

MANAGEMENT OPTIONS FOR CONTROL OF NONINDIGENOUS SPECIES IN THE  
GREAT LAKES

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**Introduction**

Species distributions are determined in part by the presence of geographic barriers to dispersal. These distributions may change naturally, but usually at very slow rates. By contrast, human activities are altering the nature and even existence of geographic barriers, and are allowing for rapid changes in the realized distributions of many species. Humans have intentionally introduced many species to North America, including most plants currently exploited for food.<sup>6</sup> Lakes throughout the world have been subjected to intensive species introduction programs, typically of sport or commercial fishes or their food species. Most of these activities are undertaken with the intention of improving human welfare, though many species introductions—both intentional and unintentional—result in profound negative consequences to human, economic or ecosystem health. The human population of North America is presently threatened by a host of nonindigenous species (NIS) from viruses associated with West Nile disease (*Flavivirus*) and with Sudden Acute Respiratory Syndrome (SARS-associated coronavirus), to killer bees (*Apis mellifera scutellata*), to name but a few examples.

Introduction of NIS also may impart huge economic costs on recipient countries. The U.S. Congress estimated that 79 NIS caused ~ \$100 billion in

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<sup>3</sup> *Infra* note 1

<sup>4</sup> Id.

<sup>5</sup> Id.

<sup>6</sup> U.S. Congress, Office of Technology Assessment. *Harmful nonindigenous species in the United States*. OTA-F-565. U.S. Government Printing Office, Washington, D.C.; (1993).

damage over an 85-year period.<sup>7</sup> More recently, Pimentel et al.<sup>8</sup> estimated losses and/or control costs to the USA economy of at least \$137 billion per annum associated with NIS. As noted by the Union of Concerned Scientists, the accuracy of these calculations is difficult to assess, but probably is a minimum.<sup>9</sup> Pimentel et al further projected total damage and control costs for NIS at more than \$314 billion USD per year in the USA, United Kingdom, Australia, South Africa, India and Brazil.<sup>10</sup>

Despite the enormous human health and economic costs associated with introduction of some NIS, the greatest impact may be the loss of biotic integrity of distinctive communities throughout the world. Introduction of NIS is viewed as one of the most serious issues affecting biodiversity of aquatic ecosystems, particularly of lakes and coastal marine ecosystems.<sup>11 12 13</sup> The Great Lakes and San Francisco Bay, for example, are among the most invaded ecosystems on earth; stocked species (e.g. fishes) are common in both systems, although a growing number of NIS have been introduced unintentionally.<sup>14 15 16</sup> Hebert and Cristescu illustrated the scale of the problem by calculating that human-mediated dispersal of crustacean zooplankton (i.e. waterfleas) to the Great Lakes exceeds

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<sup>7</sup> *Id.*

<sup>8</sup> Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. *Environmental and economic costs of nonindigenous species in the United States*. *Bioscience* 50: 53-65; (2000).

<sup>9</sup> Union of Concerned Scientists. *The Science of Invasive Species*. Cambridge, MA. 12p.; (2001).

<sup>10</sup> Pimentel, D., S. McNair, J. Janecka, J. Wightman, C. Simmonds, C. O'Connell, E. Wong, L. Russel, J. Zern, T. Aquino and T. Tsomondo. *Economic and environmental threats of alien plant, animal and microbe invasions*. *Agriculture, Ecosystems and Environment* 84: 1-20; (2001).

<sup>11</sup> Ruiz, G.M., P.W. Fofonoff, J.T. Carlton, M.J. Wonham and A.H. Hines. *Invasion of coastal marine communities in North America: apparent patterns, processes, and biases*. *Annual Review of Ecology and Systematics* 31: 481-531; (2000).

<sup>12</sup> Sala, O.E., F.S. Chapin, III, J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. Wall. *Global biodiversity scenarios for the year 2100*. *Science* 287: 1770-1774; (2000).

