaging form, which might result from those no till practices.
- We need to address drainage and tileage. Extensive tiling means that substantial runoff is never captured by buffer strips, and may bypass wetlands. We need to encourage 2-stage ditches.
- We must address the hypoxic zone in the Gulf of Mexico, our nations' largest deadzone by providing adequate conservation planning and financial assistance to farmers along the Mississippi River and its tributaries.
- Finally**,** for nutrient standards to be successful in cleaning up America's waters, they must be enforced in the 60% of the nation's waterways that flow intermittently and the wetlands associated with them. These small streams and

associated wetlands do the lion's share of the work in filtering nutrient run-off and storing sediment and floodwaters, yet they are losing Clean Water Act protections and are at increased risk of pollution and destruction in the wake of controversial Supreme Court decisions in 2001 and 2006. We urge the Committee to support efforts to restore Clean Water Act protections to these streams and wetlands.

While these recommendations are not exhaustive, I believe that if enacted, these would make a significant contribution to the reduction of nutrient pollution in our nation's waters and allow the health of their ecosystems to slowly recover. I thank you for the opportunity to discuss this most important issue with you and look forward to answering your questions.

NATIONAL WILDLIFE FEDERATION

FEAST AND FAMINE IN THE GREAT LAKES

How Nutrients and Invasive Species Interact to Glut Coasts and Starve Offshore Waters



Feast and Famine in the Great Lakes: How Nutrients and Invasive Species Interact to Glut Coasts and Starve Offshore Waters

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EXECUTIVE SUMMARY

The Great Lakes: on the road to recovery, veering close to ecosystem collapse, or both? In fact, recent research indicates the lakes have undergone profound changes over the past two decades, and ongoing changes related to various stressors threaten the ecological health of the lakes in ways unseen since human development in the region began.

In 2005, a team of Great Lakes scientists highlighted the many ongoing stressors facing the lakes, from nutrient pollution to hydrological changes to aquatic invasive species. The report, *Prescription for Great Lakes Ecosystem Protection and Restoration*, warned that the lakes could be facing a tipping point leading to "irreversible ecosystem changes" without urgent actions to address these and other stresses. The report highlighted many instances of Great Lakes "ecosystem breakdown," including dramatic declines in the lower portions of the food web, particularly of a shrimp-like organism (*Diporeia*) in the sediments that served as an important food source for many fish species. Though exact mechanisms are not clear, it appears that the widespread colonization of lake bottoms by invasive mussels has impaired the ability of *Diporeia* and similar organisms to thrive (possibly through changing nutrient cycling), which in turn continues to threaten the well-being of food webs in the Great Lakes.

Six years later, nutrient-related problems persist in the Lakes, and in some respects have worsened. New research shows that not just *Diporeia* have been decimated across the lakes—so have populations of prey fish (fish consumed by larger predators). For example, in the offshore waters of Lake Huron, **prey fish biomass has declined by 95% in less than 20 years**. Scientists predict similar declines could occur in Lake Michigan. Scientists are still researching the causes, but one likely factor contributing to widespread ecosystem change is the filtering activity of invasive quagga and zebra mussels. This filtering activity, which removes plankton and



Great Lakes from MODIS satellite (Photo: Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC)

other suspended particles (including phosphorus) from the water column, results in direct competition for food with other species and has fundamentally altered energy and nutrient flow pathways through the food web. One result is that fish in the offshore such as native lake whitefish and burbot and naturalized Chinook salmon in Lake Huron have steeply diminished in numbers and in health as their prey base is altered.

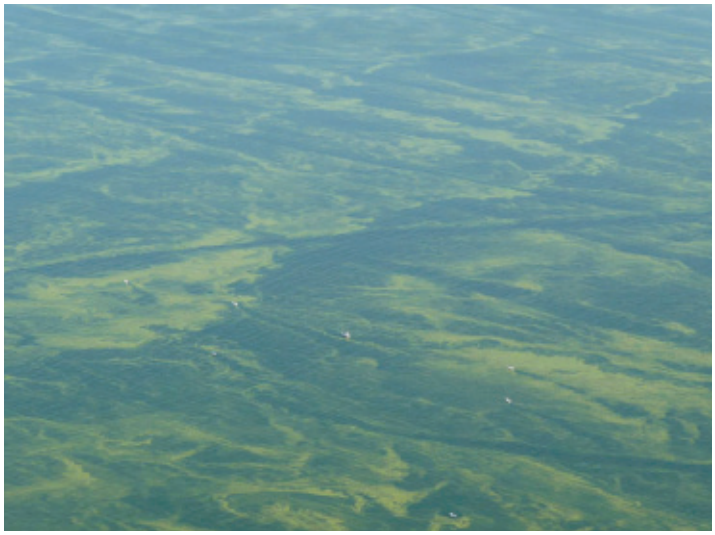
Lake Erie and nearshore waters in other Great Lakes, however, face the opposite problem: too many nutrients are wreaking a different kind of havoc. Excessive nutrients in nearshore waters — in particular phosphorus from both agricultural and point sources — have caused or contributed to problems such as toxic algal blooms, green algae blooms (including the nuisance alga *Cladophora*), avian botulism, and the Lake Erie Central Basin "dead zone". Indeed, the summer of 2011 has witnessed one of the most extensive harmful algal blooms ever recorded for western Lake Erie, leading to numerous recreational advisories.

How can one part of the Great Lakes (coastal and nearshore areas) be overcome with excessive nutrients while other parts (offshore waters) are deprived of sufficient nutrients? Invasive mussels, now numbering in the trillions in Lake Michigan alone and widespread throughout the Great Lakes, are a likely cause. Zebra and quagga mussels have sufficient filtering capabilities to sequester much of the nutrients already in or entering the lake waters and redirect them to nearshore and deeper bottom waters, reducing availability to other organisms. This phenomenon is encouraging explosive algal blooms in coastal areas and the formation of a nutrient desert in offshore waters, which has contributed to steep declines in fish populations. This is unprecedented: algal blooms caused by too many nutrients, and fish population crashes caused by too few nutrients.

There is no single solution to this ecosystem breakdown. The widespread changes in the Great Lakes nutrient cycle that are causing simultaneous feast and famine require sophisticated responses; one-size-fits-all measures are bound to fail. Three overarching approaches can help address this dichotomy. First, management actions based on whole-lake objectives alone (or alternatively, focusing on one part of the system, such as offshore waters) are unlikely to be successful. Controls and management strategies need to take into account the different conditions of nearshore and offshore areas — as has been recognized to some extent, for example, with different phosphorus targets for western and eastern Lake Erie. In short, as part of an overarching lake- or ecosystem-wide management approach, we need to refine management and policy at smaller levels (e.g., sub-basin or watershed) as appropriate. Second, while implementation of policies specific to nutrients and invasive species (in particular invasive mussels) is critical, we need to explore policies that can address both stresses in an integrated way. For example, if research indicates an invasive species may be limited in part by nutrients, reduction in nutrient loads could slow its growth and spread while also reducing risks of harmful algal blooms. Finally, further nutrient reductions (particularly in targeted watersheds) are essential. Today in the Great Lakes, new nutrient loadings will in many cases continue to feed harmful or nuisance algae, or invasive species, rather than contribute to the growth of desirable fish species. We need to identify and implement measures that promote the growth of native and naturalized species, while minimizing (or ideally avoiding) benefits to nuisance or invasive species.

With these overarching approaches in mind, there are a variety of existing policy frameworks and tools that can help further nutrient reduction efforts, including the following:

- A stronger **Great Lakes Water Quality Agreement**. The current renegotiation of the Agreement offers the opportunity to establish new goals and identify key program targets in the U.S. and Canada in order to address nutrient problems in the lakes. Given new nearshore-offshore dynamics, recognition of the importance of different forms of nutrients (e.g., soluble reactive phosphorus), and inherent natural differences between the lakes, the establishment of different nutrient target concentrations and loads is appropriate for each lake and potentially subwatersheds or basins. In addition, the Agreement should call for establishment of a basin-wide Phosphorus Task Force to research and advise the governments, and the Agreement should propose specific objectives, measurable outcomes, and timetables for achievement of nutrient reduction goals.
- Expanded efforts through **U.S. Farm Bill programs**. Programs such as the Environmental Quality Incentives Program, the Conservation Reserve Program, and Conservation Stewardship Program should be strengthened to further reduce sediment and nutrient exports from agricultural watersheds. Funding for these programs should be maintained and expanded, and the programs themselves should be more targeted. For example, they need to use a watershed-based approach to prioritize nutrient reduction efforts directed at both specific sources of nutrients as well as specific problems in tributary and nearshore waters in the region.



Harmful algal bloom near Pelee Island, Lake Erie (Photo: T. Archer, NOAA, Great Lakes Environmental Research Laboratory)

- Use of **Clean Water Act tools**, with an increased focus on nutrients. These include revisions to state water quality standards (in particular water quality criteria) for nutrients, as appropriate; consideration of more stringent permit limits for municipal wastewater treatment plants; increased development and implementation of total maximum daily loads for nutrients, and promotion (and adequate funding) of Clean Water Act Section 319 projects targeted, within states, at watersheds prioritized based on nutrient impairments.
- A special emphasis on **Lake Erie**. This should include strengthening point source and nonpoint source control programs in the watershed, including, revisiting permit limits and enhancing education and outreach efforts on agricultural application of fertilizers.
- Targeted **Great Lakes Restoration Initiative** efforts. GLRI funding should be targeted in ways that emphasize nutrient reduction projects directed at watersheds prioritized based on both sources and nutrient impairments.

Similar efforts are needed on the Canadian side. These include upgrading wastewater treatment plants to reduce nutrient loads, expanding natural vegetation cover in key watersheds, and expanding the scope and improving best management practices on agricultural lands.

While a number of efforts are needed to address ongoing nutrient problems, it is clear that increased efforts are also needed to prevent additional major ecosystem changes from aquatic invasive species. Prevention must be a cornerstone of efforts addressing major vectors, including adopting more stringent ballast water discharge standards, a more aggressive screening and control program for organisms in trade, and strong measures to address canal and waterway transfer of aquatic invasive species (including restoring the hydrological separation between the Mississippi River and Great Lakes Basins in the Chicago area.) In addition, control and eradication measures for species already established must be pursued, including innovative biocontrol measures and fishery management practices that can target species of concern with minimal risk of other negative impacts.

Finally, there is a need for increased activity and funding in two broader areas related to nutrients and invasive species. First, targeted **research and monitoring** efforts are needed, particularly in nearshore areas, as well as improved binational coordination of all aspects of monitoring. Increased research efforts are needed to better understand nutrient dynamics and ongoing ecosystem changes and to help inform resource managers and policy makers addressing these complex changes. Second, increased **education and outreach** efforts are needed to inform the public of problems associated with nutrients and invasive species, along with ways the public can contribute to solutions. These efforts should utilize the numerous existing forums well suited to conduct this work, including agency outreach, university extension, and non-profit programs.

In summary, the Great Lakes are facing feast and famine from invasive species and excessive nutrient pollution. The lakes have faced daunting environmental problems in the past; in the 1960s, Lake Erie was plagued with harmful algal blooms, and many had written it off as beyond revival. However, the concerted efforts of citizens, environmental and conservation advocates, scientists, and policy makers to implement innovative solutions succeeded in restoring the lake. The challenges are no less severe today. While it is clear that further research and monitoring are needed to better understand changes in the nutrient cycle and other lake ecosystem changes, stronger actions are needed now, and we believe a combination of targeted and holistic approaches to address nutrients and invasive species together offers great potential. The lakes remain at a tipping point, and it is time for us to join forces and develop innovative policy solutions to the feast and famine crisis that today plagues the Great Lakes.

SECTION 1

INTRODUCTION

The five North American Great Lakes—Superior, Michigan, Huron, Erie, and Ontario—comprise the largest freshwater system on Earth, containing nearly 20% of the available surface fresh water in the world.[1] This precious natural resource is the ecological, economic, and cultural backbone for a large region of the United States and Canada. The Great Lakes affect the lives of more than 40 million people who live in the basin and depend upon the lakes for drinking water,[2] and the region's population continues to grow. It is estimated that 30% of the population of the Great Lakes states (besides New York) resides in coastal communities.[3]

A diversity of plants and animals also calls the Great Lakes home. This unique freshwater system once supported 180 species of fish unique to the Great Lakes, and today is home to fish such as large- and smallmouth bass, muskellunge, walleye, yellow perch, whitefish, lake trout, and lake sturgeon. The abundant green spaces and forests in the Great Lakes basin provide vital habitat to animals such as moose, wolves, bears, foxes, deer, and bald eagles.[4] The unique coastal ecosystems and wetlands in the region support threatened and endangered birds such as the piping plover and the whooping crane.[5]

The abundant freshwater resources and wildlife of the Great Lakes form the foundation of the region's economy. If it were its own country, The Great Lakes–St. Lawrence River region (encompassing the U.S. and Canada) would be the fourth largest economy in the world.[6] Industries such as manufacturing, shipping, and commercial fishing that depend on the lakes are key components of the regional economy. In the U.S. alone, more than 1.5 million jobs are tied directly to the Great Lakes.[7] Perhaps the most vital contribution of the Great Lakes to the region's economy, however, is their importance to recreation and tourism. The unique beauty of Great Lakes shorelines is showcased through four U.S. National Lakeshores and a National Park,[8] in addition to countless state and local parks and recreation areas across the basin. Recreational fishing in the Great Lakes is worth more than $7 billion annually,[9] and recreational boating creates an economic impact of over $30 billion annually.[10] More than 200,000 jobs in the region are supported by Great Lakes recreation and tourism.[11]

A healthy Great Lakes ecosystem is vital to sustain and promote the wealth of recreational opportunities in the region. Water quality and wildlife must be protected, restored and enhanced to support tourism, economic growth, and other benefits provided by the lakes. There is a long history of cooperative efforts in the U.S. and Canada to protect and restore the Great Lakes, described in detail in Section 5. Coordination was enhanced on the U.S. side in 2005, when federal agencies, governments of the eight Great Lakes states, tribes, industry and non-governmental organizations (NGOs) recognized the need for a coordinated restoration effort and joined forces to create a shared vision for the lakes under the Great Lakes Regional Collaboration (GLRC) Strategy.[12] Through the creation of the *GLRC Strategy*, the region showed that it was ready to invest in projects that would directly advance common restoration goals. In response, the federal government created the Great Lakes Restoration Initiative (GLRI), a five-year investment that included $475 million for restoration and protection programs in its first year.

