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A pound of prevention, plus a pound of cure: Early detection and eradication of invasive species in the Laurentian Great Lakes

M. Jake Vander Zanden *, Gretchen J.A. Hansen [1], Scott N. Higgins [2], Matthew S. Kornis [3]

Center for Limnology, University of Wisconsin – Madison, 680 N. Park St. Madison, WI 53706, USA

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ABSTRACT

Ballast water regulations implemented in the early 1990s appear not to have slowed the rate of new aquatic invasive species (AIS) establishment in the Great Lakes. With more invasive species on the horizon, we examine the question of whether eradication of AIS is a viable management strategy for the Laurentian Great Lakes, and what a coordinated AIS early detection and eradication program would entail. In-lake monitoring would be conducted to assess the effectiveness of regulations aimed at stopping new AIS, and to maximize the likelihood of early detection of new invaders. Monitoring would be focused on detecting the most probable invaders, the most invasion-prone habitats, and the species most conducive to eradication. When a new non-native species is discovered, an eradication assessment would be conducted and used to guide the management response. In light of high uncertainty, management decisions must be robust to a range of impact and control scenarios. Though prevention should continue to be the cornerstone of management efforts, we believe that a coordinated early detection and eradication program is warranted if the Great Lakes management community and stakeholders are serious about reducing undesired impacts stemming from new AIS in the Great Lakes. Development of such a program is an opportunity for the Laurentian Great Lakes resource management community to demonstrate global leadership in invasive species management.

Introduction

Invasive species have imposed enormous economic and ecological costs upon ecosystems and the services they provide to humans (Lodge et al., 2006; Pimentel et al., 2000; Vitousek et al., 1996). In the Laurentian Great Lakes, over 180 aquatic invasive species (hereafter, AIS) have been established, making the Laurentian Great Lakes among the most heavily invaded ecosystems on the planet (Holeck et al., 2004; Riccardi, 2006). Though AIS in the Great Lakes have arrived as a result of a variety of pathways and vectors, ballast water of commercial ships is a major vector for AIS introductions (Holeck et al., 2004; Riccardi, 2006). In addition to the direct impacts on the Great Lakes, these systems are also a beachhead for secondary invasions into inland waters of North America (Vander Zanden and Olden, 2008), resulting in additional economic and ecological impacts.

The conventional wisdom among invasion biologists is that ‘an ounce of prevention is worth a pound of cure’: biological invasions often involve a small number of colonists, such that the cost of excluding colonists is trivial compared to dealing with the problem after populations become established and spread. In line with this, a major focus of management efforts in the Great Lakes has been the regulation of ballast water exchange (Costello et al., 2007; Ricciardi and MacIsaac, 2008). Canada and the United States enacted regulation of ballast water exchange of ocean-going vessels in the early 1990s, yet the rate of ballast-vectored invasions has not decreased in response (Holeck et al., 2004; Riccardi, 2006). This highlights the need for alternative management strategies, and a renewed effort to stem the high rates of AIS invasions into the Great Lakes region (National Research Council, 2008).

In light of the above, we consider the idea of an AIS early detection and eradication program for the Laurentian Great Lakes. There is a fundamental tension between prevention and eradication as management strategies, with prevention being proactive, and early detection and eradication being more reactive. It is possible that directing funding and effort to early detection and eradication would leave fewer resources for AIS prevention, highlighting this as a basic resource allocation issue – how should limited management resources be allocated so as to be most effective in stopping new invasions and minimizing further adverse impacts?

While we believe that efforts to prevent the entry of new AIS to the Great Lakes should continue to be the cornerstone of management efforts, we also believe that complementary management strategies such as early detection and eradication are simultaneously needed to

* Corresponding author. Tel.: +1 608 262 9464.
E-mail addresses: mjvanderzand@wisc.edu (M.J. Vander Zanden), ghansen2@wisc.edu (G.J.A. Hansen), snhiggins@wisc.edu (S.N. Higgins), kornis@wisc.edu (M.S. Kornis).
[1] Tel.: +1 608 263 2465.
[2] Tel.: +1 608 262 3088.
[3] Tel.: +1 608 263 2063.