<sup>13</sup> Rahel, F.J. *Homogenization of freshwater faunas*. *Annual Review of Ecology and Systematics* 33: 291-315; (2002).

<sup>14</sup> Mills, E.L., J.H. Leach, J.T. Carlton and C.L. Secor. *Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions*. *Journal of Great Lakes Research* 19: 1-57; (1993).

<sup>15</sup> Cohen, A. and J.T. Carlton. *Accelerating invasion rate in a highly invaded estuary*. *Science* 279: 555-558; (1998).

<sup>16</sup> Ricciardi, A. *Facilitative interactions among aquatic invaders: is an 'invasional meltdown' occurring in the Great Lakes?* *Canadian Journal of Fisheries and Aquatic Sciences* 58: 2513-2525; (2001).

the natural dispersal rate by up to 50,000 fold.<sup>17</sup> When combined with the extinction of endemic (and distinctive) flora and fauna, introductions of NIS are resulting in homogenization of lake communities world-wide.<sup>18</sup>

Mills and colleagues conducted an extensive literature review and documented 139 NIS established in the Great Lakes as of 1990.<sup>19</sup> Ricciardi revised the total to 162 NIS established in the lakes.<sup>20</sup> Grigorovich and colleagues conducted a retrospective analysis of aquatic animals and protists first reported in the Great Lakes after the opening of the St. Lawrence Seaway in 1959.<sup>21</sup> Of the 43 species they identified, nine are not on the current list of 162, bringing the documented total of NIS in the Great Lakes to 171. Nicholls and MacIsaac identified three previously undescribed, nonindigenous species of testate rhizopods (amoebae) in beach sands in the Great Lakes.<sup>22</sup> Finally, Anthony Ricciardi (personal communication) has identified several additional established invaders from literature searches, bringing the current unofficial total to at least 175. Thus, the documented number of NIS in the Great Lakes is best interpreted as a minimum. Most of the NIS identified to date are large or otherwise conspicuous (e.g. invertebrates and fish), and virtually no attention has been paid to identification of nonindigenous bacteria, viruses, protozoans and microalgae.

Introduced species now dominate most trophic levels in each of the Great Lakes. For example, benthic invertebrate production and abundance in Lake Erie is dominated by introduced zebra mussels (*Dreissena polymorpha*), quagga mussels (*Dreissena rostriformis*), and shrimp-like amphipods (*Echinogammarus ischnus*). Zooplankton of the lake is at times dominated by introduced waterfleas (*Daphnia lumholtzi*, *Cercopagis pengoi* and *Bythotrephes longimanus*), while white perch (*Morone americana*), rainbow smelt (*Osmerus mordax*), round gobies (*Neogobius melanostomus*) and common carp (*Cyprinus carpio*) are very abundant nonindigenous fishes.<sup>23</sup> Wetland sites fringing the lake are commonly dominated by purple loosestrife (*Lythrum salicaria*), cattail (*Typha angustifolia*) and other introduced plants. Alarming, some NIS appear to predispose the

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<sup>17</sup> Hebert, P.D.N. and M.E.A. Cristescu. *Genetic perspectives on invasions: the case of the Cladocera*. Canadian Journal of Fisheries and Aquatic Sciences 59: 1229-1234; (2002).

<sup>18</sup> *Infra* note 13.

<sup>19</sup> *Infra* note 14.

<sup>20</sup> *Infra* note 16.

<sup>21</sup> Grigorovich, I.A., R.I. Colautti, E.L. Mills, K. Holeck, A.G. Ballert, and H.J. MacIsaac. *Ballast-mediated animal introductions in the Laurentian Great Lakes: retrospective and prospective analyses*. Canadian Journal of Fisheries and Aquatic Sciences 60: 740-756; (2003).

<sup>22</sup> Nicholls, K.H. and H.J. MacIsaac. *Euryhaline, sand-dwelling, testate rhizopods in the Great Lakes*. Journal of Great Lakes Research 30: 123-132; (2004).