So far, the GLRI has funded numerous projects across the basin that are restoring wildlife habitats, cleaning up beaches, and educating the public on invasive species, to name a few.[13] In addition to ecological benefits, the GLRI is providing an economic boost to the region: the Brookings Institution estimates that for every $1 invested in Great Lakes restoration, $2 of economic benefit are produced.[14]

Despite this progress towards healthier Great Lakes, ecological problems remain that threaten to stall or even reverse this progress. Major threats to the lakes were highlighted in a 2005 report which noted that stresses such as invasive species, hydrologic alterations, land use changes, and nutrient loadings could interact to cause "ecosystem breakdown" in the Great Lakes, whereby resiliency is overcome and the ecosystem is pushed into a new state.[15] Among the most severe of these problems are nutrients—with too much in some places, and too little in others. Excessive nutrients sicken the Great Lakes in nearshore areas by causing toxic algal blooms in shallow areas and oxygen-poor "dead zones" on lake bottoms. This serious problem, which first appeared in the mid-1900s, has returned with a vengeance. Another dire problem facing the Great Lakes is invasive species. Currently, non-native mussels are wiping out food webs in offshore areas of the lakes, turning once-productive waters with a diversity of life into lake monocultures dominated by invasive mussels. These invasive mussels are also concentrating nutrients in nearshore waters, further exacerbating algal blooms. Thus, while harmful algae in the nearshore are feasting on excess nutrients, fish populations in deep waters are fighting famine. This dangerous dichotomy requires urgent and drastic action to restore balance to the Great Lakes.



Freighter on Muskegon Channel, Lake Michigan (Photo: NOAA, Great Lakes Environmental Research Laboratory)

SECTION 2

BACK FROM THE BRINK

Historical Nutrient Pollution and Recovery in the Great Lakes

Since European settlement, all five of the Great Lakes have progressed toward slightly more biologically productive, or eutrophic, conditions (see Box 1).[23] In the 1950s and 1960s, however, rapid and dramatic eutrophication occurred in many areas of the lakes due to human inputs of nutrients. This phenomenon, known as "cultural eutrophication," was caused by excessive watershed inputs (or **loading**) of phosphorus from human activities. Some phosphorus pollution was dumped directly into the lakes or their tributaries via "point sources" such as outflows from wastewater treatment plants and storm sewers. Excessive phosphorus loading also came from "nonpoint" sources such as fertilizer-rich runoff from agricultural fields (See Figure 1).[24]

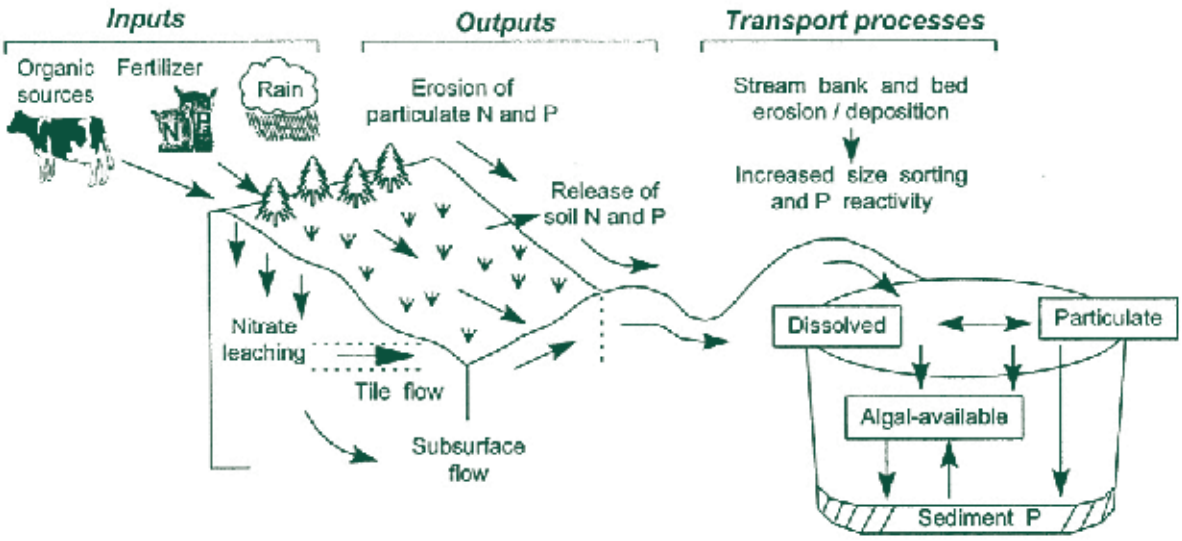


FIGURE 1. Inputs and outputs of phosphorus (P) and nitrogen (N) from agricultural land, and transport processes into lakes. (Reproduced with permission of ECOLOGICAL SOCIETY OF AMERICA, from Carpenter, S.R., et al. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8 (3), 559-568; permission conveyed through Copyright Clearance Center, Inc.)

Perhaps the most dramatic symptoms of cultural eutrophication in the Great Lakes during this period were large, harmful blooms of algae, particularly blue-green algae. These harmful algal blooms cause unpleasant drinking water taste and odor and can produce toxins dangerous to humans and wildlife.[25] Large mats of a filamentous green alga, *Cladophora*, also reached nuisance levels in many areas of the Great Lakes in the mid-1900s,[26] fouling beaches and impacting recreation. Harmful algal blooms were particularly severe in lakes Erie and Ontario, which were more eutrophic than the upper lakes, but they also affected areas of lakes Michigan and Huron such as Saginaw Bay and Green Bay.[27] In addition to impacts to beaches and human health, another consequence of massive algal blooms is **hypoxia**. When large amounts of algae die and settle to the lake bottom after a bloom, decomposition increases, consuming available oxygen. This leads to oxygen-poor bottom waters that are unable to support most forms of life—hence the term "dead zones" commonly used to describe hypoxic areas. Hypoxia can lead to fish kills and over time decreases biodiversity in eutrophic lakes.[28] At the peak of cultural eutrophication, 70% of central Lake Erie's bottom waters suffered from pronounced hypoxia, negatively affecting benthic (bottom-dwelling) organisms and fish.[29]

Community structure of phytoplankton (floating plants or algae, see Box 2) also shifted in response to increased nutrient loading and eutrophication in the Great Lakes. In Lake Erie, a major increase in blue-green

BOX 1: TROPHIC STATE

The five Great Lakes historically vary in their "**trophic states**." A body of water's trophic state represents its biological productivity, which is primarily controlled by the availability of nutrients such as phosphorus and nitrogen.[16] These nutrients limit **primary production**, which is the growth of phytoplankton and other plants (often assessed by measuring the amount of **chlorophyll a** in the water). In the Great Lakes, phosphorus is the nutrient that limits biological activity under most conditions.[17] Primary production in turn limits **secondary production** at higher **trophic levels**, or higher levels of the food web, such as fish. Thus, lakes with fewer nutrients will be less productive overall, or at lower trophic states, than those with more nutrients.

In general, lakes are classified using three trophic states: oligotrophic, mesotrophic, or eutrophic. **Oligotrophic** lakes (such as Lake Superior) have very low nutrient concentrations and thus low primary productivity. Water in oligotrophic lakes is very clear. **Mesotrophic** lakes are more productive than oligotrophic lakes, and have moderately clear water. **Eutrophic** lakes (such as Lake Erie) have the highest concentrations of nutrients and thus the most productivity. The dense growth of phytoplankton in eutrophic lakes causes their water to be murkier. The algae community in eutrophic lakes tends to have a larger abundance (especially in warmer months) of **blue-green algae** (more formally cyanobacteria), which can sometimes produce toxins. These three trophic state classifications are useful, but in reality, lakes fall along a continuous spectrum of productivity; thus, they can be described using terms such as "ultra-oligotrophic," "meso-eutrophic," or "hyper-eutrophic."[18]

In the absence of human influences, the physical qualities of the Great Lakes (such as their depth, temperature, and geologic setting) and the characteristics of their watersheds determined their trophic state. Deep, cold lakes such as Lake Superior and Lake Huron were historically oligotrophic.[19] Lake Erie, on the other hand, is much warmer and shallower and as a result is more productive (even in the absence of human activities).[20] Of course, the Great Lakes are complex bodies of water with distinct basins and embayments that often have different trophic states than their open waters. For example, Lake Huron's Saginaw Bay tends towards mesotrophic or even eutrophic conditions, even though most of the lake is oligotrophic.[21] Similarly, nearshore waters of lakes Michigan, Erie, and Ontario tend to be more eutrophic than offshore areas.[22]

BOX 2: GREAT LAKES FOOD WEBS

To appreciate the scope of recent changes in Great Lakes food webs and nutrient dynamics, it is important to understand the structure of food webs and their historic conditions. Prior to major species invasions, the Great Lakes **pelagic** (open water) fish community was dominated by lake trout and burbot – piscivorous predators (fish that prey upon other fish) that fed in deep waters on small **forage** (or prey) fishes such as lake herring, deepwater ciscoes, and bloaters.[30] In shallower, nearshore areas of the Great Lakes, the fish community was dominated by smallmouth and largemouth bass, muskellunge, northern pike, walleye, yellow perch, and smaller fishes such as emerald and spottail shiners.[31]

At the base of historic food webs, fish production has historically been supported by large populations of **benthic macroinvertebrates** (small, bottom-dwelling crustaceans and insects), dominated by the amphipod *Diporeia*.[32] *Diporeia* was vital to the diets of many fish species and was preyed upon by most Great Lakes fishes at some point in their life cycle.[33] Pelagic forage fishes also graze on **zooplankton** (tiny animals that swim in the water column) that in turn feed on **phytoplankton** (microscopic floating plants).

algae, which are well-suited to eutrophic conditions, occurred.[34] Changes in benthic communities also occurred in response to eutrophication. Declines in water and sediment quality in western Lake Erie caused populations of the mayfly *Hexagenia*, once the most dominant benthic invertebrate, to disappear beginning in the late 1950s.[35]

The serious ecological and economic impacts of cultural eutrophication were well-documented by the scientific community in the 1960s, and the media brought the issue to the public's attention. In response, the governments of the U.S. and Canada signed the landmark Great Lakes Water Quality Agreement (GLWQA) in 1972. In the agreement, the two countries pledged to solve the eutrophication problem by reducing loads of the nutrient phosphorus to the lakes, primarily through controls of point sources such as discharges from wastewater treatment plants. In addition, both the U.S. and Canada passed federal legislation and formed new agencies to implement and

enforce environmental laws protecting water quality. Phase-outs and bans on phosphorus in laundry detergents were enacted by the federal government in Canada and by individual U.S. municipalities and states in the 1970s and 1980s. Revisions to the GLWQA in 1978 recognized the importance of nonpoint sources of nutrient loading and the need for programs (such as addressing agricultural practices and urban runoff) to address these sources.[36] (For more information on policy efforts to reduce phosphorus pollution, see Section 5).

The efforts of the U.S. and Canadian governments to curb nutrient pollution paid off: the phosphorus reduction programs generally worked and the subsequent reversal of cultural eutrophication in the Great Lakes became a great environmental success story. As a result of loading reduction programs, phosphorus loadings decreased across the basin.[37] Target phosphorus loads were achieved in lakes Superior, Huron, Michigan, and Ontario by the early 1980s[38] and in Lake Erie by the mid-1980s.[39] In response to reduced phosphorus loadings, concentrations of phosphorus in open waters declined, particularly in lakes Erie and Ontario where conditions were more eutrophic.[40] In Lake Erie, target phosphorus concentrations were reached by the early 1990s in all three basins, although concentrations were quite variable and exceeded targets in some years (see data for western Lake Erie in Figure 2 below).[41] Episodes of hypoxia in Lake Erie's bottom waters were reduced.[42]

Great Lakes food webs recovered following reductions in nutrient loadings. Gradual oligotrophication (lake wide declines in primary production by algae) occurred in lakes Michigan, Huron, and Ontario following the implementation of stricter phosphorus controls,[43] with Lake Ontario reaching an oligotrophic state by the early 1990s.[44] Chlorophyll concentrations declined in all three basins of Lake Erie following phosphorus load reductions,[45] and by 1992 primary productivity in the lake indicated a shift from eutrophy to meso-oligotrophy.[46] Declines in abundance of blue-green algae led to improved drinking water taste and odor[47] and decreases in phosphorus loading were successful in reducing blooms of the harmful alga *Cladophora* throughout the lakes.[48] In lakes Erie and Ontario, shifts in phytoplankton and zooplankton communities indicated a movement away from eutrophic conditions.[49] In western Lake Erie, the burrowing mayfly *Hexagenia* made a comeback after populations had disappeared due to eutrophication.[50] Impacted fish communities rebounded as well; in Lake Erie, the reduction in phosphorus loading contributed to the revival of walleye populations[51] and improved overall fish community diversity.[52] In general, the scientific and policy communities agree that the GLWQA and programs through federal laws such as the Clean Water Act were successful in meeting the goal of halting and reversing eutrophication in the Great Lakes in the 1970s.

