

RESEARCH AND MANAGEMENT PRIORITIES FOR AQUATIC INVASIVE SPECIES IN THE GREAT LAKES

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Research and Management Priorities for Aquatic Invasive Species (AIS) in the Great Lakes

International Association for Great Lakes Research (IAGLR)

Executive Summary

Human activities are profoundly affecting the earth's support systems. Population growth has been accompanied by a variety of stresses of natural ecosystems, including habitat destruction and modification, chemical contamination, and the unintentional introduction of various nonindigenous invasive species.

Some nonindigenous invasive species have had significant adverse effects on human, plant or animal health, local and regional economies, and on the ecosystems they invade. Recent examples of notorious invasive species include fire ants and African honey bees in the southern U.S., West Nile virus and Asian longhorn beetles in the eastern U.S. and Canada, and, of course, the zebra mussel in the Great Lakes and eastern half of the U.S. and Canada.

The Office of Technology Assessment (U.S. Congress, 1993) calculated almost \$100 billion in U.S. economic losses over an 85-year period from just 79 nonindigenous species. Pimentel et al (2000) estimated losses to the United States economy of at least \$137 billion per year associated with the effects of nonindigenous species on native ecosystems, agriculture, and natural resources, including the costs for control efforts. As noted by the Union of Concerned Scientists (2001), the accuracy of the Pimentel et al. calculations is difficult to assess, but probably is a minimum. In addition to economic and human health costs, nonindigenous invasive species are anticipated to be the leading cause of biodiversity change in lakes in the coming century (Sala et al., 2000) and of extinctions in North American freshwater ecosystems (Riccardi and Rasmussen 1999).

The Great Lakes are the largest freshwater ecosystem on earth (not counting the polar ice caps). They are the economic, cultural, and recreational lifeblood of millions of North Americans. They are the gateway to the heartland waters of the United States and Canada. Threats to the ecosystem have changed through the times, and so too must responses. Introduction of aquatic nonindigenous species is arguably the most serious economic and ecological threat to the Great Lakes today.

Key conclusions and recommendations include:

- Aquatic species invasions continue to pose one of the greatest risks to the health and productivity of our coastal marine ecosystems and the Great Lakes.
- A major federal funding increase of at least \$30 million per year for the Great Lakes region is needed to push for rapid progress towards solutions to the problems outlined in this document. The piecemeal and relatively small annual funding requested by the Administration and provided by Congress, and the funds available through Canadian agencies, are not sufficient for substantive progress. Invasive species are no longer just a matter of scientific interest and local concern - they

represent a threat to the marine/aquatic biosecurity of the United States, Canada, and the other coastal nations of the world. Invasive species have a direct impact where we live and play, and they affect our standard and style of living in an adverse manner. Winning the invasive species challenge means investing in a reasonable 10-year goal: to eliminate new introductions of aquatic invasive species by 2013. Oceanic shipping (ballast tanks) has been the primary vector for new aquatic species introductions and will continue to be the most significant and high-risk vector until effective treatment technologies are developed, proven, and made suitable for installation and use aboard a variety of large ships.

- Without government leadership and funding, availability of approved ballast water/ballast tank treatment technologies is at least a decade away, perhaps longer.
- The development of an effective, practical ballast water treatment standard or standards is a major barrier to progress on the development and testing of treatment technologies. The scientific community must become engaged in this issue before the policy community unilaterally sets standards that are not scientifically supportable, or worse, ineffective.
- The lack of reliable and flexible full-scale testing platforms is an obstacle to testing promising ballast water treatment technologies. Test platforms, in the form of leased vessels, shore-based test facilities, or MARAD vessels, need to be available for full-scale tests under actual vessel operating conditions.
- Given that many of the aquatic invaders that have established in the Great Lakes in recent years originate from Eurasia, an interdiction program based on assessment of potential high-threat invader organisms in European fresh and brackish water systems should be undertaken. This will require international collaboration and cooperation.
- Information to track and identify shifts in patterns of trade coming into the Great Lakes should be compiled and maintained on an annual basis.
- Increased resources are needed to support aquatic invasion science research, to advance our understanding of the invasion process, the development of reliable risk assessment models, and the ability to identify and evaluate potential future invaders.
- Genetic tools to identify relationships among source communities and newly established communities should be emphasized. This is perhaps the best tool we have to demonstrate source-donor relationships.
- Although the ballast tank vector remains the highest prevention priority, increased resources should be directed towards other vectors, such as aquaculture, the bait industry, and the aquarium industry.
- The barrier between the Mississippi River and the Great Lakes should be maintained and upgraded to prevent movement of exotic species between both ecosystems.

I. Introduction

Human activities are profoundly affecting the earth's support systems. Population growth has been accompanied by a variety of stresses of natural ecosystems including

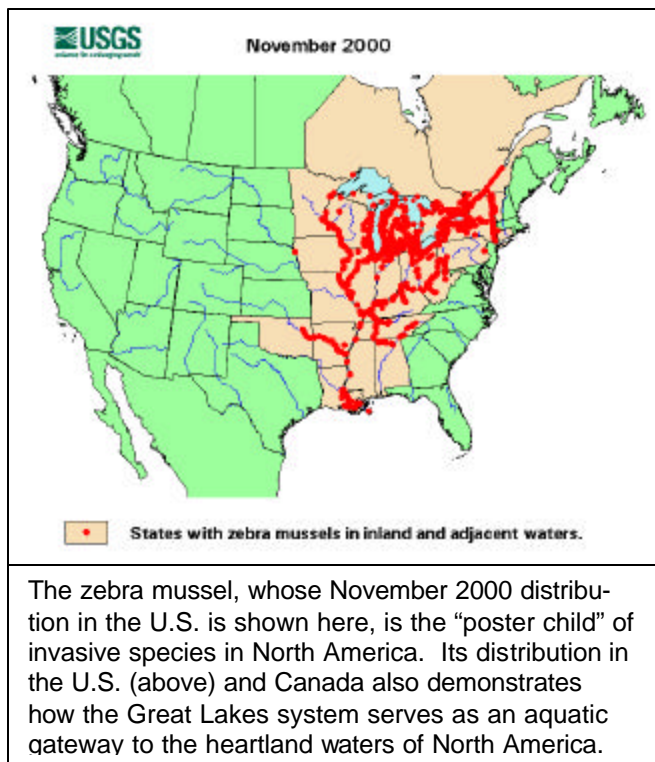
habitat destruction and modification, chemical contamination, and the unintentional introduction of various nonindigenous invasive species (NIS).

