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Research Article

Development of a surveillance species list to inform aquatic invasive species management in the Laurentian Great Lakes

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Abstract

In an effort to harmonize multi-jurisdictional surveillance and detection of aquatic invasive species, regional stakeholders have called for the development of a Great Lakes Aquatic Invasive Species Surveillance Framework to identify species that pose a risk to the basin, quantify the relative risk of various pathways of introduction, provide guidance on monitoring protocols for surveillance, and identify priority locations for surveillance based on this pathway assessment. Here, we screen 448 species to develop a surveillance list of 144 species that are relevant for Great Lakes surveillance: are not yet widespread throughout the basin, have a pathway through which they can arrive, are able to establish and are predicted to cause impacts. Using the Great Lakes Aquatic Nonindigenous Species Risk Assessment for consistent assessment across taxa, the surveillance species list consisted of 144 species: 64 plants, 4 algae, 40 fish, 5 mollusks, 28 crustaceans, 1 platyhelminthes and 2 bryozoans. While pathway risk varies by taxon, the highest risk pathways across all taxonomic groups are natural dispersal, hitchhiking/fouling, and intentional release. The taxonomic group predicted to have the most severe impacts on a per species basis is algae, followed by mollusks, and plants. However, the large number of plant and fish species on the surveillance species list means that overall predicted impact (from a taxonomic perspective) is greatest from these two groups. We recommend ways that the surveillance list could be applied to improve aquatic invasive species management efforts: engage in community-based surveillance, inform taxonomic and species surveillance priorities, provide guidance on monitoring protocols for surveillance, quantify the relative risk of various pathways of introduction and identify priority locations for surveillance based on this pathway assessment.

Key words: potential introductions, risk assessment, impact assessment, pathways, uncertainty, early detection, monitoring targets

Introduction

Aquatic invasive species (AIS) in the Great Lakes have caused significant and ongoing ecological and economic impacts to the region (Rosaen et al. 2012; Rothlisberger et al. 2012). While prevention is often the most successful and cost-effective management strategy for biological invasions, its effectiveness will never be absolute (Lodge et al. 2006). As such, federal, state and provincial governments have implemented a variety of regulatory and management approaches along with community and stakeholder engagement and education programs, to manage new introductions into the region.

Within the scope of management actions, early detection and rapid response programs attempt to identify, respond to, contain or eradicate new introductions before they establish widely. Detecting nonindigenous species soon after their introduction (or even earlier – while still in the pathway) optimizes the opportunity for effective containment, or eradication (Vander Zanden et al. 2010) and is more cost-effective than control (Leung et al. 2002).

Surveillance plans are a primary component of early detection efforts (Epanchin-Niell et al. 2012; Trebitz et al. 2017). They may consist of pathway surveillance where efforts focus on either identifying and intercepting invasive species within the transport pathway (e.g., Maki and Galatowitsch 2004; Keller and Lodge 2007; Nathan et al. 2014) or identifying introduction hotspots (e.g., identifying locations where ballast water discharge is particularly high and thus may be vulnerable to introductions; Briski et al. 2012a). Another approach is site led surveillance where monitoring occurs at locations of high ecological or economic value that are vulnerable to non-native species.

Many surveillance plans are focused on specific species or species groups (e.g., red swamp crayfish (*Procambarus clarkii* Girard, 1852); Tréguier et al. 2014, Asian carp; Asian Carp Regional Coordinating Committee (ACRCC) 2015). Surveillance site selection is typically based on complex models dependent on detailed knowledge of a species' characteristics (Epanchin-Niell et al. 2012; Kocovsky et al. 2012). These include niche models that predict species' distribution over space and time using environmental data (Bossenbroek et al. 2001; Wittmann et al. 2016; Kramer et al. 2017), which can identify surveillance priorities as an output (Egly et al. 2019). Increasingly, however, managers have identified the need to develop a comprehensive framework to guide and coordinate surveillance actions for a broad suite of AIS (Trebitz et al. 2017; GLEC 2019; USEPA 2019). Such a comprehensive surveillance plan requires *a priori* knowledge of the full suite of species likely to arrive to a region, the pathways by which they might arrive, their ability to survive, their preferred habitat, and whether they are likely to have impacts (McGeoch et al. 2016; Reaser et al. 2020).

The development of an objective "surveillance species list" would typically use a risk assessment as a metric to determine what species are of sufficient concern to warrant surveillance (Vander Zanden et al. 2010; Meyers et al. 2020). In the Laurentian Great Lakes (hereafter, Great Lakes), extensive work has been conducted on pathway-, vector-, and taxon-specific risk assessments, particularly relating to ballast introductions (Colautti et al. 2003; Grigorovich et al. 2003). More recently there has been increased emphasis placed upon the specific species risk associated with the trade in live organisms (Rixon et al. 2005; Keller and Lodge 2007; Marson et al. 2009; Mandrak 2014; Schroeder et al. 2014), recreational boating (Rothlisberger et al. 2010; Davidson et al. 2015) and canal pathways (US Army Corps of Engineers 2014). However, compiling a comprehensive list and comparing the species across taxonomic groups is made difficult by the fact that biosecurity risk assessment generally lacks consistent frameworks across taxa, pathways and regions (Dahlstrom et al. 2011).

In an effort to harmonize multi-jurisdictional surveillance and detection of AIS, regional stakeholders have called for the development of a Great Lakes Aquatic Invasive Species Surveillance Framework (hereafter, Framework) to quantify the relative risk of various pathways of introduction, identify priority locations for surveillance based on this pathway assessment, and provide guidance on monitoring protocols for surveillance (Chadderton et al. *in revision*). If fully implemented, the recommendations outlined in the Framework will provide critical information needed by decision makers to help inform potential management actions, and ultimately help to prevent future establishment, spread, and impacts of AIS in the Great Lakes. The foundation of this Framework is a list of non-indigenous and potentially invasive species that warrant surveillance (hereafter, surveillance species list), based on the probability of introduction, establishment, and impact in the Great Lakes. The approach for developing and leveraging a surveillance species list, like the one described here for the Great Lakes, could be used as a model to inform AIS management in other regions.

