Management of Biological Invasions (2021) Volume 12, Issue 3: 546–577

Risk Assessment

Assessing progress in regulation of aquatic nonindigenous species across the multijurisdictional waters of the Laurentian Great Lakes, with emphasis on the live trade pathways

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Citation: Davidson AD, Tucker AJ, Chadderton WL, Jensen E, Weibert C, Death R (2021) Assessing progress in regulation of aquatic nonindigenous species across the multijurisdictional waters of the Laurentian Great Lakes, with emphasis on the live trade pathways. *Management of Biological Invasions* 12(3): 546–577, https://doi.org/10.3391/mbi.2021.12.3.04

Received: 28 October 2020
Accepted: 1 March 2021
Published: 19 April 2021

Handling editor: Joana Dias

Abstract

The inconsistency in regulated species lists across the shared waters of the Great Lakes undermines the collective prevention efforts of the region, resulting in a "weakest link" problem; some jurisdictions regulate more than 100 species, others fewer than 20. We examine progress over the last twelve years toward more consistent regulated species lists within the 10 Great Lakes jurisdictions. Using a risk assessment framework, we assess a suite of regulated and unregulated organisms that have been identified as having the potential for introduction. Using these species assessments, we determine how sufficient current regulated species lists are in protecting against high-risk species. We also use these species assessments to transparently identify potential high-risk candidates for regional regulatory consideration. A total of 136 aquatic species were regulated by at least one jurisdiction (69 plant species and 67 animal species). The number of species regulated by 5 or more jurisdictions has gone from 10 in 2008 to 44 in 2020. However, the majority (68%) of the currently regulated species are listed in less than half of the Great Lakes jurisdictions. The number of regulated species varies widely across jurisdictions for both taxonomic groups. Wisconsin regulates the largest number of plant and animal species (104 in total), followed by Minnesota (71), New York (59), Illinois/Indiana/Michigan/Ohio (45), Pennsylvania (34), Ontario (23) and Québec (19). We observed only a weak positive correlation between impact score and regulation status. Many of the most-regulated species have impact scores in the low or low-moderate categories, and several species with high impact scores are regulated by less than half of jurisdictions. Twenty-one species (17 plant and 4 animal) are identified as priorities for future regulatory listing.

Key words: risk assessment, impact, weakest link, binational, organisms in trade, invasion

Introduction

Aquatic invasive species (AIS) threaten the ecology, economy, and quality of life in regions throughout the world. Arrival of AIS can occur through a variety of pathways, including shipping, recreational boating, and the live

trade industries. Despite the historical focus within the Great Lakes region on management of the shipping/ballast water pathway, the aquatic live trade pathway has received increasing attention (Padilla and Williams 2004) and is the primary focus of this manuscript. Studies have found, for example, that propagule pressure from the aquarium trade is high relative to the recreational boating pathway for taxa such as fish and invertebrates (Strecker et al. 2011). The live trade pathways include live bait, horticultural and water-garden plants, biological supplies, pets, and live food (Keller and Lodge 2007). In taxa such as reptiles and amphibians, the pet trade is responsible for the largest proportion of introduced species (Kraus 2009). For aquatic plants, releases include water hyacinth *Eichhornia crassipes* (Mart.) Solms (1883) and purple loosestrife *Lythrum salicaria* L.

Species introduced through live trade cause impacts when they are released (either intentionally or unintentionally) into the wild. The number of releases are difficult to quantify, but they are likely high: Gertzen et al. (2008) estimate over 10,000 fishes are released annually in Montréal (Canada). Introductions via the live trade industry have occurred in nearly all regions of the world (South Africa in Martin and Coetzee 2011, India in Singh and Lakra 2011, U.S. Pacific Northwest in Strecker et al. 2011, Poland in Lenda et al. 2014), including the Laurentian Great Lakes (Funnell et al. 2009; Sturtevant et al. 2019). The importation and sale of aquatic species is an important invasion pathway to the Great Lakes (Rixon et al. 2005; Ricciardi 2006; Keller and Lodge 2007; Pagnucco et al. 2015).

Several U.S. federal regulations exist to manage invasive species within the live trade pathway. The Federal Noxious Weed Act regulates trade and import of federally listed noxious weeds, including several aquatic plants (see Table 1). The Lacey Act gives the U.S. Fish and Wildlife Service the authority to prohibit importation of animals identified as potentially harmful to humans or other wildlife. However, this statute was weakened by the 2017 United States Association of Reptile Keepers, Inc. v. Zinke decision that changed the interpretation and enforcement of the Lacey Act so that it no longer prohibits transport of injurious wildlife between States within the continental United States. With this increased responsibility on U.S. States, and the fact the federal statutes cover a limited number of species, much of the regulation is left to jurisdictions within the Great Lakes region (Thomas et al. 2009).

Management of this pathway within the Great Lakes is complex, with eight U.S. states and two Canadian provinces (collectively, "jurisdictions") having established individual regulations to prevent species introduction and spread. Some jurisdictions regulate more than 100 plant and/or animal species, and others regulate fewer than 20. This inconsistency in regulated species lists across the shared waters of the Great Lakes undermines the collective prevention efforts of the region, resulting in a "weakest link" problem, wherein the success of AIS management efforts is limited to the

weakest regulatory approach (Peters and Lodge 2009). Regional policy makers have recognized that successful closure of this pathway requires greater coordination (Great Lakes Panel on Aquatic Nuisance Species 2014; GLEC 2019). In June 2013, the Council of Great Lakes [and St Lawrence] Governors (now the Great Lakes St. Lawrence Governors and Premiers or "GSGP") identified a list of sixteen "least wanted" AIS that they considered a grave threat to the region's economy and ecology (GSGP 2013). On May 4, 2018, the GSGP announced the addition of five more species to the "least wanted" list. The Governors and Premiers called for specific steps to manage these "least wanted" species, including taking executive action within each state or province to prohibit or restrict the transfer of these species, and cross-jurisdictional collaboration to harmonize related state and provincial policies and regulated species lists.

The application of consistent criteria to identify problematic species, particularly via risk assessment, would aid efforts to improve cross-jurisdictional collaboration and harmonization of regulated species lists. Risk assessment has been repeatedly identified as an essential tool in evidence-based identification, regulation, and management of live trade species (Mandrak and Cudmore 2015; Chan et al. 2019). Risk assessment also allows for the most efficient allocation of resources to pathways and species posing the greatest risk (Mandrak and Cudmore 2015). The agencies responsible for regulation and enforcement of species in trade at the state, province and federal levels may require a formal risk assessment framework to provide a detailed evaluation of a species' risk in order to justify removal from the trades and withstand potential judicial review. Transparent and evidence-based risk assessment are particularly important in the United States where the onus is on agencies to prove a species will likely have impact before they can regulate ("innocent until proven guilty", or the "hindsight approach") (Davidson et al. 2013). This contrasts with the approach taken by countries like New Zealand, Australia, and those within the European Union (EU), who employ rigorous risk assessment frameworks, but use a more precautionary approach that allows regulation even if data necessary to complete a risk assessment is scarce ("guilty until proven innocent") (Davidson et al. 2013).

Across the Great Lakes region, the development of risk assessment tools has continued to evolve and diverge and now includes decision trees (Kolar and Lodge 2002; Howeth et al. 2016), probabilistic models (e.g., Keller et al. 2007) as well as semi-quantitative questionnaire-based frameworks (e.g., Davidson et al. 2017) and formal literature reviews (e.g., Frederickson 2007; Department of Fisheries and Oceans 2017). In the EU, in order to address the challenges posed by the region's shared borders and waterways, and the need for harmonized risk assessment frameworks, Roy et al. (2018) reviewed 29 risk assessment schemes (including the World Trade Organization, Convention on Biological Diversity and International Plant Protection

Convention) to identify a list of components necessary for a robust risk assessment framework that covers species biology, assessment of likelihood of introduction, survival and impacts, and measures of process efficiencies and confidence.

Here, we examine progress over the last twelve years toward more consistent regulated species lists within the 10 Great Lakes jurisdictions. We compile and compare risk assessment frameworks for consistency with the minimum standards listed by Roy et al. (2018). Finally, using the risk assessment framework that best meets the minimum standards, we assess a suite of regulated and unregulated species that have been identified as having the potential for introduction to determine how sufficient current regulated species lists are in protecting against high-risk species and to transparently identify potential high-risk candidates for regional regulatory consideration. We take a broad view of "regulated", recognizing that jurisdictional regulated species lists, statutes, and administrative codes are complex and dynamic. Our intent is to focus on broad patterns that show progress and remaining major gaps in regulatory species lists for the live trade pathways, in particular.

For each section, we use the following definitions: consistent (the same suite of species are regulated across all jurisdictions), sufficient (species identified as highest risk are prioritized for regulation), and transparent (species are listed for regulation based on the consistent application of an objective and comprehensive risk assessment framework). By describing the history and current status of regulated species, reviewing the application of risk assessment in the regulatory process, and assessing patterns of regulations against each species' assessed risk, we aim to identify gaps and priority species for future regulation, particularly within the live trades.

Materials and methods

Progress toward consistent regulations

To assess regional progress toward more consistent regulated species lists, we determined the number of regulated species at three points in time (2008, 2014, and current (2020)) for each state and province included in the Great Lakes region (Illinois-IL, Indiana-IN, Michigan-MI, Minnesota-MN, New York-NY, Ohio-OH, Ontario-ONT, Pennsylvania-PA, Québec-QBC, and Wisconsin-WI). We used 2008 because this represents the state of regulated species lists when the key regional entity tasked with coordinating AIS management (Great Lakes Panel on Aquatic Nuisance Species, GLP) released their first assessment of the consistency between Great Lakes jurisdictions of organisms in trade regulations. The year 2014 represents the state of regulated species lists a year after the announcement of the first 16 "least wanted" AIS by the Council of Great Lakes [and St

Lawrence] Governors (now the Great Lakes St. Lawrence Governors and Premiers or "GSGP") in 2013. The use and definition of the term "regulated" varies between jurisdictions, but here we use it to represent all regulation types, e.g., prohibited, restricted, controlled, etc. Our intent is to encourage harmonization of lists of regulated species for which import, sale, and possession are controlled by statute. We recognize the need for a parallel process to ensure that laws and regulations governing the importation, sale, and possession of species are consistent and complementary; however, an assessment of those is beyond the scope of this paper.

State and provincial administrative code and statutes were referenced to compile a comprehensive list of regulated AIS (and dates for listing) for all Great Lakes jurisdictions. The analysis was limited to the subset of aquatic plants and animals for which sale, possession, and/or import is restricted, prohibited, or otherwise regulated. For plants, those species designated as obligate or facultative wetland plants (per U.S. Army Corps of Engineers National Wetland Plant list for Northcentral and Northeast region) were considered. If a plant was not listed by the U.S. Army Corps of Engineers, other sources such as obligate aquatic or wetland designations by Great Lakes jurisdictions and expert knowledge were used. For all species, only those species able to arrive and establish in the Great Lakes region were included (e.g., marine and tropical species were excluded; hereafter referred to as the "establishment criteria"). Using our establishment criteria, we excluded marine species such as *Caulerpa taxifolia* (Vahl) C. Ag., that clearly couldn't establish in the Great Lakes. However, the establishment ability of genera *Ulva* (synonym *Enteromorpha*) is less clear. In 2003, it reached bloom proportions in Muskegon Lake, a coastal lake of Lake Michigan (Lougheed and Jan Stevenson 2004). The ability of a recognized marine species to establish in freshwater was attributed to high nutrient levels, a history of industrial activity that led to elevated salinity and absence of grazing pressure. There is some uncertainty about its ability to survive in similar environments around the basin with salinity levels in the lower Great Lakes (Erie and Ontario) overlapping with Ulva's lower tolerance limits (Chapra et al. 2012). However, as Ulva hasn't persisted or spread since this event, we treated it as primarily a marine species and excluded it from the initial list of regulated species. Overall, thirty species regulated as "aquatic" were excluded due to their predicted inability to arrive or establish in the Great Lakes (Supplementary Table S1).