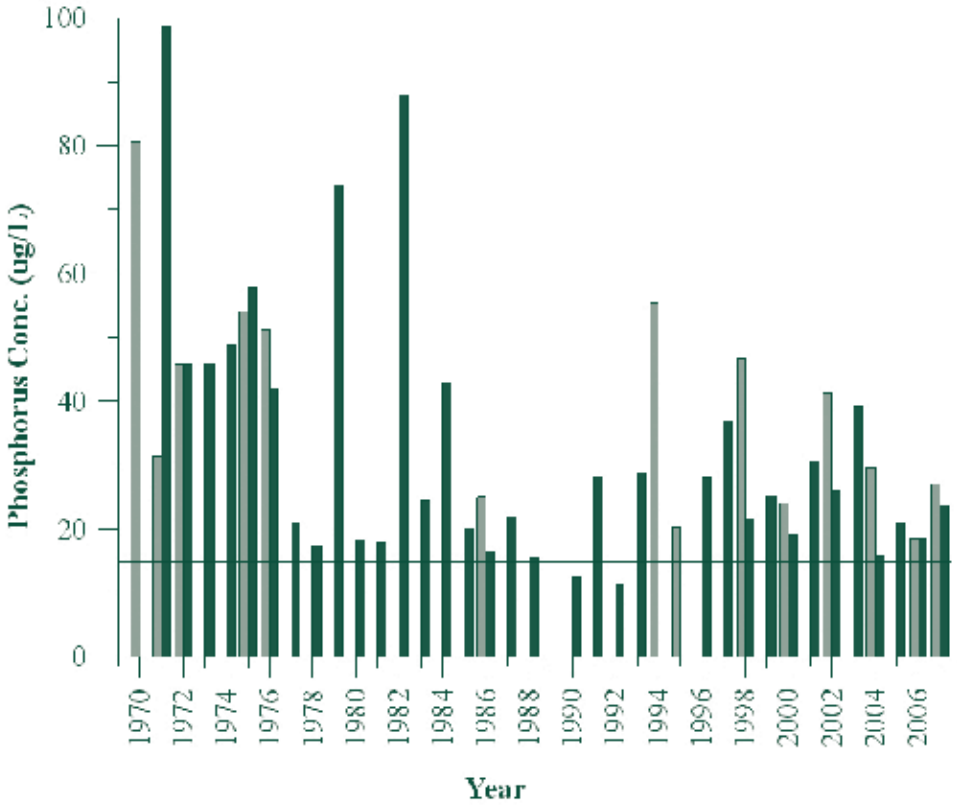


FIGURE 2
Trends in total phosphorus concentrations (ug/L) in western Lake Erie from 1970-2007. Darker bars indicate U.S. data, lighter bars Canadian data. Horizontal line represents target as established in the Great Lakes Water Quality Agreement. (Adapted with permission from Environment Canada and U.S. EPA, 2009. Phosphorus Concentrations and Loadings - Indicator #111. State of the Great Lakes 2009. Cat. No.En161-3/1-2009E-PDF, pp. 77-81.)

SECTION 3

ONGOING ECOSYSTEM SHOCK

Invasive Species in the Great Lakes

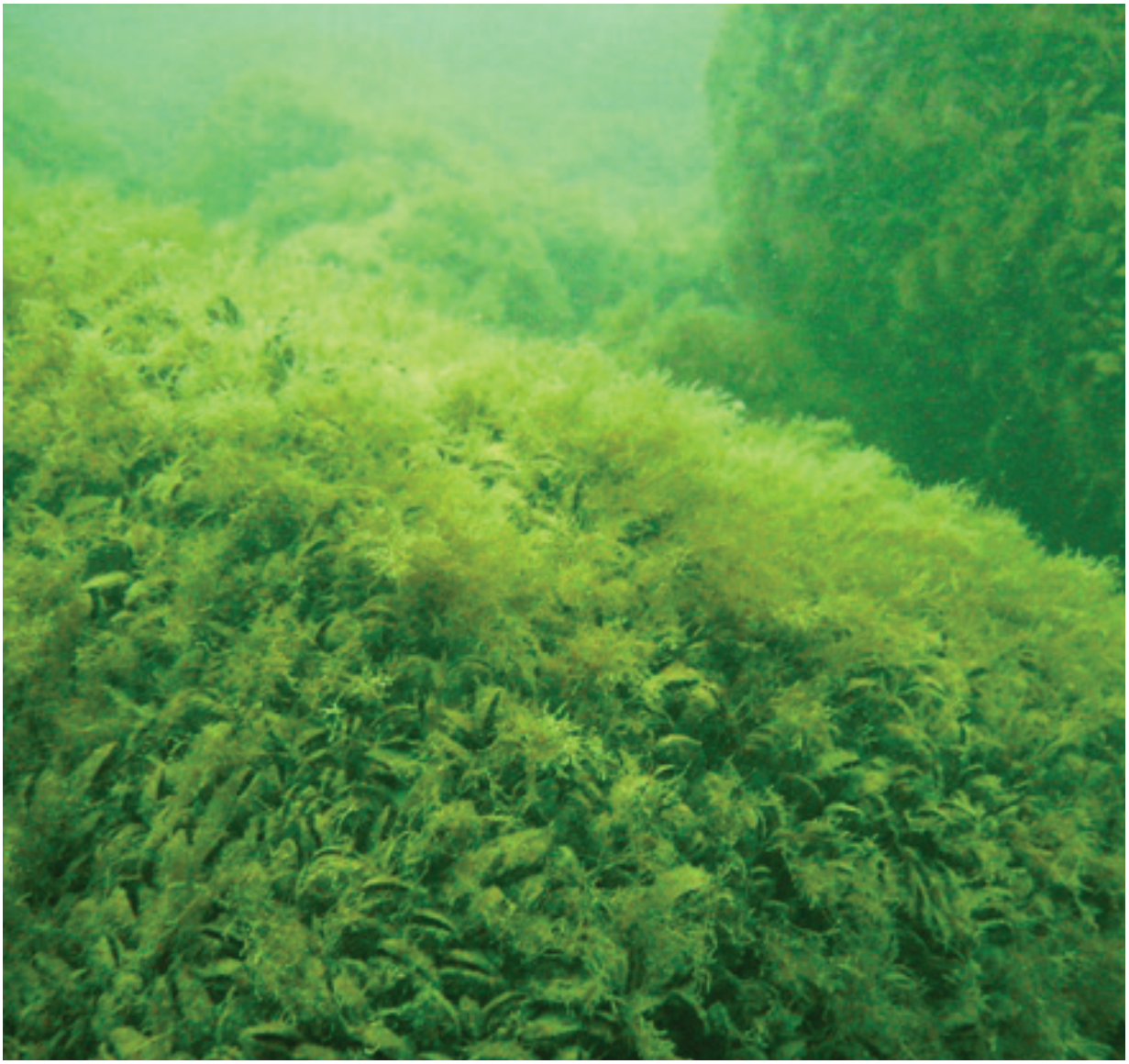
Even before excess nutrient loading caused cultural eutrophication across the Great Lakes, humans were polluting the ecosystem in another way: through the introduction of non-native species.[53] This section details two chapters in the history of invasive species in the Great Lakes: top-down food web changes caused by several invasive species that affected fish communities, and bottom-up shifts caused by invaders that have altered the base of the food web. It is important to note that in analyzing some food web changes, it is difficult to separate the effects of reduced nutrient loading from the impacts of invasive species because these changes were occurring simultaneously.[54]

Early invasions alter the fish community

Great lakes fish communities have undergone many drastic changes since human settlement of the region. Fish populations in particular were heavily impacted by several non-native species introductions that began in the mid- to late-1800s. The invasion of the sea lamprey, a species present in Lake Ontario as early as 1835 (and possibly native to the lake) that spread to Lake Erie by 1921, likely had the greatest impact on fish populations.[55] Sea lampreys are parasitic, eel-like fishes that attach to other fish and feed on their blood and bodily fluids; one adult sea lamprey can kill up to 40 pounds of fish in as little as a year. Sea lamprey predation, combined with commercial overharvesting (and in some cases other factors such as toxic contaminants[56]), led to the collapse of populations of native lake trout, burbot, and lake whitefish in the mid-1900s.[57]

The decline in abundance of top predators allowed populations of the alewife — a small, invasive forage fish that eats zooplankton — to grow unchecked. Alewives, native to the Atlantic coast of the United States, probably invaded the Great Lakes through the Erie Canal and were common in Lake Ontario by 1873, although some scientists believe they were native to that lake.[58] The opening of the Welland Canal between Lake Ontario and Lake Erie in 1829 allowed alewives to invade the rest of the Great Lakes, and they spread to Lake Superior by 1954.[59] Following the collapse of lake trout that preyed upon alewives, their abundance increased dramatically in lakes Michigan and Huron; these large populations of alewives and rainbow smelt, another introduced species, caused declines in native prey fishes such as lake herring and deepwater ciscoes.[60] Massive alewife die-offs in the 1960s resulted in carcasses washing ashore in huge numbers, impacting recreational activities.[61] In response to the alewife explosion, large-scale stocking of salmonids such as Coho and Chinook salmon was initiated in the 1960s to control nuisance levels of alewives and to establish a sport fishery.[62] These efforts were largely successful, leveling off alewife populations and launching a successful recreational fishery centered on introduced salmon.[63] In general, Great Lakes offshore fish communities have shifted from being dominated by deep-dwelling piscivores (e.g., lake trout) and native forage fishes (e.g., lake herring) to communities often dominated by introduced species that inhabit shallower waters.[64]

Although many nearshore areas of the Great Lakes still support strong recreational fisheries,[65] fish communities in the nearshore have also been impacted by invasive species. Alewife interference with reproduction was blamed for declines in populations of walleye and yellow perch between the 1950s and 1970s.[66] The invasive round goby, first discovered in the Great Lakes in 1990,[67] is an aggressive bottom-dwelling fish that can tolerate a wide range of environmental conditions, eat a variety of foods including invasive mussels, and spawn prolifically.[68] Round gobies have the potential to negatively impact native fish species by competing for food and habitat and interfering with reproduction; for example, gobies were blamed for the local extirpation of the mottled sculpin in Calumet Harbor, Lake Michigan.[69] The Eurasian ruffe, an invasive perch-like



Quagga mussels and nuisance algae *Cladophora* in western Lake Michigan (Photo: Harvey Bootsma, University of Wisconsin-Milwaukee)

fish, was found in Lake Superior in 1986 and rapidly became the most abundant fish in the St. Louis River estuary.[70] Since its introduction, the ruffe has become established in parts of Lake Michigan (Green Bay) and Lake Huron (Thunder Bay).[71] If the Eurasian ruffe becomes established in Lake Erie, it could have disastrous impacts on economically important walleye and perch fisheries.[72]

Dreissenid mussels re-engineer the Great Lakes ecosystem

Perhaps no other invasive species have had more impact on the Great Lakes ecosystem than zebra and quagga mussels.[73] The zebra mussel (*Dreissena polymorpha)* and its relative the quagga mussel (*Dreissena rostriformis bugensis),* hereafter collectively referred to as dreissenids, were introduced into the Great Lakes via ballast water from oceangoing freighters in the late 1980s.[74] Zebra mussels are well-suited to colonize nearshore areas and did so in great numbers, impacting industries, recreational activities and municipal water supplies and causing billions of dollars of damage. The quagga mussel can tolerate and reproduce in colder temperatures, and is better able to inhabit softer bottom sediments than its cousin, so it is better suited to proliferate in deeper, offshore waters.[75] Quagga mussels have replaced zebra mussels as the dominant dreissenid in many areas of the Great Lakes, and their populations continue to explode in deep areas of lakes Michigan, Huron, and Ontario.[76] By one estimate, there are over 950 trillion quaggas in Lake Michigan alone.[77]

