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GREAT LAKES SHIPPING, TRADE, AND AQUATIC INVASIVE SPECIES

Surveillance and Control of Aquatic Invasive Species in the Great Lakes

Prepared for
Committee on the St. Lawrence Seaway:
Options to Eliminate Introduction of Nonindigenous Species into the Great Lakes, Phase 2
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SUMMARY

Preventing the introduction of new invasive species should be the cornerstone of efforts to minimize their adverse ecological and economic impacts. Yet recent ballast water regulations have not slowed the rate of new invasions into the Great Lakes. This paper describes the features of a surveillance and eradication program for aquatic invasive species (AIS) in the Great Lakes. The proposed surveillance program has two purposes: assessing the effectiveness of ballast water regulations, and maximizing the likelihood of early detection, which is essential for eradication. When a new AIS is discovered, an eradication assessment (EA) is 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. This paper highlights the importance of a well-defined strategic vision for AIS management, stakeholder participation, institutional barriers, and recognition of non-target impacts as fundamental considerations in Great Lakes AIS management. Given adequate resources and a favorable institutional setting, a targeted surveillance and eradication program could be a valuable component of a broader invasive species management strategy for the Great Lakes.

1. INTRODUCTION

Invasive species are widely recognized as a leading threat to biodiversity (Wilcove et al. 1998, Sala et al. 2000) and have imposed enormous economic costs upon fisheries, agriculture, forestry, and human health (Vitousek et al. 1996, Pimentel et al. 2000, Lodge et al. 2006). In the case of the Laurentian Great Lakes, over 180 aquatic invasive species (hereafter, AIS) are known to have established populations (Holeck et al. 2004, Riccardi 2006). Though AIS have arrived as a result of a variety of different activities and vectors, ballast water of commercial ships is a dominant vector for AIS introductions (Riccardi 2006). The increasing rate of AIS introduction to the Great Lakes corresponds with the increase in ocean-going vessel traffic (Holeck et al. 2004, Riccardi 2006). As a result, regulation of ballast water exchange was enacted in the early 1990s. In spite of these regulatory efforts, the rate of invasions has increased since these regulations have been enacted (Holeck et al. 2004, Riccardi 2006), highlighting the need for alternative approaches and a renewed effort to stem the onslaught of AIS.

Not all AIS are created equal. In the Great Lakes, many species that are introduced fail to establish a self-sustaining population. Of those that establish, many appear to have no measurable ecological or economic impact on the Great Lakes. Other species such as zebra mussel and sea lamprey have generated major ecological and economic impacts, resulting in the loss of native species, altered food webs, and economic losses. A subset of these Great Lakes AIS has subsequently spread to surrounding inland lakes and streams, causing further ecological and economic harm. AIS now dominate the food webs of the Great Lakes, and provide the basis for valuable recreational fisheries. In light of this, it is unlikely that the Great Lakes ecosystems can ever be restored to anything resembling their pre-invasion state (Kitchell et al. 2000).

My task is to provide recommendations for an AIS surveillance and eradication program as part of a broader strategy for AIS management in the Great Lakes. I begin by examining several AIS control/eradication case studies, and the prospects and challenges of an eradication program in the Great Lakes. Second, I describe the features of a surveillance program for assessing the effectiveness of prevention efforts and maximizing the likelihood of early detection. Third, I address the factors to be considered in deciding whether to attempt eradication when a new invader is detected. Finally, I consider the barriers and institutional framework needed for this program to be successful in its mission.

2. GENERAL LESSONS FROM INVASION BIOLOGY AND MANAGEMENT

General management strategies for AIS include prevention, eradication, containment, and control (Table 1) (Wittenberg and Cock 2001). Aside from sea lamprey control and the stocking of Pacific salmon to control alewife populations, there is virtually no experience with the control or eradication of invasive species in the Great Lakes, and there is currently no coordinated program for assessing and implementing AIS control or eradication. Efforts to control or eradicate AIS in aquatic habitats have generally been directed towards small isolated water bodies (Vredenburg 2004, Hein et al. 2007). Resources have been invested in invasive species eradication in other ecosystem types, and there is an extensive literature dealing with AIS control and eradication in terrestrial environments, particularly for small oceanic islands (Cromarty et al. 2002, Veitch and Clout 2002). These experiences provide useful lessons for other ecosystems, including the Great Lakes (Myers et al. 2000, Cromarty et al. 2002, Simberloff 2003). In the following section, I examine a series of AIS control case studies, and consider the general features of successful AIS control programs.

TABLE 1 Definition of Terms Relating to Aquatic Invasive Species Management Used in This Paper.

