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Managing the introduction and spread of non-native aquatic plants in the Laurentian Great Lakes: a regional risk assessment approach

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Abstract

Risk assessment tools for non-native species can avert ecological and economic harm when they inform regulatory or voluntary management actions that seek to reduce the probability of introducing high-risk species. The Laurentian Great Lakes region contains many aquatic invasive plants, non-native species whose introduction causes economic or environmental harm or harm to human health. Additionally, new species continue to arrive, including through trade (e.g., aquarium, water garden). Currently, each Great Lakes jurisdiction manages a separate risk assessment program, leading to a regional situation with diverse assessment methods and large discrepancies in assessed and regulated species. Because the Great Lakes ecosystem crosses state and national borders, each jurisdiction will be best protected when all jurisdictions prevent the import of potentially harmful species. We have modified an existing risk assessment tool for use across the Great Lakes Basin to assess the invasion risks posed by aquatic plants. The tool comprises 38 questions, with points associated with each response that are summed to give a total score. We assessed all known established aquatic plant species in the Great Lakes (n=40) and found this score to be positively correlated with invasiveness, allowing thresholds to be identified that distinguish between invasive and non-invasive species with 84% to 90% accuracy. Assessing species proposed for introduction with this tool, and using these thresholds to determine acceptable risk, could reduce the number of future invasions. If widely adopted, this risk assessment tool would enable a common suite of species to be regulated and thus a more effective approach to reducing the risk of future invasions. Regional risk assessment approaches should reduce the threat of invasive species where environmental and climate conditions are relatively consistent across jurisdictional boundaries.

Key words: biological invasions, aquatic plants, aquatic weeds, thresholds, organisms in trade, plant screening, prevention

Introduction

Citizens in the US, Canada, and many other countries expect a reasonable level of protection by government from negative externalities caused by private interests. For example, by using risk assessment and management procedures, government agencies in the US strive to protect consumers from pharmaceuticals that may cause more harm than good; from food harvesting and processing practices that may introduce harmful chemicals, parasites, or pathogens into supermarkets and restaurants; and from air and water pollution that results from energy generation or industrial processes. Rigorous risk assessment practices have not, however, been consistently employed in either the US or Canada to protect citizens from harm caused by invasive plant and animal species to the environment, health of wildlife and humans, and the economy (Lodge et al. 2006). An invasive species is one that is not native to a specific location and whose introduction does or is likely to cause economic or environmental harm or harm to human health (Federal Register 1999). The absence of risk management of invasive species in previous decades resulted in part from the absence of reliable risk assessment tools. However, tools for assessing the risks of invasive species and the pathways that deliver them have become increasingly available (Lodge et al. 2006; Keller and Drake 2009).

Here we modify the US Aquatic Weed Risk Assessment (AqWRA) tool (Gordon et al. 2012), which was a modification of the New Zealand AqWRA (Champion and Clayton 2000), for use in the binational Laurentian Great Lakes region (hereafter *GL region*). The US AqWRA was developed as a pre-border biosecurity risk assessment tool for identifying high risk species before they are imported to the US, necessary because of continuing high import rates of new species (Cohen et al. 2007; Rixon et al. 2005). However, because a wide variety of non-native species are already established in parts of the US and Canada, and species native to one part of the region can become invasive elsewhere, there is a need for states and provinces to manage the movement and sale of aquatic plants within their jurisdictions and to prioritize management of invasive species. To meet this goal, we have modified the US AqWRA to make it applicable across the eight US states and two Canadian provinces that border the Great Lakes. We refer to the new tool described here as the Great Lakes (GL) AqWRA.

The significant impact and control costs associated with invasive plant management in the GL region demonstrate both the need for increased focus on prevention and consistent management, and the inadequacy of existing national pre-border prevention efforts. The Federal Noxious Weed list for the US (USDA, APHIS, PPQ 2012) includes only eight of the 40 established aquatic plants in the region (Appendix 1). The list of pests regulated by Canada (Canadian Food Inspection Agency 2014) does not include any of these species. Further, the GL region is easily defined, having narrower environmental characteristics than either the continental US or Canada, meaning that a shorter, more specific list of species are of concern in the region than at either national level.