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effectively address this issue (Fig. 1). Even the most effective prevention efforts are not guaranteed to eliminate new invasions, and some portion of these new invaders will have undesired ecological, economic, and human health impacts. In situations where prevention fails, an early detection program could alert managers to the establishment of a new invader, and a well-coordinated eradication program could contain or eliminate it before it spreads. In the absence of such a program, resource managers have no choice but to simply accept new invaders and the associated ecological and economic impacts. In fact, there are a number of examples of invasive species being detected early, and subsequently eradicated (Simberloff, 2002, 2003). In many cases, a costly eradication may be far preferable to incurring long-term damages and/or control costs. Based on this, we feel that a coordinated program aimed at early detection and eradication of AIS is worthy of serious consideration as part of the broader effort to minimize AIS impacts in the Great Lakes.

Aside from sea lamprey (*Petromyzon marinus*) control efforts coordinated by the Great Lakes Fishery Commission and the stocking of Pacific salmonids (*Oncorhynchus* sp.) to manage nuisance forage fish populations, there has been little interest in AIS control and eradication in the Great Lakes. The prospect of eradicating invasive species has received pessimism from many scientists and natural resource managers (Simberloff, 2002, 2003). Only recently has the issue of AIS control and eradication been formally taken up by the Great Lakes management community, with efforts going towards developing model rapid response plans (Great Lakes Commission, 2006b). As far as we know, there are no coordinated monitoring programs aimed specifically at detecting new AIS in the Great Lakes (Great Lakes Commission, 2006a), highlighting a major gap in our current ability to effectively respond to new invasions.

What would be the core features of an AIS early detection and eradication program? How might such a program allocate limited resources among species, habitats, and management actions to achieve program goals? In this paper, we highlight the key features of an early detection program for Great Lakes AIS """ aimed at assessing the effectiveness of prevention efforts, and maximizing the likelihood of early detection of new AIS. Second, we outline what a Great Lakes AIS eradication program might entail, using examples of successes and failures from other ecosystems, and develop a framework for deciding whether to attempt eradication when a new invader is detected. Finally, we consider the prospects and challenges of such an undertaking in the Great Lakes, and highlight program features that would help such a program to be successful. We hope to encourage discussion amongst scientists, managers, policy makers, and stakeholders on the role of early detection and eradication as part of a broader strategy to reduce the impacts of AIS in the Great Lakes and other inland waters of North America. Beyond this, we feel that an early detection and eradication program based on sound bioeconomic principles (Keller et al., 2009; Leung et al., 2002) would not only be worth the financial investment, but could be a valuable component of a broader program aimed at reducing further impacts of biological invasions in the Great Lakes.

Early detection and monitoring

Early detection and monitoring are key components of a broader invasive species management strategy, as noted in a recent position