Terms	Definition
Control	Attempt to reduce the abundance and/or adverse impact of an invasive species
Containment	Restrict an invasive species to a limited geographic range
Eradication	Elimination of entire population of a species
Surveillance	Effort to detect the presence and abundance of AIS
Aquatic Invasive Species (AIS)	Any aquatic species that has been transported beyond its native range, regardless of adverse impact
Eradication Assessment (EA)	The formal process for assessing the costs and benefits of conducting an eradication campaign for a specific AIS.
Status Assessment (SA)	A rapid assessment of the status and distribution of an AIS upon its discovery in the Great Lakes

Case Study #1: Control of Exotic Mammals on Islands

Introductions of non-native mammals, for example, rats, mice, pigs, and rabbits, represent the most significant cause of species extinctions and ecosystem perturbations on islands worldwide (Thomas and Taylor 2002, Veitch and Clout 2002). Efforts to eradicate non-native mammal populations began in the late 1950s, and achieved eradication on small islands (<10 ha). Over time, there were steady improvements in rodenticide and trapping effectiveness, leading to non-native mammal eradication on increasingly larger islands. The number of eradication projects has increased rapidly in recent decades, and several projects have eradicated mammals from islands as large as several thousand hectares in size (Thomas and Taylor 2002, Veitch and Clout 2002). This case study demonstrates that tremendous progress can be made if effort is invested, and that AIS eradication can be a viable and effective management approach.

Case Study #2: Eradication of Mytilopsis in Darwin Harbor, Australia

Mytilopsis (black-striped mussel) is native to the Caribbean and has invaded harbors in Fiji, Japan, India, Taiwan, and Hong Kong. The species was discovered in Cullen Bay, Darwin Harbor, Australia in 1999. Within days, a hazard analysis had been conducted, experiments were conducted to determine the best control method, and the bay was quarantined and treated with chemicals, effectively killing all living organisms in the marina (Bax et al. 2002). The Northern Territory government was able to mobilize the efforts of multiple agencies to rapidly eradicate this invader, and in doing so, appear to have prevented spread of this harmful invader. The eradication involved 280 people and the total cost exceeded $2 million Australian dollars. This example demonstrates that AIS can be eradicated if detected early.

Case Study #3: Eradication of *Caulerpa* in the Mediterranean and California

Caulerpa taxifolia was discovered off the Monaco coast in 1984. For several years, this species was confined to a very 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 large areas of the Mediterranean. The opportunity to eradicate was lost while management agencies squabbled. In 2000, *Caulerpa taxifolia* was discovered in a coastal lagoon near San Diego, California. Authorities were able to mount a rapid and successful eradication effort (Simberloff 2003). This example highlights the importance of the institutional situation for eradication. Though many institutional models could be successful, effective leadership and clear lines of authority are essential.

Case Study #4: Control of Sea Lamprey in the Great Lakes

Sea lamprey appeared in Lake Ontario in 1835, and spread through the upper Great Lakes during the 20^{th} century following the opening of the Welland Canal, producing dramatic declines in several important fisheries. The Great Lakes Fisheries Commission was formed in 1955, in part to manage sea lamprey populations. Control with lampricides has produced dramatic (~90%) reductions in sea lamprey populations, greatly reducing their adverse impacts on Great Lakes fisheries, and the U.S. and Canada continue to cooperatively managed sea lamprey through the efforts of the Great Lakes Fishery Commission. Sea lamprey control provides an example of the benefit of AIS management in the Great Lakes, and how directed research can lead to advances in AIS control. The situation also differs in fundamental ways from efforts to eradicate new AIS upon arrival, and will require a substantially different paradigm.

The four case studies above all provide insights into the potential for control and eradication of invasive species in the Great Lakes. Conditions that favor AIS eradication can be classified as either biological or institutional in nature (Table 2), and have been summarized in several reviews (Bomford and O'Brien 1995, Cromarty et al. 2002, Simberloff 2002, 2003). A surveillance and eradication program for the Great Lakes would need to explicitly incorporate the institutional attributes that facilitate successful eradication.

There is no doubt that eradication is costly. If eradication is attempted and the target species persists, then resources may have been wasted. The conventional wisdom in invasion biology is that 'an ounce of prevention is worth a pound of cure' – most authorities would agree with the assertion that prevention is the best and most cost-effective strategy for managing impacts of AIS. The reason for this is self-evident: any given biological invasion commences with the arrival of a small number of colonists, such that the cost of excluding colonists is trivial compared to the cost of controlling or eradicating the invader once it has become established. If substantial resources were allocated to surveillance and eradication, fewer resources would be available for AIS prevention. In light of the obvious benefits of invasive species prevention, the notion of investing in a program with the explicit goal of eradicating AIS is controversial, and there are diverse perspectives regarding the relative value of early detection and eradication of AIS. One perspective is that such a program would not be worth the effort. Resource managers have little experience eradicating freshwater invasive species, and an effective program would be exceptionally costly. If the campaign does not eradicate the target species, the effort and resources invested are largely wasted, aside from the new information generated in the process. Considering that the Great Lakes ecosystems are already dominated by invasive species, it is easy to argue that limited natural resource management resources should be directed elsewhere.