To complement national efforts to prevent importation and spread of noxious weeds, a regional approach may be needed to manage established non-native plants that could have the potential to be harmful but do not meet the national standard for noxious listing, or for species native to North America that pose a threat outside their native range. Incipient invaders and potential pathways may be managed much more effectively at the local than at the national level. In any case, coordination across national boundaries in the GL region is important.

The GL region has a long history of successful binational environmental management (e.g., GLFC 1955; the Great Lakes Water Quality Agreement). These binational efforts include one of the most successful and on-going aquatic control programs for an invasive species: the Great Lakes sea lamprey control program has run for over 50 years and successfully reduced damage to recreational and commercial fisheries to an acceptably low level (Christie 2003). Nevertheless, uniform risk assessment approaches have not been adopted across the region, and the tools that are employed are rarely applied proactively to protect the Great Lakes from new invasions via commerce in living organisms. The tool we provide is suitable for use by industry groups and by city, state, and federal governments. If such a pre-import risk assessment approach were adopted and enforced by all constituencies across the region, management of invasive plant species that come from commerce in living organisms would overcome the weakest link problems from which it now suffers (Peters and Lodge 2009).

Regulations for non-native plants vary widely across the GL region (Appendix 1). Aside from the nationally regulated species, individual species are on average regulated in fewer than four GL jurisdictions, and no species is regulated in more than 8 of the 10 states or provinces in the Great Lakes. Additionally, many established species in the region are not regulated anywhere. This patchiness in regulations across the region, coupled with the absence of inspection and compliance efforts to prevent interstate or interprovincial movement of species means that all jurisdictions remain at risk from almost all species, either through their purchase elsewhere and transport into regions where they are regulated, or through their establishment and spread. Protection against harmful and expensive invasions would be substantively improved if a regional, transparent and objective process were available for regulating species (Peters and Lodge 2009).

Several approaches to invasive species risk assessment have been developed over recent decades (see Keller and Drake 2009 for a review). We have taken the 'questionnaire' (*sensu* Keller and Drake 2009) approach, in which a series of questions are asked about a species, the responses to those questions scored, and the sum of scores is positively correlated with invasion potential. Questionnaire approaches allow for species to be assessed accurately and rapidly. The most prominent example of this is the Australian Weed Risk Assessment (AWRA), which has been used since 1997 to determine allowed and prohibited lists for plant imports to Australia (Pheloung et al. 1999). The AWRA has high accuracy across a range of global regions (Gordon et al. 2008), is already being used in New Zealand, and is being considered for adoption elsewhere (Nishida et al. 2009; Koop et al. 2011).

Here, we describe modifications to the US AqWRA to create the GL AqWRA, a tool applicable to the binational GL region. To create the GL AqWRA we modified some questions in the US AqWRA and tested it by assessing all aquatic plant species known to have been previously introduced to the GL region. Because these species have known outcomes in the region (i.e., established and invasive, established but not invasive, not established) we were able to assess the accuracy of the GL AqWRA. Based on its high performance, we then assessed a suite of species not yet introduced that are either regulated somewhere in the GL region, or considered a high risk for introduction. Our results provide a scientifically rigorous basis for developing regionally consistent aquatic plant regulations.

Methods

The NZ AqWRA (Champion and Clayton 2000), the US AqWRA (Gordon et al. 2012), and the GL AqWRA developed here are comprised of questions about the ecology, biology, temperature tolerance, and invasion history of a species. Previous experience with this tool indicates that completion of the assessment takes 8–12 hours on average. Answers to each question are converted to a numeric score based on the response. Thirty-seven of the 38 US AqWRA questions (Gordon et al. 2012) came from the NZ AqWRA (Champion and Clayton 2000, 2001) or subsequently from the New Zealand authors (Champion et al. 2008; Champion and Clayton 2010). The final score for a species is the sum of values from each question, and ranges between 3 and 91, with higher scores indicating a greater number of traits associated with invasiveness (Gordon et al. 2012). We calibrated the GL AqWRA by assessing species with a known invasion history, allowing us to identify score thresholds that distinguish invasive from not invasive species. We then validated the GL AqWRA by assessing species with a known invasion history to assess accuracy.