Some nonindigenous invasive species have had significant adverse effects on human, plant or animal health, local and regional economies, and on the ecosystems they invade. Recent examples of notorious invasive species include fire ants and African honey bees in the southern US, West Nile virus and Asian longhorn beetles in the eastern US and Canada, and, of course, the zebra mussel in the Great Lakes and eastern half of the US and Canada.

Fortunately, many releases of nonindigenous species occur with little or no apparent adverse effect, primarily because the species do not become established (i.e., form a self-sustaining, reproducing population). For example, European flounder reported occasionally in the Great Lakes (most recently in Lake Superior in 1995 and in Lake Erie in 2000) do not seem to be capable of reproducing in freshwater¹. Others may become established but remain in small, local populations that do not spread significantly (e.g., *Corbicula*, the Asian clam, in the Great Lakes).

A general rule of thumb used by many scientists is that about 10% of all introduced nonindigenous species actually become established, and about 10% of those that become established also become invasive and harmful. Some estimates place these numbers closer to 15%. In spite of the small numbers of successful introductions of invasive species that might be expected by applying this “rule of thumb”, there are thousands of invasive species in the US and Canada today, all of which have some degree of impact on the ecosystems they have invaded and on societal uses of those ecosystems, with commensurate economic costs and losses. Because of the regularity with which new species are being introduced throughout the world, some scientists are now heard to refer to our age as the ‘homogecene’.

The Office of Technology Assessment (U.S. Congress, 1993) calculated almost \$100 billion in U.S. economic losses over an 85-year period from just 79 nonindigenous species. Pimentel et al (2000) estimated losses to the United States economy of at



¹ Though not an invasive species, European flounder are, nonetheless, very important indicators. Their inability to reproduce in freshwater means that the arrival of each specimen can be dated more accurately than with invasive species, i.e. within its lifespan, and this information can be used to track the effectiveness of various ballast management strategies.

least \$137 billion per year associated with the effects of nonindigenous species on native ecosystems, agriculture, and natural resources, including the costs for control efforts. As noted by the Union of Concerned Scientists (2001), the accuracy of the Pimentel et al. calculations is difficult to assess, but probably is a minimum. In addition to economic and human health costs, aquatic invasive species (AIS) are anticipated to be the leading cause of biodiversity change in lakes in the coming century (Sala et al., 2000) and of extinctions in North American freshwater ecosystems (Riccardi and Rasmussen 1999).

The Great Lakes are the largest freshwater ecosystem on earth (not counting the polar ice caps). They are the economic, cultural, and recreational lifeblood of millions of North Americans. They are the gateway to the heartland waters of the United States and Canada. Threats to the systems have changed through the times, and so too must responses. Introduction of aquatic nonindigenous species is arguably the most serious economic and ecological threat to the Great Lakes today.

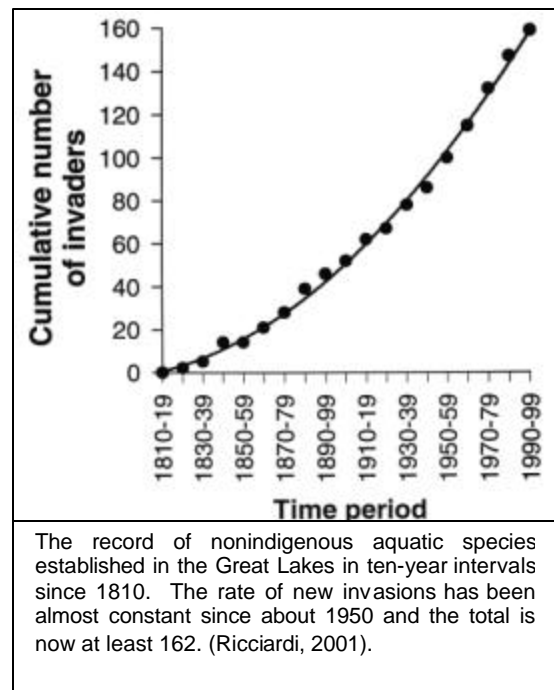
In this document we summarize the status of a variety of issues related to aquatic species invasions and the Great Lakes. We also provide analyses of what we believe are appropriate actions and priorities that are necessary if significant progress is to be made on these issues.

II. BACKGROUND INFORMATION

1. How many aquatic nonindigenous species are there in the Great Lakes?

The Great Lakes have a long history of invasion by nonindigenous aquatic species. The earliest record of an aquatic species invasion in the Great Lakes is the sea lamprey, first entering the Great Lakes from the Atlantic Ocean via the Erie Canal during the 1820s.

Mills et al. (1993) conducted an extensive literature review and documented 139 nonindigenous aquatic species established in the Great Lakes as of 1990. Ricciardi (2001) updated that list via another literature review and revised the total to 162. Of the additional 23 species identified by Ricciardi, 12 appear to have entered since 1990.



The documented number of nonindigenous aquatic species in the Great Lakes is best interpreted as a minimum. Identification depends on our ability to find, recognize, verify, and document new species, which is, in turn, dependent on our ability to adequately sample the system. Most of the nonindigenous species identified to date are large or otherwise conspicuous (e.g., invertebrates and fish). Little attention has

been paid to identification of nonindigenous bacteria, viruses, parasites, protozoans and microalgae. Indeed, since Ricciardi's update, a microsporidian new to North America, of the genus *Heterosporis*, has been reported in eastern Lake Ontario (Personal Communication, Jim Hoyle, OMNR, Picton, ON; Personal Communication, Dan Sutherland, University of Wisconsin). The Largemouth Bass Virus has extended its range into the basin, and its move into the Great Lakes appears inevitable (Personal Communication, John Hnath, MDNR, Matawan, MI). Finally, three species of Asian carp (bighead, silver, and black) are poised to move from the Mississippi River into the Great Lakes. These species, originally raised in farm ponds primarily in Arkansas for plankton and mollusk control in aquaculture, are now in the Mississippi River and are steadily moving northward (Rasmussen 2002). It is not known if the 9 April 2002 activation of an electric barrier on the Chicago Sanitary and Ship Canal will prevent Great Lakes entry.