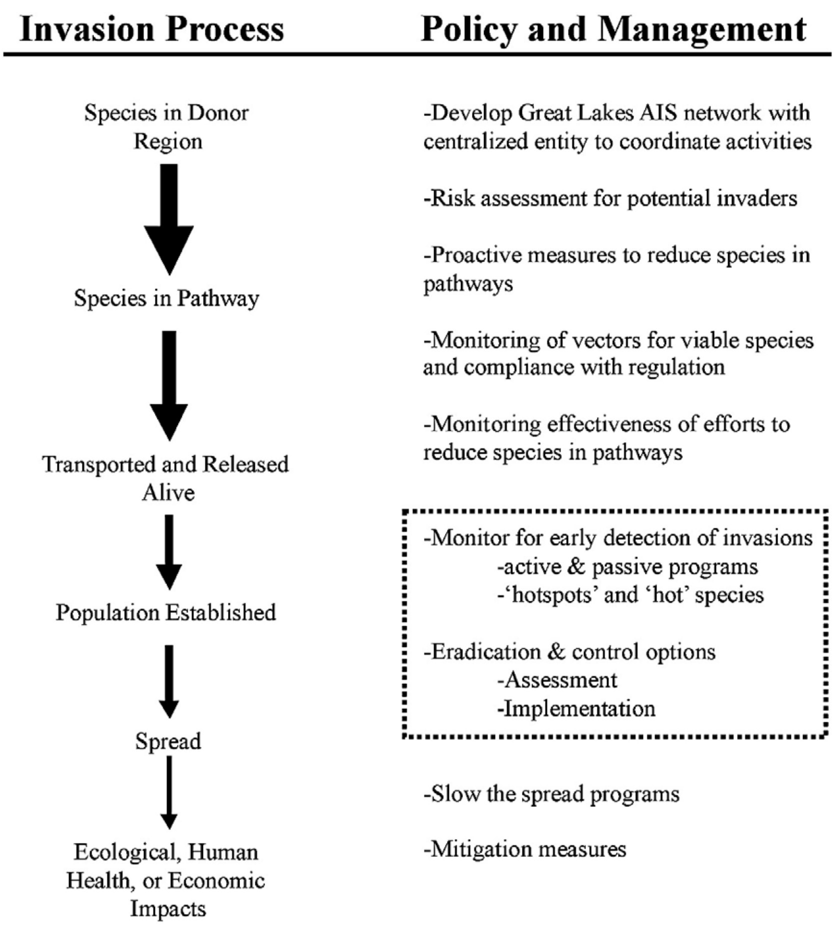

Fig. 1. Multiple stages of the biological invasion process, and the corresponding suite of policy and management actions. This paper specifically addresses the role of early detection and eradication strategies (highlighted in dotted box) for the Laurentian Great Lakes. Modified from Lodge et al. (2006).

paper from the Ecological Society of America (Lodge et al., 2006). The monitoring program outlined here focuses on detecting new invasive species in the Great Lakes, and would have two central objectives. The first is to evaluate the effectiveness of prevention measures such as regulation of ballast water exchange. The second is early detection of new invasive species in order to maximize the range of management options available, including control, containment, and eradication.

Evaluating the effectiveness of prevention

Environmental monitoring provides a basis for assessing the effectiveness of policy interventions (Walters, 1986). Data on the occurrence of ship-vectored species invasions into the Great Lakes during recent decades (Riccardi, 2006) provides a basis for assessing the effectiveness of current and future regulations (Fig. 2). In the absence of new policies to prevent AIS, invasions via ballast water might be expected to continue along this same trajectory (Scenario A). Scenario C is the desired outcome, and represents the cessation of new ship-vectored invasions following implementation of a new policy. Since there is uncertainty as to whether a new policy will reduce or eliminate new invasions, systematic monitoring is needed to assess whether the policy is effective. The above also serves as the basis for active adaptive management (Walters, 1986). For example, if a pre-designated reduction in new invasions is not achieved in response to a new policy, this could automatically trigger a shift to a more stringent standard. This management approach allows regulations to evolve in response to new knowledge, maximizes the rate of learning about the system, and may provide additional incentives to the regulated community to comply with current standards in order to avoid more stringent standards in the future.

Early detection to maximize potential for eradication

A second goal of monitoring would be the early detection of new AIS in order to maximize the potential for eradication. A number of reviews have emphasized that early detection is essential for eradication (Simberloff, 2002, 2003). The longer a new invasive species goes undetected, the lower the probability of successful intervention. As the population of the invasive expands, the costs of eradication increases, often exponentially, and the window of opportunity for eradication closes (Simberloff, 2003).

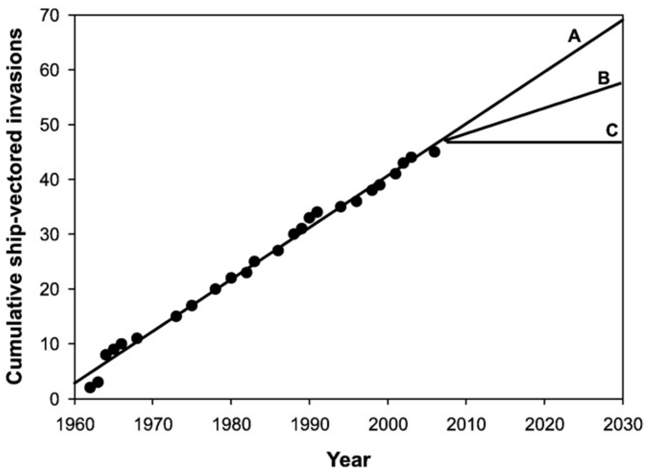

Fig. 2. Assessing the effectiveness of ballast water regulations based on in-lake invasive species monitoring. Graph shows the cumulative number of ship-vectored invasions since 1959 as a function of time (adapted from Riccardi, 2006). A — the trend for the period 1959–present continues. B – the rate of new ship-vectored introductions is reduced. C — the desired outcome, cessation of ship-vectored invasions to the Great Lakes following the new policy.