Adapting the US AqWRA for the Great Lakes region

To determine the species against which to calibrate the GL AqWRA, we first conducted a climate screen based upon USDA hardiness zones. This screen eliminated those species whose native and naturalized range does not match hardiness zones in the GL region. Hardiness zone information is readily available at a global scale and was used as an approximation for water temperature (Gordon et al. 2012). Specifically, species with ranges that encompass zones 7 and below, or for which we could find credible evidence from the aquarium and water garden trades (e.g., Speichert and Speichert 2004) that they could establish in such areas, were considered climatically suited to the GL region. Zone 7 occurs at the southern tip of the GL region based on climatic conditions over the last 30 years, and climate change projections show it extending further north in the future (NAPPFAST 2007). Species that occur solely in zones 8 or higher are unlikely to tolerate winter minimum temperatures in the GL region and were excluded from the model. The broad utility of hardiness zones suggests that few species will be incorrectly screened (USDA 2003; McKenney et al. 2005).

Two questions from the US AqWRA were changed for the GL AqWRA (Appendix 3). First, question 1.1 addresses species temperature tolerance (in relation to vegetative and/or reproductive structures such as over wintering seeds). We attempted to gather data for this on a species by species basis, but found that such data do not exist in the literature for many species. Instead, we used a climate model (PRISM Group 2007) to compare average three month low and high air temperatures (water temperatures are not available) to the GL region. Species currently established in a region that overlaps climatically with the GL region scored one for this question. Other species scored zero. Second, question 12.1 of the US AqWRA deals with invasiveness elsewhere. For the US model this was defined as invasiveness outside the US. For the GL AqWRA, species were considered to be ‘invasive elsewhere’ if we could find a description in the literature of documented ecological impacts beyond their native range and outside of the GL region.

Some species have more and/or higher quality data in the literature than others, therefore risk assessment completeness varied among species. A risk assessment was considered complete if there were no more than 4 unanswered questions. An assessment of sensitivity of the outcome to lack of data influenced our decision about completeness of each assessment (see Gordon et al. 2012).

Species selection: identifying species with known invasion status in the Great Lakes region

Species were included in our assessment pool if they are non-native in the GL region and have either established there, or if we found evidence that they had been in the US for at least 30 years (i.e., if an introduction date earlier than 1982 was found, we included the species and ceased searching for the precise date of introduction). Thirty years was selected as a time period that would allow ample opportunity for a species to establish if it is capable of doing so. This is supported by evidence that prediction accuracy of risk assessment at the US scale is independent of whether aquatic plants had 30 versus 50 years of introduction history (Gordon and Gantz 2011).

We searched online aquatic plant lists and databases (e.g., PLANTS Database - USDA, NRCS 2014), regional floras and herbaria, encyclopedias of horticulture and water gardening, and consulted with aquatic weed scientists and horticulturalists, to determine which non-native species are established in the GL region (Gordon and Gantz 2011). Although propagule pressure is a significant factor contributing to establishment and invasiveness of non-native species (Lockwood et al. 2005; Colautti et al. 2006b) and can differ among species and pathways (e.g., water garden species can have a greater potential for release than aquarium species) (Cohen et al. 2007), we have assumed that all species in trade have an arrival probability of 1. While we did not have data on numbers of species imported over a given time period, multiple reports of individual species occurrences from the literature and/or recommendations for use in water gardens or aquaria suggest that many of the species selected would have experienced multiple introductions. If these species are not established outside of cultivation, we consider them to be incapable of establishing (i.e., non-invasive).

Growth form of each species was categorized as attached-floating, erect emergent, free-floating, sprawling emergent, or submerged freshwater macrophyte (Cook et al. 1974). Obligate wetland and riparian species were excluded. The final species list includes 84 species from 43 families and all five growth forms (Appendix 4). The one bryophyte established in the region (*Ricciocarpos natans* L. 1829) was included.

Data analysis: developing the GL AqWRA with species of known invasion status

We developed a three tier *a priori* categorization for the 84 species based on their known invasion history in the GL region (Appendix 4): 1) 'Not established' (no evidence of establishment outside of cultivation over at least 30 years; n = 44); 2) 'Established, not invasive' (established with no described ecological impacts; n= 24), and 3) 'Established, invasive' (established with documented ecological impacts; n = 16). Documented ecological impacts came from peer-reviewed sources and government agency or university websites. These were included when descriptions were specific about the impact (e.g., altered water chemistry) and included experimental or observational evidence of the impact.