The scientific community believes there may be many more nonindigenous species already in the lakes that have not been found or have been misidentified as native species. There are no basin-wide coordinated monitoring programs specifically targeting identification (early warning) of new nonindigenous species. Troublingly, the possibility now exists that establishment of new nonindigenous species in the Great Lakes is being facilitated by existing native and nonindigenous species resident in the system (Ricciardi 2001). For example, establishment of zebra mussels in the Great Lakes was followed shortly thereafter by arrival and successful colonization of nonindigenous amphipods and fishes (round and tube-nose gobies). Round gobies have now achieved pest status in the lower Great Lakes, where they live in abundance and steal bait from lines of recreational anglers, and there is concern that they may displace native fishes such as darters and sculpins.

The rate at which new AIS are colonizing the Great Lakes has not declined despite implementation of Canadian ballast water exchange guidelines in 1989, followed by mandatory ballast exchange requirements established in 1993 by the U.S. for ships entering the Great Lakes (see below; Ricciardi 2001). The best indicator of the extent to which humans are intentionally or accidentally introducing AIS to the Great Lakes is provided by Hebert and Cristescu (2002), who calculated that human-mediated dispersal of crustacean zooplankton now exceeds natural dispersal by up to 50,000 fold!

2. How are nonindigenous species getting into the Great Lakes?

Mills et al. (1993) summarized the vectors by which AIS have been introduced to the Great Lakes, the primary being ships, unintentional releases, intentional releases, canals, and rail or highway.

Ships' ballast tanks were the major vector for nonindigenous species introductions to the Great Lakes during the 20th century (Mills et al. 1993; Ricciardi 2001). From 1959, when the St. Lawrence Seaway was opened, through 2000, 36 of 50 nonindigenous aquatic species established in the Great Lakes during that time period are attributed to ballast tank transport and discharge of untreated ballast water. New evidence suggests that the residual water and mud found in most "empty" ballast tanks may also

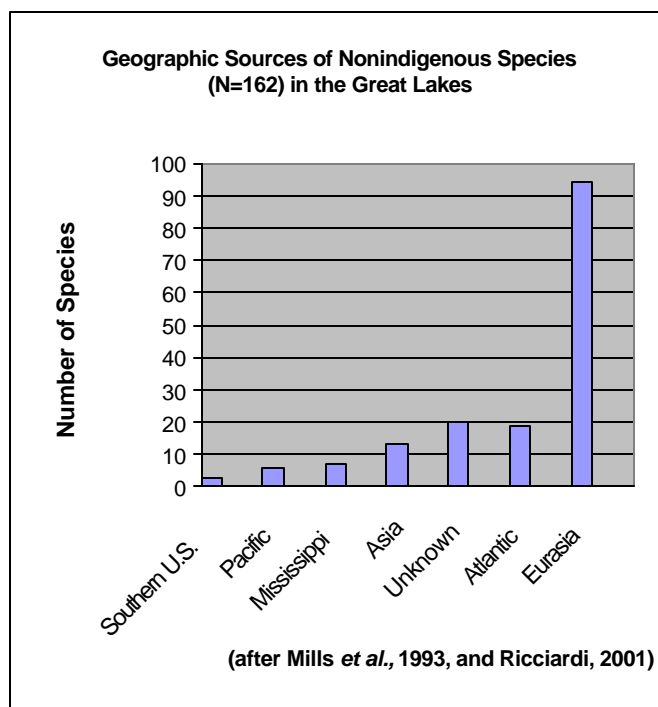
be a source for some species invasions (see below). Hull fouling may also be a contributing factor, but is not believed to be a significant vector for new introductions to the Great Lakes. Most freshwater fouling organisms are not expected to survive the osmotic stress caused by prolonged exposure to saline waters during transoceanic voyages.

Unintentional releases made the second highest contribution of nonindigenous aquatic species to the Great Lakes. This includes escape from aquaculture sites and the aquarium and bait trades. There is concern that baitfish use may help to spread the microsporidian *Heterosporis* into L. Michigan from inland lakes, to the detriment of perch, walleye, and pike fisheries. Likewise bass fishermen may introduce the Largemouth Bass Virus into the Great Lakes.

Canals, the historical vector of some significant exotic species such as sea lamprey and alewife, may once again be active. Three Asian carp species (silver, black, and bighead) are moving up the Mississippi River system and are within striking distance of the Great Lakes. The electric barrier now activated in the Chicago Sanitary Ship Canal is not thought, as presently designed and operated, to be a reliable deterrent to the movement of these fish into the Great Lakes. It was initially designed to deter movements of round goby and may require modifications to prevent movements of Asian carp and other invasive species between the Mississippi River and Great Lakes systems. Bighead carp have been reported from Lake Erie in recent years, though at very low numbers, indicating that the species may not be established yet (Personal Communication, Tim Johnson, OMNR, Wheatley, ON).

3. Where are these organisms (species) coming from?

Mills et al. (1993) identified the likely geographic source for each of the 139 species they identified. Ricciardi (2001) identified the native geographic region for the additional 23 species he identified. In the following chart we have combined the information from these two references, making the assumption that native geographic region of the species Ricciardi identified was also the source region for the invasion to the Great Lakes (this may not be true in all cases). An exception was made for *Daphnia lumholtzi*, a waterflea native to Africa, Australia and Asia, but known to have reached the Great Lakes in 1999 from an invaded reservoir in the southern U.S., probably via recreational boating activities.