Six algal species and the diatom *Didymospenia geminata* (Lyngbye) M. Schmidt were also included on the list. For animals, all regulated mammals, fish, aquatic invertebrates, reptiles and amphibians were included. The state of Illinois publishes an Aquatic Life Approved Species List and prohibits possession, sale, and import of any aquatic species not on the approved list. However, for the purposes of this analysis, only those species that were identified as "injurious species" under part 805 of the Illinois

Administrative Code and relevant plant species under the Illinois Exotic Weed Act were considered regulated.

In order to obtain a clear species list and count, we only included species that were explicitly mentioned by one or more jurisdictions. In instances where entire families or genera of species were regulated by a jurisdiction, all species within that group regulated in the Great Lakes were counted towards that jurisdiction's total number of regulated species. For example, all individually listed snakehead species were counted as regulated in those jurisdictions where Channa, Parachanna, or Channidae were regulated. Likewise, although, Québec regulates the entire family Acipenseridae, only sterlet *Acipenser ruthenus* Linnaeus, 1758 (regulated by Wisconsin) was included for Québec. All regulated taxa had at least one named species except for the genus Nymphaea (regulated by Minnesota). As highlighted by Minnesota on their public outreach page for non-native waterlilies (https://www.dnr.state.mn.us/invasives/aquaticplants/waterlilies.html), there are many native waterlilies that look similar to non-native waterlilies. Although some harmful non-native water lilies are relatively easy to distinguish (e.g., *Nymphaea mexicana* Zucc.), without a clear guide on the non-native waterlilies, a positive identification for most species is difficult for pond retailers or the public. As such, we did not include this family.

Patterns in regulated species lists across jurisdictions were examined over the last 12 years with non-metric multidimensional scaling (NMDS) on a Bray-Curtis similarity matrix using the Vegan package in R 4.0.2. Plant and animal species lists were assessed separately, and each jurisdiction by time period, for 2008, 2014 and 2020, was treated as a separate point in the analysis. Average dissimilarity between jurisdictions was calculated for each time step and significance of differences between timesteps assessed using a one-way ANOVA also in R.

Progress in coordinating regional risk assessment frameworks

We consulted regional policy reports and relevant AIS management personnel to compile a list of risk assessments that are used by Great Lakes' jurisdictions to inform state or provincial processes for listing regulated species. We included frameworks that have been used by at least one jurisdiction (state, regional or federal) for planning or regulatory purposes. We limited the comparison to those frameworks able to assess broad taxonomic groups (plants, animals or plants and animals). To compare regional risk assessment frameworks against the minimum standards described in Roy et al. (2018), three independent reviewers with risk assessment background but not directly affiliated with any of the frameworks scored each assessment according to how well it met each standard. They used completed assessments and related standard operating procedures (where available). These three scores were then reconciled to consensus, for each criterion. Criteria were scored as "fully met" if the standard

operating procedures explicitly described a criterion, or if that criterion was consistently considered in the completed assessments. Criteria were scored as "partially met" if the standard operating procedures and/or completed assessments mentioned but did not provide any detail relative to a criterion. Criteria were scored as "not met" if there was no mention of that criterion in standard operating procedures or the completed assessments. Supporting information used to determine scores are included in Appendix 1.

Progress toward sufficient and transparent regulations

To determine how well current regulated species lists protect the Great Lakes, we assumed that in an ideal world, regulated species lists should give priority to those species most likely to be introduced and cause the greatest harm. We assumed that limited resources require prioritization of a candidate pool of potential future introduced species. And that those species with highest potential for impact(s) and likelihood of introduction would be higher priority for regulation, and removal from the live trade pathways. We used the Great Lakes Aquatic Nonindigenous Species Risk Assessment (GLANSRA) to score potential environmental and socio-economic impacts and likelihood of arrival. In the absence of a comprehensive data set on all species in the live trade, we developed a candidate list of potential regulated species by combining the list of all regulated species that met the inclusion criteria above and a list of unregulated species that had been identified as potential future invaders. The list of unregulated future invaders is a subset of a list of "surveillance species" that were identified through a separate regional process (Davidson et al. 2021). The surveillance species are species that are not present in or widespread throughout the basin, have a pathway through which they can arrive in the Great Lakes, are capable of establishment and are predicted to cause impacts.

Significance of the relationship between impact scores and numbers of jurisdictions regulating that species was assessed by Kendall rank correlation. We also plotted species using their impact scores, likelihood of arrival scores and current regulatory status to identify high risk species that may be underregulated. Candidate species were divided into groups based on the GLANSRA likelihood of arrival score (high, moderate, low, unknown, unlikely, established) and then patterns between impact score (from GLANSRA) and the number of regulating jurisdictions were compared graphically. Species not regulated in all 10 states and provinces with high (> 40) or moderate (20–39) impact scores were identified for consideration as regional regulatory priorities. Thus, species recommended for regulation all meet the following criteria: not yet regulated by all 10 jurisdictions; meet minimum impact standards (impact of medium or high; total impact score of ≥ 20); and likelihood of introduction of unknown, low, moderate or high. We chose to take a precautionary approach to pathway score

because the live trade pathway continues to grow, and these scores are only likely to increase (Pagnucco et al. 2015).

Results

Progress toward consistent regulations

A total of 136 aquatic species established in or predicted to be capable of establishing in the Great Lakes are regulated by at least one jurisdiction (69 plant species and 67 animal species; Tables 1, 2). The number of species regulated by 5 or more jurisdictions has gone from 10 in 2008 to 44 in 2020 (Figure 1). In 2008, only 43 species were regulated; by 2020, 136 species were regulated, with 53 new species regulated in one or more jurisdictions between 2008 and 2014 and a further 40 new species added to one or more states or provinces after 2014 (Figure 1). However, the majority (68%) of the currently regulated species are listed in less than half (i.e., < 5) of the Great Lakes jurisdictions (Figure 1). No plant species are regulated by all ten jurisdictions (as Québec does not regulate any plant species). However, hydrilla *Hydrilla verticillata* (L.f.) Royle and water chestnut *Trapa natans* L. are regulated by nine jurisdictions. The nine animal species listed in all ten jurisdictions are: northern snakehead *Channa argus* (Cantor, 1842), grass carp *Ctenopharyngodon idella* (Valenciennes in Cuvier and Valenciennes, 1844), ruffe *Gymnocephalus cernuus* (Linnaeus, 1758), silver carp *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844), bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845), black carp *Mylopharyngodon piceus* (Richardson, 1846), round goby *Neogobius melanostomus* (Pallas, 1814), tubenose goby *Proterorhinus marmoratus* (Pallas, 1814) and rudd *Scardinius erythrophthalmus* (Linnaeus, 1758) (Tables 1, 2).

The number of regulated species varies widely across jurisdictions for both taxonomic groups. Wisconsin regulates the largest number of plant and animal species (104 in total), followed by Minnesota (71), New York (59), Illinois/Indiana/Michigan/Ohio (45), Pennsylvania (34), Ontario (23) and Québec (19) (Figures 2, 3). Between 2014 and 2020, nine out of ten jurisdictions (all except Quebec) increased the number of regulated plants, and nine out of ten jurisdictions (all except Pennsylvania) increased the number of regulated animals. The regulation of plants can be broken into four major groups: 1) few regulated species by 2008, with a jump by 2014 (IL, IN, MN, WI – with WI having another jump by 2020); 2) few regulated species by 2014, with a jump by 2020 (NY, OH, ONT, PA); 3) many regulated species by 2008, with steady increase throughout (MI); and 4) no regulated species (QBC) (Figure 2). Notably, the pattern in regulation of animals was similar for all jurisdictions, with mostly steady growth from 2008–2020 (except for PA, which stayed constant) (Figure 3). The frequency of "least wanted" species listings has increased over time. Prior to the

Table 1. Alphabetical list of 69 regulated plant/algae species with GLANSRA environmental (Env), Social/Cultural (Soc/Cult) and total (combined) impact scores. Note: *Indicates a species included on the GSGP "least wanted" list. ^Indicates a species listed as federal noxious weed under the Plant Protection Act of 2000 (7 U.S.C. 7701 et seq.). [s] Indicates species on the GLANSRA surveillance species list. For Env impact or Soc/Cult impact categories, if impact score was 0–1, impact category is considered Low or Unknown (based on number of unanswered questions, indicated by a U); if impact score was 2–5, impact category is considered Moderate; if impact score was ≥ 5, impact category is considered High.

Species name	Common name	Jurisdictions regulated	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Alnus glutinosa[s]	European alder	1	9	1	10
Alternanthera sessilis ^[s]	Sessile joyweed	1	1	6	7
Arthraxon hispidus	Small carpet grass	1	1	0	1
Arundo donax[s]	Giant reed	1	19	3	22
Azolla pinnata^[s]	Mosquito fern	5	9	3	12
Butomus umbellatus[s]	Flowering rush	6	2	4	6
Cabomba caroliniana[s,a]	Carolina fanwort	4	4	4	8
Cirsium palustre[s]	Marsh thistle	1	8	0	8
Conium maculatum	Poison hemlock	4	2	2	4
Crassula helmsii[s]	Australian stonecrop	2	6	2	8
Cylindrospermopsis raciborskii	Cylindro	2	1	2	3
Didymosphenia geminata[s]	Didymo	2	12	19	31
*Egeria densa**[s]	Brazilian elodea	8	18	25	43
Eichhornia azurea^[s]	Anchored water hyacinth	5	3	2	5
Eichhornia crassipes[s]	Water hyacinth	2	15	26	41
Epilobium hirsutum[s]		1	3	0	3
Glossostigma cleistanthum	Mudmats	1	0(U)	0(U)	0
Glyceria maxima[s]	Reed manna grass	2	12	2	14
*Hydrilla verticillata**^[s]	Hydrilla or water thyme	9	19	30	49
*Hydrocharis morsus-ranae**[s]	European frogbit	8	8	7	15
Hydrocotyle ranunculoides[s]	Floating marsh pennywort	1	13	6	19
Hygrophila polysperma^[s]	Miramar weed, Indiana swampweed	5	3	8	11
Impatiens balfourii	Balfours touch-me-not	1	0(U)	0	0
Ipomoea aquatica^[s]	Chinese waterspinach or swamp morning-glory	5	6	8	14
Iris pseudacorus	Yellow flag iris	5	8	3	11
Lagarosiphon major^[s]	Oxygen weed or African elodea	6	14	13	27
Ludwigia hexapetala [s]	Uruguayan primrose willow	2	18	10	28
Ludwigia peploides[s]	Floating primrose willow	1	19	9	28
Lysimachia nummularia	Creeping jenny	1	1(U)	0	1
Lysimachia vulgaris[s]	Garden loosestrife	2	8	0	8
Lythrum salicaria	Purple loosestrife	8	9	0	9
Lythrum virgatum[s]	Wanded loosestrife	5	18	12	30
Melaleuca quinquenervia^[s]	Broad-leaved paperbark	2	13	18	31
Monochoria hastata^	Monochoria, arrowleaf, or false pickerelweed	4	0	6	6
Monochoria vaginalis^	Heartshape or false pickerelweed	4	2	6	8
Murdannia keisak[s]	Marsh dewflower	1	12	2	14
Myosotis scorpioides	True forget-me-not	1	O(U)	0	0
Myriophyllum aquaticum[s]*	Parrot feather	8	18	3	21
Myriophyllum heterophyllum	Broadleaf water-milfoil	1	9	7	16
Myriophyllum heterophyllum x *M. laxum*[s]	Broadleaf water-milfoil hybrid	1	8	18	26
Myriophyllum spicatum	Eurasian watermilfoil	6	6	10	16
Najas marina		1	0(U)	1	1
Najas minor[s]	Brittle naiad	4	7	2	9
Nelumbo nucifera[s]	Sacred lotus	1	12	1	13
Nitellopsis obtusa[s]	Starry stonewort	4	19	7	26
Nymphaea spp.[b]	Non-native water lilies	1	3	1	4
*Nymphoides peltata**[s]	Yellow floating heart	6	2	3	5
Oenanthe javanica[s]	water-celery	1	3	2	5

Table 1. (continued).