Invasive dreissenid mussels impact the Great Lakes ecosystem via several mechanisms. With their large populations and ability to filter water at volumes and rates much greater than native grazers,[78] dreissenids can significantly decrease phytoplankton abundance and thus primary productivity.[79] This filtration can lead to drastic increases in water clarity,[80] a change that—while often welcomed by humans who use the Great Lakes—can have serious implications for the ecosystem (discussed in more detail below). In addition to influencing algal primary production, dreissenid mussel filtering and waste-producing processes have significantly altered nutrient cycling and dynamics in large areas of the Great Lakes.[81] Although dreissenids can increase the availability of nitrogen in the environment,[82] their impacts on phosphorus dynamics are of more interest because phosphorus is usually the limiting factor for algal growth in the Great Lakes.[83] Depending on environmental conditions such as existing nutrient levels in the water column, dreissenids can sometimes retain phosphorus and nitrogen in their tissues at relatively constant concentrations[84] and can therefore reduce open-water phosphorus concentrations.[85] Given their huge populations, large quantities of phosphorus are locked in dreissenid tissues, with some permanently sequestered in the shells of dead mussels.[86] Recent research suggests that up to two-thirds of the entire phosphorus inventory in Lake Michigan is tied up in quagga mussels.[87] Environment Canada and the U.S. Environmental Protection Agency (EPA) report that current offshore phosphorus concentrations in lakes Michigan, Huron, and Ontario may be too low to support healthy levels of biological productivity.[88] As discussed more fully below, however, in shallower nearshore areas dreissenids tend to regenerate soluble forms of the nutrient through excretion and waste egestion, making usable forms more available in the water column.[89] Direct filtration, changes to nutrient dynamics, and increased water clarity all contribute to food web impacts of dreissenid grazing.[90]

The dual tendencies of dreissenids in processing phosphorus have caused startlingly different impacts in nearshore and open waters of the Great Lakes. On a large scale, zebra and quagga mussels have re-engineered nutrient cycling in large areas of the Great Lakes to the extent that phosphorus is trapped in nearshore and benthic zones, depriving offshore areas (see Figure 3).[91] This hypothesized mechanism, known as the "nearshore phosphorus shunt," may encourage the growth of blooms of harmful algae such as *Cladophora*,[92] and could be largely to blame for the feast/famine imbalance currently seen in the Great Lakes. Recent research supporting the existence of the phosphorus shunt implicates dreissenid mussels in decreasing the amount of phosphorus exported from Saginaw Bay to the open waters of Lake Huron by 60%.[93] Bottom-dwelling algae species and other benthic plants favored by this phosphorus shunt may further benefit from increased water clarity due to dreissenid filtering.[94] In addition, dreissenid mussels appear to selectively reject certain toxin-producing species of the blue-green algae *Microcystis*, enabling these bloom-forming species to dominate algae assemblages.[95] Ratios of nutrients excreted by dreissenids also can cause community shifts towards blue-green algae,[96] further encouraging harmful algae. Another invasive species, the round goby, might amplify the shunt of phosphorus to the nearshore by serving as an energy and nutrients link between dreissenid mussels and nearshore fish, given the propensity of round gobies to feed on the invasive mussels. While this phenomenon potentially benefits nearshore species such as smallmouth bass, it occurs at the expense of offshore fishes.[97]

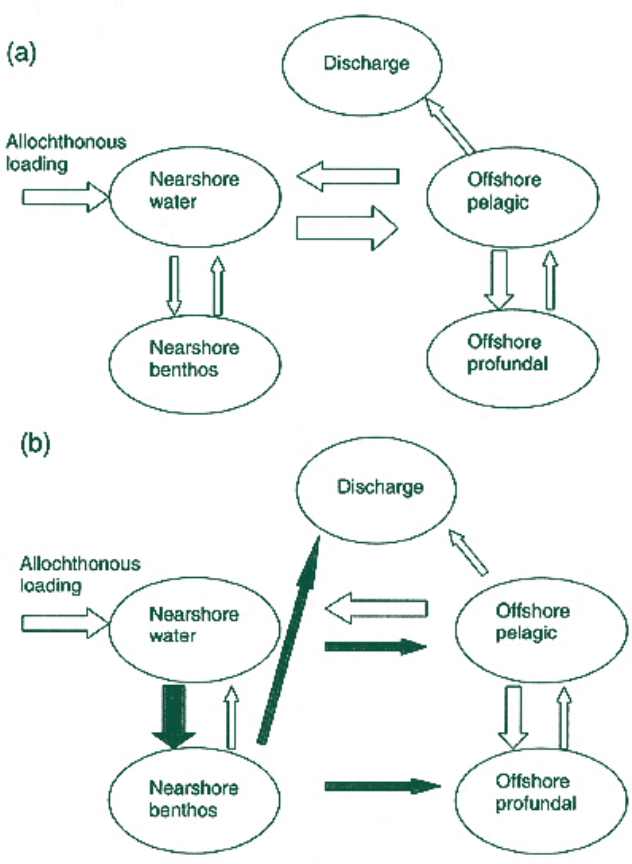


FIGURE 3
Hypothesized nearshore phosphorus shunt diagram showing transport of phosphorus between nearshore and offshore waters a) before dreissenid mussel invasion and b) after dreissenid mussel invasion. Shaded arrows represent the most altered fluxes; arrow width indicates relative size of flux. Note that "allochthonous" refers to loads from external sources to the lake, and "discharge" refers to transport of phosphorus out of the lake system (e.g., out of Lake Erie through the Niagara River). (©2008 Canadian Science Publishing or its licensors. Reproduced with permission from Hecky, R.E., et al. 2004. The nearshore phosphorus shunt: A consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 61 (7), 1285-1293.)

BOX 3: OTHER PRESSURES ON GREAT LAKES FOOD WEBS

In addition to impacts on nutrient dynamics and food webs discussed in this section, dreissenid mussels impact the Great Lakes ecosystem in numerous other ways. They can serve as "physical ecosystem engineers," altering the structure of the lakebed and impacting habitats for other species.[116] Dreissenids can attach to the shells of native mussels, which has caused extirpation of the latter in many areas of the Great Lakes.[117] Dreissenids are also implicated in a phenomenon known as "invasional meltdown," whereby they facilitate the invasion of other species; for example, dreissenids created better conditions for the round goby to establish and proliferate.[118] Zebra and quagga mussels have become integrated into food webs in some areas of the Great Lakes, altering pathways for the transfer of energy, nutrients, and contaminants to higher trophic levels. In some cases, native species such as smallmouth bass and whitefish can benefit indirectly from this integration of invasive dreissenids into food webs;[119] overall, however, the invasion of dreissenids has resulted in declines in the condition of Great Lakes fishes.[120] Invasive mussels and round gobies are also implicated in outbreaks of botulism that kill wildlife, discussed in more detail in Section 4.

While invasive dreissenids alter nutrient cycling and reduce primary production, Great Lakes food webs are also changing in response to other drivers. Large invasive, predatory zooplankton such as the fishhook waterflea (*Cercopagis pengoi*) and the spiny waterflea (*Bythotrephes longimanus*) are placing additional pressure on food webs. *Cercopagis* has impacted the Lake Ontario food web through predation pressure and by shifting zooplankton spatial distribution.[121] In lakes Michigan, Huron, and Erie, the invasion of *Bythotrephes* has caused drastic declines in the abundance of some zooplankton species and a decrease in overall species diversity.[122] In Lake Huron, consumption of zooplankton by *Bythotrephes* can exceed that due to fish and the opossum shrimp (*Mysis diluviana*) combined; the latter is an important food source for a number of fish species.[123] Both *Bythotrephes* and *Cercopagis* are implicated in recent declines in populations of *Mysis* in Lake Ontario.[124] Whereas historical Great Lakes zooplankton communities were dominated by herbivorous species that fed mostly on phytoplankton,[125] invasive predatory cladocerans, which are not a good food resource for fish, compete with fish and native invertebrates for zooplankton resources and are clearly capable of altering food webs.

Invasive species also have the potential to place pressure on Great Lakes food webs via wetlands. Coastal wetlands are being invaded by plants such as the common reed (*Phragmites australis*),[126] reed canary grass (*Phalaris arundinacea*),[127] purple loosestrife (*Lythrum salicaria*),[128] and curly pondweed (*Potamogeton crispus*)[129] that crowd out native plants and decrease the quality and availability of habitat for wildlife. Great Lakes coastal wetlands are important to the health of food webs, serving as crucial habitat for many fish species during early stages of their life cycles.[130] Some of these invasive plant species can even alter the function of the wetlands themselves; for example, *Phragmites* can "dry up" areas it invades.[131] Curly pondweed can increase phosphorus concentrations in surrounding waters, encouraging nearshore algal blooms.[132] Currently, according to Environment Canada and the U.S. EPA, coastal wetland plant communities are in only "fair" condition in lakes Michigan, Huron, and Erie, with Lake Erie's status deteriorating. Lake Ontario's coastal wetland communities are deemed to be in "poor" status.[133] If coastal wetlands continue to be lost and degraded due to invasive species and other human-induced stressors, Great Lakes food webs will be further impacted.

The ability of dreissenids to consume large quantities of phytoplankton, and to alter nutrient cycling, has had major impacts on both nearshore and offshore food webs. Dreissenid mussels are implicated in the collapse of the benthic amphipod *Diporeia* across the lakes, although exact causal mechanisms are unclear.[98] Populations of *Diporeia*, once a vital part of the diets of many Great Lakes offshore fishes and more than 70 percent of benthic biomass in deep parts of the Great Lakes,[99] have all but disappeared in shallow areas of lakes Michigan, Huron, and Ontario and are extremely depressed in deeper offshore zones.[100] *Diporeia* now appears to be completely absent from Lake Erie.[101] It is hypothesized that dreissenid filtering may cause food limitation in *Diporeia*, which relies on phytoplankton blooms settling to the lake bottom.[102] Another theory is that mussel waste products are toxic to *Diporeia*.[103] Declines in populations of other benthic invertebrates, while likely partially due to decreased nutrient loads, are also linked to the invasion of dreissenid mussels.[104] Changes in the benthic community, in particular the disappearance of *Diporeia*, have already begun to impact fish populations. Declines in the condition of fishes such as alewives,[105] deepwater sculpin,[106] and the commercially important lake whitefish[107] have been observed.

While the symptoms of nutrient pollution and dreissenid ecosystem engineering are manifested by the increased prevalence of harmful algal blooms in the nearshore (see Section 4), the picture is much different in offshore regions of the Great Lakes. Quagga mussel filtering caused dramatic reductions in spring primary production in the offshore regions of lakes Michigan and Huron beginning in the early to mid-2000s when this species became abundant in this region (see Plot 4 in "Feast/Famine" center panels).[108] Although gradual, long-term oligotrophication resulting from nutrient controls was anticipated,[109] this rapid oligotrophication in response to dreissenids has taken the scientific community by surprise. The spring diatom bloom has all but disappeared and the pelagic zones of lakes Michigan and Huron now resemble ultra-oligotrophic Lake Superior.[110] The zooplankton community, which once relied on the spring diatom bloom as an important food source, has responded with drastic declines in abundance and shifts in community structure.[111] As the foundations of the Great Lakes food web are eroded, fish communities are unable to sustain themselves. In Lake Huron, populations of deepwater prey fishes, including bloaters, sculpin, and smelt, have dramatically declined (see Plot 5 in "Feast/Famine" center panels),[112] contributing to the collapse of populations of Chinook salmon, an important sport fish.[113]

Although the impacts of dreissenid mussels on nutrient dynamics, primary production, and food webs are not yet fully understood, it is clear that these invasive organisms have caused a significant, and perhaps permanent, ecosystem shift in the Great Lakes. As described previously, dreissenids have shifted energy, nutrients, and production to benthic and nearshore areas of the Great Lakes.[114] Research also indicates that invasive mussels have "decoupled" the relationship between total phosphorus loads and chlorophyll (a proxy for primary production).[115] Thus, changes in phosphorus loading in Great Lakes waters may no longer result in a predictable, corresponding response from algae populations throughout the lakes. This alteration of the phosphorus-chlorophyll relationship, driven by invasive dreissenid mussels, further explains how Great Lakes offshore food webs can be collapsing in response to reduced primary production and nutrient depravation even while nearshore areas show symptoms of eutrophication.

These breakdowns are made worse by the incredibly fast rate at which dreissenids are driving ecosystem change. In the past, changes such as cultural eutrophication from nutrient pollution took decades to manifest; now, we are seeing dramatic alterations of the Great Lakes food web occurring in the space of several years. If these rapid ecosystem changes caused by dreissenids were not enough, other invasive species (including predatory zooplankton) have also been affecting food webs in the Great Lakes (see Box 3). In addition to these ecosystem changes, invasive species are having both direct and indirect effects on the region's economy (see Box 4).