<sup>23</sup> MacIsaac, H.J. *Biological invasions in Lake Erie: past, present and future*. In: State of Lake Erie: past, present and future. (M. Munawar and T. Edsall, eds.). pp 305-322; (1999); Backhuys, Leiden, Netherlands.

invaded lake to further invasion by facilitating other NIS through provision of habitat or food.<sup>24</sup> For example, gaps between shells of colonial zebra mussels provide excellent habitat for *Echinogammarus* amphipods, while round gobies exploit the mussels as prey. Both of these species invaded the Great Lakes only after establishment of zebra mussels, a species with which they co-evolved in the Black Sea.

#### **Ballast Water as the Dominant Vector**

Release of ballast by transoceanic commercial ships has been the strongest vector of aquatic NIS to the Great Lakes during the 20th century.<sup>25 26 27</sup> Vessels carrying a partial load of cargo add ballast to provide stability. Ballast is typically discharged when the ship loads cargo or needs to decrease its draft. Prior to about 1900, vessels entering the Great Lakes carried solid ballast, including rock, soil, or sand; many of the species introduced at that time were plants whose seeds were carried in these ballast materials.<sup>28</sup> Thereafter, ships switched to water ballast, which was usually taken on-board at a port. Because many marine ports occur in river estuaries (e.g. Rotterdam), freshwater species could be loaded into ballast. Since the opening of the St. Lawrence Seaway in 1959, 71 new NIS have been reported as established in the Great Lakes, 46 of which have been attributed to ballast water transport.<sup>29 30 31</sup> Ricciardi calculated that shipping activity accounted for 62% of the variation in the number of new NIS established per decade in the Great Lakes.<sup>32</sup> Since 1993, when mandatory ballast water exchange regulations were implemented for ships entering the Great Lakes, 11 new NIS (not including three parasites that presumably came in with host species) have been reported established, and of those, 8 were most likely introduced via transoceanic ships.

Many of the NIS that have established reproducing populations in the Great Lakes since 1986 are native to the Black-Azov and Caspian Sea regions of southeastern Europe.<sup>33</sup> This group includes most of the species that have achieved nuisance status in the Great Lakes, such as zebra and quagga mussels, round gobies, and fishhook waterfleas. Ironically, there is little direct ship traffic between these regions and the Great Lakes.<sup>34</sup> MacIsaac and colleagues proposed

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<sup>24</sup> *Infra* note 16.

<sup>25</sup> *Infra* note 14.

<sup>26</sup> *Infra* note 16.

<sup>27</sup> *Infra* note 21.

<sup>28</sup> Mills at 1-57.

<sup>29</sup> *Id.*

<sup>30</sup> *Infra* note 16.

<sup>31</sup> *Infra* note 21.

<sup>32</sup> *Infra* note 16.

<sup>33</sup> Ricciardi, A. and H.J. MacIsaac. *Recent mass invasion of the North American Great Lakes by Ponto-Caspian species*. Trends in Ecology and Evolution 15: 62-65. (2000).

<sup>34</sup> Colautti, R., A. Niimi, C.D.A. van Overdijk, E.L. Mills, K. Holeck, and H.J. MacIsaac. *Spatial and temporal analysis of transoceanic shipping vectors to the Great Lakes*. In

the existence of five invasion ‘corridors’ to the Great Lakes from this area.<sup>35</sup> One corridor provides a direct route from ports on the northern Black Sea, through the Mediterranean Sea, to the Great Lakes. Quagga mussels likely entered via this corridor.<sup>36</sup> Two indirect corridors involve inland waterways in Europe that permit transit of ships and species from the Black-Azov Sea region to the North and Baltic Seas, respectively (Danube River/Main Canal/River Rhine network; Dnieper River/Pripiat River/Dnieper–Bug Canal and either the Nemunas or Vistula Rivers to the Baltic Sea). These corridors were likely exploited by *Echinogammarus* amphipods and *Cercopagis* waterfleas to enter the Great Lakes.<sup>37</sup> Two other indirect river corridors may allow passage of species to the North and Baltic Seas from the Azov and Caspian Seas, respectively (Don River/Volga–Don Canal/Volga River/Volga-Baltic Canal; Volga River system/Volga-Baltic Canal). NIS that establish in ‘staging’ ports on the North or Baltic Seas subsequently may be loaded into ballast by vessels bound for the Great Lakes. Another waterflea, *Bythotrephes*, likely entered the Great Lakes via the Baltic staging area.<sup>38 39</sup>