Species name	Common name	Jurisdictions regulated	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Ottelia alismoides^	Duck lettuce	5	0	0	0
Phalaris arundinacea	Reed Canary grass	1	14	3	17
Phragmites australis	Common reed	6	18	5	23
Pistia stratiotes[s]	Water lettuce	1	14	30	44
Potamogeton crispus	Curlyleaf pondweed	6	5	4	9
Prymnesium parvum[s]	Golden algae	2	13	18	31
Sagittaria sagittifolia^[s]	Arrowhead	5	1	14	15
Salix atrocinerea[s]	Gray florist's willow	1	13	1	14
Salvinia auriculata^	Eared watermoss, African payal, and butterfly fern	5	1	1	2
Salvinia biloba^	Giant salvinia	5	0	0	0
Salvinia molesta^[s]	Giant salvinia	6	18	31	49
Silphium perfoliatum	Cup-plant	1	12	0	12
Solanum tampicense^[s]	Wetland nightshade	2	3	1	4
Solidago sempervirens	Seaside goldenrod	1	1	0	1
Sparganium erectum^	Exotic bur-reed	4	1	0	1
*Stratiotes aloides**[s]	Water soldier	6	3	2	5
*Trapa natans**[s]	Water chestnut	9	14	12	26
Typha angustifolia	Narrow leaf cattail	3	8	0	8
Typha domingensis[s]	Southern cattail	1	14	15	29
Typha laxmannii[s]	Graceful cattail	1	6	1	7
Typha x *glauca*[s]		2	18	0	18
Valeriana officinalis	Garden valerian	1	1	0	1

[a] *Cabomba*, while not native to the Great Lakes basin, is native to some portion of at least four Great Lakes states.
[b] This species was not counted toward the total because there are no species identified in the associated regulation.

announcement of a list of "least wanted" species in 2012 (GSGP 2013) only 5 of these high-risk species were regulated in at least half of all jurisdictions, but by 2020, 19 of the 21 species were regulated across the majority of jurisdictions. Exceptions are New Zealand mudsnail (*Potamopyrgus antipodarum* J.E. Gray, 1853) (4 jurisdictions) and marbled crayfish (*Procambarus virginalis* Hagen, 1870) (1 jurisdiction) which was only announced as "least wanted" in May 2018. No jurisdiction regulates all 21 "least wanted" species.

For animals (Figure 4), by 2020, the lists appear to be converging into two locations in the ordination. A group of seven jurisdictions (IL, IN, MI, MN, OH, ON, QBC) appear to show an increasing level of similarity towards the top of axis 2 between 2008 to 2020. The second smaller group of states (NY, WI) in contrast, is showing similarity towards the far right of axis 1, and Minnesota is intermediate between these two groups. This latter group (NY, WI) differs from the main cluster in that they regulate stone moroko (*Pseudorasbora parva,* Temminck and Schlegel, 1846), Wels catfish (*Silurus glanis* L., 1758) and yabby (*Cherax destructor* Clark 1936). For plants (Figure 5) all jurisdictions appear to be moving towards a similar list of taxa to the far right of axis 1. Average dissimilarity was significantly different between 2008 timestep and 2014 or 2020 for both animals and plants ($F_{2,115} = 2.52$, $P = 0.085$ and $F_{2,76} = 6.82$, $P = 0.002$ respectively), but there were no significant differences between 2014 and 2020 for either plants or animals.

Table 2. Alphabetical list of 67 regulated animal species with GLANSRA environmental (Env), Social/Cultural (Soc/Cult) and total (combined) impact scores. *Indicates a species included on the GSGP "least wanted" list. ^Indicates a species listed as "injurious wildlife" under the Lacey Act (18 U.S.C. 42). [s] Indicates species on the GLANSRA surveillance species list. For Env impact or Soc/Cult impact categories, if impact score was 0–1, impact category is considered Low or Unknown (based on number of unanswered questions, indicated by a U); if impact score was 2–5, impact category is considered Moderate; if impact score was ≥ 5, impact category is considered High.

Species name	Common name	Jurisdictions regulated	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Acipenser ruthenus	Sterlet	2	18	6	24
Alosa aestivalis[s]	Blueback herring	1	6	0	6
Alosa pseudoharengus	Alewife	2	18	14	32
Bithynia tentaculate	Faucet snail	3	7	2	9
Bythotrephes longimanus (*cederstroemi*)	Spiny waterflea	3	7	1	8
Carassius auratus	Goldfish	3	1(U)	0	1
Carassius carassius^	Crucian carp	2	0	0	0
Carassius gibelio^[s]	Prussian carp	2	9	6	15
Cercopagis pengoi	Fishhook waterflea	2	7	1	8
*Channa argus**^[s]	Northern snakehead	10	7	2	9
*Cherax destructor**[s]	Yabby	6	2	1	3
Cherax tenuimanus[s]	Marron	1	2	0	2
Cipangopaludina chinensis	Chinese mystery snail	3	0(U)	0(U)	0
Cipangopaludina japonica	Japanese trap door snail	3	1	1(U)	2
Corbicula fluminea	Asian clam	3	2	2	4
*Ctenopharyngodon idella**[s]	Grass carp	10	20	1	21
Cyprinella lutrensis[s]	Red shiner	2	14	0	14
Cyprinus carpio	Common carp	3	12	1(U)	13
Daphnia lumholtzi[s]	Water flea	2	2	0	2
*Dikerogammarus villosus**[s]	Killer shrimp	5	7	0	7
Dreissena bugensis	Quagga mussels	9	25	20	45
Dreissena polymorpha^	Zebra mussel	9	30	25	55
Eriocheir sinensis^[s]	Chinese mitten crab	5	8	8	16
Faxonius rusticus	Rusty crayfish	6	19	7	26
Fundulus diaphanus diaphanous	Eastern banded killifish	1	0(U)	0	0
Gambusia affinis[s]	Western mosquitofish	3	9	1	10
Gambusia holbrooki[s]	Eastern mosquitofish	2	19	9	28
Gasterosteus aculeatus	Three spine stickleback	2	3	1	4
Gymnocephalus cernuus[s]	Eurasian river ruffe	10	12	12	24
Hemimysis anomala[s]	Bloody red shrimp	2	7	0	7
*Hypophthalmichthys molitrix**^[s]	Silver carp	10	15	7	22
*Hypophthalmichthys nobilis**^[s]	Bighead carp	10	8	12	20
Lepomis microlophus[s]	Redear sunfish	1	8	0	8
Leuciscus idus	Ide	3	0	0	0
*Limnoperna fortunei**[s]	Golden mussel	5	30	9	39
Misgurnus anguillicaudatus[s]	Weatherfish	4	14	0	14
Morone americana	White perch	4	18	2	20
*Mylopharyngodon piceus**[s]	Black carp	10	7	0	7
Myocastor coypus	Nutria	3	6	13	19
Neogobius melanostomus	Round goby	10	13	13	26
Oncorhynchus gorbuscha	Pink salmon	1	1(U)	1	2
Oncorhynchus kisutch	Coho salmon	1	3	0	3
Oncorhynchus mykiss	Rainbow trout	1	9	0	9
Oncorhynchus tshawytscha	Chinook salmon	1	2	0	2
Osmerus mordax	Rainbow smelt	2	12	0(U)	12
Perca fluviatilis^[s]	European perch	3	18	2	20
Perccottus glenii^[s]	Amur sleeper	2	8	1	9
Petromyzon marinus	Sea lamprey	4	12	18	30
Phoxinus phoxinus^[s]	Eurasian minnow	2	2	1	3
*Potamopyrgus antipodarum**[s]	New Zealand mud snail	4	13	0	13
Procambarus clarkii[s]	Red swamp crayfish	3	24	7	31
*Procambarus virginalis**[s]	Marbled crayfish	1	14	2	16

Table 2. (continued).

Species name	Common name	Jurisdictions regulated	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Proterorhinus marmoratus	Tubenose goby	10	1	0	1
*Pseudorasbora parva**^s*	Stone moroko	7	19	1	20
Rhodeus sericeus[s]	Bitterling	3	6	0	6
Rutilus rutilus^s	Roach	2	11	2	13
Salmo salar	Atlantic salmon	1	5	0	5
Salmo trutta	Brown trout	1	9	0	9
Salvelinus alpinus	Arctic char	1	1	0	1
*Sander lucioperca**^s*	Zander	9	8	0	8
Scardinius erythrophthalmus[s]	Rudd	10	4	0	4
*Silurus glanis**^s*	Wels-catfish	7	6	0	6
*Tinca tinca**[s]	Tench	5	2	0	2
Trachemys scripta elegans	Red eared slider	2	13	6	19
Valvata piscinalis	European valve snail	1	1	0	1
Viviparus georgianus	Banded mystery snail	2	1	0	1
Xenopus laevis	African clawed frog	1	9	0	9