TABLE 2 The Literature on AIS Control Has Identified the Conditions that Favor Successful Invasive Species Eradication (Bomford and O'Brien 1995, Myers et al. 2000). A Summary of this, Adapted for the Great Lakes, Is Given Below. Factors Are Divided into Two Categories, Institutional and Biological.

Institutional

- **Economic and financial resources** sufficient to carry an effort to its conclusion
- **Leadership -** proper planning and organization, clearly-defined lines of authority, and the ability to inspire the cooperation of partners
- **Broad support** and public participation
- **Power** – lead organization able to take necessary action immediately
- **Knowledge** – the basis for making wise decisions

Biological

- **Invader detected early** in invasion sequence
- Invader detectable at low densities
- Invader must be **susceptible** to control – habitat type, life history, ability to access entire population: possible to **remove species** faster than reproductive rate
- low **likelihood of reinvasion**

An alternative perspective derives from the precautionary principle. AIS will continue to invade and have ecological and economic impacts. Though eradication is costly and there is a high degree of uncertainty as to which species will have adverse impacts, these concerns should not discourage efforts to limit AIS impacts, including the option of eradication in cases where prevention fails and managers can be reasonably certain that eradication is achievable. Both of the above perspectives stem from acknowledging the harsh realities of AIS management in the Great Lakes: the ecosystems have already been deeply impacted, and there is a high degree of uncertainty as to the identity and impact of future AIS.

Based on the above, there is no doubt that preventing new invasions should comprise the core of an integrated invasive species management strategy. Yet even the most well-conceived and effective prevention program is unlikely to eliminate new invasions. AIS have been eradicated in many cases, and eradication is far preferable to incurring long-term control costs. Because many tools and techniques for AIS eradication have not yet been developed, the envisioned program for the Great Lakes would need to be at the forefront of developing and advancing eradication methods (section 5).

I conclude that a program aimed at eradication of AIS should comprise a secondary component of a broader program to minimize AIS impacts in the Great Lakes. How would the eradication program be structured? There is perhaps only one certainty in environmental management: that resources are limited, and will appear inadequate to accomplish the stated management goal. This is likely to be the case with invasive species surveillance and eradication, particularly because these activities are costly. In light of this, how should the program allocate limited resources among species, habitats, and management actions to achieve program goals? This situation highlights the need to carefully prioritize management efforts and allocate resources accordingly (Byers et al. 2002). Prioritizing requires the ability to identify the sites and species of greatest concern, though predicting invasions remains controversial and uncertain (Lodge 1993, Williamson 1996, Williamson and Fitter 1996). I focus on two levels of prioritization: 1) prioritized surveillance efforts aimed at maximizing the likelihood of early detection of new AIS, and 2) upon detection, a process for deciding whether to attempt to eradicate. Both approaches rely on the general principles of risk assessment to provide guidance for environmental decision-making.

3. SURVEILLANCE

The surveillance program outlined here focuses on detecting new invasive species in the Great Lakes ecosystems, and has two objectives: 1) detecting new invasive species soon after their arrival and establishment in order to evaluate the effectiveness of prevention measures (i.e., ballast water regulations), and 2) early detection of new invasive species in order to maximize the likelihood of eradication.

Evaluating the Effectiveness of Prevention

The charge of this NRC committee was to offer policy recommendations to halt new ballast water invasions to the Great Lakes. Fig. 1 is a hypothetical graph showing the cumulative number of ship-vectored species invasions into the Great Lakes since 1960. In the absence of new policy to prevent new AIS, ballast water invasions would 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 the new policy. Yet there is uncertainty as to whether the new policy will achieve the desired outcome. In light of this, monitoring the Great Lakes ecosystems to detect new invasions is necessary to assess whether the policy is successful and new invasions are halted (Scenario C), or whether current trends continue into the future (Scenario A). A third scenario is that the rate of ballast water invasions is reduced, but not eliminated (Scenario B). Surveillance to document new invasions upon arrival and establishment in the Great Lakes is the basis for differentiating between these scenarios, and whether the new policy produces the desired outcome (Figure 1).