Materials and methods

The scope of the current surveillance framework is the U.S. waters of the Great Lakes, their connecting channels, and major tributaries up to the first barrier to fish movement. However, the surveillance species list described here is effectively a binational surveillance list that covers the U.S. and Canadian waters of the Great Lakes. Aquatic invasive species do not recognise political boundaries that separate these connected waters, hence the surveillance list was derived for the entire Great Lakes and draws on data from both Canadian and U.S. sources.

The surveillance framework targets a full range of taxonomic groups, including aquatic algae, plants and animals (invertebrates and fishes) and obligate or facultative wetland plants. Semiaquatic birds, reptiles, amphibians, or mammals and viruses, bacteria and unicellular parasites were not considered (Figure 1). We exclude unicellular parasites such as microsporidia, that we believe fit better under the purview of fish health and microbiology departments (this was also the rationale for excluding viruses and bacteria in the original screen). We include species that would represent novel introductions to the basin and 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

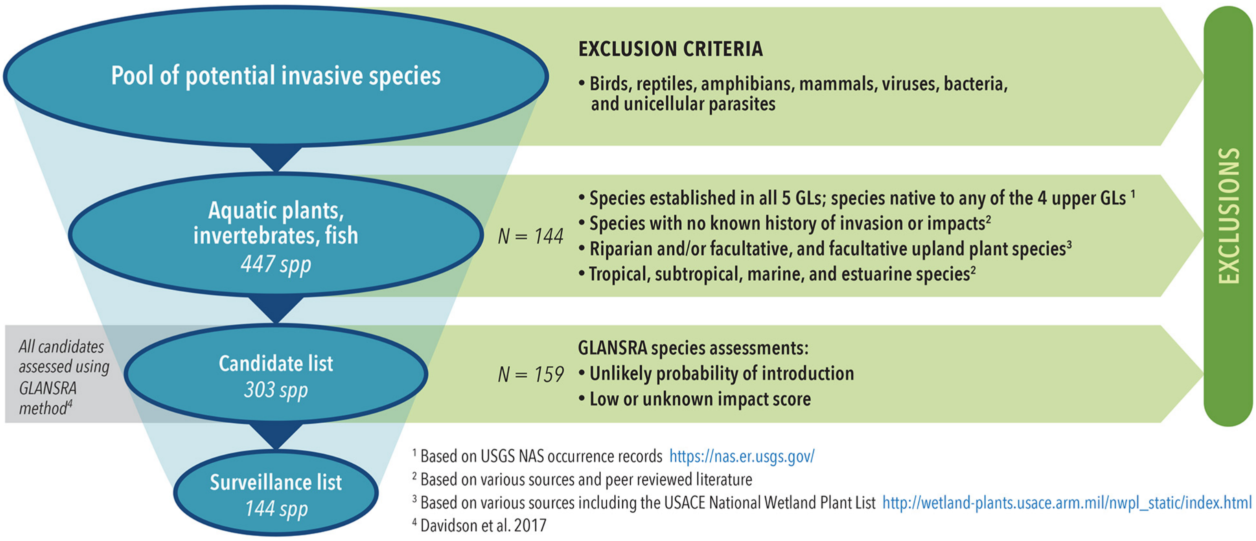

Figure 1. Decision tree and exclusion criteria applied to refine pool of potential invasive species and identify surveillance list.

associated with aquatic habitats, and plants or animals not suited to temperate freshwater habitats were also excluded from any further consideration (Figure 1).

The pool of non-indigenous and potentially invasive species was compiled from various sources including state and federal agency species lists (Supplementary material Table S1): 447 species were initially identified; 303 candidate species remained after we applied the first two sets of exclusion filters (Figure 1, Table S2). The Great Lakes Aquatic Nonindigenous Species Risk Assessment (GLANSRA) framework developed by Davidson et al. (2017) was then used to determine likelihood of introduction and assign a pathway (or pathways) of introduction and evaluate the potential for negative environmental or socio/cultural impacts, for the remaining 303 candidate species. The GLANSRA method provides a consistent approach for risk assessment across all taxonomic groups based on semi-quantitative measures of socio-cultural and environmental impacts, as well as for each of the major invasion pathways (Table 1). Uncertainty associated with impact and pathway measures are incorporated and identified in the final risk assessment scores.

The candidate list was further refined based on pathway and impact scores (results from the GLANSRA framework), in order to focus efforts on the higher risk AIS. We applied a conservative inclusion criteria for pathway scores. Species were only excluded if their probability of introduction was assessed as “unlikely” (i.e. pathway risk score = 0) with high confidence (i.e. zero unknowns). Otherwise, species with high (80–100), moderate (40–79), or low (1–39) introduction scores were included (unlikely scores were also included when confidence was assessed as very low to moderate). Thereafter, species with the requisite pathway risk score and high or moderate impact scores were included, whereas species with low or unknown impacts were excluded from the list. Based on these criteria, we

Table 1. Description of Great Lakes Aquatic Nonindigenous Species Risk Assessment (GLANSRA) pathways used for assessment (Davidson et al. 2017).

Pathway name	Pathway description
Natural dispersal	Occurs near waters (natural or artificial) connected to the Great Lakes basin (e.g., streams, ponds, canals, or wetlands)
Hitchhiking/fouling	Likely to attach to or be otherwise transported by, or along with, recreational gear, boats, trailers, fauna (e.g., waterfowl, fish, insects), flora (e.g., aquatic plants), or other objects (e.g., packing materials), including as parasites or pathogens, entering the Great Lakes basin
Shipping	Likely to be taken up in ballast, and capable of surviving adverse environments (i.e. extreme temperatures, absence of light, low oxygen levels) and partial-to-complete ballast water exchange/flushing (e.g., is euryhaline, buries in sediment, produces resistant resting stages, has other attributes or behaviors facilitating survival under these conditions
Intentional release	Sold at aquarium/pet/garden stores ("brick & mortar" or online), catalogs, biological supply companies, or live markets (e.g., purchased for human consumption, bait, ornamental, ethical, educational, or cultural reasons) and as a result may be released into the Great Lakes basin
Stocking, planting, escape	Being stocked/planted to natural waters or outdoor water gardens around the Great Lakes region
Commercial culture	Known to be commercially cultured in or transported through the Great Lakes region

determined the final set of surveillance list species. The trends in pathway and impact scores were summarized, then discussed relative to their implications for surveillance efforts.