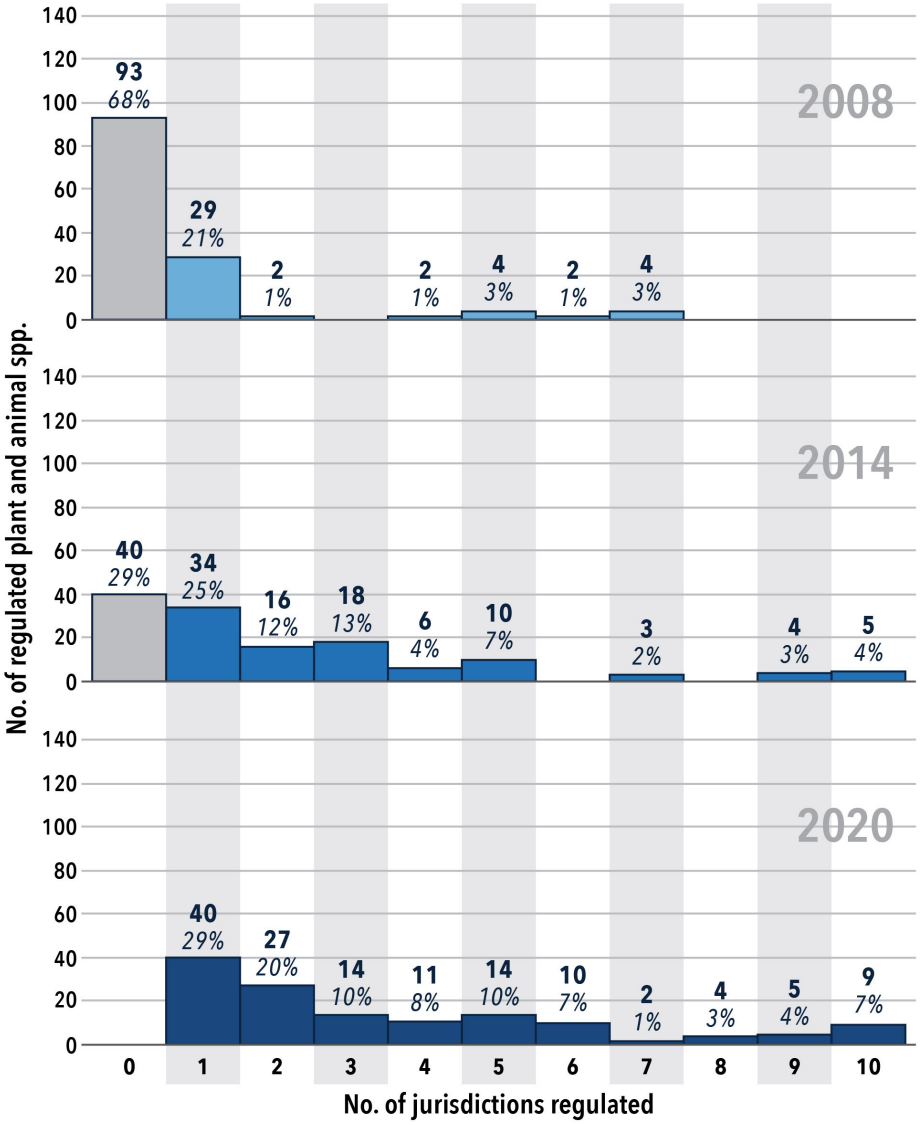

Figure 1. The cumulative number of species (out of 136 unique species) regulated by one to all (ten) jurisdictions. The "zero" jurisdiction column represents species that are regulated in 2020 but were not regulated in 2008 (93 species) or 2014 (40 species).

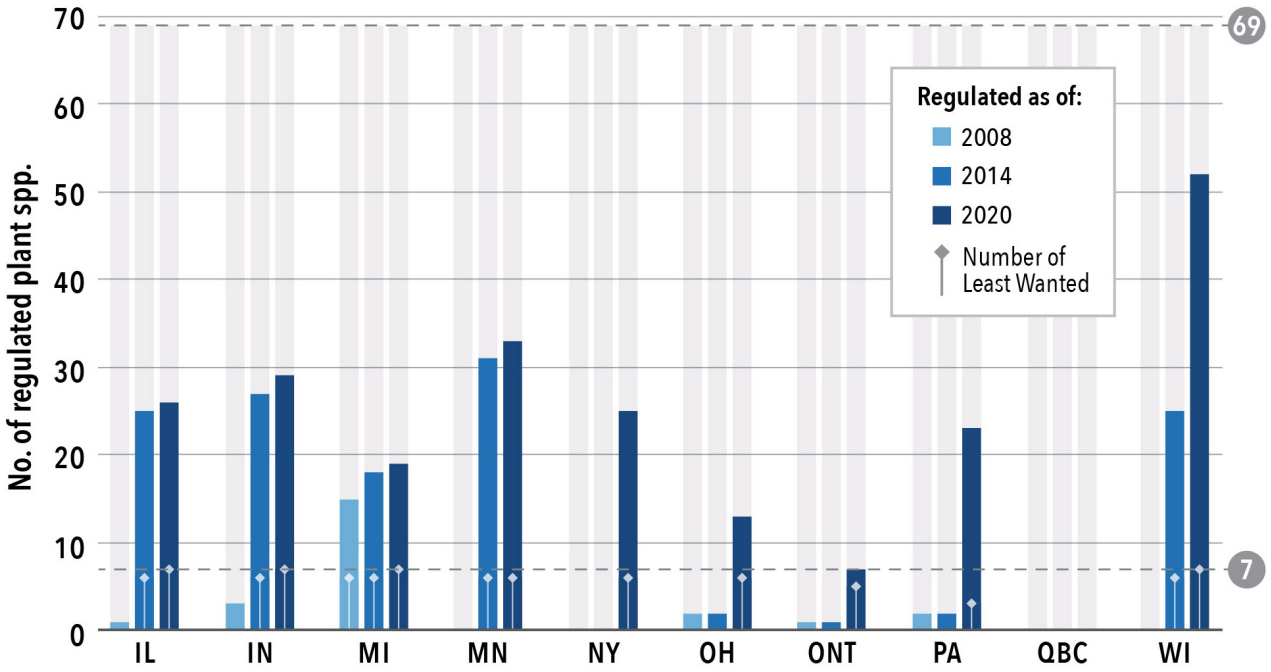

Figure 2. Number of plant species regulated by jurisdiction, as of the start of 2008, 2014 and 2020, with the total number of unique species regulated in one or more jurisdiction (69) and the number of regulated "least wanted" species (out of 7).

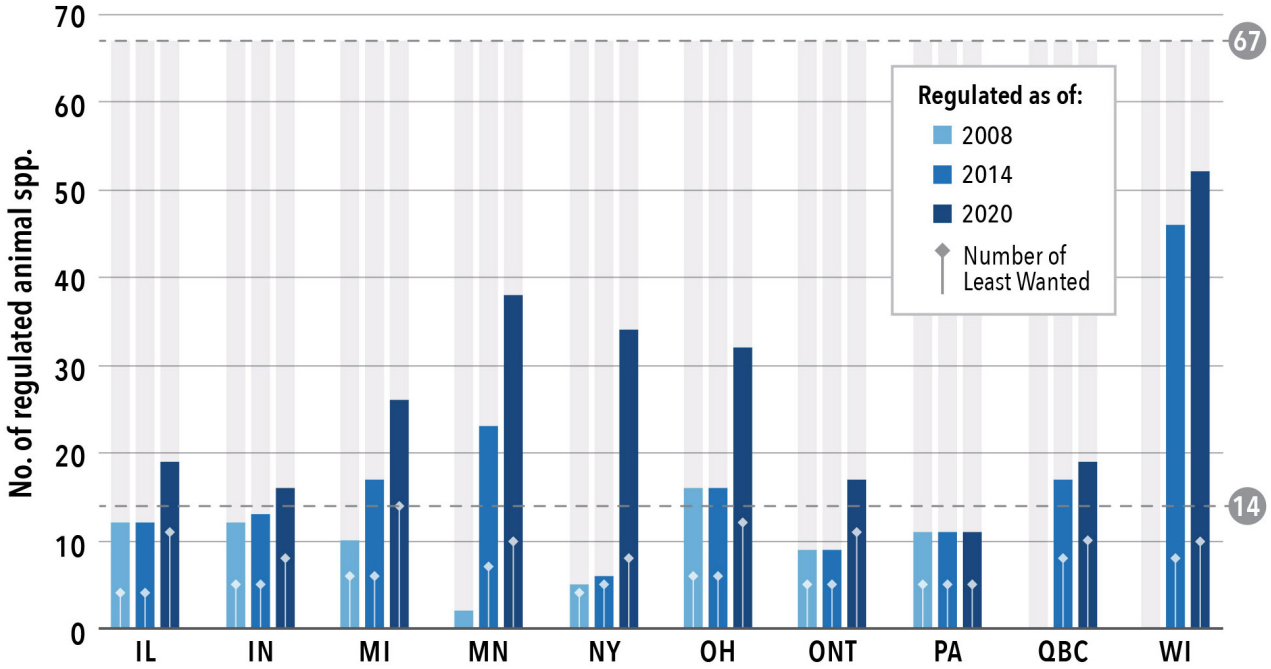

Figure 3. Number of animal species regulated by jurisdiction, as of the start of 2008, 2014 and 2020 with the total number of unique species regulated in one or more jurisdiction (67) and the number of regulated "least wanted" species (out of 14).

Progress in regional risk assessment framework development

In all, six risk assessment frameworks are identified and assessed (Table 3; Appendix 1). Three risk assessments evaluated risk for both plants and animals and three were specific to just plants. The assessments range from semi-quantitative questionnaire-based assessments, to screening level assessments based on literature review and a climate matching tool. In addition to different formats, the frameworks were designed to achieve

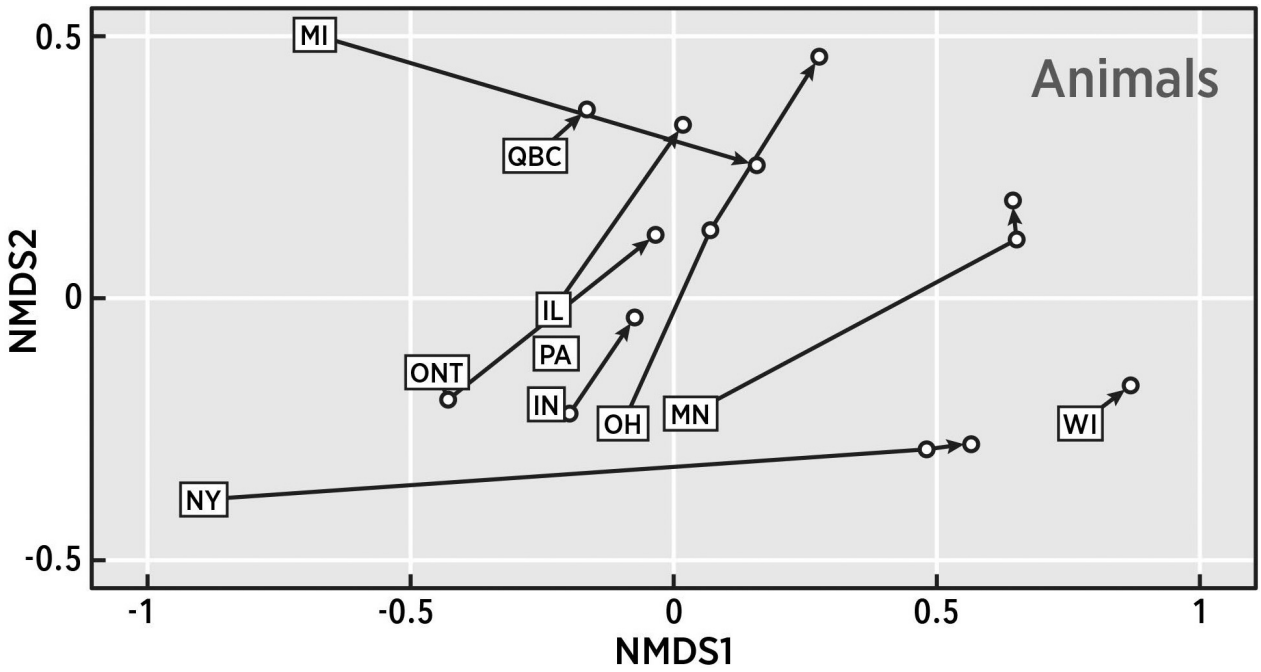

Figure 4. Plot of axis 1 and 2 from a Nonmetric multidimensional scaling ordination (NMDS: stress = 0.12) based on Bray-Curtis dissimilarity of jurisdictional regulated aquatic animal species lists in 2008, 2014 and 2020. The lists in each jurisdiction are joined in sequence from 2008 to 2020. IL = Illinois, IN = Indiana, MI = Michigan, MN = Minnesota, NY = New York, OH = Ohio, ONT = Ontario, PA = Pennsylvania, QBC = Québec and WI = Wisconsin.