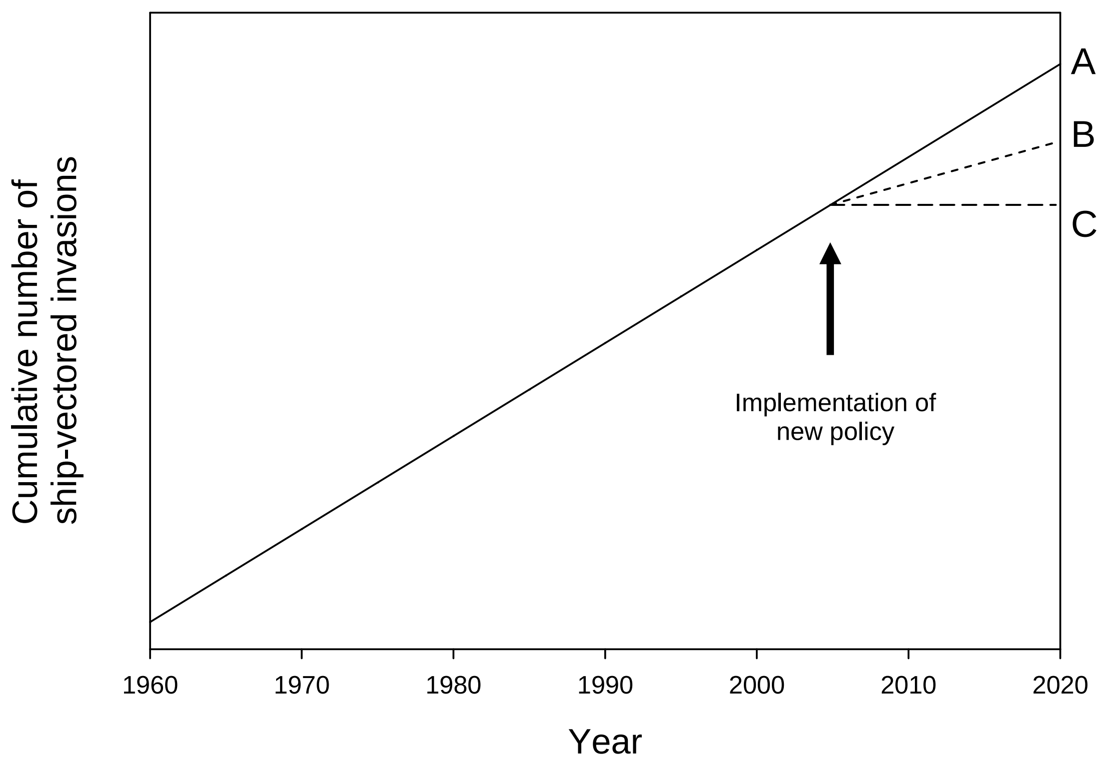

FIGURE 1 A conceptual approach for assessing the effectiveness of new ballast water policy based on in-lakes invasive species surveillance data. Graph shows the cumulative number of ship-vectored invasions as a function of time. In Scenario A, the trend observed for the period 1960-present continues following implementation of the new policy to eliminate new invasions. In Scenario B, the rate of new ship-vectored introductions is reduced relative to the period 1960-present, but new ship-vectored invasions continue. Scenario C is the desired outcome, and represents no new ship-vectored invasions to the Great Lakes following the new policy.

The above serves as the basis for an adaptive management approach to preventing Great Lakes invasions (Walters 1986). Specifically, if the committee's recommended policy is implemented, but ballast water invasions continue at the same rate as prior to the new policy (Scenario A), or even at a reduced rate (Scenario B), this reveals a fundamental gap in human understanding of the system. An adaptive management strategy would establish a timeline for tightening the regulations if specific goals are not achieved over a prescribed time period. For example, if 10 years after the new policy has been enacted, the rate of ballast water introductions has not declined by at least 70% of the pre-implementation invasion rate, a more stringent standard would automatically be enacted. This management approach allows regulations to evolve in response to new knowledge, maximizes the rate of learning about the system, and may provide incentives to industry to comply with current standards in order to avoid more stringent standards in the future.

Early Detection to Maximize Potential for Eradication

The second goal of surveillance is the early detection of new AIS in order to maximize the potential for eradication. A number of reviews have emphasized that early detection is an essential ingredient for eradication (Simberloff 2002, 2003). The longer an invasive species goes undetected in a new ecosystem, the lower the probability of successful intervention. As the population of the invasive species expands, the costs of eradication increases (usually exponentially), and the opportunity window for enacting an eradication program closes (Simberloff 2003). Unlike eradications on oceanic islands, the Laurentian Great Lakes are large, open ecosystems, and are inherently less amenable to AIS eradication. This situation highlights the importance of early detection if eradication is to be successful.

For a given invader, sites differ in probability of receiving colonists and suitability for establishment. Similarly, certain species may be more likely to be introduced and become invasive. Is it possible to predict which species are most likely to invade and which sites are most vulnerable to invasion? There is pessimism in the literature surrounding our ability to predict invasions (Williamson 1999). Yet there has been recent progress in identifying the sites and species most likely for biological invasions (Kolar and Lodge 2001, Kolar and Lodge 2002). Species risk assessments have been used to create lists of prohibited species and regulate intentional species introductions. This approach can also help guide the management of unintentional introductions. If "hot spots, hot moments, and hot species" can be identified, surveillance can be allocated accordingly.

Species Risk Assessment

In a general sense, the pool of potential Great Lakes invaders is the global aquatic species pool. Yet certain species have a higher likelihood of being introduced and becoming invasive. A surveillance program needs focus, for example, a list of target species that are the strongest candidates to become invasive, and a list of location most likely to be invaded. Such lists would evolve through time as new research is conducted.