The Laurentian Great Lakes are large, open ecosystems, and if a new invader is allowed to spread, the opportunity for eradication may be quickly lost. The importance of early detection of AIS in open ecosystems can be highlighted using two examples. Black striped mussel (*Mytilopsis sallei*) is native to the Caribbean and has become a problematic biofouling invader in harbors in Fiji, Japan, India, Taiwan, and Hong Kong. The species was discovered in Cullen Bay, Darwin Harbor, Australia in 1999. Within days, authorities had conducted a hazard analysis, as well as experiments to determine the best control method. The bay was quarantined and treated with chemicals, effectively killing all living organisms in the marina (Bax et al., 2002). The eradication involved 280 people and the total cost was approximately $2 million (AUD). The Northern Territory government was able to mobilize the efforts of multiple agencies to rapidly eradicate this invader, and in doing so, prevented their establishment in Australia. The Darwin Harbor example highlights the potential value of an effective early detection and rapid response program. Had black striped mussel not been detected early in the invasion process, eradication would not have been possible. It is likely that economic and ecological damages of black striped mussel in Australia would have greatly exceeded the eradication expenditures.

A success and a failure of eradicating an invasive green algae, *Caulerpa taxifolia*, provides another illustrative example. An introduced population of *Caulerpa* was discovered off the Monaco coast in 1984. For several years, this species was confined to a small area, though eradication was not attempted because management agencies were not willing to take responsibility for eradicating the invader. *Caulerpa* has since become a problematic invader throughout much of the Mediterranean Sea. In 2000, *Caulerpa* was discovered in a coastal lagoon near San Diego, California. Authorities were able to mount a rapid and successful eradication effort by isolating the benthic algal mats with PVC tarps and treating with chlorine (Simberloff, 2003). The contrast in outcomes between the two invasion events highlights the importance of clear lines of authority, effective coordination among agencies, and the ability to take management actions before the species has the chance to spread.

Species risk assessments

The above examples demonstrate that AIS can be eradicated in large, open ecosystems. Yet it is important to note that not all introduced species are of equal concern. Many species that are introduced to the Great Lakes do not establish a self-sustaining population. Of those that establish, many have no measurable ecological or economic impact (Ricciardi and Kipp, 2008). It is a select group of invasive species that have devastated native fisheries, transformed aquatic ecosystems, and exacted major economic impacts in the Great Lakes (Mills et al., 1993; Pimentel et al., 2000, 2005). Furthermore, only a fraction of the Great Lakes invaders have subsequently spread to surrounding inland lakes and streams (Vander Zanden and Olden, 2008).

That being the case, is it possible to identify the subset of species that are most likely to become problematic invaders? There has been recent interest in identifying species and donor regions that represent the highest risk to the Great Lakes. In an analysis of invasive fishes, Kolar and Lodge (2002) identified species traits associated with establishment, spread, and impact within the Great Lakes and identified 5 out of 66 (7.5%) fish species from the Ponto-Caspian basin with potential to become nuisance species (having the potential to establish, spread, and have undesired impacts) in the Great Lakes. Grigorovich et al. (2003a) identified 26 out of 293 invertebrate species with histories of invasions from three donor regions that represented a high risk of becoming established and spreading in the Great Lakes. A complementary approach to risk assessments identifying high-risk species is to identify regions from which many invaders originate, and focus monitoring efforts on detecting species from these regions. All ships from these regions could be considered potential vectors, and areas visited by these ships could be the focus of monitoring. The Ponto-Caspian is a major donor basin for AIS in both Eurasia and North America, and comprises an invasion corridor with the Laurentian Great Lakes (MacIsaac et al., 2001). The invasion corridor concept coupled with previous patterns of invasion in Eurasia has already provided the basis for forecasting invasions in the Laurentian Great Lakes (Ricciardi and Rasmussen, 1998).

Because resources for monitoring and eradication will be limited, efforts could be further targeted to taxa that are most likely to become problematic invaders. Additional species risk assessments should be conducted for other taxonomic groups and donor regions. Tools have been developed that can accommodate the high levels of uncertainty associated with species-based risk assessments, and quantify risks identified through a variety of sources (Sikder et al., 2006). In the Great Lakes, species risk assessments have successfully forecasted invasions. For example, both Ricciardi and Rasmussen (1998) and Grigorovich et al. (2003a) listed the bloody-red Mysid, *Hemimysis anomala*, as a high-risk invader well before this species was reported in Lake Michigan and Lake Ontario in 2006. In designing a monitoring program, personnel could be trained to identify species identified as potential high-impact invaders, and monitoring could be tailored to detect these species.