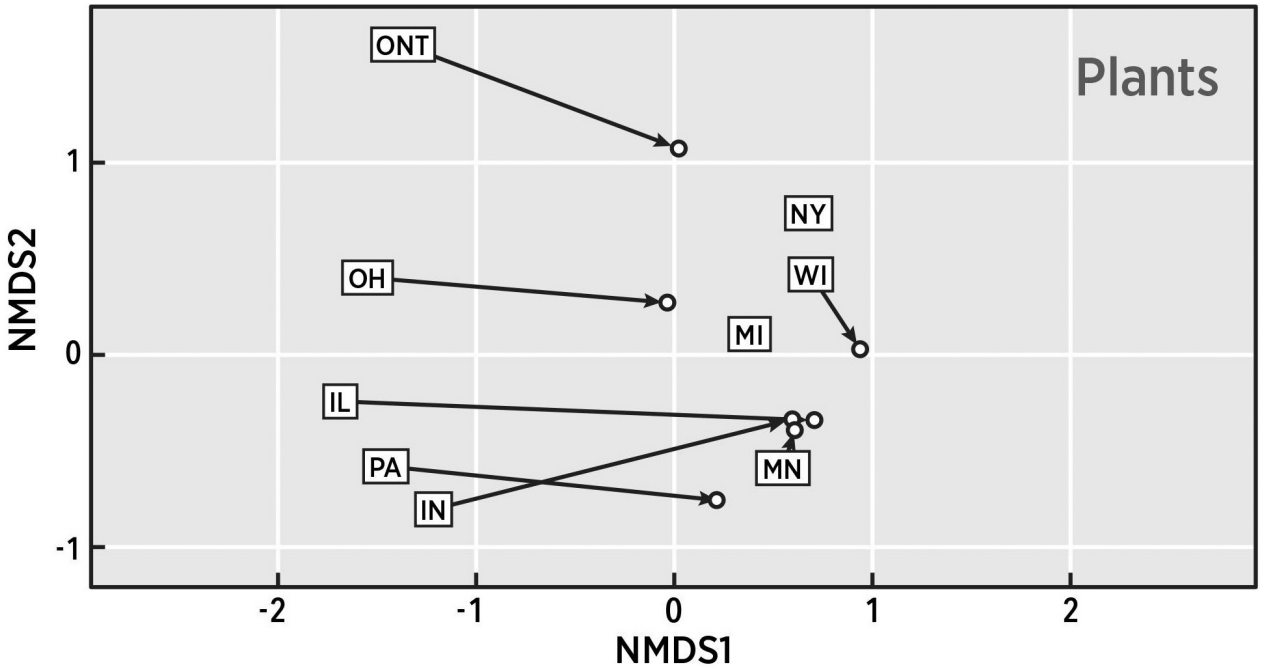

Figure 5. Plot of axis 1 and 2 from an NMDS (stress = 0.08) based on Bray-Curtis dissimilarity of jurisdictional regulated aquatic plant species lists in 2008, 2014 and 2020. The lists in each jurisdiction are joined in sequence from 2008 to 2020. IL = Illinois, IN = Indiana, MI = Michigan, MN = Minnesota, NY = New York, OH = Ohio, ONT = Ontario, PA = Pennsylvania, QBC = Québec and WI = Wisconsin.

different goals (Appendix 1). The frameworks that most closely met the full suite of risk assessment standards from Roy et al. (2018) are the Great Lakes Aquatic Nonindigenous Risk Assessment (GLANSRA), United States Department of Agriculture Animal and Plant Health Inspection Service plant protection and quarantine weed risk assessment protocol

Table 3. Comparison of regional risk assessment frameworks: Great Lakes Aquatic Nonindigenous Species Risk Assessment (GLANSRA); United States Department of Agriculture, Animal and Plant Health Inspection Service (USDA APHIS); Ecological Risk Screening Summaries, U.S. Fish and Wildlife Service (ERSS); Wisconsin Literature Review (WI); Great Lakes Aquatic Weed Risk Assessment (GL AqWRA); and New York State Ranking System (NY). The rows represent each standard: (1) basic species description; (2) likelihood of invasion; (3) distribution, spread and impacts; (4) assessment of introduction pathways; (5) assessment of impacts on biodiversity and ecosystems; (6) Assessment of impact on ecosystem services; (7) assessment of socio-economic impacts; (8) consideration of status (threatened or protected) of species or habitat under threat; (9) assessment of effects of future climate change; (10) completion possible even when there is a lack of information; (11) documents information sources; (12) provides a summary in a consistent and interpretable form; (13) includes uncertainty; (14) includes quality assurance (Roy et al. 2018). A score of 0 = did not meet; 0.5 = partially met; 1 = fully met.

	GLANSRA	USDA APHIS	ERSS	WI (SAGs/lit review)	GL AqWRA	NY
Spp. description (1)	1	1	1	1	0.5	0.5
Invasion likelihood (2)	1	1	0.5	0.5	0.5	1
Distribution, spread, impacts (3)	1	1	1	1	0.5	1
Introduction pathways (4)	1	0.5	0.5	0.5	0.5	0
Biodiversity/ecosystems impacts (5)	1	1	1	1	1	1
Ecosystem services impacts (6)	0.5	1	0.5	0.5	0.5	0.5
Socio-economic impacts (7)	1	0.5	1	1	0.5	0
Impacts to critical spp./habitats (8)	0.5	1	1	0	0	0
Climate change (9)	1	0	0.5	1	0	0
Results despite information gaps (10)	1	1	1	0	0	1
Documents information sources (11)	0.5	0.5	0.5	0.5	0.5	0.5
Provides usable summery (12)	1	1	1	0.5	1	1
Includes uncertainty (13)	1	1	1	0	1	0
Includes quality assurance (14)	0.5	0.5	0.5	0.5	0.5	0.5
Total score (out of 14)	**12**	**11**	**11**	**8**	**7**	**7**

(USDA APHIS) and United States Fish and Wildlife Service Ecological Risk Screening Summary (ERSS) tool. These frameworks included assessment of ecosystem services, threatened species/habitat and climate change, whereas the lower scoring frameworks did not. The U.S. Fish and Wildlife Service's Ecological Risk Screening Summary tool recently revised their standard operating procedure to provide for a supplementary assessment of future climate scenarios, upon request. However, this is not included as part of the core assessment so was scored as partially met.

Only two states (Michigan and New York) use risk assessment frameworks to identify and justify listing of both plants and animals, with Michigan the only state to legislatively mandate these frameworks (Heathcote 2015). Michigan initially mandated the U.S. Fish and Wildlife Service's Ecological Risk Screening Summary tool (US Fish and Wildlife Service 2020) for animals and the USDA's plant protection and quarantine weed risk assessment protocol (USDA APHIS 2020) for plants, although the state has since expanded the list of potential risk frameworks. New York has developed their own scoring tool that includes ecological and socio-economic benefits and impacts (New York Invasive Species Council 2010). Indiana has used the U.S. AqWRA tool for plants (Gordon et al. 2012; Gantz et al. 2015) and is developing a tool for animals. Other jurisdictions apply risk assessments more informally, using different approaches based on the species, or instead relying on an expert panel process (e.g., MN, OH). Wisconsin uses a standardized literature review and formalized species assessment group to identify and assess species for regulation (Wisconsin Invasive Species Council 2018). Some jurisdictions are attempting to standardize their risk

assessment approach by legislating the use of specific risk assessment frameworks (e.g., Pennsylvania) (Stahlman *pers. comm.*).

Progress toward sufficient and transparent regulated species lists

Based on the GLANSRA surveillance list (Davidson et al. 2021), 58 surveillance species are not regulated by any jurisdiction (Table 4; plotted as "0" jurisdictions in Figures 6, 7). There was a weak correlation between impact score and number of jurisdictions regulating all animal species (Tau = 0.26, P = 0), and all species (animals and plants) (Tau 0.21: P = 0) known to be in the live trade pathways, but not for plants (Tau = 0.14: P = 0.08). Many of the most-regulated species have impact scores in the low or low-moderate categories, and several species with high impact scores are regulated by less than half of jurisdictions (Figures 6, 7). Twenty-one species (17 plant and 4 animal) are identified as priorities for future regulatory listing because they meet the criteria for minimum impact (moderate or high) and likelihood of arrival from GLANSRA (excluding shipping/ballast pathway-only species) and are not yet regulated by all ten Great Lakes' jurisdictions (Table 5).

Discussion

The Great Lakes has been at the forefront of the scientific development of aquatic risk assessment methods and has demonstrated invasive species can be accurately predicted through trait-based analysis (Kolar and Lodge 2001; Keller et al. 2007). Management uptake of these methods was initially slow, and in 2008 when the GLP assessed interjurisdictional patterns in regulated species, many jurisdictions were reliant on expert panels to identify potential species for listing. At the time, state and federal prevention efforts were focused on the shipping pathway and awareness of the risk posed by the live trade pathways was low (Padilla and Williams 2004; Rixon et al. 2005; Keller and Lodge 2007). It is therefore not surprising that in 2008, regulated species lists were a disparate collection of species with limited similarity across the jurisdictions. Twelve years later, in concert with a growing number of risk assessment methods (Mandrak 2014; Gantz et al. 2015; Howeth et al. 2016; Davidson et al. 2017; Marcot et al. 2019), there is increasing recognition of the need for regional coordination and information sharing. These efforts have led to the establishment of two risk assessment clearinghouses (Great Lakes Aquatic Nonindigenous Species Information System 2020; Invasive Species Centre 2020) and regionally agreed-upon lists of "least wanted" species (GSGP 2013). Nevertheless, despite the region's wealth of risk assessment tools and species risk assessments, there remains both significant differences in regulated species lists between jurisdictions and under-regulation of potentially harmful AIS in most jurisdictions. This "weakest link" dilemma is shared by other regions where multiple jurisdictions share management of large aquatic ecosystems (e.g., the Colorado and Murray-Darling River basins; Wheeler

Table 4. List of surveillance species not regulated by any jurisdictions (58), assessed using the GLANSRA framework. The surveillance species list includes species present in at least one introduction pathway and would represent novel introductions to the Great Lakes basin, as well as established species with localized distribution in the Great Lakes (in ≤4 Great Lakes) but capable of range expansion. Species with no known history of invasion, plants not generally associated with aquatic habitats, and plants or animals not suited to temperate freshwater habitats are also excluded from this list.