Results

A total of 144 species have been identified as Great Lakes surveillance priorities, based on pathway (i.e., probability of introduction) and impact score criteria. The surveillance species are native to five continents (Asia, Australia, Europe, North and South America), with the majority coming from Europe followed by Asia. The most common reason for exclusion of species was low or unknown impacts (147), followed by widespread distribution in all five Great Lakes (63) and inability to establish (49). Plants (n = 64) and fish (n = 40) constitute 72% of the surveillance list species. The invertebrate group is comprised primarily of crustaceans (n = 28) including seven crayfish species. Plants, fish and crustaceans are predicted to have the highest likelihood of introduction, across a variety of pathways (Table 2, Figure 2). While pathway risk varies by taxon, the highest risk pathways across all taxonomic groups are natural dispersal, hitchhiking/fouling, and intentional release (Table 2, Figure 2).

The taxonomic group predicted to have the most severe impacts on a per species basis is algae, followed by mollusks, and plants (Table 3). However, the large number of plant and fish species on the surveillance species list means that from a taxonomic perspective plants and fish are predicted to inflict the most damage overall. Although species with low impact scores in both environmental and socio-cultural assessments were excluded, many species with moderate or high scores in environmental had a low score in socio-cultural (Figure 3). Only four species with a low environmental score had a moderate or high socio-cultural score (spiny cheek crayfish (*Orconectes limosus* Rafinesque, 1817), sessile joy weed (*Alternanthera sessilis* (L.) R. Br. ex DC.), variable flat sedge (*Cyperus difformis* L.) and arrowhead (*Sagittaria sagittifolia* L.)). Two-thirds of surveillance list species are predicted to have

Table 2. Mean pathway score (± SE). Pathway scores reflect the probability of introduction for a species in each pathway from 0–100. "Taxon score" is the sum of all pathway scores within each taxonomic group. "Pathway score" is the sum of all pathway scores within each pathway. Total number of species in each taxonomic group is in parentheses.

	Natural dispersal	Hitchhiking/ Fouling	Shipping	Intentional release	Stocking, planting, escape	Commercial culture	Taxon score (all pathways combined)
Plants/Algae (68)	47 ± 6	52 ± 5	7 ± 3	42 ± 6	41 ± 6	11 ± 4	13490
Plants (64)	45 ± 6	51 ± 6	4 ± 2	54 ± 6	44 ± 6	11 ± 4	12540
Algae (4)	75 ± 25	78 ± 23	60 ± 25	25 ± 25	0	0	950
Fish (40)	32 ± 7	19 ± 6	14 ± 4	28 ± 7	22 ± 7	5 ± 3	4798
Invertebrates (36)	30 ± 8	31 ± 7	45 ± 6	14 ± 6	3 ± 3	0	4369
Crustaceans (28)	27 ± 8	28 ± 8	39 ± 6	14 ± 6	4 ± 4	0	3076
Mollusks (5)	25 ± 19	24 ± 19	52 ± 15	20 ± 20	0	0	443
Platyhelminthes (1)	100 ± 0	100 ± 0	80 ± 0	0	0	0	280
Bryozoan (2)	50 ± 50	55 ± 45	100 ± 0	0	0	0	410
Pathway score (all taxa combined)	5575	5400	2692	4840	3250	900	

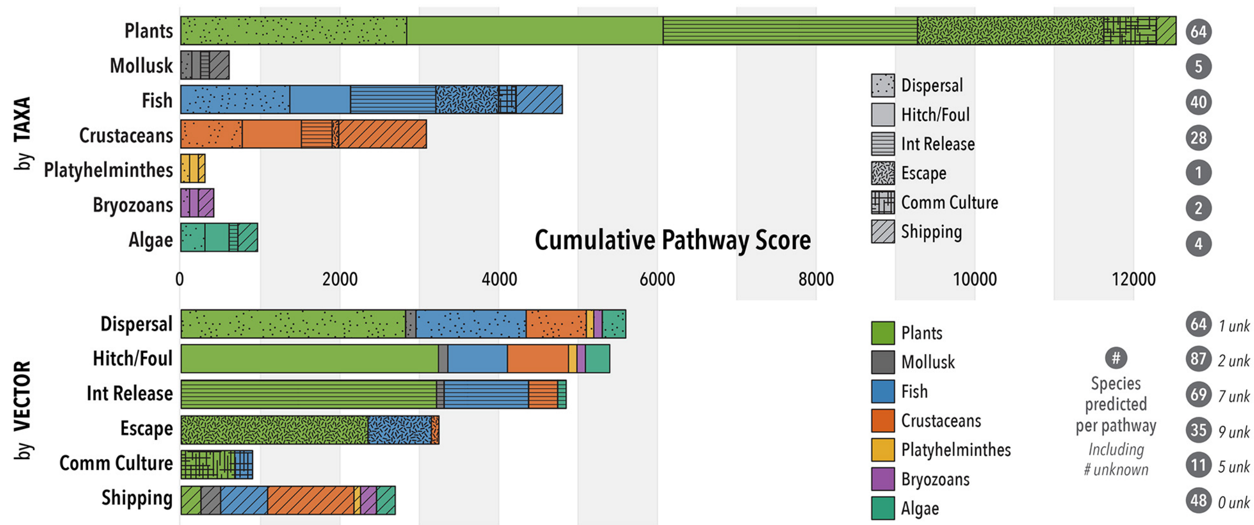

Figure 2. Cumulative pathway scores by vector and taxa. Pathways (represented by patterns within bars) appear in same order that they are listed in the legend key.

high environmental impact scores, and approximately half of surveillance list species will have low socio-cultural impacts.