By far, the majority of aquatic species invading the Great Lakes are native to Eurasia. Since the mid-1980s species native to the Ponto-Caspian basins (Black, Caspian, and Azov Seas) have been remarkably successful in establishing new populations in the Great Lakes. Of 15 new organisms since 1986, 11 are attributed to ballast tank discharges. Of these 11 ballast-implicated organisms, 8 are Ponto-Caspian species. Prominent among Ponto-Caspian invaders are zebra mussels, quagga mussels, round gobies, fishhook waterfleas and *Echinogammarus* amphipods. These Ponto-Caspian taxa now constitute a very significant component of biomass, abundance and productivity of food webs in the Great Lakes. These species are also moving or being exported to inland lakes and rivers in the U.S. and Canada, where they also have disruptive influences. It would be naive to suggest that 'the worst have arrived' to the Great Lakes, as many additional species, some with prominent histories of invasiveness, are currently spreading throughout Europe; if these species reach key low salinity ports (e.g., Rotterdam, Antwerp, etc.), they may be picked up by ships destined for North America.



There are at least five invasion corridors from SE Europe that may allow species from the Black, Azov and Caspian Seas to move within Europe and later to the Great Lakes (MacIsaac et al. 2001). Genetic evidence has been used to link AIS in the Great Lakes to different source populations in Eurasia (e.g., Cristescu et al. 2001).

Coastal North Atlantic is the second most important known source for nonindigenous species (e.g., sea lamprey, alewife) in the Great Lakes, although it ranks far behind

SE Europe as a source of new species. Examples of AIS from this region include sea lamprey, alewife and blueback herring. Importantly, this region is an historic source of AIS to the Great Lakes, but has recently been supplanted by the Ponto-Caspian region.

4. What effect are these organisms having on the Great Lakes?

There is accumulating and rather strong evidence supporting the notion that AIS are having dramatic and damaging impacts on the Great Lakes ecosystem. The most obvious change has been the remarkable improvement in water clarity, especially in Lake Erie, much to the delight of recreational users and lakeshore residents. However, such changes, although benefiting some users, can be seriously damaging to the Great Lakes ecosystem, resulting in loss of organisms and biodiversity, disruption of various food webs, and impacts on economically important fish species.

Losses of organisms from the Great Lakes are difficult to detect without a structured monitoring program, however, several species of native invertebrates have shown dramatic declines following the invasion of zebra and quagga mussels. One of the most significant of these has been the decline, and in some areas, depletion, of *Diporeia*. *Diporeia* is a deep-water macro-invertebrate that has been a dominant

benthic organism since the formation of the Great Lakes at the end of the Ice Age. Populations of *Diporeia* have declined from 1,000s of animals per square meter to zero in many locations in lakes Michigan (Nalepa et al. 1998), Huron (Personal Communication, Tom Nalepa, NOAA, Ann Arbor, MI), Erie (Dermott and Kerec 1997), and Ontario (Dermott 2001; Lozano et al. 2001) since establishment of zebra and quagga mussels. Moreover, native clams and mussels have also dramatically declined in numbers in response to zebra mussels (Ahlstedt 1994; Nalepa 1994; Schloesser and Nalepa 1994). Evidence suggests that zebra mussels may be out-competing native bivalves for food and may be fouling their shells and causing additional stress to these native species, ultimately causing populations to decline and possibly causing extinction of some of the rarer species.

Aquatic invasive species (AIS) are also being felt throughout the entire food web through the process of *food web disruption*. AIS change the structure and function of the food web by causing shifts and reductions of important food web components (e.g., *Diporeia*) or by creating conditions that facilitate change. For example, food web disruption can be directly linked to declines in the body condition of lake whitefish, a commercially valuable fish species in the Great Lakes, following the decline in *Diporeia* (the primary food resource for lake whitefish). As a result, lake whitefish are becoming thinner and less marketable for the commercial fisheries. Moreover, declines in the popular yellow perch population in Lake Michigan followed the establishment of zebra mussels, but like the decline in *Diporeia*, a direct cause and effect relationship has not been established. Aquatic invasive species facilitation of ecosystem change also appears to be responsible for the increased frequency of toxic algal blooms (*Microcystis*) in the Great Lakes (Vanderploeg et al. 2001), where zebra mussels may be selectively rejecting bluegreen algae as food, while removing competing algae instead.

The accumulation of disruptions of the food web, caused by AIS, may also manifest itself in the ability of an ecosystem (i.e., the Great Lakes) to support the total fish community. For example, recent evidence suggests that zebra mussels have decreased the efficiency at which carbon and energy are transferred up the food web. The implication is that less energy is making its way up the food web to support the popular recreational fisheries (Personal Communication, Doran Mason, NOAA, Ann Arbor, MI). If the three species of Asian carp (see Item 1, above) become established in the Great Lakes, even more food web disruption is anticipated since bighead and silver carp are voracious feeders on plankton and black carp consume mollusks and crustaceans, and they range in size from 40 to over 100 lb. (Rasmussen 2002).

In summary, there have been major negative impacts on the Great Lakes ecosystem that appear to be directly, and indirectly, linked to the establishment of AIS. These impacts have appeared at every level of the food web and appear to be affecting both the commercial and recreational resources for which the Great Lakes are best known.

III. ISSUES AND PRIORITIES

1. PREVENTION – THE #1 PRIORITY

The first-line of defense and, over the long term, the only cost-effective strategy against aquatic invasive species is preventing them from being introduced or from becoming established.

BALLAST WATER AND INTERNATIONAL SHIPPING

Ballast water transport poses the most significant threat as a vector for the potential introduction of new species to the Great Lakes and marine coastal waters; no other vector challenges our ecosystems with as many species, numbers of organisms, and numbers of inoculations or exposures. Ballast is used to provide stability and maintain the trim of vessels when traveling on open seas. Since 1900 ocean-going and coastal commercial vessels have employed water as ballast. In doing so, via the discharge of ballast water, they became the largest “single” vector for aquatic species introductions worldwide.