BOX 4: ECONOMIC IMPACTS OF DREISSENID-DRIVEN FOOD WEB CHANGES

In addition to their serious ecological impacts, zebra and quagga mussels have had major economic consequences in the Great Lakes. The invasive mussels clog water intake pipes in huge numbers, impacting power plants, municipal water suppliers, and other users.[134] Between 1993 and 1999, zebra mussels are estimated to have cost the power industry in the U.S. $3.1 billion, and significant impacts to other sectors have also been seen. [135] Zebra mussels have also impacted recreation and tourism around the Great Lakes basin, fouling boats and docks and washing up on beaches in huge numbers.[136] A recent study estimated losses to the region associated with ship-borne invasive species broadly to be at least $200 million annually.[137]

The indirect economic effects of dreissenid mussel invasion may be even more severe than the direct impacts to infrastructure and beaches. Food web changes (likely caused in large part by dreissenid filtering) contributed to the collapse of the Lake Huron Chinook salmon fishery in the mid-2000s. Coastal communities and businesses such as charter boat companies and tackle shops around the Lake Huron basin were hit hard by the loss of this important fishery. The Michigan Department of Natural Resources estimates that 10 ports in Michigan alone have lost more than $19 million annually since 2004 as a direct result of the Chinook salmon collapse.[138] Fishery scientists are beginning to see warning signs that a similar Chinook salmon collapse could occur in Lake Michigan, and managers are seeking ways to manage effects of a declining forage base. The economic ramifications of a salmon collapse on Lake Michigan would be severe: in 2009 alone, the fishery brought over $32 million to coastal communities around the lake.[139]

SECTION 4

EUTROPHICATION RELAPSE

Current Nutrient and Water Quality Trends and Issues

Despite the success of phosphorus control programs under the GLWQA and federal legislation, changes such as the invasion of dreissenid mussels and their re-engineering of nutrient dynamics have resulted in recent declines in nearshore water quality in the Great Lakes. Indicators suggest that some areas of the Great Lakes might be slipping back towards the eutrophication problems of the 1960s and 1970s due to both point and nonpoint sources of phosphorus pollution.

As previously discussed, GLWQA target phosphorus loads had been met across the lakes by the mid-1980s. Between 1996 and 2002, the Lake Erie target load was met in most years, except in 1997 and 1998 when tributary loads increased due to heavy precipitation.[140] In recent years, however, phosphorus loads to some areas appear to be increasing after a long period of overall decline.[141] Although target phosphorus loads continue to be met consistently for the open waters of lakes Superior, Michigan, and Huron, recent loads exceed targets in some historically eutrophic areas of those lakes such as Green Bay and Saginaw Bay.[142] In lakes Erie and Ontario, inter-annual variability in loading is high and targets are not being met every year (see Figure 4).[143] As discussed below, exceeding these targets even occasionally is having dire consequences for portions of the Great Lakes.

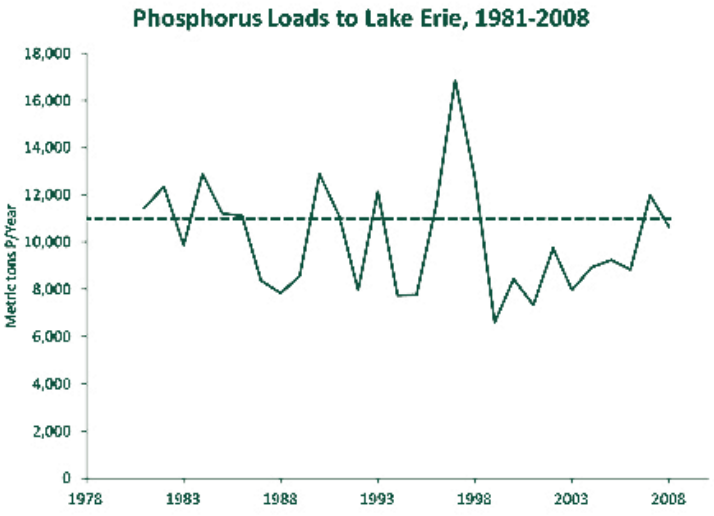


FIGURE 4
Estimated total phosphorus loads to Lake Erie from all sources (point and nonpoint), 1981-2008. Dashed line represents the Great Lakes Water Quality Agreement target load of 11,000 metric tons annually. (Graph courtesy Dolan, D., Univ. of Milwaukee-Green Bay, unpublished data.)

The original GLWQA of 1972 focused on point source phosphorus loads, and much of its success can be attributed to subsequent federal regulation of dischargers such as wastewater treatment plants. Subsequent revisions to the Agreement increased emphasis on nonpoint source pollution. Recently, however, the scientific community has raised concerns that point source pollution is still a serious problem in the Great Lakes. Recent research confirms other work indicating that point source phosphorus loads, particularly from municipal wastewater treatment plants via the Detroit River, are an important contributor to overall loading to western Lake Erie.[144] Continuing elevated loadings are likely due in part to the fact that cash-strapped municipalities across the region are struggling to maintain crumbling wastewater infrastructure, with federal funding inadequate to fulfill all needs. Outdated sewer systems that combine stormwater and sanitary wastewater are often overwhelmed by large rain events, resulting in combined sewer overflows (CSOs) that dump tens of billions of gallons of untreated sewage into the lakes each year.[145] Besides contributing phosphorus pollution to the Great Lakes, CSO events pose serious human health risks and can lead to beach closures.

Despite the importance of point sources, nonpoint sources such as runoff from agricultural fields are the primary contributor to Great Lakes total phosphorus loads. While acknowledging that other sources con-

BOX 5: IMPORTANCE OF NITROGEN AND OTHER NUTRIENTS TO ALGAL GROWTH

Phosphorus typically limits primary production in freshwater lakes,[177] but the importance of nitrogen should not be ignored, as it too can encourage algal growth under certain conditions. Recent research shows that phytoplankton in Lake Erie can be seasonally co-limited by nitrogen,[178] which can encourage blooms of nitrogen-fixing toxic blue-green algae such as *Anabaena*.[179] Nitrogen can be an important contributor to phytoplankton biomass in Lake Erie, particularly when phosphorus concentrations are high.[180]

The potential contribution of nitrogen to recent algal blooms is not necessarily due to changes in loading, but is primarily attributed to the alteration of in-lake nutrient dynamics by dreissenid mussels.[181] Experiments have shown that dreissenid mussels cause shifts in nitrogen-to-phosphorus ratios, favoring algae that are well-suited to N-limited conditions.[182] Once again, as with phosphorus and its relationship to algal growth, dreissenid mussels serve to decouple landscape nutrient inputs and primary production in the lakes. In addition to nitrogen, other nutrients such as iron and silica can contribute significantly to the growth of algae in the Great Lakes.[183]

tribute to nutrient pollution, scientists recognize that a majority of phosphorus loading to areas like Saginaw Bay and western Lake Erie come from agricultural nonpoint runoff,[146] and some experts recommend focusing efforts and resources on reducing loads from these sources to maximize water quality improvement.[147] The lack of systematic declines in total phosphorus loading in some areas of the Great Lakes — and potential recent increases — discussed above are largely due to inadequate agricultural practices to control phosphorus pollution in runoff.

In addition to total phosphorus loads exceeding targets in some areas, another troubling statistic suggests that the fraction of phosphorus entering the Great Lakes as dissolved or soluble reactive phosphorus (that is, biologically available phosphorus more easily taken up by algae) is increasing. In recent years, concentrations of soluble reactive phosphorus (SRP, also called dissolved reactive phosphorus) in nearshore Lake Ontario and the western basin of Lake Erie have increased.[148] Increases in SRP concentration may be due in part to dreissenid mussels, which can uptake phosphorus in biologically unavailable forms and release it to the water column as SRP.[149] Increases in loading of SRP from streams and rivers may also be responsible for increased concentrations in the lakes. Current loads of SRP in the Maumee and Sandusky Rivers, two tributaries to western Lake Erie, are the highest they have been in 35 years.[150] Exact causes of increased SRP loads in tributaries are uncertain, but experts believe they primarily result from farming practices in agriculture-heavy watersheds and from climate-related factors.[151]

In response to increased phosphorus loads and increases in the fraction of SRP, current phosphorus concentrations in some areas of the Great Lakes are not consistently meeting GLWQA targets (see for example, Figure 2). Total phosphorus concentrations in Lake Erie, especially in the spring, began increasing as early as 1995.[152] Environment Canada and the U.S. EPA report that recently, concentrations in that lake are highly variable and frequently exceed targets, particularly in the western basin.[153] With respect to phosphorus concentrations, the two agencies rate the current condition of Lake Erie as "poor" with a trend of increasing phosphorus levels. [154] Environment Canada and the U.S. EPA also report that phosphorus concentrations in nearshore areas of lakes Michigan, Huron, and Ontario are high enough to support nuisance algae growth, even though phosphorus levels in offshore areas are at or well below targets.[155]

Impacts of excessive nutrients

Elevated concentrations of phosphorus in nearshore areas of lakes Huron, Erie, and Ontario are high enough to encourage harmful blooms of algae such as *Cladophora* and *Microcystis*;[156] indeed, symptoms of eutrophication including harmful algal blooms and hypoxic zones have returned to parts of all the Great Lakes except Superior.[157] Water quality parameters and phytoplankton and zooplankton communities indicated a return to eutrophic conditions in Lake Erie, particularly in the western basin, beginning in the mid-1990s.[158] Blooms of blue-green algae re-appeared in Lake Erie in the mid-1990s and have since become an annual occurrence, with extensive blooms of *Microcystis* observed in 2007, 2008, and 2009.[159] As of late August, the summer 2011

BOX 6: ECONOMIC IMPACTS OF GREAT LAKES EUTROPHICATION

The return of harmful algal blooms and hypoxia to the Great Lakes poses economic risks. The presence of smelly, unsightly, and potentially toxic algal blooms keeps people away from beaches and other recreational activities, resulting in lost tourism dollars. Across the U.S., blooms of harmful alga cause more than $80 million in economic damage annually.[184] *Cladophora* mats that wash ashore house *E. coli* bacteria whose concentrations are used as indicators of fecal contamination, meaning algal blooms potentially contribute to poor water quality and can trigger beach closures. Recent research suggests, however, that measuring *E. coli* at beaches plagued by *Cladophora* does not provide an accurate assessment of risks to human health.[185] Thus, it is possible that the presence of *Cladophora* has led to unnecessary beach closures – and beach closures are very costly in the Great Lakes, where coastal recreation provides the foundation for a vital tourism industry. For example, closing a Lake Michigan beach for a single day is estimated to result in economic losses of up to $37,000.[186] At the same time, current information does indicate continuing concerns about beach health: In 2006-07, only 47% of the Lake Erie beaches on the U.S. side were open for more than 95% of the beach season, and the EPA and Environment Canada report that beach water quality conditions on the lake are deteriorating.[187]

The potential impacts of eutrophication on Great Lakes fish communities are equally troubling. Recurring hypoxic zones in Lake Erie threaten the habitats and food resources that support economically important sport fish such as walleye and yellow perch.[188] Lake Erie, the most biologically productive of the Great Lakes, forms the basis of a regional recreational fishery whose estimated worth exceeds $7 billion annually in the U.S.[189] Clearly, symptoms of nutrient pollution such as harmful algal blooms and hypoxia in the Great Lakes have serious economic implications, and these problems will only worsen as eutrophication accelerates.

Microcystis bloom in western Lake Erie was 2.5 times denser than the previous record bloom of 2009 (See "Feast/Famine" center panels).[160] While not all types of *Microcystis* produce toxins, research shows that toxin-producing strains of these blue-green algae are present in lakes Erie and Ontario and are capable of producing toxin concentrations high enough to be harmful to human health.[161] Levels of *Microcystis* in early stages of the summer 2011 western Lake Erie bloom reached more than 1000 times World Health Organization guidelines for drinking water safety. [162] Recent research indicates that toxic blue-green algal blooms in tributaries to western Lake Erie are starting earlier in the year and farther upstream than was previously the case.[163] Washed-up mats of *Cladophora* are once again a common sight along shorelines of lakes Erie and Ontario, and in some areas of lakes Michigan and Huron.[164] In addition to the resurgence of harmful blooms of *Cladophora* and toxic blue-green algae such as *Microcystis*, new bloom-forming algae are beginning to appear in the Great Lakes. *Lyngbya wollei,* a potentially toxic, mat-forming blue-green alga from the southeastern U.S., was discovered washing onshore in western Lake Erie beginning in 2006. *Lyngbya* has different light and habitat requirements than similar mat-forming algae like *Cladophora*, so it may be able to colonize areas the latter has not.[165]

Coincident with the return of large algal blooms, the size and duration of hypoxic areas in the bottom waters of Lake Erie are increasing.[166] In 2005, a hypoxic zone with an area of about 10,000 square kilometers developed in central Lake Erie — one of the largest "dead zones" ever recorded in the lake.[167] In addition to negatively impacting fish and other organisms, hypoxia can re-release phosphorus formerly bound up in sediments. Thus, Lake Erie's hypoxic zones may alter phosphorus cycling to further encourage algal blooms[168] — creating a harmful feedback loop.

Great Lakes food webs are already being impacted by the reappearance of eutrophic conditions. Hatches of Lake Erie walleye and perch were below average in 5 out of 6 years from 2004 to 2009.[169] Hypoxia in Lake Erie's central basin has reduced habitat quality for many species of fish and has the potential to impact fish community structure and population dynamics.[170] Cyanobacterial toxins such as those produced by *Microcystis* can be harmful to invertebrates and fishes and can accumulate up food webs, significantly impacting their structure and function.[171] Mats of *Cladophora* harbor bacteria responsible for recent outbreaks of avian botulism that have killed thousands of birds along the Great Lakes.[172]

The resurgence of eutrophication in nearshore areas of the Great Lakes also has serious implications for human health. As previously discussed, chemicals produced by some blue-green algae can be toxic to humans,

causing respiratory and gastrointestinal symptoms, damaging liver tissue, and promoting tumors.[173] In 2010, nine people were sickened by toxic blue-green algae in an inland lake in Ohio, and three pets died after coming in contact with the water.[174] Blue-green algal toxins can even lead to death in humans; in an infamous example, 55 people in Brazil were killed by toxic *Microcystis* that had contaminated dialysis units.[175] *Cladophora* blooms harbor and encourage the growth of harmful bacteria such as *E.coli* and *Salmonella* that can be released to surrounding waters, sickening humans who come in contact with contaminated water or beaches. [176]

It is clear from the return of eutrophic conditions in nearshore areas of the Great Lakes that algae are booming, feasting on nutrients from the land and encouraged by invasive species. These algal blooms and other manifestations of eutrophication can cause a number of economic impacts (see Box 6). These "feast" conditions are even more striking when compared to the "famine" that is devastating offshore food webs (see Section 3, Part 2 and "Feast/Famine" center panels).