An additional consideration for an early detection program is the potential for eradication of a species once it is detected. Habitats and taxonomic groups differ widely in terms of susceptibility to control/eradication efforts. Taxa inhabiting open (pelagic) habitats with high population growth rates, high mobility, and dormant resting stages would tend to be poor candidates for eradication. On the other hand, taxa with low population growth rates and low mobility inhabiting isolated environments such as coastal wetlands or embayments would be more amenable to eradication (Bomford and O'Brien, 1995; Myers et al., 2000). Though monitoring should cover the full range of habitats and taxa, they could be most heavily directed towards detecting taxa that are amenable to eradication.

Time and place risk assessment

Just as risk assessments can help detect species with the greatest invasive potential, there may be times and places that are more likely to experience invasions. Grigorovich et al. (2003b) examined the location of first detection for Great Lakes invaders for the past 50 years, and identified invasion 'hotspots' – areas with high concentrations of new invasive species. Approximately 5% of the Great Lakes surface area supported >50% of recent invasions — these hotspots were ~20 times more highly invaded than non-hotspot areas. Indeed, propagule pressure is often argued to be the most important determinant of invasion success (Kolar and Lodge, 2001; Ricciardi and MacIsaac, 2000), and including metrics of propagule pressure in predictive models can increase their accuracy (Leung and Mandrak, 2007). Additionally, invaders may be more likely to arrive and establish during certain times of year or under certain environmental conditions. For example, Drake et al. (2006) reported a window of invasion opportunity for *Bythotrephes* during the summer months. Though the invasion window might differ among species, the idea of 'hot times' merits further research, and could further improve the effectiveness of monitoring.

Specifics of an early detection program

The above sections provide an overarching framework for a monitoring program aimed at detecting the most probable, harmful, and controllable AIS at high-risk locations for the Laurentian Great Lakes. The many programmatic details of an on-the-ground AIS early detection program are beyond the scope of this paper, though we feel strongly that there needs to be a central agency or binational commission that funds, coordinates, and oversees management activities, which would inevitably span the adjoining Great Lakes states and provinces.

We envision the creation of a new and basin-wide 'active' AIS monitoring program. The focus would be to target high-risk areas for new invasive species, with particular emphasis on species identified as high-risk invaders. In the event that a new invader is detected, a second function of the program would be to serve as first responders, validating the occurrence, and conducting an AIS status assessment (SA). With assistance of other resource management agencies, their task would be to rapidly assess the magnitude of the invasion in terms of spatial extent, population density, rate of spread, habitat use, and the presence of species life-history stages. The SA would be a critical document in the decision-making process of whether to attempt eradication, which we refer to as the eradication assessment (EA).

In addition to the new program of active AIS monitoring noted above, the program would also link to the many ongoing monitoring and research efforts being carried out by agencies, industry, citizen groups and academics (Great Lakes Commission, 2006a). Existing monitoring programs do detect new AIS, though such discoveries are generally incidental. Such programs are termed 'passive' monitoring programs since the detection of AIS is not their primary objective. Existing monitoring programs in the Great Lakes are diverse and extensive, and have potential to aid in AIS surveillance. Increased training, coordination, and funding could greatly improve the value of existing monitoring efforts for AIS detection (Great Lakes Commission, 2006a), but would require close involvement of a coordinating body. One major challenge of both active and passive monitoring efforts would be to provide species identifications in a timely manner following sample collection in order to allow for a management response.

To eradicate, or not to eradicate?

Upon discovery of a new AIS, a response decision must be made. Eradication can be costly in the short-term, but may be a cost-effective option if the invader can be eliminated. The decision of whether or not to attempt eradication is a serious one, and needs to weigh several factors: the costs of eradication, the likelihood of success, and in the absence of eradication, the expected impact or costs of the invader on the Great Lakes and surrounding ecosystems (Table 1). Evaluating these factors requires a process for examining

Table 1
Factors to consider in assessing whether to attempt to eradicate an invasive species.

What is the cost of action?
What is the expected cost (time and money) of eradication?
What is the probability of having to repeat the eradication attempt, due either to failure or reinvasion?-What is the expected cost of collateral damage (ecosystems or humans)?
What is the cost of any additional ecological restoration?
What is the likelihood of eradication success?
Biological factors:
Is the invader detected early in invasion sequence?
What is the status of the invader (density, area infested, rate of range expansion)?
Is the species/habitat amenable to eradication?
What is the likelihood of reinvasion?
Social and institutional factors:
Are there sufficient resources to carry the project to completion?
Are institutions capable of carrying out an eradication (leadership, funding, well-defined lines authority, ability to harness efforts of other institutions)?
Is there public support and participation?
Are there other legal or institutional barriers that would limit or delay eradication?
What is the cost of inaction?
What are the anticipated economic and ecological costs/impacts of the invader?
What is the probability of the invader causing negative impacts?

existing information, comparing alternative options, and making a management decision – most importantly, whether or not to attempt eradication (Bax et al., 2001).