The opening of the St. Lawrence Seaway in 1959 also opened the Great Lakes to discharges of foreign ballast water and the species contained therein. In response to increasing concerns about the impacts of biological invasions, ballast exchange guidelines were introduced by Canada in 1989. U. S. regulations, which require ships inbound to the Great Lakes to use at least one of a suite of suggested ballast water management practices, were promulgated in 1993 by the U. S. Coast Guard (CG). Options include exchange of ballast water beyond the Economic Exclusion Zone (EEZ), retention of ballast water on board, use of a CG-approved treatment method or reception facility, or exchange of ballast water in a CG-approved alternate exchange area. Ballast water exchange is the only approved treatment to date.

Exchanged ballast water must have a salinity of >30 parts per thousand, which should kill most – but probably not all – freshwater organisms not flushed from the tanks during exchange. However, the record of new species invasions in the Great Lakes since the implementation of mandatory ballast exchange in 1993 shows that at least four new organisms can be attributed to an apparent ballast tank vector: the amphipod, *Echinogammarus ischnus*, the waterflea, *Cercopagis pengoi*, the ciliate *Acineta noticae*, and the copepod *Schizopera borutzkyi*.

BALLAST WATER EXCHANGE

Published studies of the effectiveness of ballast water exchange indicate that actual physical exchange of greater than 85% of the water carried in a ballast tank can be achieved. However, the commensurate removal of organisms is not necessarily the same and could be much lower, depending on the taxonomic groups examined and ballast tank designs used in the study (Rigby and Hallegraeff 1994; Smith et al. 1996; Dickman and Zhang 1999; Zhang and Dickman 1999; Taylor and Bruce 2000).

An important consideration for the Great Lakes is the effectiveness of open-ocean ballast exchange when the original ballast is fresh or low salinity water, which differs in density and biota from high salinity water. As noted above, the brackish and freshwater regions of Europe and especially the coastal regions of the Baltic and Black Seas have been implicated as source regions for many of the Great Lakes invaders found since 1985. Many of the aquatic organisms found in these regions are (a) euryhaline and can survive exposure to saline water and (b) form resting stages that accumulate in sediments and are difficult to remove with exchange. Therefore, the biological effectiveness of exchanging freshwater ballast from these regions for open-ocean saltwater is an important, largely unresolved question to consider when evaluating how well ballast exchange protects the Great Lakes from new invasions.

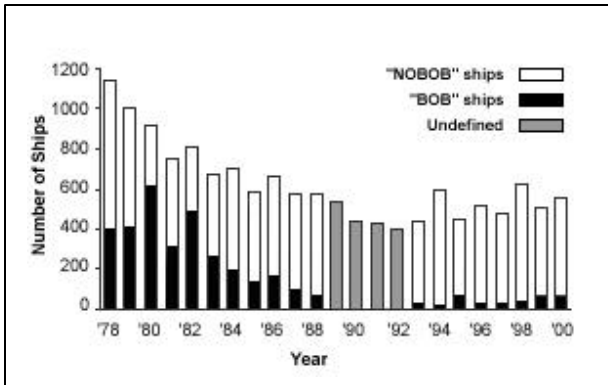
NOBOB VESSELS

Vessels carrying less than full cargo must load ballast water for trim and stability and are therefore subject to the Coast Guard ballast exchange requirement. Vessels fully loaded with cargo require no ballast water other than for adjusting trim, and generally their ballast tanks have been pumped out. Such vessels are called “NOBOBs” (NO-Ballast-On-Board). This is the most economical and therefore the most desirable operating condition for commercial vessels. NOBOB vessels are not subject to ballast exchange since, theoretically, they have no ballast water on board.



Residual mud in the bottom of a ballast tank on a transoceanic vessel in the Great Lakes during 2001. (Great Lakes NOBOB Project Team)

However, vessels cannot completely discharge all their ballast water because the pump-out port cannot be closer than a few inches off the bottom plating of the tank, and therefore a few inches (or less) of residual water and sediment will remain in the bottom after pump-out. In addition, ballast tanks accumulate fine sediment that settles to the bottom of the ballast tank and is deposited on ledges and in dead zones along structural supports. These residues can contain a wide assortment of live larval and mature plants, animals, and viable microorganisms, as well as so-called “resting stages” (Hallegraeff and Bolch 1992; Locke et al. 1993; Galil and Hülsmann 1997; Dickman and Zhang 1999; Hamer et al. 2000).



The number of vessels entering the Great Lakes with ballast on board (BOB) vs. those entering with no ballast on board (NOBOB) from 1978 through 2000 (Coulatti *et al.* 2002)

Resting stages (variously called cysts, ephippia, resting eggs, or spores according to taxon) are dormant reproductive cells produced by many species. Resting stages are extremely resistant to harsh conditions such as lack of oxygen, exposure to toxic chemicals, low and high temperatures, and even survive passage through the digestive systems of fish and waterfowl. They may remain in sediment in a state of virtual suspended animation for decades or even centuries. Once exposed to the right combination of favorable environmental conditions, they can hatch or germinate to

produce live organisms capable of reproducing.

Vessels entering the Great Lakes in ballast have decreased in both absolute and relative importance over the past 25 years, and constituted only ~10% of inbound traffic to the lakes during the 1990s. NOBOB vessels constituted the majority (~90%) of inbound vessel traffic, largely because they carry cargo in each direction to maximize economic efficiency.

Great Lakes water taken on as ballast by a NOBOB vessel to maintain trim and stability during operations can mix with residual ballast water, sediment, and any associated nonindigenous organisms, and later be discharged into the Great Lakes as the vessel moves between a succession of ports. Thus, ballast-water operations of NOBOB vessels present an invasion risk, but the magnitude of such risk remains unresolved.

Research is presently underway to evaluate the risk posed by NOBOB vessels. A mathematical model of risk posed by waterborne organisms suggests that ballast water exchange effectively reduces (but does not eliminate) risk as compared to unexchanged vessels. NOBOB vessels appear to constitute a significant threat today, largely because they are a major, if not dominant, component of in-bound vessel traffic to the Great Lakes, and because live freshwater organisms are contained in residual water and sediments when they arrive in the Great Lakes system.