Algae in Maumee Bay (Photo: Sandy Bihn, Lake Erie Waterkeeper)

FEAST

High levels of phosphorus in nearshore areas of the Great Lakes, particularly in western Lake Erie, are causing toxic and nuisance algal blooms and creating oxygen-poor "dead zones" in deep areas. While both nutrient loads and concentrations have declined over the past few decades, concentrations (in particular in nearshore areas such as western Lake Erie) often remain above target levels. Excessive nutrient loads come from nonpoint sources such as fertilizer-rich runoff from agricultural fields and from point sources such as sewage treatment plants. Invasive zebra and quagga mussels exacerbate this problem by shunting phosphorus already within the lakes towards shore and trapping phosphorus coming from the land. In addition, the proportion of phosphorus loads entering western Lake Erie from tributaries that consists of dissolved phosphorus is increasing—meaning more phosphorus is readily available to algae (see Plot 1). The combination of available phosphorus and other factors (including adequate light and warm water temperatures) can lead to large harmful algal blooms, as was the case in the August-September 2011 western Lake Erie bloom, in which high concentrations were observed throughout most of the basin (see image at bottom left).

In the summer of 2011, western Lake Erie experienced the most severe bloom of toxic algae ever recorded. The species of blue-green algae primarily responsible for the bloom, *Microcystis*, produces a chemical that is toxic to humans and wildlife and can cause sickness and even death. Levels of toxins measured in the 2011 bloom were more than 1000 times the World Health Organization guidelines for drinking water. Advisories were posted on beaches along the western basin of Lake Erie, warning swimmers against contacting the water.

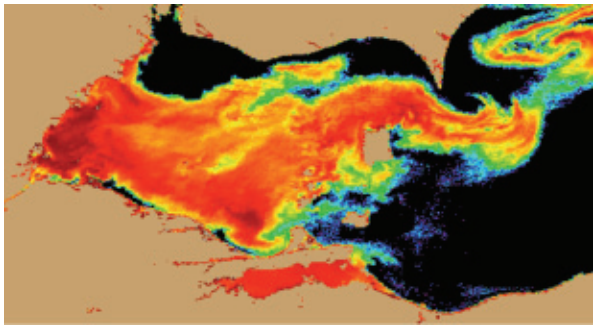


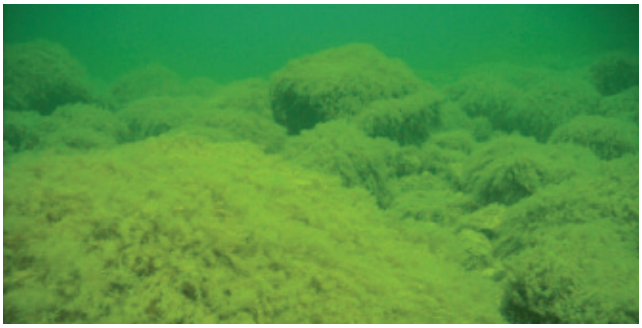
A toxic Microcystis *bloom washes up on the shore of Maumee Bay in western Lake Erie on August 29, 2011. (Photo: Sandy Bihn, Western Lake Erie Waterkeeper)*



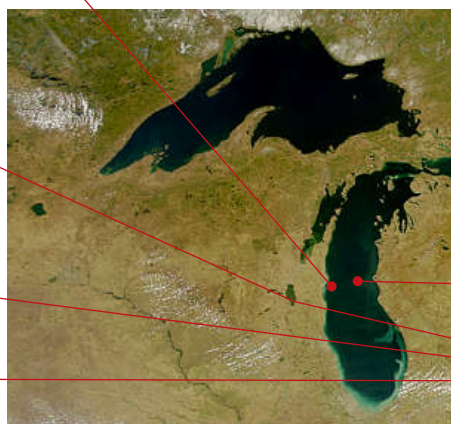
A public health advisory at a Maumee Bay, Lake Erie beach warns swimmers against contacting water contaminated with a toxic bloom of Microcystis. *(Photo: Sandy Bihn, Western Lake Erie Waterkeeper)*

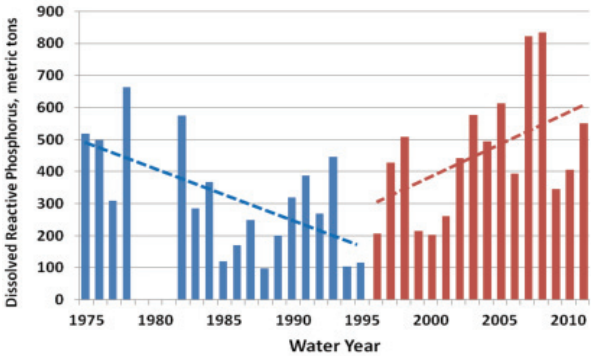
MERIS satellite image from European Space Agency showing massive Microcystis *bloom in western Lake Erie on September 3, 2011. Red indicates highest concentrations of toxic algae. (Image from NOAA Great Lakes Environmental Research Laboratory Experimental Lake Erie Harmful Algal Bloom Bulletin, 8 September 2011, available from: http://www.glerl.noaa.gov/res/Centers/HABS/lake_erie_hab/archive/bulletin_2011-014.pdf).*





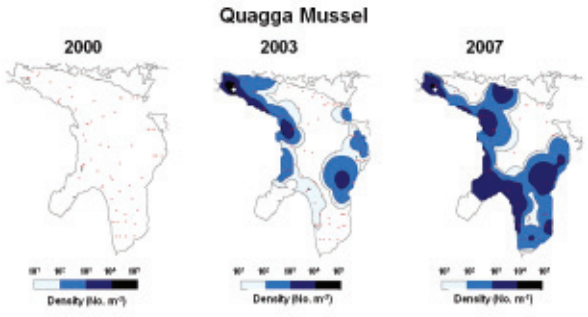
Nuisance algae cladophora blanketing bottom surface in western Lake Michigan. (Photo: Harvey Bootsma, University of Wisconsin-Milwaukee)



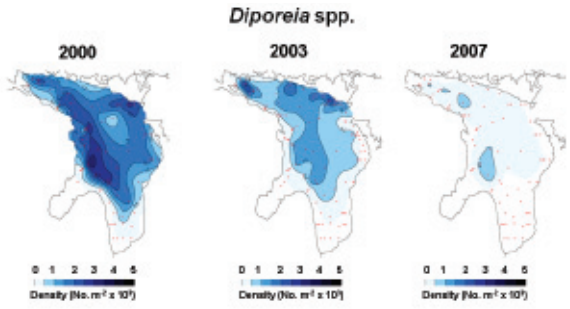


PLOT 1. Annual export of dissolved reactive phosphorus in metric tons from the **Maumee River at Waterville, OH**, as measured by the National Center for Water Quality Research at Heidelberg University. (Graph courtesy of D. Baker, Heidelberg University, unpublished data).

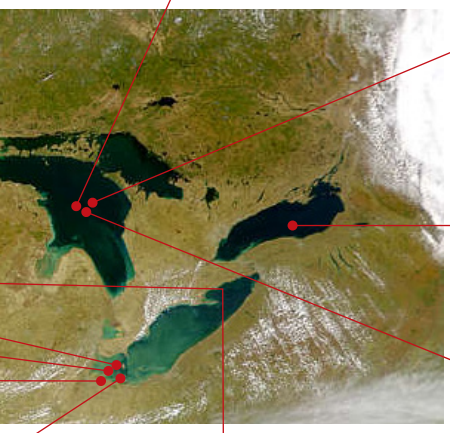
In contrast to the nearshore region, offshore areas of the Great Lakes have too few nutrients that are unable to support healthy biological communities. Invasive quagga mussels have expanded rapidly offshore and number in the trillions (see Plot 2). These tiny organisms are capable of filtering huge amounts of water, removing nutrients and algae from the water column, and pushing phosphorus to nearshore areas. Although excessive amounts of nutrients and algae in the nearshore are causing serious problems, their relative absence in the offshore is causing different but equally serious ecosystem changes. One dramatic change has been the drastic declines in the bottom-dwelling organism *Diporeia*, which has essentially disappeared in most areas of the lower lakes (see Plot 3). Significant changes have also occurred in the offshore, open waters—for example, springtime primary production in Lake Michigan has declined by over 80% since the mid-1980s (see Plot 4). Due to the crash in the lower levels of the food web of Lake Huron, prey fish populations have declined as well, with 95% of the deepwater prey fish biomass lost in less than two decades (see Plot 5); also see lake whitefish photo). The loss of prey fish populations has contributed to the crash in Chinook salmon in Lake Huron, a recreationally and economically important fishery.



PLOT 2. Expansion of invasive quagga mussels (densities in numbers of individuals per square meter) in the waters of **Lake Huron** between 2000 and 2007. (Courtesy Nalepa, T., NOAA Great Lakes Environmental Research Laboratory.)

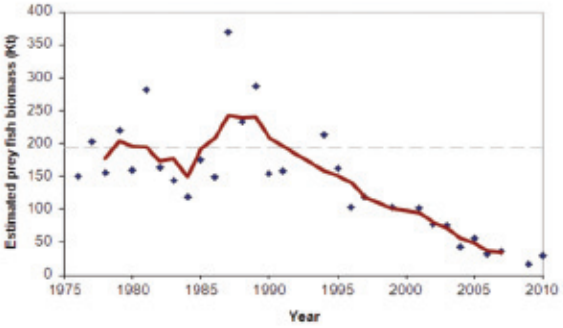


PLOT 3. Disappearance of the bottom-dwelling shrimp-like organism Diporeia in the waters of **Lake Huron** between 2000 and 2007. Note densities are in numbers of individuals per square meter, divided by 1,000; hence, the zone in the western portion of the lake in 2000 with the highest abundance was over 3,000 individuals/m2. (Courtesy Nalepa, T., NOAA Great Lakes Environmental Research Laboratory.)

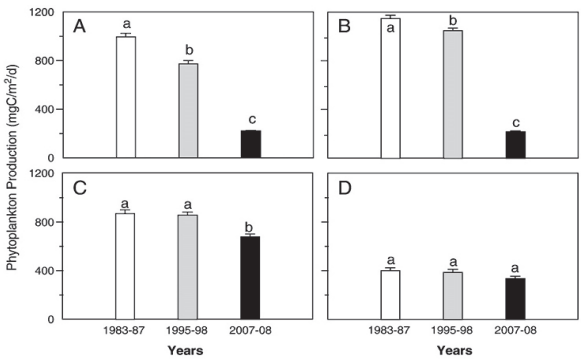


Emaciated (top, bottom) lake whitefish. (Photo: Ontario Ministry of Natural Resources)





PLOT 5. Estimated total lakewide biomass of offshore demersal (deepwater) prey fishes (kilotons) in **Lake Huron**. The solid line is the 5-year moving average of biomass, and the dashed line represents the average biomass from 1976-1994. Offshore demersal prey fishes include bloater, rainbow smelt, alewife, ninespine stickleback, trout perch, sculpins (deepwater and slimy), and round goby. Data are from the U.S. Geological Survey long-term fall bottom trawl survey (Graph courtesy Riley, S.C. USGS Great Lakes Science Center, unpublished data).



PLOT 4. Estimates of daily, areal integrated primary production in **Lake Michigan**, by thermal periods of the year, over three decades. A. spring isothermal mixing; B. May isothermal mixing; C midstratification, (D) late stratification. Means with different letters (a,b,c) indicating significant differences. Note significant declines for last decade, for each thermal period except late stratification. (Reprinted from Journal of Great Lakes Research, V. 36, Supplement 3, Fahnenstiel, G., Pothoven, S., Vanderploeg H., Klarer, D., Nalepa, T., and Scavia, D. Recent changes in primary production and phytoplankton in the offshore region of southeastern Lake Michigan, pp. 20-29, 2010, with permission from Elsevier.)

SECTION 5

EXISTING NUTRIENT REDUCTION PROGRAMS/POLICIES

The Great Lakes are among the most intensely managed bodies of water in the world. There are hundreds of laws, programs, action plans and task forces from the local to the international level to protect Great Lakes resources. To provide an overview of efforts to reduce nutrient pollution and address ecosystem changes in the Great Lakes, this section highlights several significant laws and programs pertaining to phosphorus reduction and features several example state and municipal programs.