Taxa	Species name	Common name	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Bryozoan	*Fredericella sultana*		8	12	20
Bryozoan	*Lophopodella carteri*		3	1	4
Crustacean	*Apocorophium lacustre*		2	0	2
Crustacean	*Argulus japonicus*	Japanese fishlouse	6	6	12
Crustacean	*Calanipeda aquaedulcis*		6	0	6
Crustacean	*Chelicorophium curvispinum*	Caspian mud shrimp	3	0	3
Crustacean	*Cyclops kolensis*		3	0	3
Crustacean	*Daphnia galeata galeata*	Waterflea	7	0	7
Crustacean	*Dikerogammarus haemobaphes*		2	0	2
Crustacean	*Echinogammarus warpachowskyi*		2	0	2
Crustacean	*Gmelinoides fasciatus*	Baikalian amphipod	8	0	8
Crustacean	*Limnomysis benedeni*		4	0	4
Crustacean	*Obesogammarus crassus*		6	0	6
Crustacean	*Obesogammarus obesus*		8	0	8
Crustacean	*Faxonius limosus*	Spinycheek crayfish	1	2	3
Crustacean	*Pacifastacus leniusculus*	Signal crayfish	14	3	17
Crustacean	*Paramysis ullskyi*		7	0	7
Crustacean	*Paramysis lacustris*		3	0	3
Crustacean	*Podonevadne trigona ovum*		2	0	2
Crustacean	*Pontastacus leptodactylus*	Danube crayfish	2	1	3
Crustacean	*Pontogammarus robustoides*		4	0	4
Crustacean	*Schizopera borutzkyi*	Oarsman	6	0	6
Fish	*Acanthogobius flavimanus*	Yellowfin goby	7	0	7
Fish	*Alburnus alburnus*	Alver, bleak	14	0	14
Fish	*Atherina boyeri*	Big-scale sand-smelt	2	0	2
Fish	*Babka gymnotrachelus*	Racer goby	2	1	3
Fish	*Benthophilus stellatus*	Starry goby	3	0	3
Fish	*Gobio gobio*	Gudgeon	6	0	6
Fish	*Hypomesus nipponensis*	Wakasagi	6	0	6
Fish	*Ictalurus furcatus*	Blue catfish	2	1	3
Fish	*Leuciscus leuciscus*	Dace	7	6	13
Fish	*Menidia beryllina*	Inland silverside	7	0	7
Fish	*Morone saxatilis x chrysops*	Hybrid striped bass/wiper	3	0	3
Fish	*Neogobius fluviatilis*	Babka goby	3	0	3
Fish	*Oncorhynchus keta*	Chum salmon, Keta salmon	3	0	3
Fish	*Osmerus eperlanus*	European smelt	7	0	7
Fish	*Siniperca chuatsi*	Mandarin fish	6	1	7
Mollusk	*Sinanodonta woodiana*	Chinese pond mussel	8	0	8
Mollusk	*Lithoglyphus naticoides*	Gravel snail	7	0	7
Mollusk	*Mytilopsis leucophaeata*	Dark false mussel	14	7	21
Plant	*Alternanthera philoxeroides*	Alligator weed	18	24	42
Plant	*Aponogeton distachyos*	Cape pondweed	2	0	2
Plant	*Azolla filiculoides*	Pacific mosquitofern	8	14	22
Plant	*Cyperus difformis*	Variable flat sedge	1	6	7
Plant	*Egeria najas*		3	2	5
Plant	*Juncus compressus*	Flattened rush	2	1	3
Plant	*Juncus gerardii*	Black-grass rush	7	2	9
Plant	*Juncus inflexus*	European meadow rush	2	1	3
Plant	*Limnobium spongia*	American spongeplant	2	3	5
Plant	*Ludwigia adscendens*	Water primrose	2	4	6
Plant	*Ludwigia grandiflora*		18	10	28
Plant	*Oxycaryum cubense*	Cuban bulrush	7	1	8
Plant	*Rotala rotundifolia*	Roundlaf toothcup	2	1	3
Plant	*Sagittaria platyphylla*	Delta arrowhead	12	13	25

Table 4. (continued).

Taxa	Species name	Common name	GLANSRA Env Impact Score	GLANSRA Soc/Cult Impact Score	Total impact score
Plant	*Salvinia minima*	Water spangles	8	8	16
Plant	*Typha orientalis*	Bullrush/raupo	6	0	6
Plant	*Vallisneria spiralis*	Eelgrass	7	2	9
Platyhelminthes	*Ichthyocotylurus pileatus*	Digenean fluke	7	0	7

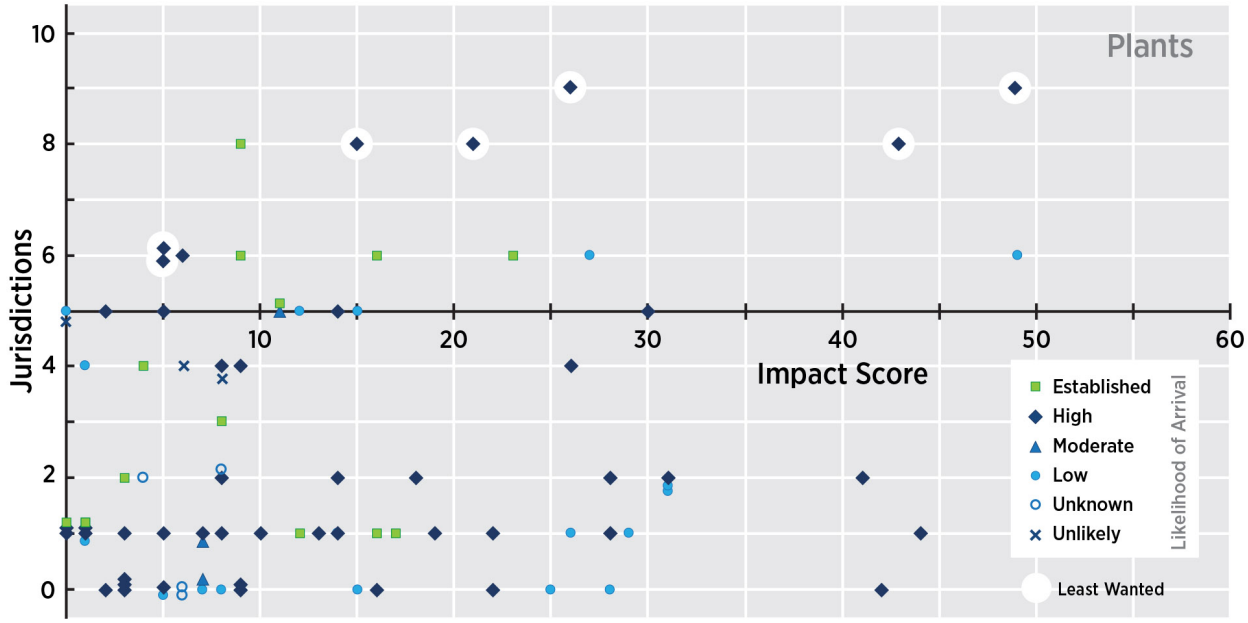

Figure 6. Plot of regulated and surveillance (unregulated) plant/algae species capable of arriving and establishing in the Great Lakes basin, showing total impact score (environmental plus social/cultural, based on GLANSRA framework) against number of regulating jurisdictions. Likelihood of arrival is highest score from all pathways in GLANRA assessment. Those species established in the Great Lakes did not receive a likelihood of arrival score. "Least wanted" indicates a species included on the GSGP "least wanted" list.

Figure 7. Plot of regulated and surveillance (unregulated) animal species capable of arriving and establishing in the Great Lakes basin, showing total impact score (environmental plus social/cultural, based on GLANSRA framework) against number of regulating jurisdictions. Likelihood of arrival is highest score from all pathways in GLANRA assessment. Those species established in the Great Lakes did not receive a likelihood of arrival score. "Least wanted" indicates a species included on the GSGP "least wanted" list.

Table 5. List of 17 plant and 4 animal species for regulatory consideration and "least wanted" status. ^Indicates a species listed as "injurious wildlife" under the Lacey Act (18 U.S.C. 42). [s] Indicates species on the GLANSRA surveillance species list. Pathway score is for the trade pathways. * indicates a score for a non-trade pathway if a species scores unlikely for a trade pathway; () indicates a higher-scoring non-trade pathway. Unk = unknown. Risk assessments include: Great Lakes Aquatic Nonindigenous Species Risk Assessment (GLANSRA); United States Department of Agriculture, Animal and Plant Health Inspection Service (USDA APHIS); Ecological Risk Screening Summaries, U.S. Fish and Wildlife Service (ERSS); Wisconsin Literature Review (WI); Great Lakes Aquatic Weed Risk Assessment (GL AqWRA); and New York State Ranking System (NY).

Taxa	Species name	Common name	Jurisdictions regulated	GLANSRA Total impact score	GLANSRA pathway score	Completed risk assessments
Plant	*Salvinia molesta*^[s]	Giant salvinia	6	49	L*	GLANSRA, ERSS, WI, NY
Plant	*Pistia stratiotes*[s]	Water lettuce	1	44	H	GLANSRA, ERSS, GL AqWRA, WI, NY
Plant	*Alternanthera philoxeroides*	Alligator weed	0	42	L (H*)	GLANSRA, ERSS, GL AqWRA
Plant	*Eichhornia crassipes*[s]	Water hyacinth	2	41	H	GLANSRA, ERSS, GL AqWRA, WI, NY
Plant	*Didymosphenia geminata*[s]	Didymo	2	31	H*	GLANSRA, WI
Plant	*Melaleuca quinquenervia*^[s]	Broad-leaved paperbark	2	31	L*	GLANSRA, ERSS
Plant	*Prymnesium parvum*[s]	Golden algae	2	31	M*	GLANSRA, WI
Plant	*Lythrum virgatum*[s]	Wanded loosestrife	5	30	H	GLANSRA, WI
Plant	*Typha domingensis*[s]	Southern cattail	1	29	L (M*)	GLANSRA, WI
Animal	*Gambusia holbrooki*[s]	Eastern mosquitofish	2	28	H	GLANSRA, ERSS, WI
Plant	*Ludwigia grandiflora*	Water primrose	0	28	L*	GLANSRA, ERSS, GL AqWRA, NY
Plant	*Ludwigia hexapetala* [s]	Uruguayan primrose willow	2	28	H	GLANSRA, GL AqWRA, NY
Plant	*Ludwigia peploides*[s]	Floating primrose willow	1	28	H	GLANSRA, NY
Plant	*Lagarosiphon major*^[s]	Oxygen weed or African elodea	6	27	Unk (L*)	GLANSRA, ERSS, GL AqWRA, WI
Plant	*Myriophyllum heterophyllum* x *M. laxum*[s]	Broadleaf water-milfoil hybrid	1	26	Unk (L*)	GLANSRA
Plant	*Sagittaria platyphylla*	Delta arrowhead	0	25	L	GLANSRA
Animals	*Acipenser ruthenus*	Sterlet	2	24	H	GLANSRA, WI
Plant	*Arundo donax*[s]	Giant reed	1	22	H	GLANSRA, USDA APHIS, ERSS, WI
Plant	*Azolla filiculoides*	Pacific mosquitofern	0	22	H	GLANSRA, ERSS
Animal	*Mytilopsis leucophaeata*	Dark false mussel	0	21	M*	GLANSRA, ERSS
Animal	*Fredericella sultana*	Branching bryozoan	0	20	H*	GLANSRA

et al. 2018). In addition to the "weakest link" issue, interpreting the codes and statutes covering each jurisdiction's regulated species can be challenging. For example, one of the jurisdictions regulates crayfish three different ways: a general legislative code that is extremely difficult to find and interpret, a list from the fishing department and a list related to aquaculture. The fact that interpreting these conflicting lists posed a significant challenge in the writing of a manuscript dedicated to this topic has implications for how these statutes are interpreted by the wider public.

To continue progress in harmonization of regulated species, a key challenge is how to objectively identify the next set of regional priorities. Here we discuss progress toward species' regulation that is consistent (the same suite of species is regulated across all jurisdictions), sufficient (species identified as highest risk are prioritized for regulation), and transparent (species are listed for regulation based on the consistent application of an objective and comprehensive risk assessment framework).