Several recent risk assessments have identified species most likely to become invasive in the Great Lakes. Kolar and Lodge (2002) used a quantitative risk assessment modeling approach to generate a list of fish species that are most at risk of invading Great Lakes. Another approach is to identify 'invasion corridors', along with species that have become invasive elsewhere but have not yet invaded the Great Lakes. The Ponto-Caspian is a tremendous '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 and patterns of invasion in Eurasia has provided the basis for predicting future AIS to the Laurentian Great Lakes (Ricciardi and Rasmussen 1998). Grigorovich et al. (2003a) developed a multi-filter risk assessment approach to identify invertebrate species at risk of invading the Great Lakes. This analysis produced a list of high risk and low risk AIS based on consideration of transport vectors, donor regions, invasion history, environmental match, and potential for ballast water uptake.

Though efforts to identify species most likely to become invasive are imperfect, this approach provides a useful tool for enabling readiness and guiding surveillance efforts. Lake surveillance teams would be trained to search for and identify high-risk invaders. Watch cards and training sessions for local agency staff, non-profits, and citizens groups would focus on the identification of high-risk species. It is notable that both Ricciardi and Rasmussen (1998) and Grigorovich et al. (2003a) listed *Hemimysis* as a high-risk invader prior to this species being reported in Lake Michigan and Lake Ontario in 2006.

Time and Place Risk Assessment

Just as the above studies 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 several invasion 'hot spots' – areas with high concentrations of new invasive species. 5% of the Great Lakes surface area support >50% of recent invasions, and that hotspots were ~ 20x more highly invaded than non-hot spot areas. Drake et al. (2006) found a window of invasion opportunity for *Bythotrephes* during the summer months. Though the invasion window might differ for other species, the idea of 'hot moments' merits further research, and could further improve the effectiveness of surveillance.

Potential to Eradicate

An additional consideration is the likelihood of eradication upon detection. Habitats and taxonomic groups differ widely in terms of vulnerability to control. Taxa inhabiting open (pelagic) habitats with high population growth rates and dormant resting stages would be poor candidates for eradication (Table 3). On the other hand, taxa with low population growth rates that inhabit isolated environments such as coastal wetlands or embayments are more amenable to eradication. A goal of the surveillance program is early detection in order to maximize the potential for eradication. Though surveillance efforts should cover the range of habitats and taxa, they should also be biased towards taxa and habitats that are most amenable to eradication.

Specifics of a Surveillance Program

The above section provides a risk assessment framework for a surveillance program aimed at detecting the most probable, harmful, and controllable AIS at the most probable locations and times. The strategy is to maximize the potential for early detection and eradication. Here, I outline elements of an on-the-ground surveillance program. The proposed early detection and surveillance program has the following general features:

TABLE 3 Rules of Thumb Concerning Where Eradication Is Likely to Be Successful

Eradication unfavorable	**Eradication favorable**
High population growth rate, fecundity	Low population growth rate
Open habitat (pelagic)	Isolated habitats (coastal wetlands)
Highly mobile organisms	Stationary organisms
Species with dormant resting stages	Species lacking dormant resting stages

- **Targeted** - Identify and focus surveillance on hot spots, hot moments, hot species, and situations where there is high eradication potential
- **Opportunistic –** harness and influence efforts of ongoing research programs, fisheries assessments, and citizen monitoring programs
- **High tech** - Use of remote sensing, aerial imagery, molecular markers
- **Dynamic surveillance –** improve understanding of vectors and pathways through surveillance efforts

How would AIS surveillance be carried out? This is part of the larger issues of program design which is briefly described in Box 1. I envision a surveillance program with three major components:

1. **Lake teams**. Each lake or region would have a dedicated field sampling team to conduct targeted and routine field surveys directed at hot spots and hot species. Lake team sampling would use standard sampling protocols to sample zoobenthos, zooplankton, fish, algae, and higher plants in coastal wetlands, harbors, embayments, shallow water coastal habitats, and offshore habitats. An example of an effective AIS sampling protocol is found in Grigorovich et al. (2003b). The 'hub' (central office) would coordinate efforts among lake teams and provide resources, guidance, data management, and analysis.
2. **Academic researchers and resource managers.** Each lake team would coordinate with ongoing Great Lakes sampling efforts carried out by academics, as well as state, provincial, and federal resource managers. Biotic samples collected through these efforts would be subsampled and provided to lake teams to be examined for invasive species, as appropriate.
3. **Other local efforts**. Lake teams would contribute to public education and outreach though existing extension programs, Sea Grant, etc. Lake team personnel would provide training in invasive species monitoring to local resource managers, non-profits, citizens groups (for select species and habitats, such as coastal marshes and estuaries).

The lake teams would play the central role in surveillance efforts, not only by conducting targeted monitoring, but by also providing funding, guidance, and expertise to local monitoring efforts. Lake teams would also play the lead role as 'first responders' in the event that a new invader is detected. Reports of a new invasion by local surveillance efforts would be immediately confirmed by lake teams. Upon confirmation, the lake team would be responsible for an AIS status assessment (SA). With assistance of other resource management agencies, the lake team would 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, called an eradication assessment (EA, section 4).