Owing largely to problems caused by zebra mussels, the United States implemented legislation in 1993 that requires open-ocean ballast exchange by vessels carrying fresh or brackish (i.e. low salinity) ballast water if that water is to be discharged later into the Great Lakes.<sup>40</sup> Although the use of approved alternative ballast water treatments is incorporated into the legislation, open-ocean ballast water exchange remains the only approved treatment to date. Exchange greatly reduces the number of freshwater organisms because most are purged when the ballast tanks are flushed with seawater, and remaining individuals should be killed when immersed in the highly saline water loaded as replacement ballast. Salt-water taxa present in exchanged ballast water pose a low risk of invasion to the Great Lakes because most cannot live in fresh water.

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Invasive Species: Vectors and Management Strategies. (eds. G. Ruiz and J.T. Carlton) pp. 227-246; (2003); Island Press.

<sup>35</sup> MacIsaac, H.J., I.A. Grigorovich and A. Ricciardi. *Reassessment of species invasions concepts: the Great Lakes basin as a model*. Biological Invasions 3: 405-416; (2001).

<sup>36</sup> Therriault, T.W., M.I. Orlova, M.F. Docker, H.J. MacIsaac, and D.D. Heath. *Invasion genetics of a freshwater mussel (Dreissena rostriformis bugensis) in Eastern Europe: high gene flow and multiple introductions*. Heredity (in press).

<sup>37</sup> Cristescu, M., J. Witt, P.D.N. Hebert, H.J. MacIsaac and I.A. Grigorovich. *An invasion history for Cercopagis pengoi based on mitochondrial gene sequences*. Limnology and Oceanography 46: 224-229; (2001).

<sup>38</sup> Therriault, T.W., I.A. Grigorovich, M.E. Cristescu, H.A.M. Ketelaars, M. Viljanen, D.D. Heath, and H.J. MacIsaac. *Taxonomic resolution of the genus Bythotrephes Leydig using molecular markers and re-evaluation of its global distribution*. Diversity and Distributions 8: 67-84; (2001).

<sup>39</sup> Berg, D.J., D.W. Garton, H.J. MacIsaac, V.E. Panov and I.V. Telesh. *Identification of a source and erosion of founder effects in an exotic species*. Freshwater Biology 47:275-282; (2002).

<sup>40</sup> U.S. Coast Guard. *Ballast water management for vessels entering the Great Lakes*. Code of Federal Regulations 33-CFR Part 151.1510; (1993).

Despite mandatory ballast exchange, the rate of new NIS invasions in the Great Lakes has not abated.<sup>41 42</sup> However, no new nonindigenous fish have been documented as becoming established since the implementation of mandatory ballast exchange, except the blueback herring (*Alosa aestivalis*), whose introduction has been attributed to canals.<sup>43</sup> In fact, since 1993, a number of new invaders documented in the Great Lakes and attributed to the ballast vector are small invertebrates native to the Black Sea, which possess the ability to withstand exposure to moderate salinities for extended periods of time.<sup>44 45 46 47 48</sup> These invertebrates also can produce resistant resting stages that are unlikely to be removed by exchange and may not be killed by contact with seawater. Factors that may account for the on-going invasion problem include incomplete ballast exchange by some vessels, which would allow for salinity-tolerant NIS to survive and establish, or the presence of other vectors that facilitate transfer of NIS to the Great Lakes.