We followed standard practice for evaluating the performance of a risk assessment tool by testing how accurately it categorized species in the test data set relative to the known invasion history of those species (Keller and Drake 2009). Following Gordon et al. (2012) we assessed the GL AqWRA by evaluating its accuracy (percent of species correctly classified) at all possible threshold score values (i.e., 3 to 91) that could be used to distinguish 'not established' from 'established' species.

One problem in assessing overall accuracy is that the proportion of species in each category of our dataset (i.e., not established, established, invasive) is unlikely to be identical to the proportions of species that have actually been introduced. In particular, there are likely to be introduced species that died out without being recorded. This *base-rate problem* (*sensu* Smith et al. 1999) means that calculated accuracies from our test dataset may not be the same as expected accuracies when the tool is applied to new species. To account for this potential bias, we use the Receiver Operating Characteristic (ROC) curve as an additional metric of risk assessment tool performance. The Area Under the Curve (AUC; Fawcett 2006) is independent of the proportion of species in each category (Caley and Kuhnert 2006). A perfect tool would give an AUC of 1; a score of 0.5 would indicate that the tool is no better than tossing a coin, and scores greater than 0.7 are generally considered to indicate good performance (Hosmer and Lemeshow 2000).

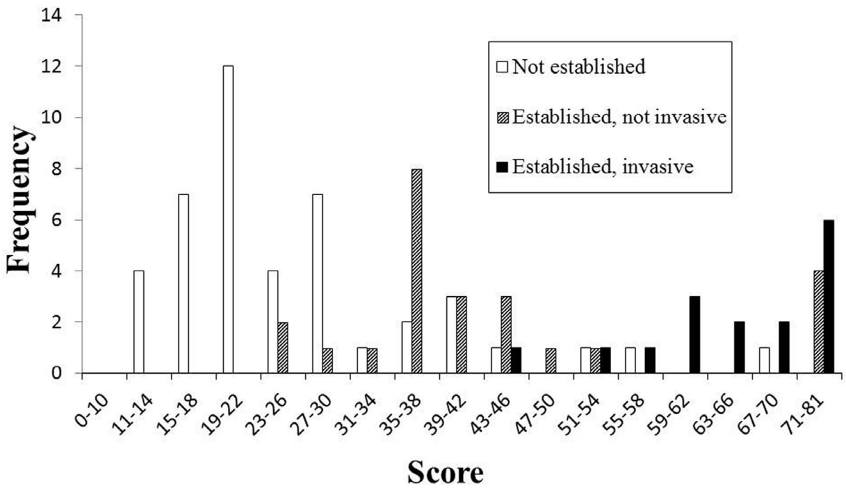


Figure 1. Frequency of species grouped by *a priori* category and score for the 84 species assessed using the GL AqWRA.

Because 'Established, not invasive' species may become invasive over time, we calculated the AUC when these species were classified with 'Not established' species, and when they were included with 'Established, invasive' species. Additionally, we calculated AUC for the comparison of 'Not established' and 'Established, invasive' species (i.e., excluding the 'Established, not invasive category). These analyses can provide decision makers with information on which to base regulation of import or sale based upon their determination of the acceptable levels of risk.

Application of risk assessment to additional species

To further evaluate the utility of the GL AqWRA and associated score thresholds, we assessed two additional sets of species. The first set includes species listed in Appendix 1 that were not used to calibrate the GL AqWRA. These were initially excluded as calibration species because they are either on the USDA Federal Noxious Weed List (USDA, APHIS 2012) or are native to some, but not all, GL states or provinces. The second set includes species that have been in trade for fewer than 30 years (Appendix 2). As they all have been identified as having a risk of invasion or introduction to the region, we examined whether the GL AqWRA confirmed that identification.

Species on the USDA Federal Noxious Weed List were excluded for two reasons. First, noxious weeds are already prohibited from trade and transportation across state lines, so those that are not established have little chance of being introduced. Second, many of these species have been on the noxious weed list since the early 1980s (Federal Noxious Weed Act of 1974), so have been out of trade and not had the same opportunities to establish as the species used to calibrate the GL AqWRA.