Traditional benefit–cost analysis could be used to decide whether to eradicate a new invader (Naylor, 2000). Upon detection of a new invader, eradication should proceed only if the expected net benefits (costs or impacts avoided) of the control program exceed the expected direct cost of eradication plus collateral damage costs, and incorporating a weighting for the likelihood of eradication. Several recent studies have compared costs and benefits of invasive species control. An *ex post* analysis for Tamarisk in the southwestern U.S. found that the benefits of control generally outweighed costs (Zavaleta, 2000). The cost of clearing invasive plants in South African fynbos ecosystems was small relative to the value of the services provided by these ecosystems, such that proactive management substantially increased the value of those services (Turpie and Heydenrych, 2000). In the above examples, it was possible to directly quantify invader impacts because they had already established and had produced measurable impacts. Unfortunately, *ex post* benefit–cost analyses are not particularly relevant to the case of AIS eradication in the Great Lakes because the AIS of interest have not yet been established, thus making it impossible to directly measure impacts. More appropriate are *ex ante* benefit–cost analyses, in which analysis is conducted prior to the occurrence of the AIS. *Ex ante* analyses involve predicting how the invasion would affect the ecosystem, and quantifying impacts in monetary terms. An example of a theoretical *ex ante* benefit–cost framework for AIS eradication is provided by Bax et al. (2001). Though benefit–cost analysis provides an appealing framework for assessing AIS eradication, there remains a gap between theory and our ability to apply it to environmental decision-making in many situations (Naylor, 2000).

Despite such challenges, resource management in the Great Lakes is often based on consideration of costs and benefits. Sea lampreys spread through the upper Great Lakes during the 20th century following the opening of the Welland Canal, producing dramatic fisheries declines (Smith and Tibbles, 1980). The Great Lakes Fisheries Commission was formed in 1955, in part to control sea lamprey populations. Ongoing control with lampricides has produced sustained reductions (~90%) in sea lamprey populations, greatly reducing their adverse impacts. The U.S. and Canada continue to cooperatively manage sea lamprey through the efforts of the Great Lakes Fishery Commission. Though the sea lamprey control program costs approximately $15 million annually, it sustains widespread support because the benefits of sea lamprey control to commercial and recreational fisheries far outweigh the annual control costs (Lupi et al., 2003).

There is a diversity of approaches for assessing management options. Leung et al. (2005) presented mathematical "rules of thumb" describing conditions under which invasive species control measures may be warranted, and the functional forms of equations for calculating optimal expenditures on prevention and control measures. Using this approach, managers could calculate under what conditions eradication may be warranted for a given invader. As with benefit–cost approaches, the application of this approach requires estimates of parameters that are difficult to quantify. Even when a species has known ecological impacts, these impacts are rarely quantified in dollar terms. Non-market valuation methods provide a way of evaluating the ecological impacts of AIS. For example, a combined contingent-valuation travel-cost study of invasive species that cause harmful algal blooms found that management actions costing less than 225 million euro would produce a net economic benefit (Nunes and Van den Bergh, 2004). A hedonic study of Eurasian watermilfoil (*Myriophyllum spicatum*) in Wisconsin lakes found that land parcels on milfoil-invaded lakes experience a 13% decrease in land value (Horsch and Lewis, 2009). Valuation studies such as these are tremendously useful for determining reasonable expenditures on prevention, control, and eradication of invasive species. Quantifying non-consumptive, indirect-use, and non-use impacts of Great Lakes AIS should be an important research priority, and will allow benefit-cost approaches to be applied in the future. If reasonable distributions for these parameters can be generated, risk assessments and decision analyses could be used to assess the range of conditions under which eradication may be warranted.