Binational, federal, and state nutrient reduction strategies

The first international effort to protect the Great Lakes was the **1909 Boundary Waters Treaty**. The treaty obliged the U.S. and Canada to protect international waters from pollution, but provided no monitoring or enforcement mechanism to ensure that the Parties abided by their commitments. The Treaty formed the **International Joint Commission (IJC)**, a binational advisory board, to advise both nations on the administration of their shared bodies of water. In response to widespread eutrophication and phosphorus loading in the Great Lakes during the 1960s that lead to fish die-offs, toxic algal blooms and the biological "death" of Lake Erie (see Section 2), the IJC recommended in 1970 that both nations enter into a phosphorus control agreement.

The early 1970s saw both extensive environmental activism and the fruition of numerous environmental advances in North America. The **Great Lakes Water Quality Agreement (GLWQA)** was signed in 1972 by the U.S. and Canada, ushering in an array of state and federal programs to address water quality issues in the Great Lakes Basin. Concomitant with this binational development, and to provide the legislative muscle to implement water quality controls across the U.S., Congress passed the **Clean Water Act** earlier that year. Both governments had recognized the need for federal agencies to monitor and enforce environmental laws, leading to the creation of the **U.S. Environmental Protection Agency (EPA)** in 1970 and **Environment Canada** in 1971.

The GLWQA was a watershed agreement in the area of nutrient reduction, particularly from point sources. Following implementation of programs in both countries, annual phosphorus loadings decreased due to several pollution reduction measures, some mandated by law and some implemented voluntarily. Important measures for reducing point sources of pollution included the promotion of phosphorus-free detergents, limits on phosphorus concentrations in wastewater effluent, and improvements made to sewage treatment plants and sewer systems. These controls on point sources were vital, but a 1978 report to the IJC from the **International Reference Group on Great Lakes Pollution from Land Use Activities (PLUARG)** recognized the importance of nonpoint nutrient loadings and proposed solutions. Revisions to the GLWQA in 1978 included recommended measures to reduce nonpoint pollution, which included changes in agricultural practices such as conservation tillage, animal husbandry control measures, and other practices.

Under the Clean Water Act, states must set ambient water quality standards to define acceptable pollutant levels in water bodies, as well as conduct monitoring and assessment to gauge whether standards are being met. States must identify waters not meeting water quality standards as "impaired" and are required to develop **total maximum daily loads (TMDLs)** for the pollutant(s) of concern (including nutrients such as phosphorus and nitrogen).[190] However, a number of states have lagged in developing and implementing TMDLs, including for nutrients. Perhaps the single most effective requirement of the Clean Water Act in the reduction of phosphorus is the **National Pollutant Discharge Elimination System (NPDES)** program, requiring permits for the release of wastewater from point sources. Permit limits for nutrients have been

increasingly included in discharge permits over the past two decades.

Another important Clean Water Act provision that addresses nutrients is the Section 319 provision addressing nonpoint source (NPS) pollution , added to the CWA in 1987. Section 319(h) established a grant program whereby EPA is authorized to award states funds to implement programs to reduce nonpoint source pollution (including nutrient pollution), if they have approved Nonpoint Source Assessment Reports and Nonpoint Source Management Programs. The program has included both base funds (for base NPS program operations) and incremental funds (designated for watershed-based plans and TMDLs); from 1999-2005, over $150 million annually was awarded to states through the program.[191]

BOX 7: FEATURED STATE PROGRAM

In 2007, the Ohio EPA created the multi-stakeholder **Ohio Lake Erie Phosphorus Task Force** and charged it with studying the issue of increasing soluble reactive phosphorus (SRP) loads to Lake Erie. Specific tasks included identifying potential sources, determining the importance of each source, and recommending policy and management solutions to decrease SRP loads to Lake Erie. In its 2010 final report,[195] the Task Force concluded that runoff from applications of nutrients to agricultural fields was the primary cause of increased SRP loads to Lake Erie and recommended specific actions for farmers to take. The report also investigated the contribution of other pollution sources, such as lawn fertilizers and point sources, and provided suggestions on reducing SRP loads from these sectors. Additionally, Task Force members made recommendations on improvements to monitoring activities and identified research needs to further understanding of SRP loading.

The **U.S. Farm Bill** includes a number of conservation incentive programs for farmers, including programs to reduce phosphorus-rich agricultural inputs, control runoff, protect wetlands and groundwater, and prevent erosion that contributes to nutrient loading into public waters. Programs include the Environmental Quality Incentives Program, the Wildlife Habitat Incentives Program, Agricultural Management Assistance, the Conservation Reserve Program, the Conservation Stewardship Program, the Conservation Reserve Enhancement Program, and the Wetlands Reserve Program. Participation in these voluntary programs helps agricultural operations reduce pollution (potentially including soluble reactive phosphorus) which otherwise contributes to violations of water quality standards while also improving the efficiency of operations.[192]

Binational and federal efforts to control phosphorus were largely successful in reversing eutrophication in the Great Lakes in the 1970s and 1980s, as documented in Section 2. Despite these earlier successes, signs of cultural eutrophication have returned to the Great Lakes in recent years. As discussed in Section 4, ecosystem changes driven by invasive species and increases in the amount of dissolved phosphorus in agricultural runoff have led to a return in harmful algal blooms and dead zones. Clearly, efforts by the U.S. and Canada to reduce nutrient pollution are no longer sufficient.

In recognition of the need for more aggressive efforts to address impairments in the Great Lakes, and following on the production of the Great Lakes Regional Collaboration Strategy report in 2005, the **Great Lakes Restoration Initiative** (GLRI) was proposed by President Obama in 2009, with $475 million appropriated the first year, and $300 million the second year. The five-year GLRI effort is dedicated to five major focus areas, including Nearshore Health and Nonpoint Source Pollution and Invasive Species.[193] Concurrent with initial funding of the program, the EPA developed the GLRI Action Plan, which identifies broad goals, measurable ecological targets and specific actions for each of the five focus areas. Strategic actions related to nutrients will identify sources and reduce loadings of nutrients and soil erosion, and research and modelling will identify effective actions to prevent and reduce the number and severity of incidences of ecosystem disruptions such as harmful algal blooms and other issues associated with eutrophication. Sustainable watershed management practices will be developed and applied to reduce export of nutrients and soils to the nearshore waters. In addition, the Action Plan includes a goal of establishing and implementing TMDLs for phosphorus. [194]

Finally, there are a number of programs at the state, provincial, and municipal levels addressing nutrients, including programs distinct from other federal programs or mandatory requirements. One example is the Ohio Lake Erie Phosphorus Task Force (see Box 7).

SECTION 6

LOOKING TO THE FUTURE

Nutrient loadings and dynamics in the Great Lakes ecosystem have been altered by humans since the first days of European settlement in the basin. In the future, new stressors are anticipated to impact the Great Lakes, and current problems such as invasive species will continue to worsen in the absence of additional action. Scientists have identified several of these future stressors that could influence Great Lakes nutrient dynamics.

Perhaps the most serious threat to the future of the Great Lakes is global climate change. It is predicted that by the end of the century, air temperatures in the Great Lakes region could warm by up to 12°F in winter and 20°F in summer. [196] In fact, climate change is already occurring in the Great Lakes. Annual average temperatures have increased by 2 to 4°F and extreme heat and heavy precipitation events are increasing in frequency by up to 100%. Winters and the duration of lake ice cover are getting shorter, with spring ice breakup occurring earlier by 2 days per decade.[197] These changes will only become more extreme as climate change progresses. Average surface water temperatures will likely increase; in 2010, several of the Great Lakes reached the warmest surface water temperatures on record;[198] as of August 2011, summer temperatures in most of the lakes were well above recent (1992-2010) averages.[199] Due to increased air and water temperatures and shorter periods of ice cover, lake levels are expected to decline,[200] though some models indicate more ambiguous trends in water levels.[201] Great Lakes water levels naturally fluctuate, but levels over the past decade in lakes Michigan, Huron, and Superior have been low compared to historic averages.[202]

These climatic changes have serious implications for nutrients and eutrophication. Warming water temperatures will alter the thermal structure of the lakes, which in turn influences nutrient cycling and the development of hypoxic zones.[203] Changes in thermal structure leading to decreased mixing could cause larger and more frequent hypoxia in some parts of the Great Lakes.[204] Warmer water temperatures can further stimulate algal blooms, through, for example, increased activity of microorganisms releasing phosphorus from organic matter.[205] More frequent and severe precipitation events in the future will cause increased loads of phosphorus to wash from the landscape into the lakes. High phosphorus loads to Lake Erie in 1997 and 1998 were blamed on increased tributary loads resulting from large, anomalous storms.[206] More frequent and intense large storms



Storm surge at Canal Park, Duluth, MN (Photo: Minnesota Sea Grant)

will also increase nutrient pollution from CSOs.[207] Clearly, climate change has the potential to exacerbate eutrophic conditions in the Great Lakes through several mechanisms.



Invasive silver carp on Illinois River (Photo: T. Lawrence, Great Lakes Fishery Commission)

Other future stressors on the Great Lakes that will influence nutrients include human population growth and land use change. The population of the Great Lakes region continues to grow, and the density of people living in urban areas (metropolitan census areas, including suburbs) is increasing.[208] As more people move to cities, and as land is developed at a faster rate than population growth (i.e., as sprawl increases), the percentage of impervious surfaces in the Great Lakes watershed will also increase, causing more nonpoint pollution. According to the U.S. EPA, all of the Great Lakes except Lake Superior are in degraded condition with respect to the proportion of impervious surface in their watersheds; Lake Erie in particular is at risk with more than 15% of its U.S. watershed impervious.[209] Larger populations will also place more stress on already inadequate wastewater infrastructure. As the Great Lakes population grows, land cover patterns are also changing. The extent and composition of coastal wetlands across the Great Lakes are classified generally as "deteriorating" by Environment Canada and U.S. EPA.[210] Natural areas such as forests are being converted to developed land. From 1992 to 2001, there was a 33.5 % increase in the area of low-intensity development in the U.S. Great Lakes states.[211] During this period, Lake Erie's watershed experienced the largest proportion of land converted to development. Destroying forests and wetlands — which provide buffers that keep nutrients and other pollutants out of waterways — and replacing them with development will add more stress to areas of the Great Lakes already facing eutrophication.

Agriculture is perhaps the most important land use category influencing nutrients and eutrophication. In areas with significant agricultural development, a majority of phosphorus loads result from runoff from farm fields. Thus, future changes in agricultural land use practices will be important in determining future loading scenarios. Although agricultural lands are actually being lost to development in the Great Lakes watershed,[212] changes in the way land is farmed may be more important in determining future nutrient loads. Current policies encouraging the development of biofuels (e.g. promotion of ethanol made from corn) are driving agricultural land use practices that could result in added pressure on Great Lakes water quality. Research being coordinated by the U.S. EPA is examining how future land use scenarios will impact ecosystem services; part of this work will predict how trophic states of the Great Lakes will respond to potential future nutrient loading scenarios.[213]

It is clear that invasive species can alter nutrient dynamics in the Great Lakes, as evidenced by the role of dreissenid mussels in nearshore eutrophication and offshore oligotrophication. The basin is also faced with the threat of numerous future invaders[214] that have the potential to significantly affect the ecosystem. Of particular concern are two species of Asian carp that are taking over the Mississippi River watershed and are at risk of entering the Great Lakes via several pathways, including the Chicago Area Waterway System. Asian carp are filter feeding fish that feast voraciously on phytoplankton and zooplankton, and if they successfully invade the Great Lakes they have the potential to further deplete the already-stressed lower food web and outcompete native fishes.[215] Research suggests that the western basin of Lake Erie would provide particularly suitable habitat for Asian carp, in part because of its greater productivity.[216] As eutrophication progresses, food resources for hungry Asian carp will increase. In addition, a recent study found that Asian carp can consume *Cladophora*.[217] Ongoing expansion of blooms of harmful algae like *Cladophora* would mean conditions for Asian carp could improve at the same time they are degraded for native fishes. Obviously, eutrophication has the potential to facilitate the invasion of non-native species into the Great Lakes — and only time will tell how new invaders might in turn further influence nutrient cycling.

SECTION 7

RECOMMENDATIONS

Current nutrient and invasive species management policies and programs are insufficient to protect the Great Lakes. Hypoxia persists in central Lake Erie and eutrophication and algal blooms continue to plague western Lake Erie and other nearshore areas of the lakes while many offshore waters (in particular in Lake Huron) have very low nutrient levels and declining fish production. Immediate action must be taken to prevent further deterioration of these ecosystems on which fish, wildlife and humans depend. This complex problem will require creative and integrated solutions in policy, research and monitoring, and public education.