Results

Assessments were completed for all but one species (Soft hornwort; *Ceratophyllum submersum* L. 1763 - Appendix 4) in the calibration data set, with scores (n=84) ranging from 11-81 (Figure 1). Scores for species classified as 'Not established' ranged from 11–69 (n = 44; mean (S.D.) = 26.1 (12.5)); scores for species classified as 'Established, not invasive' ranged from 25–81 (n=24; mean (S.D.) = 44.3 (15.6)); and scores for species classified as 'Established, invasive' ranged from 44-81 (n=16; mean (S.D.) = 66.1 (9.6)). 'Not established' species scored significantly lower on average than 'Established, not invasive' species, which scored significantly lower than 'Established, invasive' species ($F = 57.28$; $df = 2$; $p<0.001$) (Figure 1).

When 'Not established' and 'Established, not invasive' species were grouped and compared to 'Established, invasive' species, the threshold score maximizing accuracy was 57, giving an AUC of 0.931 (Figure 2a). The more precautionary grouping of 'Established, not invasive' with 'Established,

Figure 2a. Accuracy of the Great Lakes model for 'Not established' and 'Established, not invasive' species combined, versus 'Established, invasive' species (n=84). Cumulative percent accuracy, maximized at 90.5% at a threshold score of 57 differentiating the two groups.

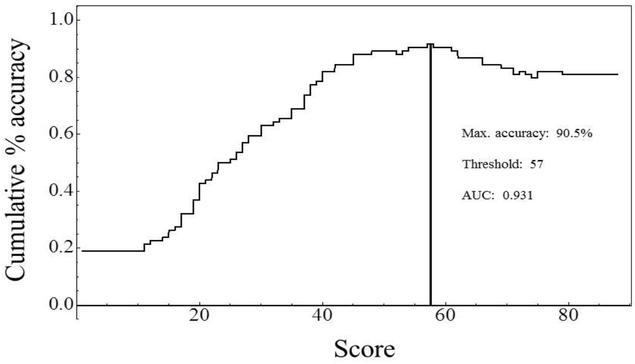


Figure 2b. Accuracy of the Great Lakes model for 'Not established' versus 'Established, not invasive' and 'Established, invasive' species combined (n=84). Cumulative percent accuracy, maximized at 84.5% at threshold scores of 30, 31, 33, 34 (equivalent accuracy at these thresholds) differentiating the two groups.

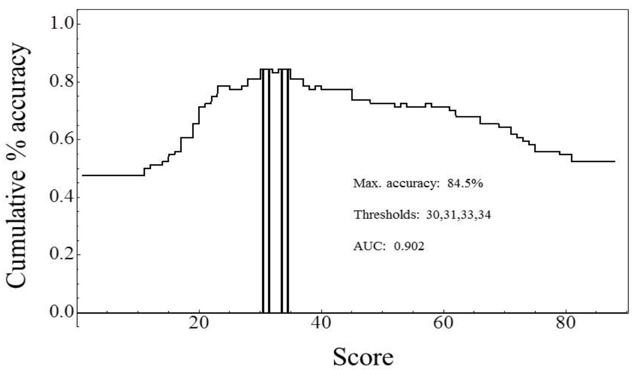
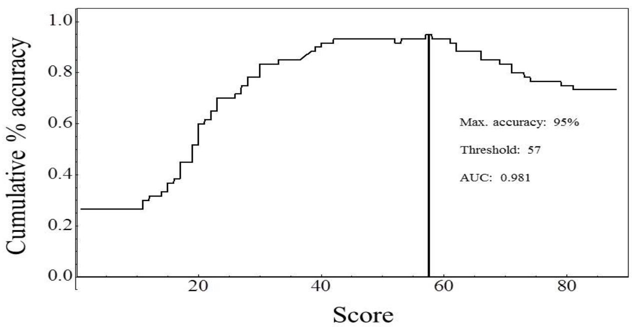


Figure 2c. Accuracy of the Great Lakes model for 'Not established' versus 'Established, invasive' species combined (n=60). Cumulative percent accuracy, maximized at 95% at a threshold score of 57 differentiating the two groups.



invasive' species gave equivalent accuracy at thresholds of 30, 31, 33, 34, and an AUC of 0.902 (Figure 2b). Excluding 'Established, not invasive' species from the analysis resulted in a threshold of 57 and AUC of 0.981 (Figure 2c).