It is crucial that there be a formal process for guiding AIS eradication decision-making. A number of alternative risk assessment approaches, such as rule-based models and decision trees, provide qualitative or semi-quantitative frameworks for assessing costs and benefits of invasive species eradication (Reichard and Hamilton, 1997; Wittenberg and Cock, 2005). A primary task of a newly established early detection and eradication program would be to develop an AIS eradication assessment (EA) process to be applied to a new invasion upon discovery. Development of the process would involve participation from state, federal, and provincial resource management agencies, as well as other experts from a range of disciplines, including economics, ecology, risk assessment, statistics and decision sciences. The EA process would need to be capable of synthesizing the available information and provide short- and long-term guidance on AIS eradication. In a basic sense, the assessment would weigh the cost of action (attempting eradication), the consequences of inaction (not attempting eradication), and the likelihood of success (Table 1). Likelihood of success is affected by biological attributes of the invader, geographic extent and susceptibility to control efforts, as well as social and institutional factors, including the availability of resources and institutional barriers to eradication (Table 1).

The theory of decision-making under high uncertainty is an area of interest in diverse disciplines (Popper et al., 2005), but has not been widely applied to invasive species management (but see Sikder et al., 2006). For a given AIS, a wide range of realistic impact scenarios could be generated, and it may be impossible to identify which scenarios are most likely. Even if a 'most likely' impact scenario can be generated, is it appropriate to manage for this scenario, the worst-case scenario, or the best-case scenario? A 'low-impact' scenario may lead to the decision not to eradicate, while a 'high-impact' scenario for the same species may generate a decision to attempt eradication. Resolving this issue can benefit from application of decision theory, explicitly considering outcomes from different decision rules across a range of future scenarios. Rather than attempting to identify the most likely impact scenario and making a decision based upon this, an alternative approach is to search for the management option that is most robust across a broad range of impact scenarios, and most capable of preventing unacceptably catastrophic outcomes (Lempert et al., 2003; Popper et al., 2005). This decision strategy is analogous to Savage's (1951) 'minimax regret' criterion, which aims to minimize the maximum regret across the range of scenarios considered (Savage, 1951). Recent advances in computing power allow a diversity of scenarios to be generated in search of the most robust management strategies (Lempert et al., 2003).

AIS eradication has traditionally been viewed as a simple yes–no decision (Wittenberg and Cock, 2001). Incorporation of robust decision-making may lead to alternative options, particularly on short-term time horizons. For example, the most robust short-term management option in the face of uncertainty could be to contain the further spread of the AIS while additional information about population growth rates and eradication prospects is gathered. This strategy maintains the option to eradicate without immediately committing to a costly and potentially unsuccessful eradication program. By preserving future management options, this strategy allows collection of information that can reduce uncertainty and provide for more informed decision-making (Naylor, 2000).

Prospects and challenges of early detection and eradication for the Great Lakes

The goal of this paper was to outline and stimulate discussion of an early detection and eradication program for AIS in the Great Lakes. Our proposed approach is based on two pillars: 1) monitoring aimed at early detection of new AIS, and 2) upon detection of new AIS, making a management decision, which could include eradication. It is essential for an invasive species management program to have clearly defined goals, in order to provide a sound basis for management decisions and prioritization (Lodge and Shrader-Frechette, 2003). Is the broader goal to eliminate new invasions, to minimize adverse economic impacts, to protect native biotic communities, or to minimize further changes to Great Lakes food webs? Considering that AIS management funding is limited and that many AIS appear to have little economic or ecological impact, the goal of completely stopping new invasions may not be realistic. Risk assessment strategies are therefore needed; in this case, preemptively identifying and targeting species likely to spread and have adverse economic and ecological impacts.

Implementation of an early detection and eradication program would face many challenges. First and foremost, the current legal capacity of federal, state, and provincial governments for rapid response management of AIS is poorly developed (reviewed for the live fish trade by Thomas et al., 2009). It is imperative that the coordinating body for invasive species early detection and eradication has the legal authority to act promptly in response to new invasions. Entrustment of such authority will not come easily, and is very much a political issue. Educating the public and the relevant interest groups of the value of early detection and rapid response to species invasions would help build support for expanded AIS management powers.

Another constraint is the current lack of taxonomic expertise that would be needed to process large numbers of biological samples and identify new AIS. Such a program would necessitate a major investment in training biologists and taxonomists (Lodge et al., 2006). Furthermore, methods for control and eradication of AIS may not exist in many cases, and there is a need for leadership in developing, testing, and implementing new methods of AIS control and eradication. Past experience with eradication of non-native mammals on oceanic islands (Cromarty et al., 2002; Veitch and Clout, 2002) may provide valuable lessons for the Great Lakes. Efforts to eradicate non-native mammals began in the late 1950s, with early projects successfully eradicating mammals on small islands (<10 ha). Gradual improvements in rodenticide and trapping methods allowed mammal eradication on increasingly larger islands. The number of eradication projects on islands has continued to grow, and recent projects have eradicated mammals from islands as large as several thousand hectares in size (Thomas and Taylor, 2002; Veitch and Clout, 2002).