Progress toward consistent regulated species lists

Great Lakes jurisdictions have regulated many high impact species; in fact, all species for which risk assessment predicted the highest impact (total impact score of 40–60; Tables 1, 2; Figures 6, 7) are regulated by at least one jurisdiction, except one (alligator weed *Alternanthera philoxeroides* Mart. Griseb., discussed below). Brazilian elodea (*Egeria densa* Planch.) and hydrilla (*Hydrilla verticillata* (L.f.) Royle) are regulated by eight and nine jurisdictions, respectively. State and provincial regulated species lists, and the number of species within these lists included by the majority of Great Lakes jurisdictions, have increased over the last 12 years (Figures 1–3). We venture that this is due in part to the increasing use of evidence-based decision-making. There appears to be a general trend towards increasing similarity across animal and plant regulated species lists. For animals there appear to be two clusters of jurisdictions developing. Average dissimilarity is decreasing but was not significantly different across years, probably because these two groups appear to be diverging. The two outlying jurisdictions (WI, NY) and Minnesota (intermediate between these two groups) are also the jurisdictions with the greatest number of regulated animal species (Figure 4) and their divergence is presumably driven by the regulation of a group of unique species across these three jurisdictions. For plants, three states (MN, IL, IN) form a tight cluster, noting that the Illinois regulated species lists was based off Indiana's list and the same risk assessment data. All other jurisdictions appear to be trending towards this group, but average dissimilarity does not appear to be declining. However, the higher similarity in 2008 is an artefact of the few species listed then, and the absences (zeros) making these jurisdictions appear similar in ordination space. Unlike animals, those states with the highest similarity have intermediate numbers of listed species. The two jurisdictions with the fewest listed species (ON, OH) are two of the least similar lists by 2020, whereas Wisconsin (most comprehensive list) appears to be trending towards the IL, IN, MN cluster. New York seems to be the other outlier, and while it has a reasonably comprehensive list of species, the differences may in part reflect the marine coastal geography of the state and different introduction risks associated with neighbouring eastern seaboard states. As state and provincial regulated species lists are informed by regional risk assessment and clearinghouse data, and there is a more deliberate effort to complement neighboring regulatory efforts, we would expect these two groups to continue to come together and the average level of dissimilarity to decline.

Additional gains towards regional efforts to harmonize regulated species lists across the region could be achieved through progress on aquatic plants by a subset of jurisdictions (notably Ontario and Québec). Some Great Lakes jurisdictions have initiated discussions to inform regional harmonization efforts across neighboring states and provinces, but to date

there do not appear to have been any formal resolutions. For animals, most states have made progress to list additional high-risk species and continued progress towards consistent regulation of the agreed upon "least wanted" species is evident. A notable exception is Pennsylvania, where no "least wanted" species that were not already regulated by the state in 2013 have been listed since publication of the "least wanted" list (but as noted above efforts to develop AIS listing criteria are underway in that state). Existing gaps in the "least wanted" list may be due to socio-political factors, given that regionally recognized scientific evidence for risk would appear to provide the evidential basis to justify prohibition (for example, current "least wanted" species New Zealand mudsnail *Potamopyrgus antipodarum* and marbled crayfish *Procambarus virginalis* are regulated by only four and one jurisdictions, respectively).

Progress toward sufficient regulated species lists

Despite substantial progress, there remain 21 species with GLANSRA impact scores of medium or high (total impact score of 20–60) and likelihood of introduction of unknown, low, moderate or high that are not yet regulated across all jurisdictions. Notably, the two species predicted to have the greatest impact and a high likelihood of arrival are regulated by very few jurisdictions (water hyacinth *Eichhornia crassipes* – 2 and water lettuce *Pistia stratiotes* – 1). These two species are economically valuable to the live trade industry, and there has been some uncertainty about the ability of these plants to over winter in the Great Lakes or produce viable seeds (Adebayo et al. 2011). However, repeated detections in the same locations in Frank and Poet Drain (Detroit River) may provide anecdotal evidence of seed production; understanding if and under what circumstances sexual reproduction occurs in the Great Lakes is a critical research need (Cahill et al. 2018). Furthermore, as the region warms these species are more likely to be able to overwinter in sheltered locations and spread rapidly in spring. Given their global history of invasion and damages (*E. crassipes* listed on the "100 of the World's Worst Invasive Alien Species" by the Global Invasive Species Database, with *P. stratioties* having similar effects), their predicted high impact in the Great Lakes, and the success of "least wanted" designation in increasing the number of regulating jurisdictions, all Great Lakes states and provinces could consider these two as future "least wanted" species to increase consistency (and subsequent likelihood of prevention). But this will require consultation with the aquarium and water garden industries.

Alligator weed (*Alternanthera philoxeroides*) is one high risk species that is not regulated by any jurisdiction, despite its presence in Illinois and states on the southern border of the Great Lakes states. It is another species for which the Great Lakes may be at the northern limits of its range, given its intolerance of extended periods of freezing (Shen et al. 2017). Nevertheless,

given its high potential for impact, proximity to the basin, and the likelihood that climate change-induced milder winters and warmer summers will increase the chance for establishment throughout the Great Lakes basin (Stefan et al. 2001), this species would seem to be a high priority for regulation and advanced planning could allow industry to find an alternative during the regulatory process.

There are also species in the moderate impact category that are either not regulated or appear to be underregulated (less than 5 jurisdictions). Those unregulated live trade species with total impact scores of 20–39 include Pacific mosquitofern *Azolla filiculoides* Lam. and Delta arrowhead *Sagittaria platyphylla* (Engelm.) J.G. Sm. Those underregulated live trade species with total impact scores of 20–39 include broadleaf water-milfoil hybrid *Myriophyllum heterophyllum* Michx. × *M. laxum* Shuttlw. ex Chapm., floating primrose willow *Ludwigia peploides* (Kunth) P.H. Raven, eastern mosquitofish *Gambusia holbrooki* Girard, 1859, Uruguayan primrose willow *Ludwigia hexapetala* (Hook. & Arn.) Zardini, H.Y. Gu & P.H. Raven, southern cat-tail *Typha domingensis* Pers., giant reed *Arundo donax* L., sterlet *Acipenser ruthenus* Linnaeus, 1758 and red swamp crayfish *Procambarus clarkii* (Girard, 1852). While it is up to each jurisdiction's risk management staff to determine the impact threshold warranting regulation, some jurisdictions have often used moderate or high impact scores to justify regulation (e.g., New York Invasive Species Council 2010). Regulating species with predicted high or moderate impacts may be particularly relevant for species, like those listed above, with a high likelihood of arrival via the live trade pathway.

Progress toward transparent regulated species lists

One of the most challenging aspects about regulating the live trade pathway is that the outcomes of a risk assessment are not usually the only factor considered when deciding to mitigate risk and regulate a species. All species in trade have a varying degree of economic value that influences whether they are regulated even when evidence suggests the species will have negative impacts to the environment and/or human health. For example, in the U.S., revenues from reptile sales are estimated at US$1.4 billion (Collis and Fenili 2011), with each additional species sold generating about US$90,000 in profit (Springborn et al. 2011). While many suppliers, retailers and consumers are interested in preventing harmful AIS impact, sectors of the aquarium industry such as the Pet Industry Joint Advisory Council have opposed past proposals on importation restrictions for nonnative wildlife species (Strecker et al. 2011). As such, adding species to regulated species lists already perceived as overly long requires transparency on behalf of the responsible agency, as well as coordination with the live trade industry.

As noted above, of the 136 regulated plant and animal species, the 6th (*Pistia stratiotes*, water lettuce) and 9th (*Eichhornia crassipes*, water hyacinth) highest-scoring species are only regulated by one (Wisconsin) and two (Wisconsin and Minnesota) jurisdictions, respectively. Both of these are popular commercial plants. In contrast, while there are several species with high impacts that justify their status as "least wanted", over half (11 of 21) of the "least wanted" species have low total impact scores. Several other species could be considered "overregulated". For example, tubenose goby *Proterorhinus marmoratus* is regulated by all 10 jurisdictions despite having a total impact score of one. Of the 73 regulated species with total impact less than 10 ("very low" impact category), 18 are regulated in at least half of the jurisdictions. Of the 136 regulated species, 74% have low impacts; only seven have high impacts (note: this is for all regulated species, not just those in trade). In addition, three of the regulated species (arrowleaf *Monochoria hastata* (L.) Solms, heartshape pickerelweed *Monochoria vaginalis* (Burm. f.) C. Presl ex Kunth and giant salvinia *Salvinia biloba* Raddi) are predicted to be unlikely to arrive via any pathway, the latter likely regulated by jurisdictions due to its status as a species within a federally regulated taxon (genus *Salvinia*). Finally, several species unlikely to establish due to abiotic conditions in the Great Lakes (freshwater or cold winter temperatures) are regulated by multiple jurisdictions (e.g., marine *Caulerpa taxifolia* (Vahl) C. Ag. is regulated by four jurisdictions without marine coastlines). While we do not necessarily suggest that species like *Caulerpa* be de-regulated (especially for those Great Lakes jurisdictions that also contain Atlantic coast marine habitats that would be vulnerable to marine species), it is important to note this issue of species with potentially low impacts (or low likelihood of arrival or establishment) being regulated, while others with the ability to arrive, survive and have larger impact are not.

There are several species not present in the live trade pathway (e.g., zebra mussel *Dreissena polymorpha* Pallas, 1771) that are regulated by at least one jurisdiction. Although presence in the live trade pathways is the primary reason to regulate a species, other reasons exist that justify regulation. For example, New Zealand mud snail and starry stonewort are found in the hitchhiking/fouling pathway and are commonly transported on recreational boats. Regulation of these species would ensure, e.g., that inspection officers and volunteers would be able to identify them during watercraft inspections, thus limiting their transfer between water bodies. While regulation of individual species is appropriate for pathways such as live trade and even hitchhiking/fouling, we acknowledge that regulation of individual species may not be appropriate for pathways such as shipping (ballast water). As such, we did not include species as candidates for regional regulatory consideration whose only pathway of introduction is ballast water (full pathway scores included in Supplementary Table S2.

Resources for regulation and enforcement are limited; effort spent focusing on a low impact species is effort not spent on a higher impact species. In addition, if a species is predicted to have no or very low impact, regulation may harm the live trade industry unnecessarily. To some extent, existing patterns may reflect the role that "expert panels" played in identifying species for regulation in the early efforts to manage this pathway. It is therefore encouraging that there appears to be an evolution to increasing adoption of semi-quantitative and formal data driven assessment processes, that are less prone to individual bias. This is perhaps a function of both management's acceptance of the science of risk assessment and the development of risk assessment tools that provide the range of information needed for regulatory processes.

Notably, while academic risk assessment efforts have been directed to more statistical-based and parsimonious models (e.g., Keller et al. 2007; Howeth et al. 2016), in part assuming that reduced data needs results in a more efficient screening process, the frameworks developed by management agencies have tended towards semi-quantitative systems that cover a broad range of information consistent with recommendations of Roy et al. (2018; Leung et al. 2012). We speculate that this is not due to reluctance by the agencies to adopt these parsimonious models, but rather, the agencies' need for detailed assessments that document the full spectrum of factors related to invasion (e.g., introduction, establishment, and both ecological and socio-economic impact).

Given the economic and social value of aquatic live trade activities, it is important to maintain the sale of a variety of organisms. Yet, given the environmental costs of harmful live trade releases, and value of prevention vs. control, it is also important to regulate those species that should not be traded. Therefore, it is essential that the regulatory process for listing species be transparent, objective and consistent. Risk assessment is a rigorous tool that can inform the risk management process when attempting to list species for regulation (Mandrak and Cudmore 2015) and provide justification for limitations on live trade (Roy et al. 2018). For the Great Lakes, a range of risk assessment methods exist that meet Roy et al. (2018) recommendations to varying degrees (Table 3).