At the higher threshold (57), 88% (14/16) of the 'Established, invasive' and 98% (43/44) of 'Not established' species were correctly classified, with 83% (20/24) of the 'Established, not invasive' species classified as not invasive.

The lower thresholds (30, 31, 33, 34) all correctly classify 100% of 'Established, invasive' and 77% (34/44) of 'Not established' species. The majority of the 'Established, not invasive' species (88%; 21/24) are classified as invasive with these thresholds.

Scores for species already regulated in the Great Lakes

All of the regulated species in the GL region have a score of 36 or higher (Figure 3). 'Established, invasive' species under regulation have a score of 58 or above, consistent with the GL AqWRA score threshold of 57. Additionally, all 'Native and invasive' and one of the 'Established, not invasive' species have scores above 58, which is similar to our score threshold of 57 for 'Established, invasive' species (Figures 2a and 2c). While some regulated species are not established, regulation at the lower score threshold (any of 30, 31, 33, 34; Figure 2b) includes the other 'Established, not invasive' species. From a regulatory perspective, this threshold would guard against further introduction or movement of all established species.

Application of risk assessment to additional species

No species on the federal aquatic noxious weed list is naturalized in the GL region; however, at the score thresholds of 30–34, all would be considered a high risk for invasiveness. At a threshold of 57, three species (*Azolla pinnata* R. Br. 1810 (67), *Crassula helmsii* A. Berger 1930 (70), *Lagarosiphon major* (Ridley) Moss 1928 (67)) would be considered high risk, and three (*Monochoria vaginalis* (Burm. f.) C. Presl ex Kunth 1843 (36), *Sagittaria sagittifolia* L. 1753 (51), *Sparganium erectum* L. 1753 (44)) would fall below the threshold and be considered low risk. Three species (*A. pinnata*, *M. vaginalis*, *S. erectum*) are naturalized non-natives in other states in the U.S. and all are naturalized outside of their native range in at least one other country.

The four species that are considered both native and non-native in the GL region: *Cabomba caroliniana* A. Gray 1837 (score = 67), *Ludwigia peploides* (Kunth) P.H. Raven 1963 (76), *Myriophyllum heterophyllum* Michx. 1803 (72) and *Phragmites australis* (Cav.) Trin. ex Steud. 1840 (75), scored well above both sets of thresholds. *Ludwigia grandiflora* (Michx.) Greuter and Burdet 1987 is naturalized in two GL states, New York and Pennsylvania, but is native to other states in the southern US, and was not included in the analysis. This species also has a score (70) above both sets of thresholds (Appendix 1).

We identified 20 species that have been in the aquarium and water garden trades for less than 30 years (Appendix 2). To account for potential lag time between introduction, establishment and invasion, these species were not included in the development of the GL AqWRA. All of these species have low risk outcomes at all thresholds except Broadleaf cumbungi (*Typha orientalis* C. Presl 1851, score = 70). Broadleaf cumbungi has been in the US trade for at least 27 years, and in the global trade for at least 62 years. The species is tolerant of USDA hardiness zones 3–11. The GL AqWRA scores suggest that the remaining species pose a low invasion risk in the region.

Discussion

The GL AqWRA distinguishes invasive and not established species well for the GL region. This result is important when considering a method of determining which species to accept or not accept for import, commercial sale, possession, or for prioritizing management of invasive species. All species regulated in the Great Lakes were assessed using the GL AqWRA (Figure 3). The minimum score found was 36, so use of the lower score threshold of 30 or above (instead of 57 or above) would apparently be consistent with the current approaches of at least some of the Great Lakes jurisdictions. Application of the GL AqWRA to these species provides support for their prohibited status and provides a method to harmonize existing regulatory lists across Great Lakes jurisdictions. In addition, our results suggest that there are a number of additional species that warrant examination, and the GL AqWRA provides a quick, objective tool for identifying problematic species that may be added to voluntarily restricted or regulated lists.