Another important program consideration is the prospect of unwanted collateral impacts of eradication efforts. Eradication efforts could have impacts on non-target species, ecosystems, and human health. Such concerns are greatest with the use of chemical control methods. For example, the widely used chemical rotenone is an effective tool for control of invasive fish, but would also kill other aquatic animals in the treated area. Many of the other chemicals potentially used for invasive species control could have toxic impacts on humans and wildlife. Such factors are additional costs of control, and could severely limit control options. The situation could also create conflict between regulatory agencies with different and competing mandates, as well as with the general public.

The prospect of non-target impacts could generate opposition from the public. Citizen opposition could delay or halt the implementation of AIS eradication during the critical early stages of invasion. The general public will demand answers to questions such as: What are the non-target impacts? Will doing this eliminate the invasive species? To address this, stakeholders would ideally be involved in planning exercises *before* the discovery of new AIS. Though stakeholder involvement is generally viewed as an important component of natural resource decision-making, a lengthy stakeholder participation process could severely limit the ability of resource managers to take appropriate action following discovery of a new invader.

Collateral impacts may also manifest themselves through complex food web interactions. For example, eradication of an invasive species may have adverse consequences for native species that rely on the invasive for food or habitat, or could release a second invasive species from predation, resulting in a secondary species outbreak (Bergstrom et al., 2009; Vander Zanden et al., 2006; Zavaleta et al., 2001). This highlights the importance of viewing invasive species eradication not as an end in itself, but rather as a part of a broader effort to achieve restoration goals, such as restoring the diversity and functioning of ecosystems (Vander Zanden et al., 2006; Zavaleta et al., 2001). Collateral impacts of an eradication campaign can only be assessed through post-eradication monitoring. Understanding the broader, non-target effects of AIS eradication through follow-up monitoring is essential if we are to improve the effectiveness of eradication efforts.

It is also important to consider how biological invasions relate to site attributes. Invasion research in a wide variety of ecosystem types indicates that disturbed sites tend to be more vulnerable to invasion (Orians, 1986). For example, reservoirs appear to be more susceptible to invasion than natural lake ecosystems (Havel et al., 2005). Human-disturbed wetland patches may provide a foothold to invaders, thereby opening the broader ecosystem to species invasions. In Lake Tahoe (CA-NV), exotic fishes established initial populations in the highly disturbed marinas, and have subsequently spread to surrounding undisturbed habitats (Kamerath et al., 2008). In some of these cases, it can be difficult to sort the effects of habitat disturbance from increased rate of propagule introduction. Nevertheless, aquatic invasions are often linked to human disturbance, and efforts to maintain natural ecosystems and reduce such disturbances will reduce the potential for species invasions. Where disturbance is unavoidable (for example, at construction sites), monitoring can be directed to these locations to detect invaders before they have the chance to spread.

The Great Lakes have already been deeply impacted by AIS. Impacts will continue to increase as established invaders spread within the basin, and new invasive species arrive. There is a need for an intensified and more diverse range of management strategies in order to minimize further impacts of AIS (Lodge et al., 2006). With this in mind, we believe that early detection and eradication have a role to play in the broader program of proactive AIS management for the Great Lakes. Not only would successful eradication result in the evasion of additional economic and ecological costs of invasive species, but expanded AIS monitoring would also provide a basis for assessing whether policies aimed at preventing new AIS were effective.

Our ultimate intention is to encourage a broader debate on AIS management strategies for the Great Lakes – whether current effort and expenditures are sufficient, and how effort and resources are allocated among management activities. The fundamental question that is not quantitatively addressed in this review is whether the expected benefits (i.e., economic and ecological losses avoided) of an early detection and eradication program for the Great Lakes would exceed the costs of such a program. Though there is high uncertainty associated with many of the parameters required for such a comparison, an assessment of this question, across a range of scenarios, is an important next step. The often fatalistic view that AIS cannot be stopped or managed needs to be reassessed and revisited (Simberloff, 2002). We feel that an early detection and eradication program based on sound bioeconomic principles (Keller et al., 2009), and with the authority to act in response to eradication opportunities, has the potential to play an important role as part of a broader AIS management strategy in the Laurentian Great Lakes.

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