Fish

Fish account for 27% of the surveillance species list, including six species that are established in the basin but with localized distributions (Table 4). This diverse group of species includes high profile invasive species like bighead carp (*Hypophthalmichthys nobilis* Richardson, 1845), silver carp (*Hypophthalmichthys molitrix* Valenciennes in Cuvier and Valenciennes, 1844), grass carp (*Ctenopharyngodon idella* Valenciennes in Cuvier and Valenciennes, 1844), black carp (*Mylopharyngodon piceus* Richardson, 1846),

Table 3. Total and mean (± SE) combined impact scores for each taxonomic group. Total number of species in each taxonomic group is indicated in parentheses. Maximum possible combined impact score (environmental + socio-cultural) per species = 72.

	Total combined impact score (all species)	Mean ± SE combined impact score (per species basis)
Plants/Algae (68)	1106	16.3 ± 1.5
Plants (64)	1002	15.7 ± 1.6
Algae (4)	104	26.0 ± 3.5
Fish (40)	407	10.2 ± 1.2
Invertebrates (36)	311	8.6 ± 1.4
Crustaceans (28)	192	6.8 ± 1.2
Mollusks (5)	88	17.6 ± 5.9
Bryozoan (2)	24	12.0 ± 8.0
Platyhelminthes (1)	7	—

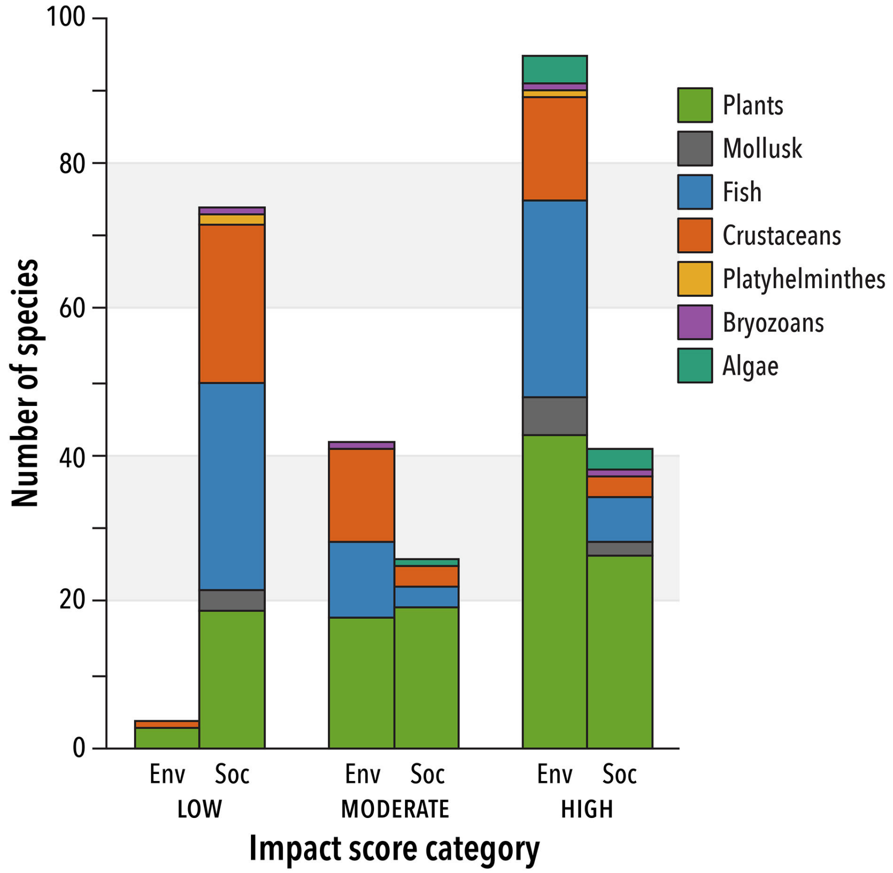

Figure 3. Number of species in each environmental (Env) and socio-cultural (Soc) impact score category, by taxonomic group. For each category, if impact score was 0–1, impact category was Low; if impact score was 2–5, impact category was Moderate; if impact score was ≥ 5, impact category was High.

blue catfish (*Ictalurus furcatus* Valenciennes in Cuvier and Valenciennes, 1840), European perch (*Perca fluviatilis* Linnaeus, 1758), bleak (*Alburnus alburnus* Linnaeus, 1758), stone moroko (*Pseudorasbora parva* Temminck and Schlegel, 1846), northern snakehead (*Channa argus* Cantor, 1842), and roach (*Rutilus rutilus* Linnaeus, 1758). Natural dispersal (facilitated by human-modified connections like channels and navigation locks), intentional release, and hitchhiking/fouling are the three most important potential pathways of introduction for fish (Table 2).

Table 4. Fish on the surveillance species list. Categorical impact and pathway scores based on the GLANSRA are shown ([H]igh, [M]edium, [L]ow, or [U]nknown). Species with localized Great Lakes distributions are in brackets.