Three species that are established but not invasive in the GL region were predicted to be a high invasion risk regardless of the threshold selected: Water hyacinth (*Eichhornia crassipes* (Mart.) Solms 1883: score 81), Alligator weed (*Alternanthera philoxeroides* (Mart.) Griseb. 1879: 75) and Water lettuce (*Pistia stratiotes* L. 1753: 72). These species, all highly invasive elsewhere, likely warrant monitoring to allow for a rapid response should their status in the GL change, consistent with a previous warning (Adebayo et al. 2011).

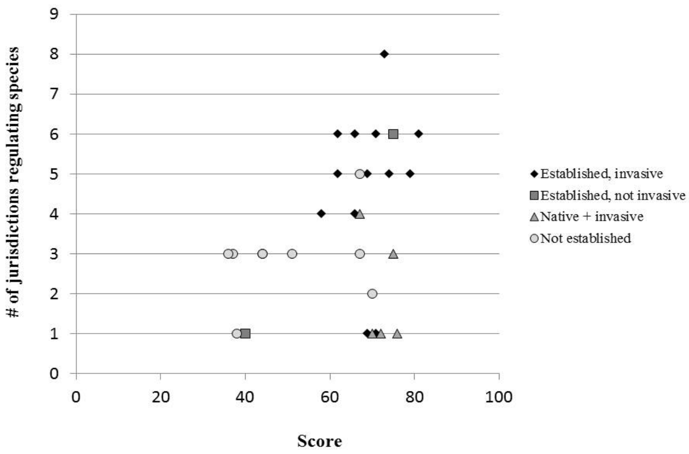


Figure 3. GL AqWRA scores of species regulated in the Great Lakes. Symbols indicate the degree to which the regulated species has become invasive in the region.

Another potential application of the GL AqWRA is the ability to develop "clean lists" of species acceptable for import. Globally, clean lists have only been developed by Australia (Australian Government Department of Agriculture 2011), New Zealand and Israel (vertebrate animals - Nemtzov 2008). New Zealand does not have a separately posted clean list, but has assessed some species as part of their pre-border screening and determined that they are acceptable for import (Environmental Protection Authority 2014). Opportunities exist to involve industry in discussions, to make importers responsible for items brought in through commerce, and to encourage voluntary efforts or sustainability marketing to promote adoption and sale of clean list species.

Evolution during establishment and spread, change in propagule pressure for a particular species, or changes in climate or habitats may lead to some species becoming more or less invasive over time (Cox 2004; Lockwood et al. 2009; Rahel and Olden 2008). New data should trigger re-assessment; having this system in place across jurisdictional boundaries would make this iterative evaluation process easier and more transparent as efforts will not need to be duplicated once assessments are completed or new information is provided for updates. Species whose native and naturalized ranges do not match hardiness zones in the GL region are not considered by the GL AqWRA to be a risk on the basis that they are unlikely to establish. However, caution should be used in making the assumption that a species is at equilibrium with its environment or that it has been exposed to a full range of climates, particularly where the native and invaded distribution is restricted by biogeography, dispersal limitations and/or biotic interactions (Elith and Leathwick 2009; Larson and Olden 2012). These issues could be exacerbated by responses to climate change that increase reproductive success or survival. In addition to introductions into novel climates, once an organism has established, it may adapt or expand its range in the future (Hill et al. 2012). In light of changing climate conditions globally, and uncertainty about environmental limits, periodic re-evaluation of species risk assessments will be important to their continued utility in the GL region and elsewhere.

Regulatory decisions are based on determination of acceptable risk. The different outcomes for different score thresholds presented here are intended to inform regional decisions about acceptable risk. The GL AqWRA works very well at both sets of thresholds presented. Using the higher threshold of 57 indicates greater acceptance of the risk that species that are currently established but not invasive may become invasive over time. In our model, two established, invasive species fall below the threshold (e.g., were incorrectly identified as not invasive) and 17 established, not invasive species fall below the threshold that would not under the lower threshold. One benefit of the higher threshold is that more species are available for trade. Using the higher threshold does not, however, take into account the potential higher cost of controlling a species once it has become established, or that an error in assuming low risk is more costly than an error in assuming high risk (Springborn et al. 2011). If the goal is to prevent entry of more non-native species that are likely to establish, a lower threshold (30–34) should be used. Because the score of 32 has slightly lower accuracy than the other scores within this range, we suggest 31 be used as the threshold (i.e., species with scores above 31 are considered high risk) if a more precautionary policy is desired. Such a decision would mean that more species would be restricted, as all established species (invasive or not) are treated with caution. Potential undesirable impacts and costs would be avoided with higher frequency using this approach. The lower threshold appears consistent with many existing regulatory decisions across the GL region.