TREATMENT TECHNOLOGY DEVELOPMENT

Treatment of ballast water to reduce or eliminate the biota it contains has been the primary focus of efforts to address the ballast water issue. Many different technologies are being tested for their applicability, either alone or in combination, including filtration, ultracentrifugation, exposure to intense ultraviolet light (UV), ozone, heat, oxygen removal, ultrasound, and use of biocides such as hypochlorite, gluteraldehyde, and commercial products such as SeaKleen™.

Ultra-centrifugation uses centripetal forces to separate solid particles from a spinning flow stream. It is most effective on particles whose density is significantly greater than water, such as the minerals that are components of mud. Biota, on the other hand, tend to have densities much closer to that of water, and thus are not easily or efficiently separated from the water stream by centrifugation. Therefore ultracentrifugation in combination with downstream exposure to intense UV radiation is being studied.

Ultraviolet radiation (UV) will kill even microbes if the dose is high enough. However, achieving a lethal dose of UV radiation in a ballast flow faces several difficult problems related to exposure time, power, and effectiveness across the broad range of organisms found in ballast water.

Filtration can remove particles down to micron sizes, but filters easily clog and require regular back-flushing. Larger filter openings require less back-flushing, but let more of the small biota through. At present the achievable flowrate, the minimum particle size that is removed, and the number and size of the filters/filtration units required to meet the ballast treatment needs of a full-size ship are serious issues that must be overcome before practical application is possible.

At least two physical methods to strip dissolved oxygen from ballast water are being considered, one based on vacuum removal and the other based on inert gas (nitrogen) stripping. There is some concern that the resulting anaerobic (oxygen-free) environment may promote the production of hydrogen sulfide, a toxic gas. The biological effectiveness, practicality, and economics of oxygen removal need to be determined and demonstrated at bench and then shipboard scale.

The use of ozone as a biocide (ozonation) has been tested in a full scale application on board a U.S. oil tanker with promising results. Other biocides such as hypochlorite and gluteraldehyde are known to be effective against many biota including many microbes. Gluteraldehyde and hypochlorite are likely impractical for treatment of the large volumes of water in full ballast tanks on board typical transoceanic ships. Biocides have more likely utility in treating NOBOB tanks where the residual water volume is small. However, laboratory-based studies have shown that these biocides may be less effective on biota buried in sediments, unless the sediment can be stirred-up and resuspended. The presence of organic matter also reduces the effective concentration of hypochlorite, thus requiring a higher initial concentration. In addition, the shipping industry has concerns about the effects of hypochlorite on the coatings and steel of ballast tanks. Chloride ion is very reactive with exposed iron and the concern is that regular use of hypochlorite would increase the rate of deterioration of the ballast tank structure. In addition, the environmental community, and some regulatory agencies are concerned, if not resistant, to the idea of discharging biocide-laden ballast water to the environment. In some cases, such as gluteraldehyde and ozone, the biocide will break down into non-toxic chemicals, mainly water and carbon dioxide, while still in the ballast tank or shortly after exposure to sunlight.

Although several of these treatment approaches show promise, no one technology appears on the horizon as a "silver bullet." All have limitations that make them less than 100% effective. Some presently have serious practical limitations that must be

overcome or which may ultimately make them unusable, such as large size, high power requirements, costs, and maximum achievable treatment rate. With time and money, engineering solutions are likely for many of these problems, but perhaps one of the largest hurdles in the future may be finding adequate test platforms for technologies that are ready for on-board testing.

BALLAST WATER TREATMENT STANDARDS

Progress on the development of ballast water treatment systems is impeded by the lack of a treatment standard or standards to serve as the basis for a program of enforcement and other initiatives. Yet development of a suitable treatment standard is one of the most difficult hurdles presently facing the scientific and regulatory community. The difficulties related to this issue are concisely discussed in the recent “Advanced Notice of Proposed Rulemaking” (U.S. Coast Guard 2002) and will not be detailed here. There is disagreement on what measures or treatment outcomes represent an acceptable standard, and whether a single standard is suitable nationwide, or if different standards and indicators should be developed for different ecosystems.

Part of this problem stems from the fact the aquatic invasion science is in its infancy and thus we have little confidence in our understanding of aquatic species invasions or our ability to predict them. We do not fully understand what makes some species successful invaders and others not, or what conditions are needed for successful invasion and establishment by an organism.

RELATED RESEARCH ISSUES

Effective treatments for ballast water have yet to be developed and applied at full scale on operating vessels. Research to determine their efficacy is in its infancy and there are many research needs and issues that must be resolved in order to eliminate the risks posed by ballast water, including:

- Compilation of patterns of shipping and ballasting in the Great Lakes;
- Ballast discharge standards that will prevent introductions of nonindigenous species to the Great Lakes;
- Development and implementation of technologies and ballast management practices that prevent or reduce the risk of ballast-mediated introductions of nonindigenous species;
- Introduction of new-ship designs that will prevent or reduce introduction of new species via ballast tanks;
- Design standards for new ship ballast systems that will permit mass production and installation of technologies that may be developed in the lifetime of ships now being built;
- Determination of relative risk posed by ballast water from ports in different areas of the world;
- Research on the vulnerability of different life stages (adults, larvae, resting eggs) to ballast water exchange and alternative treatments;

- The relative effectiveness of purging (dilution) and physiological stress in reducing the number of live organisms in exchanged ballast water;
- Data on species-specific survival rates in ballast water;
- Determination of differential vulnerability to ballast water exchange between benthic (i.e., bottom-dwelling) versus planktonic (i.e., waterborne) species.

2. IDENTIFICATION AND MANAGEMENT OF OTHER VECTORS

While the majority of AIS that have invaded the Great Lakes over the past 50 years have arrived via international shipping, other mechanisms exist and are contributing to the problem. These mechanisms include the intentional and unintentional releases of 'aquarium' species, importation of live species for bait and for human consumption, and activities related to aquaculture. It is possible to identify the risk points and regulate each of these other vectors accordingly. Indeed, these vectors should be addressed in concert with the ballast water problem, since the introductions they may produce are no less irreversible. The Great Lakes Sea Grant Network is working closely with the aquaculture and bait industries on the problem of invasive species and has made some progress, especially in sensitizing these communities to the issue and in identifying best practices to reduce the threat. With the support of Great Lakes fishery agencies and the Great Lakes Fishery Commission, an interactive Environmental Assessment Protocol for Great Lakes Aquaculture (Brister and Kapuscinski 2002) has been posted on the web for reference by regulating agencies, fish farmers, and the public.