Methods available for detecting new invasions range from the standard sample collection methods of 19th century field biology (i.e., ropes and buckets), to high tech methods such as the use of remote sensing and molecular markers to detect non-native genotypes. Molecular markers have the greatest potential for detecting newly invasive microbes and algae. These taxonomic groups have such high population growth rates that a successful eradication is improbable. In addition, the problem of cryptic invasions is particularly vexing for these taxa. If new genotypes are discovered, it may be uncertain whether they are invasive genotypes, or simply previously unrecognized native genotypes. For these reasons, the surveillance program would emphasize traditional sample collection methods, but should also be open to the use of molecular tools to address specific AIS questions.

One area where high tech approaches would be likely to aid in AIS surveillance is the use of remote sensing, particularly the use of satellite imagery and aerial images to detect plant invasions in coastal habitats (Pengra et al. *in press*). This approach is particularly useful if the invasive plant species has spectral characteristics that differ from native plants. Even when it is not possible to identify specific invasive plant species from spectral characteristics, comparing satellite or aerial images through time can be used to detect changes in coastal vegetation cover - a potential sign of species invasion that can be investigated through on-the-ground surveys (Mack 2000).

BOX 1

AIS Surveillance and Eradication Program Design

Though several institutional models could be envisioned, I propose a structure comprised of a central ‘hub’ that oversees a series of ‘lake teams’. The hub houses the central program administration. It is here where planning, risk assessments, bioeconomic assessments, decision making for control, and central information management are based. At the regional level are lake teams. Each lake team would be responsible for the Great Lakes waters of a given state/province. Lake teams would be responsible for conducting targeted field sampling, species identification, coordinating efforts of local monitoring, and leading AIS control efforts when appropriate. Lake teams would also coordinate monitoring efforts of local citizens and resource managers, both of whom contribute effort towards eradication efforts when necessary.

AIS surveillance and eradication as forwarded here requires the designation of a lead biosecurity agency. The program could involve the creation of a new bi-national organization (similar in spirit to International Joint Commission or Great Lakes Fishery Commission) responsible for Great Lakes AIS management. A preferred option would be to expand the funding and mission of the Great Lakes Fishery Commission to include AIS surveillance and eradication.

4. DECIDING WHETHER TO ERADICATE

Upon discovery of a new AIS, an assessment needs to be made as to whether to attempt to eradicate. Eradication can be costly in the short term, but is also an effective option in the long-term since the goal is to eliminate the invader population. In a general sense, the decision of whether or not to attempt eradication needs to weigh the likelihood of eradication, the costs of action, and the costs of inaction. A formal process is needed for examining the existing information, comparing alternative options, and making a decision of whether or not to attempt to eradicate (Bax et al. 2001). An obvious approach is a traditional benefit-cost analysis (Naylor 2000). The basic idea is that eradication should proceed if the expected net benefits (costs or impacts avoided) of the control program exceed the expected direct cost of eradication + 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 measurable impacts. *Ex post* benefit-cost analyses are not particularly relevant to the case of AIS eradication in the Great Lakes because the AIS have not yet established, making it impossible to quantify impacts. More appropriate are *ex ante* benefit-cost analyses, in which analysis is conducted prior to the occurrence of the AIS. In *ex ante* analyses, the first step is to predict how the invasion will affect the ecosystems. The second is to assess the value of the impacts (for example, in terms of decline in species and ecosystem services) in monetary terms. An example of a theoretical benefit-cost framework for AIS eradication is provided in Bax et al. (2001).

Though benefit-cost analysis provides an appealing framework for assessing AIS eradication, there is a gap between theory and our ability to apply it to AIS management (Naylor 2000). First, predicting or forecasting impacts of a particular AIS that has not yet established is fraught with uncertainty. Only a small proportion of introduced species establish, and a fraction of these ultimately have adverse impacts (Williamson 1996, Williamson and Fitter 1996). Second, even in cases where an AIS has adverse impacts, the effects are notoriously difficult to quantify in dollar terms. How might one have quantified the impacts of round goby or spiny water flea invasion into the Great Lakes? These species have disrupted Great Lakes food webs and affected public goods, but may not have had impacted direct use values of these ecosystems. Incorporating the ecological impacts of AIS is essential, but requires non-market valuation methods, which are notoriously difficult to apply. In short, difficulty in predicting invasions and quantifying non-market impacts limit the use of a benefit-cost approach. Quantifying non-consumptive, indirect-use, and non-use impacts of Great Lakes AIS should be an important research priority, and will allow benefit-costs approaches to be applied in the future.

It is essential 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 the newly established surveillance and eradication program would be to develop a formal AIS eradication assessment (EA) process to be applied to a new invader upon its discovery. Developing the details of the process should involve participation from experts from a range of disciplines, including economics, ecology, risk assessment, statistics and the decision sciences. The details of the process are beyond the scope of this paper, though below I highlight the types of information that should be considered by the decision maker:

What Is the Likelihood of Success?