Progress in regional risk assessment framework development

Despite the availability of risk assessment frameworks relevant to the Great Lakes region (Table 3), only Michigan and New York legislate the use of a risk assessment framework as part of the regulatory decision making process. New York uses the same framework for both plants and animals, whereas Michigan uses two frameworks, one for plants and another for animals. Indiana, which is close to finalizing a risk assessment process for both plants and animals, will also use a different framework for the two

groups. The application of a multitude of assessments across the basin likely results in duplication of effort and may impede knowledge sharing and the ability to reach regional consensus. The GLANSIS Risk Assessment Clearinghouse has developed a Methods Explorer that allows a side-by-side comparison of a variety of frameworks, which further demonstrates the number and variety of risk assessments.

The fact that some jurisdictions currently implement risk assessment as part of the regulatory decision making process and that other jurisdictions are currently working towards adoption of a similar model presents an opportunity for jurisdictions to work together to ensure that the same (or very similar) frameworks are selected for use across the region. Adopting the same risk assessment framework would allow jurisdictions to save resources and use (or use with modifications) existing species risk assessments completed by other jurisdictions in the region (Heathcote 2015). This is a model that has been implemented in the European Union (EU), where a consistent risk assessment framework is applied across Member States to inform an agreed upon list of regulated species. In 2018, the European Commission (executive body of the EU) approved a risk assessment template that met 14 minimum standards, as described in Roy et al. (2018). This template is used to assess priority species, to decide whether they should be included on the list of invasive species under Regulation (EU) 1143/2014 on the prevention and management of the introduction and spread of invasive alien species (European Commission 2020). The list of invasive species (and any related management actions) applies across all Member States (H. Roy *pers. comm.*).

Although none of the risk assessments we evaluated meet all of the criteria laid out by Roy et al. (2018), some measure up well (GLANSRA, APHIS, and ERSS) and all of them meet at least half of the minimum standards. GLANSRA, which can be used to assess both plants and animals, scored highest, yet is not widely used for regulatory decision making across Great Lakes' jurisdictions. USDA APHIS, which is used by Michigan to inform invasive plant listings, meets most of the criteria, but does not assess animals. The ERSS can assess both plants and animals but does not assess likelihood of introduction. The ERSS is intended as a risk screening tool to identify species that merit additional and more detailed risk screening (S. Jewell *pers. comm.*). If a species scores highly in an ERSS, and is considered for listing under the Lacey Act, a more in-depth analysis is completed and published in the Federal Register (US Fish and Wildlife Service 2001, e.g., US Office of the Federal Register 2016). Furthermore, the Ontario Ministry of Natural Resources and Forestry is also developing its own risk assessment tool. No assessment is perfect and no single assessment is likely to meet every jurisdictions' wants and needs. Nevertheless, a regional process to consider how existing risk assessment tools could be adopted or adapted to meet regional needs and an agreed

upon set of minimum standards could help to move the region towards more consistent, sufficient, and transparent regulated species lists, and reduce duplication of effort.

Beyond risk assessment: other issues facing live trade pathway regulations and enforcement

Adoption of a uniform framework and process to apply risk assessment in a regulatory context will improve consistency, sufficiency, and transparency of regulated species lists. But regulatory challenges may be caused by factors unrelated to risk assessment, per se, such as inconsistent risk management, jurisdictional prerogative, insufficient funding, species native ranges, enforcement terminology and authority, and supplier/distributor issues. These issues will also need to be addressed for effective management of the live trade pathway.

In general, risk assessment is the understanding of likelihood and impact; risk management is the action taken based on this understanding (e.g., regulation). Risk management includes both the decision-making body and other stakeholders in order to identify value judgements and determine the risk tolerance (also known as the acceptable level of risk). This may present a challenge because the acceptable level of risk can differ, so that one jurisdiction may aim to regulate any species with an impact of low, moderate or high, while another may only aim to regulate species with a high impact (Davidson et al. 2015). Thus, jurisdictions must not only apply consistent risk assessment outcomes, but also make consistent decisions on how "strong" their link will be in the proverbial chain of protection.

Jurisdictional prerogative reflects the fundamental differences in regulatory philosophy that exist across the basin. Most jurisdictions take a prohibited species approach (only species listed in specific legislation are regulated), while one (Illinois) takes a mostly allowable species list approach (only species listed in specific legislation are allowed in trade) (Sturtevant et al. 2016). Allowed lists are a precautionary option to regulating species (Padilla and Williams 2004) but can be difficult to implement and enforce due to the large number of species in some aspects of live trade, e.g., the aquarium industry (Heathcote 2015). When neighboring jurisdictions vary between allowed and prohibited species lists approach, it can be challenging to understand what, and how, species are regulated. Regional agreement on a risk assessment and framework for application could help to alleviate this issue.

Insufficient funding is another impediment to the development and enforcement of regulated species lists. In the U.S., most jurisdictions have little to no funding to support their invasive species programs apart from federal assistance funding. Several jurisdictions have relatively significant budgets due to monies specifically allocated to AIS management, e.g., Minnesota uses a portion of boat and trailer license fees, New York uses a

portion of real estate transfer taxes and unclaimed bottle deposit bottles, and Wisconsin uses a portion of the gas tax (Heathcote 2015). Relatively well-funded jurisdictions (and especially those relying on "soft money") are nevertheless constrained by budgets insufficient to implement jurisdictional AIS management plans. Significant time is required to assess species for regulatory consideration; insufficient funding to support this endeavor is also a contributing factor to inconsistent regulations, including jurisdictions that do require risk assessments. Finally, even after regulations are passed, such laws are rendered ineffective without funding to hire trained staff to enforce them (Heathcote 2015).

Species native ranges can make universal regulation difficult. For example, the ghost shiner *Notropis buchanani* Meek, 1896 is native to the southern Great Lakes basin (and endangered in Pennsylvania), but it is invasive in other parts of the basin (Sturtevant et al. 2016). Four cryptogenic species (rusty crayfish *Faxonius rusticus* Girard, 1852, red swamp crayfish *Procambarus clarkii*, broadleaf water-milfoil *Myriophyllum heterophyllum* Michx. and spiny naiad *Najas marina* L.) are on the regulated species list in the Great Lakes, despite being considered by some jurisdictions to be native. The regulation of these species in jurisdictions where they have native and non-native populations is inconsistent. For example, rusty crayfish is regulated by IL (where it has native populations, though not in the basin, and non-native populations in the basin) and MI (where it has native and non-native populations, both in the basin) but not IN and OH (where is also has native and non-native populations in the basin). Although these species are considered native to a subset of Great Lakes jurisdictions, and thus would not be expected to be regulated in these jurisdictions, the number of these native species are small and wouldn't be expected to change the observed patterns in regulation.

Even when there is a consistent list of species between jurisdictions, the terminology surrounding the regulation may vary, with "injurious", "restricted" and "prohibited" having different definitions and penalties. Addressing such differences in legislative terminology and definitions have reduced confusion and increased compliance in other areas of AIS management, including recreational boating (Otts and Nanjappa 2014). Furthermore, responsibility for regulation of species may be split between agencies within a jurisdiction. For example, in Pennsylvania, the authority for regulation of aquarium fish is under the State Fish and Boat Code, but enforcement is under the Department of Agriculture. Enforcement of this pathway is already difficult owing to the vast number of bait/aquarium/pond/aquaculture retailers and the associated suppliers and consumers, as well as the vast number of species in trade and the associated difficulty in identifying them. Attempting to coordinate such efforts across agencies only increases the burden (Heathcote 2015).

Regulation is important because awareness of the potential for species in live trade to become invasive is limited (Seekamp et al. 2016). However, regulation alone has not been effective at reducing trade in regulated species (Diaz et al. 2012; June-Wells et al. 2012; Patoka et al. 2018). If profit from trade in regulated species exceeds the associated fines, for example, retailers may continue to offer banned species for sale (Drew et al. 2010). The proliferation of online commerce also makes enforcement difficult and complex (Lenda et al. 2014). Kay and Hoyle (2001) found sites selling nearly every aquatic or wetland plant listed in the United States as either a Federal Noxious Weed or as a noxious weed in one or more states.

Even if retailers attempt to comply, they often face additional barriers to success. Inconsistent regulations pose challenges for multi-state retailers or their suppliers (Peters and Lodge 2009; Drew et al. 2010). Unlabeled or mislabeled specimens hinder retailers' (and inspection officers') ability to identify regulated species and remove them from trade; the presence of "hitchhikers" associated with the intended species makes this even more difficult (Maki and Galatowitsch 2004; Keller and Lodge 2007). For example, in a study of eDNA from bait and pond stores in the Great Lakes, 88% of bait stores had AIS present in stocked bait. Samples from pond stores found eDNA from species such as bighead carp, silver carp, European ide, zebra mussels, invasive bryozoans, and invasive snails (Snyder et al. 2020). Educational efforts focused on existing regulations, species identification and best management practices for nonindigenous species could help to improve compliance and overall effectiveness of regulations (Oele et al. 2015), especially if coupled with regular surveillance of the pathway. New high throughput sequencing eDNA survey methods are becoming cost effective and overcome the reliance on visual inspections that can have low levels of detection sensitivity and be time and cost prohibitive (Nathan et al. 2015).

Conclusion

Live trade is a major pathway for the introduction of non-indigenous species, with thousands of species from a variety of taxa transported globally (Lockwood et al. 2019). In addition, climate change will shift the suite of plants and animals able to establish in many regions of the world, including the Great Lakes, and therefore risk-screening should be applied to new species and reviewed for species currently allowed for sale (Bradley et al. 2012). To address the threat of invasive species in trade in a "weakest link" regional management context, the Great Lakes needs to harmonize and increase the number of species listed for regulation. In the near-term, we have identified the next suite of priority high-risk species for consideration for regulation across the region. In the long term, we believe the region should work towards investing in a consistent (set of) risk assessment(s) that meet the minimum criteria for risk assessments, and

whose results can be used by all jurisdictions. Adoption of a consistent risk assessment(s) would help establish a transparent process for state and federal stakeholders to consistently regulate live trade species. It would aid data sharing and reduce duplication of efforts related to assessing species. Such transparency and efficiency are essential given the economic importance of the live trade industries and the limited resources available to manage new and established AIS.

Acknowledgements

This manuscript has evolved out of an initial assessment by the Research committee of the Great Lakes Panel on Aquatic Nuisance Species, and from discussions by the panels Ad Hoc Trade in live organisms subcommittee. We thank David Hamilton, Katie Kahl, Sarah LeSage and Eric Fischer for their advice, and many discussions over the last 12 years, that have helped inform our thinking. We would like to acknowledge several individuals who provided input and data used in this study. Rochelle Sturtevant and GLANSIS provided risk assessment data for several species. Kristina Davis (Notre Dame Center for Research Computing) formatted the figures included in this manuscript. Patrick Canniff assisted in the risk assessment framework review. Comments from Katherine Wyman-Grothem and an anonymous reviewer significantly improved the manuscript.

Funding Declaration

ADD, AJT, WLC, CW and EJ contributions were partially funded through the Blue Accounting Initiative. Blue Accounting receives funding support from the Charles Stewart Mott Foundation, the Fred A. and Barbara M. Erb Family Foundation, the Joyce Foundation, and the Herbert H. and Grace A. Dow Foundation. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. Description of risk assessment frameworks relevant to the Great Lakes region.
Table S1. Table of regulated aquatic species not expected to arrive or establish in the Great Lakes basin.
Table S2. Table of GLANSRA pathway scores for all species.

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