Species name	Common name	Environmental Impact Category	Socio/Cultural Impact Category	Highest categorical pathway score (any pathway)
Acanthogobius flavimanus	Yellowfin goby	H	L	H
Acipenseridae	Non-native sturgeon	H	H	H
Alburnus alburnus	Alver, bleak	H	L	M
Alosa aestivalis	Blueback herring	H	L	H
Atherina boyeri	Big-scale sand smelt	M	L	M
Babka gymnotrachelus	Racer goby	M	L	M
Benthophilus stellatus	Starry goby	M	L	L
Carassius gibelio	Prussian carp	H	H	U
Channa argus	Northern snakehead	H	M	M
[*Ctenopharyngodon idella*]	Grass carp	H	L	H
Cyprinella lutrensis	Red shiner	H	L	H
[*Gambusia affinis*]	Western mosquitofish	H	L	H
Gambusia holbrooki	Eastern mosquitofish	H	H	H
Gobio gobio	Gudgeon	H	L	L
[*Gymnocephalus cernua*]	Eurasian ruffe	H	H	H
Hypomesus nipponensis	Wakasagi	H	L	L
Hypophthalmichthys molitrix	Silver carp	H	H	M
Hypophthalmichthys nobilis	Bighead carp	H	H	M
Ictalurus furcatus	Blue catfish	M	L	H
Lepomis microlophus	Redear sunfish	H	L	H
Leuciscus leuciscus	Eurasian dace	H	H	M
Menidia beryllina	Inland silverside	H	L	H
[*Misgurnus anguillicaudatus*]	Oriental weatherfish	H	L	H
Morone saxatilis x chrysops	Hybrid striped bass	M	L	H
Mylopharyngodon piceus	Black carp	H	L	L
Neogobius fluviatilis	Babka goby	M	L	M
Oncorhynchus keta	Chum salmon	M	L	L
Osmerus eperlanus	European smelt	H	L	M
Perca fluviatilis	Eurasian perch	H	M	M
Perccottus glenii	Amur sleeper	H	L	M
Phoxinus phoxinus	Common minnow	M	L	M
Pseudorasbora parva	Stone moroko	H	L	L
Pylodictis olivaris	Flathead catfish	H	L	H
Rhodeus sericeus	Bitterling	H	L	H
Rutilus rutilus	Roach	H	M	M
Sander lucioperca	Zander	H	L	L
[*Scardinius erythropthalmus*]	Rudd	M	L	H
Silurus glanis	Wels catfish	H	L	U
Siniperca chuatsi	Chinese perch	H	L	H
[*Tinca tinca*]	Tench	M	L	L

Invertebrates

Invertebrates account for 25% of surveillance list species, with crustaceans accounting for 75% of invertebrates (Table 5). Where pathways are known, invertebrate taxa are predominately associated with the shipping pathway (Table 2). An exception is crayfish, where red swamp crayfish, signal crayfish (*Pacifastacus leniusculus* Dana, 1852), hairy marron (*Cherax teniumanus* Smith 1912), marmorkrebs (*Procambarus fallax* Hagen, 1870) and yabby (*Cherax destructor* Clark 1936) are all associated with intentional release (live trades) pathways.

Table 5. Aquatic invertebrates on the surveillance species list. Categorical impact and pathway scores based on the GLANSRA are shown ([H]igh, [M]edium, or [L]ow). Species with localized Great Lakes distributions are in brackets.

Species name	Common name	Environmental Impact Category	Socio/Cultural Impact Category	Highest categorical pathway score (any pathway)
Bryozoan				
Fredericella sultana		H	H	H
Lophopodella carteri		M	L	H
Platyhelminthes				
[*Ichthyocotylurus pileatus*]	Digenean fluke	H	L	H
Mollusk				
Anodonta woodiana	Chinese pond mussel	H	L	H
Limnoperna fortunei	Golden mussel	H	H	L
Lithoglyphus naticoides	Gravel snail	H	L	M
Mytilopsis leucophaeata	Dark false mussel	H	H	M
[*Potamopyrgus antipodarum*]	New Zealand mudsnail	H	L	H
Crustacean				
Apocorophium lacustre		M	L	M
[*Argulus japonicus*]	Japanese fishlouse	H	H	H
Calanipeda aquaedulcis		H	L	M
Chelicorophium curvispinum	Caspian mud shrimp	M	L	M
Cherax destructor	Yabby (crayfish)	M	L	M
Cherax tenuimanus	Hairy marron (crayfish)	M	L	L
Cyclops kolensis		M	L	M
[*Daphnia galeata galeata*]	Waterflea	H	L	H
[*Daphnia lumholtzi*]	Waterflea	M	L	H
Dikerogammarus haemobaphes		M	L	M
Dikerogammarus villosus	Killer shrimp	H	L	M
Echinogammarus warpachowskyi		M	L	M
Eriocheir sinensis	Chinese mitten crab	H	H	H
Gmelinoides fasciatus	Baikalian amphipod	H	L	M
[*Hemimysis anomala*]	Bloody red shrimp	H	L	H
Limnomysis benedeni		M	L	M
Obesogammarus crassus		H	L	M
Obesogammarus obesus		H	L	L
Orconectes (*Faxonius*) *limosus*	Spinycheek crayfish	L	M	L
Pacifastacus leniusculus	Signal crayfish	H	M	L
Paramysis (*Metamysis*) *ullskyi*		H	L	M
Paramysis (*Serrapalpisis*) *lacustris*		M	L	M
Podonevadne trigona ovum		M	L	L
Pontastacus leptodactylus	Danube crayfish	M	L	M
Pontogammarus robustoides		M	L	M
[*Procambarus clarkii*]	Red swamp crayfish	H	H	H
Procambarus fallax f. virginalis	Marmorkrebs, marbled crayfish	H	M	H
[*Schizopera borutzkyi*]	Oarsman	H	L	H

Golden mussel (*Limnoperna fortunei* Dunker, 1857) and red swamp crayfish were the two highest scoring invertebrate species for combined impact (Table S2).

Plants and algae

Aquatic plants and algae are the most prolific taxonomic group on the surveillance species list (Table 6). Almost one-third are already locally established in the Great Lakes Basin and have documented impacts. The most important sources of introduction or range expansion for plants are associated with hitch hiking on boats or equipment, natural dispersal (through

Table 6. Aquatic plants on the surveillance species list. Categorical impact and pathway scores based on the GLANSRA are shown ([H]igh, [M]edium, [L]ow or [U]nknown). (^) indicates algae. Species with localized Great Lakes distributions are in brackets.