Policies that result in more than two (regulated versus unregulated species) categories are also possible using these data. Species with scores of 32 to 57, for example, could be permitted for use under specific management practices or conditions. Again, these decisions will be based on the degree to which regulatory authorities are risk-averse with respect to invasion in the GL region.

The GL AqWRA is a rapid risk assessment process that can be applied to all states and provinces that border the Great Lakes. If implemented, it would provide the private sector and legal jurisdictions with a robust justification for voluntary management and regulations, respectively. Importantly, if regulations were coordinated across jurisdictions, it would be especially useful for at least two reasons. First, it would address the problem of uncoordinated regulations across a connected ecosystem (see Appendix 1). Second, the use of a consistent tool would reduce total costs because the assessment effort would not need to be duplicated by the different jurisdictions. Some species regulations in the GL appear currently to be made at similar score thresholds to those found in our analysis (Figure 3). Application of the GL AqWRA would provide a defensible and consistent justification for decisions.

Implementation of a regional tool, especially when the region is multinational, could be complementary to risk assessment and prevention policies at national levels. Pre-border prevention, the most effective and efficient risk reduction approach (Keller et al. 2007), is necessary for excluding species not yet introduced into the US or Canada. Further, national regulated species lists would further safeguard any internal region from influx of species from elsewhere in the country. Australia and New Zealand provide examples of complementary pre- and post-border approaches (Australian Government, Department of the Environment 2014; Champion et al. 2014). As both the US (Federal Register 1999; Lodge et al. 2006; Fowler et al. 2007) and Canada (Colautti et al. 2006a) have affirmed the need to reduce harm from biological invasions, the development of national risk assessment efforts is likely to continue. In the meantime, local and regional policies present important opportunities for improvement.

Despite these national efforts, the US states bordering the Great Lakes each have a variety of policy tools and management procedures by which they attempt to reduce future invasions (Appendix 1). In 2013, the Great Lakes governors and premiers affirmed the importance of reducing future invasions, and agreed to work toward more consistency in invasive species management among states and provinces (Council of Great Lakes Governors 2013). The Great Lakes AqWRA provides a method to make transparent and harmonize prohibited aquatic plant species lists and aid Great Lakes leaders and their agencies to better accomplish their goals of reducing harm from invasions. Other regions might benefit from this approach as well.

The choice of whether to conduct a regional (based on ecoregions) or national scale risk assessment (based more on political boundaries) is ultimately motivated by determining at what scale the risk assessment can be implemented by resource managers. In this study, we have tailored the risk assessment to the Great Lakes region because of a desire by Great Lakes resource managers to prevent further spread and establishment of aquatic invasive plants while further evaluation, refinement, and motivation for a US risk assessment develops at federal levels. In larger countries with many ecoregions like the US, a regional approach might make sense if a federal approach is not immediately feasible, does not sufficiently address regional environmental differences or to prevent movement or sale within national borders. In the latter cases, a regional approach could also help inform a national one. Smaller countries with few ecoregions may benefit more from national scale risk assessments or in collaboration with bordering countries with similar environmental characteristics (e.g., eastern European countries). However this will again depend on the scale of implementation by resource managers and the political framework in which the risk assessment occurs.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. Regulated freshwater aquatic plant species listed in one or more Great Lakes jurisdictions, modified and updated from table produced by Great Lakes Panel on Aquatic Nuisance Species (2013).

Appendix 2. Twenty species assessed for potential invasiveness in the Great Lakes region.

Appendix 3. The Great Lakes Aquatic Weed Risk Assessment Tool (GL AqWRA).

Appendix 4. List of species used to calibrate the GL AqWRA, showing scores and current status in the Great Lakes.

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