The practice of open-ocean ballast water exchange is thought to reduce the threat of new NIS invasions by vessels carrying ballast into the Great Lakes between two and four orders of magnitude relative to a vessel that carries freshwater ballast directly from a European port.<sup>49</sup> Additional research is needed however, to determine survival functions for freshwater species immersed in saline ballast water, during and subsequent to exchange, to establish the efficacy of this procedure. Available evidence indicates that some life stages produced by some invertebrate species may survive exposure to brackish or salt-water, and, if released into the Great Lakes could facilitate an invasion.<sup>50</sup>

#### Temporal Changes in Vectors

Recent studies indicate that the nature of the invasion threat posed by shipping vectors to the Great Lakes may be in transition. The ballast water threat can be divided into three distinct components. First, some vessels may discharge

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<sup>41</sup> *Infra* Note 16.

<sup>42</sup> *Infra* Note 21.

<sup>43</sup> U.S. Geological Survey. Invasive Species Fact Sheet ID 488: *Alosa aestivalis*, found at <http://nas.er.usgs.gov/queries/SpFactSheet.asp?speciesID=488> on 01/09/2004) (2003).

<sup>44</sup> *Infra* Note 33.

<sup>45</sup> Horvath, T.G., R.L. Whitman and L. Last. *Establishment of two invasive crustaceans (Copepoda: Harpacticoida) in the nearshore sands of Lake Michigan*. Canadian Journal of Fisheries and Aquatic Sciences 58: 1261-1264; (2001).

<sup>46</sup> *Infra* note 16.

<sup>47</sup> *Infra* note 21.

<sup>48</sup> Bailey, S.A., I.C. Duggan, C. van Overdijk, T.H. Johengen, D.F. Reid and H.J. MacIsaac. *Salinity tolerance of diapausing eggs of freshwater zooplankton*. Freshwater Biology 49:286-295; (2004).

<sup>49</sup> MacIsaac, H.J., T.C. Robbins, and M.A. Lewis. *Modeling ships' ballast water as invasion threats to the Great Lakes*. Canadian Journal of Fisheries and Aquatic Sciences 59: 1245-1256; (2002).

<sup>50</sup> *Infra* note 47.

foreign freshwater ballast, in contravention of applicable law. Second, vessels may legally discharge exchanged ballast water with a salinity exceeding 30 ppt (as described above). The third and arguably most important mechanism by which ships may facilitate NIS invasions today involves vessels that enter the Great Lakes loaded with cargo, and thus carry only residual, unpumpable water, sediments and associated NIS in their 'empty' ballast tanks.<sup>51</sup> This water could be fresh, brackish or saline depending on the recent ballasting history of the vessel. These vessels are officially classified as No-Ballast-On-Board (i.e. NOBOB), and are exempt from extant legislation covering ballast-related activities while operating on the Great Lakes. Still, NOBOB vessels may pose a significant threat for a variety of reasons.<sup>52 53</sup> First, these vessels accounted for approximately 90% of all inbound traffic to the Great Lakes for approximately the last ten years, the majority of which arrive from European ports.<sup>54</sup> Second the activity of these vessels poses a real but as yet undefined risk. They typically discharge steel or chemical cargo at a port on the lower Great Lakes (e.g., Hamilton, Ontario or Cleveland, Ohio), and then load Great Lakes' water into their 'empty' tanks, which mixes with the residual ballast water, sediment and NIS. This process may be repeated at each port visited on the upbound voyage where cargo is off-loaded. At the terminal port-of-call on the Great Lakes, NOBOB vessels discharge the mixed ballast water in preparation for loading of cargo for the outbound voyage. Thus, NIS present in the residual ballast water and now resident in the mixed ballast water could be introduced to the Great Lakes at or close to the destination port.