Species name	Common name	Environmental Impact Category	Socio/Cultural Impact Category	Highest categorical pathway score (any pathway)
Akebia quinata	Chocolate vine	H	L	H
[*Alnus glutinosa*]	Black alder	H	L	H
Alternanthera philoxeroides	Alligator weed	H	H	H
Alternanthera sessilis	Sessile joyweed	L	H	M
Aponogeton distachyos	Cape pondweed	M	L	H
Artemesia absinthium	Absinthe wormwood	M	M	H
Arundo donax	Giant reed	H	M	H
Azolla filiculoides	Pacific mosquito fern	H	H	H
Azolla pinnata	Asian mosquito fern	H	M	L
[*Butomus umbellatus*]	Flowering rush	M	M	H
[*Cabomba caroliniana*]	Carolina fanwort	M	M	H
[*Cirsium palustre*]	Marsh thistle	H	L	H
Colocasia esculenta	Coco-yam	H	L	H
Crassula helmsii	New Zealand pygmy weed	H	M	U
Cyperus difformis	Variable flat sedge	L	H	L
Didymosphenia geminata^	Didymo	H	H	H
Egeria densa	Brazilian waterweed	H	H	H
Egeria najas		M	M	H
Eichhornia azurea	Anchored water hyacinth	M	M	H
[*Eichhornia crassipes*]	Water hyacinth	H	H	H
[*Epilobium hirsutum*]	Great hairy willow herb	M	L	H
[*Frangula alnus*]	Glossy buckthorn	H	H	H
[*Glyceria maxima*]	Reed mannagrass	H	M	H
Hydrilla verticillata	Hydrilla	H	H	H
[*Hydrocharis morus-ranae*]	European frog-bit	H	H	H
Hydrocotyle ranunculoides	Floating marsh pennywort	H	H	H
Hygrophila polysperma	Indian hygrophila	M	H	M
Ipomoea aquatica	Swamp cabbage	H	H	H
[*Juncus compressus*]	Flattened rush	M	L	H
[*Juncus gerardii*]	Black-grass rush	H	M	H
[*Juncus inflexus*]	European meadow rush	M	L	H
Lagarosiphon major	African elodea	H	H	L
Limnobium spongia	American spongeplant	M	M	L
Ludwigia adscendens	Water primrose	M	M	U
Ludwigia grandiflora		H	H	L
Ludwigia hexapetala	Uruguayan primrose willow	H	H	H
Ludwigia peploides	Floating primrose willow	H	H	H
[*Lysimachia vulgaris*]	Yellow loosestrife	H	L	H
Lythrum virgatum	Wanded loosestrife	H	H	H
Melaleuca quinquenervia	Punk tree	H	H	L
Murdannia keisak	Wart removing herb	H	M	L
Myriophyllum aquaticum	Parrot feather	H	M	H
Myriophyllum heterophyllum × *M. laxum*		H	H	L
[*Najas minor*]	Brittle waternymph	H	M	H
Nelumbo nucifera	Sacred lotus	H	L	H
[*Nitellopsis obtusa*]^	Starry stonewort	H	H	H
Nymphaea spp. (except *Nymphaea odorata*, and *N. leibergii*)	Non-native water lilies	M	L	H
Nymphoides peltata	Yellow floating heart	M	M	H
Oenanthe javanica	Water celery	M	M	H
Oxycaryum cubense	Cuban bulrush	H	L	L
[*Pistia stratiotes*]	Water lettuce	H	H	H
Prymnesium parvum^	Flagellated algae	H	H	M
Robinia pseudoacacia	Black locust	H	L	H
Rotala rotundifolia	Roundlaf toothcup	M	L	H

Table 6. (continued).

Sagittaria platyphylla	Delta arrowhead	H	H	L
Sagittaria sagittifolia	Arrowhead	L	H	L
Salix atrocinerea	Smooth twig gray willow	H	L	H
Salvinia minima	Water spangles	H	H	H
Salvinia molesta	Kariba weed	H	H	L
Solanum tampicense	Wetland nightshade	M	L	U
Stratiotes aloides	Water soldier	M	M	H
[*Trapa natans*]	Water chestnut	H	H	H
Typha domingensis	Southern cattail	H	H	L
Typha laxmannii	Graceful cattail	H	L	H
Typha orientalis	Bullrush/raupo	H	L	U
Typha x glauca	Hybrid cattail	H	L	H
[*Ulva species*]^	Green alga	H	M	H
Vallisneria spiralis	Eelgrass	H	M	H

canals or headwater connections), intentional movement, and cultivation or stocking (Table 2). The commercial shipping pathway is an important dispersal vector for algae but not for plants (mean probability of introduction via shipping for algae = 60 (out of 100); for plants = 4).

As a group, aquatic plants and algae have the highest combined impact scores (Table 3), more than double the next highest group (fish), and 75% have either high environmental or socio-cultural impacts. Many of the plant species (e.g., giant salvinia (*Salvinia molesta* Mitch.), water lettuce (*Pistia stratiotes* L.), and water hyacinth (*Eichhornia crassipes* (Mart.) Solms)) form highly visible, dense, floating mats that have both environmental and socio-cultural impacts that are easily observed and measured. Some algae species also exhibit these traits (didymo (*Didymosphenia geminata* Lyngbye M. Schmidt), golden algae (*Prymnesium parvum*) and starry stonewort (*Nitellopsis obtusa* (Desv.) J. Grove).

Discussion

We identify 144 species that have either already been locally introduced or have a potential pathway of introduction, and the ability to cause environmental and/or socio-cultural impacts in the Great Lakes. Hence just under half of the 303 species assessed (from an original pool of more than 400) using the GLANSRA framework fulfilled our introduction, establishment and impact criteria. The benefit of using a risk assessment, like GLANSRA, to develop and refine the surveillance species list is made evident in that we were able to assess the key elements of risk for all species, across multiple taxonomic groups, using a single uniform approach, thereby facilitating the efficient development of multi-species, multi-taxa surveillance plans by natural resource managers (sensu Davidson et al. 2017). Here we recommend ways that the surveillance list could be applied to inform AIS management efforts, including: highlight the importance of community-based surveillance; inform taxonomic and species surveillance priorities including guidance on parasites, range expanders and monitoring protocols; quantify the relative risk of various pathways of introduction; and identify priority locations for surveillance based on the intersection of pathways and the relative assessed risk of species within those pathways.