The Corps of Engineers has built a demonstration electrical barrier, activated 9 April 2002, in the Chicago Sanitary and Ship Canal. Originally constructed to prevent movement of round gobies from Lake Michigan to the Mississippi River System, this barrier has the potential, perhaps with augmentation, to prevent the invasion of the Great Lakes by Asian carps. However, there are no long-term provisions for operations, maintenance, monitoring and improving the barrier between the Great Lakes and Mississippi River ecosystems.

In addition, global warming will certainly affect the potential for species invasions by expanding (or contracting) the geographic range of ecosystems in climatically acceptable locations. For example, under some global warming scenarios, it would prove exceedingly difficult to prevent movement of southern species into the Great Lakes as the climate warms.

3. INTERDICTION

Federal government agencies in both the US and Canada monitor in-bound goods and products to North America as part of routine surveillance programs to prevent nonindigenous pest species arriving as hitchhikers. At present, no similar interdiction programs exist to evaluate risk posed by vessels entering the Great Lakes, other than mandatory ballast exchange for vessels carrying fresh or brackish water from outside the EEZ. Given that many of the AIS that have invaded the Great Lakes in recent years originate from Eurasia, an interdiction program based on risk assessment of potential invader organisms may prove useful. Genetic surveys play a useful role in

identification of invasion pathways and ought to be expanded. Better protocols for inspection and testing compliance in support of sound enforcement need to be developed.

The implications of non-compliance can be severe. Not only can one negligent ship jeopardize an ecosystem and the interests of its users, undetected non-compliance can result in misdirected regulations that affect the responsible members of the shipping community.

4. CONTROL AND ERADICATION

Control and eradication of AIS poses a dilemma to managers in North America. In general, eradication of an established aquatic invader is very difficult at best, and more often impossible unless the established population is localized, and can be isolated before it spreads.

However, there have been some recent success stories worthy of note, when conditions allowed action to be taken rapidly:

- Australia eradicated an invading mollusc, the Black-striped mussel *Mytilopsis sallei*, from its coastal waters through quarantine and chemical treatment of the entire affected harbor (Ferguson 2000). They were able to do so because: 1) the harbor had a narrow opening to the ocean that could be blocked off; and 2) the Australian federal government had the complete and sole authority to make the decision.
- Recently, managers in southern California have been using a biocide treatment to attempt eradication of *Caulerpa taxifolia*, an invasive nuisance species of green algae discovered in a coastal lagoon (Withgott 2002). Mortality in the original patch is estimated to be about 97%, but additional patches have been found in the same lagoon and treatment is on-going. There is an unconfirmed report that another patch has been found at a location far removed from the original infestation, and there may be problems with the chemical treatment reaching and destroying the entire organism.

The experience in the Great Lakes with the sea lamprey illustrates both the difficulty with eradication and the potential benefits of attempting control. After almost 50 years, the sea lamprey has resisted eradication and its numbers are controlled only via chemical and other treatments at great expense and effort. The sea lamprey's unique biology and devastating effect on Great Lakes fisheries made control a worthwhile approach and research made it possible. Barriers have been successfully employed to curtail sea lamprey entry into Lake Winnebago, Lake Simcoe, and numerous tributaries. The only other NIS that fishery managers have sought to control is the alewife – by stocking trout and salmon to supplement the population reduction of native predators caused by sea lamprey.

5. RAPID RESPONSE vs. RAPID SCIENTIFIC ASSESSMENT

Rapid response to new species invasions may help managers, industries, and researchers establish the nature of a new invasive species, its current and potential distributions, vectors of dispersal, potential ecological and industrial impacts, and the potential control and/or eradication options. For example, when notified of a new invasive species in the U.S., the Animal and Plant Health Inspection Service (APHIS) under the U.S. Department of Agriculture, one of the oldest invasive species-fighting organizations in the United States, organizes a 'New Pest Advisory Group' consisting of government officials and appropriate experts. This group meets and acts quickly to discuss the known biology of the organism, its potential damage and range, mitigation strategies, and possible actions. Based on these discussions, the group makes a recommendation to APHIS to either take action, or not, on the newly detected exotic pest. This process was used to respond to the discovery of the invasive pine shoot beetle in 1992 on a Christmas tree plantation near Cleveland. Within a few days of being notified, APHIS brought together concerned parties from industry, academia, and state and federal agencies in a "New Pest Advisory Group" to share information and develop response strategies. Through this process, they were able to rapidly establish the extent of its distribution and potential impacts on industry, and start the process to develop a regulatory response (Haack and Poland 2001).

The idea of developing a rapid response capability for the Great Lakes is more controversial, especially if eradication is the goal. However, rapid response plans are under consideration at various levels of government and therefore cannot be ignored. The nature of the aquatic environment generally makes rapid response for eradication impractical, except when the nonindigenous population is small, localized, and located where it can be easily and rapidly isolated (see Section 4, above). Consequently, dedicating resources to a stand-by generic rapid response team aimed at quickly responding to and eradicating a new invasion is impractical and economically inefficient. From an aquatic perspective, rapid response is a very poor and inadequate second choice, not a substitution for prevention. Eradication of AIS is virtually never a possible response in the Great Lakes.

There presently does not exist an established framework under which rapid scientific assessment of new aquatic invader populations can be supported and carried out. Yet gathering and verifying information and compiling it into summary findings and recommendations is a necessary precursor in support of informed and effective resource management decisions that do not waste taxpayer funds jousting with "aquatic windmills". When a new invasion is reported, a team of appropriate experts needs to be quickly assembled to gather and verify information and assess whether the invasion is a candidate for attempted eradication, control, or adaptive management. Adaptive management is likely to be the end-strategy of most aquatic species invasions, (i.e., due to changes in the invaded ecosystem caused by introduction of a nonindigenous species, such as changes in light, turbidity, nutrients, and populations of existing species, management of such ecosystems for water quality and fisheries must be adapted to the altered conditions). This requires revision of management strategies (i.e., adaptive management) that can only be accomplished on the basis of scientific understanding of the changes that have occurred.