Biological Factors

What is the population status of the invader (density, area infested, expanding)?
Is the species life history and invaded habitat susceptible to eradication efforts?

Institutional Factors

Are there sufficient resources to successfully eradicate the population?
Are there barriers that would constrain or delay the eradication response?

What Is the Cost of Action?

How much time and money will be committed to eradication?
Will there be collateral ecosystems or human impacts?
Will there be need for additional ecological restoration?

What Is the Cost of Inaction?

What are the anticipated economic impacts if the invader establishes?
What are the anticipated ecological impacts if the invader establishes?
What is the ‘value’ of invaded and vulnerable habitats and species?

The eradication assessment (EA) needs to be capable of synthesizing the available information and providing short- and long-term guidance on AIS eradication. The primary consideration should be the cost and likelihood of eradication success. If eradication can be achieved at a relatively low cost, the eradication should proceed with little consideration of potential AIS impact – this is the obvious choice in light of the high uncertainty associated with AIS impacts. If the potential for success and cost of eradication appear to be high, a more careful assessment of the costs and benefits will be required.

There is a high degree of uncertainty associated with the estimated costs of eradication and anticipated ecological and economic impacts. 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. 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 generate a decision not to eradicate, while a ‘high-impact’ scenario for the same species may generate a decision to eradicate. Resolving this issue can benefit from application of decision theory, and 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, a more appropriate goal may be 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. 2005, Popper et al. 2005). This decision strategy is analogous to Savage's (1951) 'minimax regret' criterion, which minimizes 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. 2005).

AIS eradication has traditionally been viewed as a simple yes-no decision (Wittenberg and Cock 2001). Incorporation of robust decision-making may lead to some alternative options on short-term time horizons. For example, the most robust short-term management option in the face of uncertainty may 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).

5. ERADICATION

Imagine the following scenario: an invasive species has been detected, the eradication assessment is highly favorable of eradication, and the decision has been made to attempt to eradicate. In order for the eradication assessment (EA) to favor an eradication attempt, the situation would have to be favorable in terms of the species biology: the invader is detected early in the invasion process, the species is vulnerable to control, and is unlikely to recolonize. In addition, the EA would have explicitly considered institutional factors. For the EA to favor eradication, there would have to be few barriers that would thwart the eradication program, and sufficient financial and human resources to carry the project to completion.

Now imagine another scenario: an invasive species has been detected. The invader was detected early, the species is vulnerable to control, and is unlikely to recolonize. In terms of the species biology, the situation is favorable. On the institutional side, financial resources for eradication are limited due to budget constraints, and may not be sufficient to carry out the eradication campaign. Opposition from local citizens threatens to slow down or derail eradication. Under this scenario, the eradication assessment would probably not recommend that eradication be attempted.

Comparing the above scenarios highlights the central importance of institutional factors (Table 2). It is imperative that the program: 1) rapidly mobilize the funding and human resources for eradication, and 2) avoid the legal, social, and cultural barriers to rapid eradication. The program itself must possess the institutional features of a successful eradication program (Table 2). If the institutional situation is not favorable for eradication, the eradication assessment process will probably not favor eradication. In this situation, one must ask: 'What is the purpose of an eradication program if institutional and financial constraints make it such that eradication is not a viable option?' The most important biological factor is to detect AIS before they have the chance to spread. Program design is also under human control, and it is imperative that the program be designed so that it is able to respond immediately upon the recommendation of the EA (Table 2).

In the case where the decision has been made to eradicate an invasive species, it is critical that there be a clear, yet flexible eradication plan to guide management efforts. For species identified as 'high risk' invaders in species risk assessments (section 3), an eradication plan should be devised and ready to implement prior to their discovery. This level of advanced readiness will greatly hasten the ability of the program to respond to an invasive species upon detection.

General approaches for invasive species eradication include mechanical, chemical, biological, and habitat management. Past eradications have generally involved the combination of multiple control methods. Eradication programs must also involve monitoring to document effectiveness and collateral impacts. For some taxa, efforts have been directed towards developing and assessing AIS control methods, though results of such efforts are often not published. Based on this, we highlight two important needs that would fall under the responsibility of the program: 1) to compile existing knowledge on control and eradication strategies for potential Great Lakes invaders, and 2) to develop, test, implement, and document new methods for AIS control and eradication.

Compile Existing Knowledge

The program would be tasked with compiling resources and creating a 'technical handbook' for eradication and control methods and strategies for freshwater invaders. Since there have been relatively few eradication efforts directed at freshwater AIS, marine ecosystems would provide an important set of case studies and experiences from which to draw. The handbook would also highlight more general eradication approaches such as site containment and monitoring protocols. This resource would be made widely available on the web.

Invest in New Methods and Technology for Control

An important lesson from case study #1, the eradication of mammals on oceanic islands, is that tremendous advances in our ability to control AIS can be achieved if efforts are invested. There have been numerous innovations in AIS control in recent years. An example is that researchers in the U.K. have developed an encapsulation method for delivering a toxic agent to zebra mussels, providing invasive species control without polluting the surrounding environment (Aldridge et al. 2006).