Community- vs. single species-based surveillance

Implementation of species-specific surveillance programs for all high-risk species is probably not a viable option given the large number of species on the surveillance list (144). But the surveillance list could be used to prioritize or inform single-species based surveillance efforts, and the list underscores the importance of community-based surveillance approaches across key taxonomic groups. For fish, whereas current surveillance efforts in the basin already target some specific fish species (e.g. invasive carps, Eurasian ruffe (*Gymnocephalus cernuus* L.)), the large number of fish species on the surveillance list points to the importance of a community-level surveillance program not unlike the current program employed by USFWS (e.g. Harris et al. 2018). Traditional methods used to surveil fish communities (including a range of gear types such as minnow traps, fyke nets, micromesh gill nets) have the potential to detect other taxa, like crayfish. Thus, an ancillary benefit of a community-based fish surveillance program could be early detection of high-risk crayfish species on the surveillance list, including *Procambarus clarkii.* Red swamp crayfish is already established in parts of Lake Erie, a number of inland waters in Michigan (Smith et al. 2018) and the Chicago Area Waterway System (Simon 2001). Management agencies have demonstrated a desire to contain its spread by the active responses to a number of these inland incursions (Behm 2009) and there is evidence of active pathways of introduction and spread (Smith et al. 2018).

Aquatic plants are the most numerous taxonomic group on the surveillance species list. Almost one-third are already locally established in the Great Lakes Basin and have been identified as high risk by previous risk assessments (Gantz et al. 2015). The large number of invasive plants highlights an important gap in current community surveillance effort. State and federal surveillance efforts are largely focused on fish and crustaceans (Harris et al. 2018), while plant management is largely focused on monitoring of existing populations and spread in inland waterways (Mikulyuk et al. 2010). Great Lakes coastal systems contain habitats (e.g. coastal wetlands, estuaries and shallow embayments) and ecosystem services (e.g. municipal and industrial water supplies, marinas) that are vulnerable to invasive aquatic plants. Many probable points of introduction (Tucker et al. 2020) either overlap with these values or could act as important steppingstones for coastal spread. In addition, while the most common direction of spread is from inland waters to the Great Lakes proper (Rothlisberger and Lodge 2013), the movement of species within a key vector (recreational boating) is bidirectional and has likely contributed to inland spread from the Great

Lakes proper (e.g., starry stonewort *Nitellopsis obtusa* Desv.; Midwood et al. 2016). Protection of Great Lakes coastal ecosystems, ecosystem services and regional plant surveillance programs could be improved by directing more effort to locations in the Great Lakes proper, with methods appropriately designed to detect the full range of emergent, floating, and submerged species on the surveillance list.

Invertebrate species are an important component of this surveillance list, but invertebrate surveillance (with the possible exception of crayfish) is still hampered by sample collection, and numerous challenges that prevent the timely processing of the large number of samples necessary to achieve acceptable detection sensitivity (Hoffman et al. 2011). Meanwhile, invasive invertebrate species have already demonstrated their potential to significantly alter food webs, habitats and ecosystem processes including nutrient cycling across the Great Lakes as illustrated by the impacts of dreissenid mussels (Schloesser et al. 1998; Fahnenstiel et al. 2010) and the spiny waterflea (*Bythotrephes longimanus* Leydig, 1860) and fishhook waterflea (*Cercopagis pengoi* Ostroumov, 1891) (Yan et al. 2001). Issues with collecting and processing samples may be partly ameliorated by the adoption of high-throughput sequencing methods that have the potential to speed up processing times and rapidly confirm presence of high risk species (Darling and Blum 2007; Trebitz et al. 2017; Martinez et al. 2020), provided invertebrate barcode libraries can be improved (Trebitz et al. 2015). The invertebrate component of the surveillance species list should be a priority for sequencing.

The absence of a cost-effective community-level invertebrate sampling methodology could justify in the interim a more targeted species-specific sampling focus on a small number of sites and imminent invertebrate invaders or range expanders. Criteria to select candidates from the surveillance species list that would warrant target surveillance efforts could include instances where potential impacts are high (Homans and Horie 2011; Epanchin-Niell et al. 2012), the most probable pathway and points of introduction can be defined, when invasion appears imminent, or to support response efforts to contain or eradicate newly established species or range expansions. The decision to target specific species could be triggered by scores from the risk assessments (determined *a priori* in a risk management context). The potential need for targeted surveillance is especially urgent where multi-species surveillance programs are not focused on the areas with greatest potential for a specific high-risk species introduction or spread, or where alternative methods or sampling approaches might be needed to increase the probability of detection. An example of a high-risk invertebrate species includes the scud (*Apocorophium lacustre* Vanhöffen, 1911), a hull fouling species with potentially significant impacts and the potential to ability Lake Michigan via the Chicago Area Waterway System where it is established (Keller et al. 2017).

Parasites

Aquatic invasive parasites are under-represented in literature, with few studies and taxonomic surveys of this group (Smit et al. 2017). Indeed, Smit et al. (2017) suggested that in South Africa the current distribution records of invasive parasites in South Africa is more related to the distribution of fish parasitologists than that of the parasites themselves. Although parasites are often co-introduced with their hosts, we included them as separate species because of their potential impacts, and to expand their representation in the literature and in a management context. We did this while also considering the scope of this framework – we included multicellular parasites that are more likely to be visible, and therefore identifiable, to management agency staff. Consistent with our general exclusion criteria, we excluded unicellular parasites such as microsporidian, that were beyond the scope of the surveillance framework and given current resources and staff capabilities, probably fit better under the purview of fish and wildlife health and microbiology departments (this was also the rationale for excluding virus and bacteria in the original screen). Invasive unicellular parasites likely infect all major components of the food web with significant potential to negatively impact host species. As additional molecular tools become available, and agency staff are better able to identify and manage unicellular AIS, it may be appropriate to add these microscopic species to surveillance lists. Even with the current multicellular distinction, however, identification remains difficult and therefore we support the suggestion of Smit et al. (2017) that monitoring methods should include molecular approaches for identifying these species.