Sediments of NOBOB vessels also pose an invasion risk.<sup>55 56</sup> Ballast sediment may range from a thin veneer up to 10s of cm in depth, and results from sedimentation of fine mineral matter (e.g. silt and clay) and biological matter while the ship is in transit. Many species of bacteria, phytoplankton and invertebrate animals have evolved the capability to produce 'resting stages' (e.g. cysts, ephippia, diapausing eggs) during periods of unfavorable conditions. Resting stages produced by species resident in ballast tanks may be discharged with ballast water or can settle to the tank bottom, where they remain in a viable

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<sup>51</sup> Bailey, S.A., I.C. Duggan, C.D.A. van Overdijk, P. Jenkins and H.J. MacIsaac. *Viability of invertebrate diapausing stages collected from residual ballast sediment*. *Limnology and Oceanography* 48:1701-1710; (2003).

<sup>52</sup> *Infra* note 49.

<sup>53</sup> Niimi, A.J. and D.M. Reid. *Low salinity residual ballast discharge and exotic species introductions to the North American Great Lakes*. *Marine Pollution Bulletin* 46: 1334-1340; (2003).

<sup>54</sup> *Infra* note 34.

<sup>55</sup> Weathers, K. and E. Reeves. *The defense of the Great Lakes against the invasion of nonindigenous species in ballast water*. *Marine Technology* 33: 92-100; (1996).

<sup>56</sup> *Infra* note 51.

condition for protracted time periods.<sup>57</sup> If these resting stages are discharged directly they may hatch in the more favorable conditions in the Great Lakes. Alternatively, resting stages may be stimulated to hatch when Great Lakes' water is loaded into ballast tanks containing unpumpable residual water. If this water is subsequently discharged into the Great Lakes, an invasion may result from hatching of even one resting egg because most of these organisms are capable of asexual reproduction. For example, Hairston and colleagues postulated that Onondaga Lake, New York, was invaded by either one or two individuals of an asexually reproducing waterflea (*Daphnia exilis*).<sup>58</sup> The same evolutionary strategy that allows species to produce resistant resting stages, survive unfavorable periods, and reproduce quickly via asexuality during favorable times increases the risk of NIS invasions through ballast discharges by commercial ships.

The notion that the nature of the ballast water problem has changed is supported by a review of ship traffic patterns into the Great Lakes over the past twenty-three years. Between 1978 and 1982, for example, an average of 51.6% of transoceanic vessels entering the Great Lakes declared NOBOB status.<sup>59</sup> This value increased to 91.8% of inbound vessels between 1996 and 2000.<sup>60</sup> Consequently, the threat of new NIS invasions appears to have tilted in recent years toward NOBOB vessels.

As ships are the greatest threat to the Great Lakes, it may be instructive to determine where fresh or saline ballast water is discharged to determine which lake is at greatest risk. Colautti and colleagues reviewed spatial and temporal patterns of ballast release by foreign, transoceanic ships entering the Great Lakes system with either saline ballast water (BOB ships) or residual water and sediments (NOBOB ships).<sup>61</sup> Even though a large percentage (79.5%) of inbound vessels stop at sites on Lake Ontario or Lake Erie as their first port-of-call, most NOBOB vessels (74.5%) that deballasted freshwater ballast into the Great Lakes did so into Lake Superior, particularly near the ports of Duluth-Superior and Thunder Bay. A majority (55.4%) of BOB ships also discharged (saline) ballast water into Lake Superior. Consequently, it appears that Lake Superior should be at greatest risk of new NIS invasions owing to discharge patterns of inbound, foreign vessels, yet relatively few NIS have been first discovered in Lake Superior before having been documented elsewhere in the Great Lakes. This may reflect the scant attention focused on NIS issues in this

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<sup>57</sup> *Id.*

<sup>58</sup> Hairston, N.G., Jr., L.J. Perry, A.J. Bohonak, M.Q. Fellows, and C.M. Kearns. *Population biology of a failed invasion: paleolimnology of Daphnia exilis in upstate New York*. *Limnology and Oceanography* 44: 477-486; (1999).