6. DISCUSSION

My task was to consider the essential features of a surveillance and eradication program for AIS in the Great Lakes. I have forwarded a strategy based on the following: 1) monitoring guided by species risk assessments and monitoring directed to hot spots, hot species, and those with the greatest eradication potential, with emphasis on early detection, 2) upon detection of a new AIS, an eradication assessment is conducted to guide whether to proceed with eradication.

It is important that the broader invasive species management program have clearly-defined goals to provide a basis for management decisions and prioritization efforts (Lodge and

Shrader-Frechette 2003). Is the program goal to eliminate new invasions altogether, to minimize adverse economic impacts, to protect remaining native biotic communities, or to minimize changes to the current configuration of the Great Lakes food webs? Considering that AIS management funding will likely be severely limited and many AIS have no measurable economic or ecological impact, the goal of completely stopping new invasions may not be realistic (Lodge and Shrader-Frechette 2003). This highlights the need for risk assessment strategies, for example, preemptively identifying and targeting species likely to spread and have adverse economic and ecological impacts (section 3). A prediction of species impact is critically important information for the formal eradication assessment (section 4).

Another program consideration is the prospect for unwanted collateral impacts of eradication efforts. Species eradication efforts will undoubtedly have impacts on non-target species, ecosystems, and human health. Such concerns are greatest with the use of chemical control methods. For example, the chemical rotenone is likely to be an effective tool for control of invasive fish, but would also kill all organisms with gills in the treated area. Other chemicals used for invasive species control may have toxic impacts on humans and wildlife, and preventing human exposure to harmful chemicals would need to be a top priority. Such factors can be viewed as 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 will generate opposition from the general public and citizens groups. Citizen opposition may generate lawsuits, thereby delaying or halting 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? How do you know you can really eradicate the AIS? Is eradication worth the resources being invested? Intense citizen opposition to eradication should be anticipated and planned for. Local opposition should be explicitly considered as a barrier to eradication response in the eradication assessment, and will require careful attention and serious investment in mediation, public relations, and outreach.

The issue of citizen opposition can be partially addressed through directly involving stakeholders in the decision process, which would include groups with a stake in the invasion as well as control options. Stakeholder involvement should begin prior to the discovery of the AIS though workshops designed to examine scenarios of AIS eradication. Though stakeholder involvement is increasingly viewed as an important element in natural resource decision-making, it may also produce an important constraint. Perhaps the key feature of an AIS eradication program is early detection and rapid and intense response. A stakeholder participation process will draw out the diverse perspectives on AIS control and eradication options, and threatens to slow down the decision process. It is imperative that stakeholder participation be a part of the decision process, but it must be designed to yield a rapid decision if eradication is to proceed.

Collateral impacts may also manifest themselves through complex food web interactions. For example, native consumers may have shifted to feeding on the invasive species (in the case of an invasive invertebrate), or using the invasive species as habitat (in the case of a macrophyte or coastal plant). Successful eradication of an invasive species may have adverse consequences for native species that have adapted and come to rely on the invasive species (Vander Zanden et al. 2006). Removal of an invasive species could have unpredictable consequences stemming from complex food web interactions – for example AIS removal could release a second invasive species from predation resulting in a secondary species outbreak (Zavaleta et al. 2001, Zavaleta 2002, Vander Zanden et al. 2006).

The above examples highlight 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 native ecosystems (Zavaleta et al. 2001, Zavaleta 2002, Vander Zanden et al. 2006). Whether an eradication campaign has collateral impacts 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 continually improve our ability to eradicate.

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 invasible than natural lakes (Havel et al. 2005). Human-disturbed patches in wetlands may provide a foothold to invaders, thereby opening the broader ecosystem to species invasions. In alpine lakes such as Lake Tahoe, exotic fishes establish initial populations in marinas, and subsequently spread to surrounding undisturbed habitats. In some of these examples, it can be difficult to sort the effects of disturbance from increased rate of propagule introduction. Still, it seems clear that aquatic invasions are 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 early in the invasion process.

SUMMARY

In the past few decades there have been impressive advances in the area of AIS eradication, and eradication will likely continue to play a growing role in the broader field of AIS management. The Great Lakes have already been deeply impacts by AIS, but also provide an opportunity to demonstrate global leadership in eradication as a part of an integrated AIS management strategy. How to best prioritize efforts is a key management challenge (Byers et al. 2002). The approach outlined here incorporates surveillance to monitor the effectiveness of ballast water regulations and maximize early detection. Detection of a new AIS is followed by a formal eradication assessment (EA), which is intended inform decision making relating to eradication. In light of high uncertainty, the program should aim to make management decisions that are robust to a range of futures. Stakeholders should be involved in decision making prior to the detection of AIS. The institutional structure of the program is fundamentally important to program success. Finally, for the program to be effective, it must have sufficient power and resources to proceed with AIS eradication when deemed beneficial.

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