A framework needs to be developed under which a rapid scientific invasion assessment team can be assembled and activated in response to reports of new species. Rapid assessment of new AIS arrivals can be useful in helping resource managers become aware of new demands on the ecosystem and to plan management actions. For example, the Fish Health Committee under the Great Lakes Fishery Commission has developed a model program and risk assessment guidelines for evaluating new fish diseases that may be useful in developing a similar AIS framework.

6. REGIONAL COOPERATION

Aquatic invaders may originate from an adjacent ecosystem or from an ecosystem on the other side of the globe, and they do not honor political boundaries. The Great Lakes are subdivided by the international boundary between the U.S. and Canada, and state, provincial, tribal, and First Nation boundaries within each country. Since the late 1980s, when species invasions came to the forefront of public awareness, we have seen one country (Canada) implement voluntary guidelines for ballast water exchange, one country implement mandatory requirements for ballast water exchange (U.S.), and the State of Michigan and Province of Ontario have proposed to protect their respective waters through legislation independent of any other jurisdiction.

In the meantime, NIS keep on coming (Ricciardi 2001). Implementation of individual ballast water regulations by one or several states or provinces will prove meaningless because AIS can and do move quickly from one region of the Great Lakes basin to another. Effective management of the problem will require collaboration and cooperation between all affected states and provinces and between the two federal governments. It is, therefore, imperative that development and implementation of legislation be conducted using a basin-wide approach.

7. INTERNATIONAL COOPERATION

The transfer of aquatic species is occurring on a global scale. Carlton and Geller (1993) estimated that on any day, several thousand aquatic species may be in transport in the ballast tanks of ship's worldwide. It is essential that the U.S. and Canada cultivate a sustainable international approach to prevention of aquatic species invasions through international scientific cooperation, information sharing, and student/young scientist training.

As previously noted, 8 ballast-implicated new organisms found in the Great Lakes since 1986 are native to the Ponto-Caspian region of Europe. Many more fresh and low-salinity tolerant organisms from this region are either already moving or likely to be mobilized during the next decade. Russia signed a new trade agreement in 2000 with India, Iran, and Oman to create a united transport corridor from the Persian Gulf and Indian Ocean to the Baltic Sea. The projected increase in ship traffic on the Volga-Baltic Waterway almost guarantees that more Ponto-Caspian species will move to the Baltic and become available for transport to North American coastal ecosystems. A risk-based model indicated that there exists in coastal waters of Europe at least 26 species with invasion histories and life-history characteristics required for survival in

ballast tanks that could invade the Great Lakes (Personal Communication, Igor Grigorovich, GLIER, University of Windsor). A high priority for the Great Lakes region should be development of methods for screening and assessing the risk posed by the many fresh and brackish-water tolerant organisms in key ballast water source regions.

In order to obtain the necessary scientific information about species in foreign ecosystems, international cooperation among scientists is essential. For example, the best and most complete information about Ponto-Caspian species moving through Europe is contained in the European and Russian literature and not easily accessible to North American scientists. Collaboration among Great Lakes, Russian, and European scientists potentially would yield important heretofore unavailable information.

As global shipping and trade changes with time, so too will the “hot” source regions for invasive species change. Therefore, it is essential that information be compiled on a long-term basis to track the trade characteristics of the overseas vessels that enter the Great Lakes every year.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. Aquatic species invasions continue to pose one of the greatest risks to the health and productivity of our coastal marine ecosystems and the Great Lakes.
2. A major federal funding increase of at least \$30M per year for the Great Lakes region is needed to accelerate progress towards solutions to the problems outlined in this document. The piecemeal and relatively small annual funding requested by the Administration and provided by Congress, and the funds available through Canadian agencies, are not sufficient for substantive progress. Invasive species are no longer just a matter of scientific interest and local concern - they represent a threat to the marine/aquatic biosecurity of the United States, Canada, and the other coastal nations of the world. Invasive species have a direct impact where we live and play, and they affect our standard and style of living in an adverse manner. Winning the invasive species challenge means investing in a reasonable 10-year goal: to eliminate new introductions of aquatic invasive species by 2013. Oceanic shipping (ballast tanks) has been the primary vector for new aquatic species introductions and will continue to be the most significant and high-risk vector until effective treatment technologies are developed, proven, and made suitable for installation and use aboard a variety of large ships.
3. Without government leadership and funding, availability of approved ballast water/ballast tank treatment technologies is at least a decade away, perhaps longer.
4. The development of an effective, practical ballast water treatment standard or standards is a major barrier to progress on the development and testing of treatment technologies. The scientific community must become engaged in this issue before the policy community unilaterally sets standards that are not scientifically supportable, or worse, ineffective.

5. The lack of reliable and flexible full-scale testing platforms is an obstacle to testing promising ballast water treatment technologies. Test platforms, in the form of leased vessels, shore-based test facilities, or MARAD vessels, need to be available for full-scale tests under actual vessel operating conditions.
6. Given that many of the aquatic invaders that have established in the Great Lakes in recent years originate from Eurasia, an interdiction program based on assessment of potential high-threat invader organisms in European fresh and brackish water systems should be undertaken. This will require international collaboration and cooperation.
7. Information to track and identify shifts in patterns of trade coming into the Great Lakes should be compiled and maintained on an annual basis.
8. Increased resources are needed to support aquatic invasion science research, to advance our understanding of the invasion process, the development of reliable risk assessment models, and the ability to identify and evaluate potential future invaders.
9. Genetic tools to identify relationships among source communities and newly established communities should be emphasized. This is perhaps the best tool we have to demonstrate source-donor relationships.
10. Although the ballast tank vector remains the highest prevention priority, increased resources should be directed towards other vectors, such as aquaculture, the bait industry, and the aquarium industry.
11. The barrier between the Mississippi River and the Great Lakes should be maintained and upgraded to prevent movement of exotic species between both ecosystems.

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