<sup>59</sup> *Infra* note 34.; *Spatial and temporal analysis of transoceanic shipping vectors to the Great Lakes*. In *Invasive Species: Vectors and Management Strategies*. Edited by G. Ruiz and J.T. Carlton. pp. 227-246; Island Press; (2003).

<sup>60</sup> *Id.*

<sup>61</sup> *Id.*

lake, or the lake's relatively cold, oligotrophic physical-chemical environment and the long duration potential invaders must survive in a ballast tank before they are discharged into Lake Superior.<sup>62</sup>

#### **Research and Management Needs**

Although data are incomplete, available evidence indicates that the nature of the ballast water problem has evolved over the past two decades, and that management strategies need to change accordingly. Particular attention must be focused on threats posed by NOBOB vessels. In addition, ballast treatment options must be greatly expanded to alleviate the residual ballast and resting stage threat so that it can be assured that all vessels entering the Great Lakes pose little risk of new NIS invasions regardless of their ballast status.

While a predominant number of NIS that have invaded the Great Lakes over the past 45 years have arrived *via* ballast water discharged by international ships, other mechanisms exist and contribute to the problem. It is possible that some species arrive to the Great Lakes fouled to exterior hull surfaces of ships, or attached to anchor chains, etc. The importance of these mechanisms has yet to be determined for the Great Lakes, although they almost certainly pose far less threat to the Great Lakes than to marine coastal ports. Other introduction mechanisms of concern include the intentional release of 'aquarium' species, importation of live species for human consumption, aquaculture and possibly, global warming. Rixon and colleagues identified six fish species and four aquatic plant species sold in aquarium stores or live food markets in Ontario and Quebec that pose an invasion risk to the Great Lakes.<sup>63</sup> Similarly, Kolar and Lodge identified 22 fish species that pose an invasion risk to the Great Lakes, of which six were deemed capable of causing significant harm should they establish successfully.<sup>64</sup> It will prove very difficult to prevent movement of southern species into the Great Lakes as the climate warms, however it is possible to identify and regulate each of the former three mechanisms. Indeed, once a solution to the ballast water problem is developed and implemented, these mechanisms will become increasingly important vectors for the delivery of new NIS to the Great Lakes. Additional research is needed to identify the characteristics of each of these mechanisms, including the potential vector strength, as well as the types of species each is likely to contribute.

Government agencies in both the USA and Canada agree that prevention is the most cost-effective response to the NIS problem, and currently, both federal governments monitor products inbound to North America as part of routine surveillance programs to prevent entry of pest NIS from other continents. At

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<sup>62</sup> Grigorovich, I.A., A.V. Kornushin, D.K. Gray, I.C. Duggan, R.I. Colautti and H.J. MacIsaac. *Lake Superior: an invasion coldspot?* *Hydrobiologia* 499: 191–210; (2003).

<sup>63</sup> Rixon, C.A.M., I.C. Duggan, N.M.N. Bergeron, A. Ricciardi and H.J. MacIsaac. *Invasion risks posed by the aquarium trade and live fish markets on the Laurentian Great Lakes*. *Biodiversity and Conservation*; (in press).

<sup>64</sup> Kolar, C.S. and D.M. Lodge. *Ecological Predictions and Risk Assessment for Alien Fishes in North America*. *Science* 298: 1233-1236; (2002).

present, no similar interdiction programs exist to address the risk posed by vessels entering the Great Lakes, other than mandatory ballast exchange for vessels carrying fresh or brackish water, and that requirement only applies to vessels originating from ports outside the exclusive economic zone. Given that many NIS that have invaded the Great Lakes in recent years originate from Eurasia, an interdiction program based on risk assessment may prove useful. Genetic surveys also may play a useful role in identification of invasion pathways and ought to be expanded.<sup>65 66 67 68</sup>