Policy and Management

Existing policies and management programs fall short in recognizing that invasive species such as zebra and quagga mussels have changed the fundamental structure of the lakes. Three overarching recommendations are the following:

1. **While emphasizing a broad lake- or ecosystem-wide management approach to nutrient problems, management and policy need to be refined at smaller scales (e.g., sub-basin or watershed) as appropriate, to take into account different extents of problems in different areas.**
2. **Recognizing that while implementation of policies specific to nutrients and invasive species (in particular invasive mussels) is critical, we need to explore policies that can address both stresses in an integrated way.**
3. **Further reductions in nutrient loading are necessary, in particular in priority watersheds and from agricultural sources, where targeted programs should be pursued to address specific nutrient impairment problems.**

There are many agreements, policies and programs that do or can address nutrient problems in the Great Lakes, and it is essential that such efforts be updated as necessary to keep pace with changing ecosystems. Some potential changes in agreements, policies, and programs include the following:

- The Great Lakes Water Quality Agreement (GLWQA), the primary framework for coordinated phosphorus reduction efforts between the U.S. and Canada, must recognize that **the Great Lakes are not a single ecosystem**, nor can each lake be treated as a single unit. Different areas of the lakes will respond to nutrient inputs in different ways; thus, water quality standards and GLWQA phosphorus loading targets should be developed for individual regions of the lakes (including nearshore vs. offshore). Phosphorus loading targets for western Lake Erie may well be different from targets for the eastern basin. Given that zebra and quagga mussels are redirecting phosphorus away from the offshore and negatively impacting offshore food webs, innovative policy tools and solutions will need to be applied to regain balance in the lakes.
- The current renegotiation of the GLWQA is an excellent opportunity to encourage policies that build on the scientific advances (including understanding food web changes and ecosystem modeling) that have occured since the last update to the Agreement. **Updated phosphorus targets must be calculated using the best available scientific information** on the state of the Great Lakes. Target levels of phosphorus and chlorophyll representing improved water quality and reduced algae production should be established for distinct lake regions, and scientific models should be used to calculate load reductions required to meet in-lake targets. Additionally, targets for community composition of phytoplankton (which are tied to water quality parameters) should be established.
- It is important to continue monitoring and regulating total phosphorus loads, because target loading levels are not being met consistently across the Great Lakes basin. However, **the significant contribution of soluble reactive phosphorus (SRP) in western Lake Erie in particular and the fact that SRP loads are increasing must be recognized**. Agricultural practices targeted to reducing SRP should be encouraged in addition to those that reduce overall phosphorus loading. See more specific recommendations in report of the Ohio Lake Erie Phosphorus Task Force.[218]
- To increase the effectiveness of the GLWQA, **changes should be made to its structure and implementation**.

The Agreement should include enforcement mechanisms to ensure targets are met, with agreed-upon time tables for meeting water quality objectives. In addition, given the new paradigm of rapid ecosystem change brought about by invasive species, the GLWQA review process might need to be adjusted so that water quality targets are reevaluated on shorter time scales.

- The renegotiated GLWQA should include creation of a Great Lakes-wide **Phosphorus Task Force**, similar to the Ohio Lake Erie Phosphorus Task Force, to further investigate the issues of eutrophication and changes in phosphorus loads and concentrations (and components of phosphorus, such as SRP) in the nearshore and offshore. The Task Force should provide the U.S. and Canadian governments and the International Joint Commission with detailed management and policy recommendations for meeting water quality goals across the basin. Such an entity should be well integrated with other relevant bodies (such as Lakewide Management Plans (LaMPs)), and have representatives from all relevant sectors, including federal, state municipal and tribal agencies, the International Joint Commission, academia, agriculture and industry, and NGOs.

In addition to working binationally, we need to **maximize the ability of existing laws, regulations and programs** to control nutrient pollution, including at the municipal, state, and federal level. Recommendations here are focused on the U.S. side, while it is recognized that strengthening of Canadian programs is also essential to fully address nutrient problems in the Great Lakes. Some key measures/changes needed on the U.S. side include the following:

- Programs to reduce nonpoint runoff from agricultural land, including under the **Farm Bill,** must be strengthened.
  - Assist farmers in pursuing financial assistance through Farm Bill Programs, including the Environmental Quality Incentives Program, the Conservation Reserve Program, the Conservation Stewardship Program, and other programs on targeted priority watersheds, as well as other federal funding sources, to reduce nutrient and sediment runoff from agricultural lands.
  - Nutrient management programs should use a watershed-based approach to tailor efforts to specific areas.[219] Funding should be targeted to priority areas contributing large amounts of phosphorus loading as identified by research.
  - Provide more oversight of agricultural operations participating in Farm Bill programs,, and recommend wider buffer zones between all row crops and surface waters.
  - Re-invent the Great Lakes Basin Program for Soil Erosion and Sediment Control—currently authorized in the Farm Bill—into a solution based restoration implementation program. This program has had much success and should be re-designed to improve water quality in targeted areas around the Great Lakes by controlling sediment and reducing nutrient runoff that causes harmful algae blooms.
  - For Lake Erie in particular, prioritize and implement key recommendations of the Ohio Lake Erie Phosphorus Task Force, including increase training/outreach on appropriate rates and timing of agronomic application of fertilizers; strengthen and expand use of phosphorus soil test programs; develop or strengthen nutrient management tools (including for phosphorus runoff risk screening and assessment tools); and optimize and expand implementation of best management practices, including adoption by cost-share agencies of innovative approaches (e.g. fund allocation based on screening tool).
- Although efforts should be centered on reducing nonpoint phosphorus loading, point source pollution should be further addressed through aggressive implementation of **Clean Water Act** programs. This will include increased activities through:
  - Establishment of protective nutrient water quality criteria by each of the Great Lakes states (including potentially revising existing criteria);
  - Effective development and implementation of total maximum daily loads, with U.S. EPA playing a key role in coordinating individual Great Lake or basin total maximum daily loads for nutrients;
  - Tighter National Pollutant Discharge Elimination System permit limits, where necessary, for wastewater treatment plants;
  - Consideration of additional limits for nutrients in municipal stormwater permits.

The Clean Water Act should also be used as a vehicle to encourage the reduction of nonpoint source pollution through fully funded and implemented Section 319 programs, including emphasizing watersheds with particular nutrient problems.

On the Canadian side, policy advances are needed at the local, provincial, and federal levels. Though the regulatory and voluntary frameworks differ from the U.S. side, similar types of actions are needed, including the following:[220]

- Address loadings from point sources, including upgrading municipal wastewater treatment plants and reducing levels of phosphorus in detergents;
- Promote expansion or retaining of natural cover, to reduce flows, sediment, and nutrient export from watersheds;
- Expand the scope and intensity of best management practices in agricultural lands, including through improved tillage practices, improved manure management, and adopting new technologies for erosion control;
- Ensure that all municipalities have a Pollution Prevention Control Plan, with components that may include the retrofit/design of stormwater facilities and adoption of sustainable planning to reduce flows, sediment and nutrient loads to surface waters.

Also, **improved coordination among programs** at all levels of government is needed. Linkages between the GLWQA and Farm Bill programs, for example, should be explored and encouraged. Managers should pursue harmonization of ecosystem goals as appropriate (e.g., GLWQA water quality targets, LaMP objectives,[221] fish community objectives as set by the Great Lakes Fishery Commission[222], and state water quality criteria). Fishery management is a valuable tool for dealing with ecosystem changes, and while managers must adjust to new ecosystem regimes with changes in stocking and other practices,[223] innovative solutions to the feast/famine dichotomy might be found by working with fisheries resource groups. For instance, managers could alter stocking practices to focus on top-level predators such as Atlantic salmon that are better adapted to new offshore food webs.[224]

Finally, it is critical that **adequate funding** be provided for all programs, including through the Great Lakes Restoration Initiative Focus Area 3: Nearshore Health and Nonpoint Source Pollution.[225] The current higher levels of federal funding for the Great Lakes on the U.S. side must be invested wisely, including in efforts to restore aquatic habitats as well as in projects that reduce runoff from targeted watersheds. Similar increased funding efforts are needed on the Canadian side as well.

Research and Monitoring

Research and monitoring programs must evaluate and **adjust to and study new ecosystem regimes** to improve our understanding of nutrient dynamics in the Great Lakes. For instance, eutrophication models need to be improved to account for altered nutrient processes following the dreissenid invasions.[226] Current monitoring programs, such as the EPA's offshore surveillance program,[227] leave a gap in monitoring nearshore areas of the lakes that prevents better understanding of that important part of the ecosystem. Open water monitoring efforts are important and should be sustained; however, given the new feast/famine dichotomy, **standardized, regular, and targeted monitoring is needed in nearshore areas**. Monitoring in the nearshore zone is particularly important because blooms of harmful algae such as *Microcystis* and *Cladophora* occur there, and human uses are concentrated along shorelines. Continued and enhanced tributary monitoring is also needed to better understand how phosphorus is moving from the land into the lakes. Additionally, **monitoring efforts could be improved through coordination**. For example, EPA's offshore surveillance program performs more frequent, regular monitoring than Environment Canada, but Canada's program has greater spatial coverage in each lake. Working together, these two programs could increase the frequency and extent of monitoring. The Binational Coordinated Science and Monitoring Initiative[228] offers promise to help integrate and coordinate monitoring efforts, but needs adequate sustained funding and would benefit from ongoing input from various stakeholders in each lake basin. Finally, fish population and broader monitoring of organisms must adjust to new ecosystem paradigms. Current fishery assessments and research are focused on the offshore. There is a need to develop new fisheries assessment programs that include both nearshore and offshore habitats. Similarly, increased monitoring of other aspects of the altered nearshore waters and habitats is necessary. [229]

In spite of new efforts such as the GLRI, scientists in the Great Lakes are faced with limited funding and resources to carry out research and monitoring programs. Thus, **scientific efforts must focus on priority topics and geographic areas as identified through expert deliberations.** For example, the Lake Erie Millenium Network's 2011 Synthesis Team Report[230] identifies specific research needs to better understand processes of nutrient transport from the landscape to the lakes. The role of nitrogen in encouraging blooms of toxic *Microcystis* is poorly understood and should be further studied.[231]

Finally, there is a need to **better integrate the results of research and monitoring into development and implementation of policy**. As science advances our understanding of new nutrient dynamics, invasive species changes and ecosystem impacts, this knowledge must help guide the development of water quality objectives and loading targets, as well as programs to meet the targets.

Education/Outreach

Changes to policies and research efforts are necessary to solve the nutrient problems in the Great Lakes, but on their own will not be sufficient. An educated and informed public of water quality stewards will be necessary to ensure that nutrient reduction efforts are successful. Thus, we must **enhance outreach and education to inform the public on the feast/famine problem,** its causes, and its solutions. It is vital that the public understands both nearshore eutrophication and offshore oligotrophication and that the two problems are linked. This can be partially accomplished through the promotion of existing outreach and education efforts, such as EPA's Nitrogen and Phosphorus Pollution Outreach Portal.[232] Outreach efforts must be ramped up across the basin to empower the public by providing simple actions they can take (see "What You Can Do" below). The public should be made aware of opportunities to weigh in on policies and planning efforts such as watershed plans, and should also be encouraged to actively participate in the governance of their precious water resources. Existing public engagement and outreach efforts through bodies and institutions such as LaMP Public Forums, Sea Grant outreach programs, and university extension programs must be fully supported.

Invasive Species

This report has focused on the dichotomy between feast and famine in the Great Lakes, where two invasive mussel species the size of a fingernail have changed the way an entire ecosystem functions and responds to human-induced stressors. Clearly, invasive species can impact the lakes in ways we cannot anticipate. Thus, we must make every effort to **prevent the introduction and spread of invasive species in the Great Lakes.** Example measures that should be taken include supporting strict regulation of organisms in trade, tightening controls on ballast water in commercial ships, and preventing the movement of organisms through canals and waterways (e.g., through building a permanent separation between the Mississippi River and Great Lakes Basins in the Chicago area). In addition, efforts to include a comprehensive invasive species annex in the GLWQA must be encouraged to reflect the important connections between non-native organisms and water quality.

At present, there is little that can be done to control or eradicate the invasive dreissenid mussels that are wreaking havoc on Great Lakes water quality and food webs. However, we must continue to **explore innovative control methods for zebra and quagga mussels** and other harmful invasive species. Important work is already underway and should continue to be supported. For example, scientists have developed, and a private company is now marketing, a product that kills only invasive dreissenid mussels. Currently, studies are examining the use of this control method in open waters such as the Great Lakes.[233] Researchers at the U.S. Geological Survey are studying the biology of invasive mussels to inform selective control methods.[234] Additionally, many fish species in the Great Lakes consume dreissenids,[235] potentially representing a powerful biological control method that could be encouraged.[236] These and other efforts to develop creative invasive species control solutions should be supported.

WHAT YOU CAN DO

Although residential areas contribute only a small amount to phosphorus pollution, every effort helps to prevent eutrophication in the Great Lakes. There are simple things the average citizen can do to reduce runoff of nutrients from their yards:[237]

- Use only phosphorus-free fertilizer that is designated for lawns;
- Apply fertilizer in smaller quantities and less often, and not before anticipated heavy rainfall;
- Do not apply fertilizer within 25 feet of any body of water;
- Get your soil tested to see what nutrients your lawn needs;
- Pick up all pet waste and dispose in a garbage can;
- Maintain your septic system properly;
- Keep water on your property by installing rain gardens and/or rain barrels.

There are also actions you can take to prevent the introduction and transfer of invasive species that might otherwise harm the Great Lakes. If you boat or fish in the Great Lakes or any inland waters in the basin, follow recommended guidelines to prevent the spread of invasive species. Visit http://www.protectyourwaters.net/ for more information. Aquarium enthusiasts and water gardeners should be aware of invasive species and avoid releasing them into the environment. See http://www.habitattitude.net/ for recommended guidelines.

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Exhibit 2- Algal Blooms in the Great Lakes from Above and Below

Algal blooms in Maumee Bay, Lake Erie







Chladorphora in western Lake Michigan