Control and eradication of NIS poses a dilemma to managers in North America. Numerous eradication and control methods exist to manage NIS, each of which must be tailored to the target species. For example, mechanical harvesting is a useful mechanism for control of some aquatic plant pests, while chemical control may be more effective against algae and molluscs. Australia effectively eradicated an invading zebra mussel-like species, the Black striped mussel (*Mytilopsis sallei*), from its coastal waters through quarantine and chlorine treatment of the affected harbor.<sup>69</sup> However, North American managers have typically been reticent to apply chemical treatments to control or eradicate invading NIS, especially in the face of strong opposition by environmental groups and the general public to any additional chemical discharges to the Great Lakes. Concerns over environmental quality prevented managers from applying biocide to Duluth Harbor, Minnesota, to attempt control or eradication of the Eurasian ruffe when this fish species first invaded the Great Lakes in 1986. Consequently, the species has slowly dispersed to other regions of Lake Superior, as well as to Lake Huron and Lake Michigan. Conversely, managers successfully used localized, controlled application of liquid chlorine to eradicate an invading nuisance species of green alga (*Caulerpa taxifolia*) discovered during 2000 in coastal waters near San Diego, California. This species previously invaded and formed a nearly continuous carpet on the bottom of a large area of the Mediterranean Sea, off the coast of France.<sup>70</sup>

Development of control and eradication plans ought to be made in advance of new NIS invasions in the Great Lakes. Key to decisions regarding whether or not control programs should be implemented is an intimate knowledge of the nonindigenous species' life history, its population size and dispersion within the Great Lakes, and the likelihood of achieving complete population eradication

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<sup>65</sup> *Infra* note 37.

<sup>66</sup> *Infra* note 38.

<sup>67</sup> *Infra* note 39.

<sup>68</sup> *Infra* note 17.

<sup>69</sup> Ferguson, R. *The effectiveness of Australia's response to the Black striped mussel incursion in Darwin, Australia*. A report of the Pest management Workshop, 27-28 August 1999. The Department of Environment and Heritage, Canberra, Australia; (2000).

<sup>70</sup> Withgott, J. *California tries to rub out the monster of the lagoon*. *Science* 295: 2201-2202 (2002).

with application of the control measure. At a minimum, however, managers and other stakeholders should evaluate the relative risk posed by the continued establishment of potentially harmful NIS in the Great Lakes versus that of localized and ephemeral chemical contamination associated with application of a control compound.

The Great Lakes are the economic, cultural, and recreational lifeblood of millions of North Americans. Threats to these systems have changed through time, and so too must our responses. Introduction of NIS is arguably the most serious threat to these systems today. By their very nature, NIS pose a serious human health, economic and ecological threat to the Great Lakes. Implementation of ballast water regulations by individual states or provinces will prove meaningless because NIS 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 USA and Canadian federal governments. It is, therefore, imperative that development and implementation of legislation be conducted using a basin-wide approach. Earlier, water quality in the Great Lakes was seriously compromised by cultural eutrophication resulting from phosphorus addition to the system. The governments of the USA and Canada responded to this challenge by jointly adopting the Great Lakes Water Quality Agreement in 1972, which led to successful development and implementation of a scientifically based, phosphorus abatement program. In 2002 the U.S. General Accounting Office and the Auditor General of Canada jointly studied the status of the aquatic invasive species problem in the Great Lakes and assessed the responses of their respective governments.<sup>71 72</sup> Both reports, although issued independently, found that their respective Federal governments have made little progress, and remained generally unfocused and poorly coordinated more than a decade after the zebra mussel brought attention to the issue. Resolution of the NIS issue in the Great Lakes will require the same level of joint commitment and coordination from both countries as was used to solve the eutrophication problem under the Great Lakes Water Quality Agreement.

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<sup>71</sup> Office of the Auditor General. *Report of the Commissioner of the Environment and Sustainable Development to the House of Commons*. Chapter 4: Invasive Species. Ottawa, Canada. 28 pp. (2002).

<sup>72</sup> U.S. General Accounting Office. *INVASIVE SPECIES: Clearer Focus and Greater Commitment Needed to Effectively Manage the Problem*. Rep. 03-1, Washington DC, 101 pp; (2002).

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