In addition to identification challenges, availability of impact data also impedes parasite risk assessment. We screened 17 parasite species, but only one species had impact data sufficient to include it on the surveillance species list (Japanese fishlouse *Argulus japonicus* Thiele, 1900). Two species (eel parasites; *Pseudodactylogyrus anguillae* Yin and Sproston, 1948 and *P. bini* Kikuchi, 1929) were known to have impacts in commercial eel farms but were not included due to the absence of commercial eel operations in the Great Lakes. One species scored unlikely in the pathway assessment (parasitic copepod *Salmincola lotae* Olsson, 1877), and the remaining 13 parasite species had no impact data available. Additional studies of invasive parasites (and even the publication of "non-significant" findings) is crucial to the characterization of a potentially important group of AIS, and should be a priority for future research.

Range expanders

Given the overall goal of the Framework is to prevent future establishment, spread, and impacts of AIS in the Great Lakes, the surveillance list did not include those species already widespread in the basin (i.e., in all five Great

Lakes). In compiling the list, however, we identified several species that are already in the Great Lakes basin but whose distribution is localized (i.e., in ≤ 4 Great Lakes).

We chose not to include on our list species such as gizzard shad (*Dorosoma cepedianum* Lesueur, 1818) that are considered native to at least one of the upper Great Lakes (Erie, Huron, Michigan, Superior). Our rationale is that these species could theoretically disperse through the entire Great Lakes without human assistance. However, we realize this is not a straightforward decision, as temporal or spatial characteristics of a new introduction (e.g., a new introduction far from the original population, over a short amount of time) or the physiological characteristics of the species in question (e.g., a species with very limited dispersal abilities) may suggest that the source of the new population is actually anthropogenic in nature. Essl et al. (2019) have characterized the increasingly difficult distinction between native and nonindigenous species as human-induced environmental change occurs. As such, these upper Great Lakes native species (of which there were fourteen in our candidate list, see Table S2) may best be considered for inclusion in monitoring and surveillance programs on a per species basis (Essl et al. 2019 provide guidance for this effort). For example, in the short-term, detection in western Lake Superior of a species like gizzard shad, which has had significant negative impacts on native fish populations elsewhere, might elicit an active response to eradicate. However, in the long-term, detections of gizzard shad consistent with natural dispersal into Lake Superior (especially as the lake warms owing to climate change) might not prompt a management response.

On the other hand, we would have included on the surveillance species list any species native to Lake Ontario only and not yet present in all five lakes (though none were apparent from our species screen). Considering Lake Ontario was historically physically separate from the remaining Great Lakes, any species movement would ultimately be anthropogenic. Likewise, a precautionary approach would include on the surveillance species list any species that is cryptogenic in origin (Carlton 1996). Cryptogenic species can form a significant portion of species surveys despite improvements in knowledge of regional aquatic community taxonomy (Hewitt et al. 2004). However, apart from a small number of widespread cryptogenic species (e.g. rusty crayfish (*Orconectes rusticus* Girard, 1852)) our species screen did not identify any additional species in this category.

Monitoring protocols

The information that can be gleaned from the GLANSRA method for surveillance list species could be used to help managers make decisions around where and what gear (and associated deployment methods) are most likely to encounter target species so that surveys most cost-effectively maximize the probability of detection in a given management unit.

For example, a qualitative look at the surveillance list fish species suggests no clear pattern in habitat association across the group. These fish have preferences for a range of substrate types (soft, hard, and mixed) and while there tend to be a larger number of open water littoral and pelagic fish species (as compared to benthic fish species) the list includes representatives from each group. Hence sampling with multiple kinds of equipment that are collectively capable of sampling a full range of substrates and depths is important to maximize the probability of capturing the full range of surveillance species by exploiting gear-specific differences in species detection (Hoffman et al. 2016). As methods are refined based on gear- and habitat-optimization processes, (including the adoption of new gears to improve sampling performance; sensu Harris et al. 2018), the surveillance species list and associated habitat information available via GLANSRA provides provide a set of data to cross reference against, to ensure managers are still sampling all potential habitats and have not dropped potentially important habitats because of poor historic returns based on the current fauna. Once an incipient population of a new AIS is detected, habitat association and related information gathered through the GLANSRA method can help inform and prioritize delineation efforts.

Pathways of introduction

The three primary pathways of introduction for all species on the surveillance species list were dispersal (present in waters connected to Great Lakes), hitchhiking and fouling, and intentional release (via the "live trade" industry). The large number of plant species included on the surveillance species list is a driver of this result; they are predicted to arrive via all potential pathways except commercial shipping (and, to a lesser extent, escape from commercial culture; Table 2). Fish and crustacea are also predicted to arrive from non-shipping pathways. Although some microscopic taxa are predicted to arrive via shipping (primarily invertebrates and algae), non-shipping pathways accounted for the majority of predicted arrival pressure for surveillance list species (Table 2). This contrasts some past trends in pathway analysis. For example, Ricciardi (2006) found shipping accounted for more than half of introductions to the Great Lakes since 1959. Regional assessments in other parts of the world have also identified ballast water as a primary vector for AIS (e.g., the Mediterranean; Flagella and Abdulla 2005). However, since the incorporation of ballast water exchange and management for maritime ships entering the Great Lakes, shipping as source of new introductions into the Great Lakes has declined relative to other pathways (Bailey et al. 2011). It nevertheless remains a potentially important pathway for range expansion once species establish in the lakes (Briski et al. 2012b; Sieracki et al. 2014).

Uncertainty remains an impediment to effective aquatic invasive species management and is often discussed relative to understanding impacts, but our assessment highlights the importance of resolving uncertainty related to pathways of introduction. For example, the number of species scoring ‘unknown’ for presence in each pathway underscores the emphasis on shipping in past AIS pathway research; there were no unknowns recorded for introduction via shipping, whereas the live trade pathways had a significant number of species for which unknowns were recorded for probability of introduction: intentional release (7), recreational escape (9), and commercial culture (5). Owing to its historic importance, multiple research groups have quantified and documented species composition of ballast water (e.g., Rup et al. 2010; Briski et al. 2012a, b, Egan et al. 2015) whereas there are fewer publications reviewing live trade pathways and these only encompass some of the multiple unique pathways that make up the live trades (e.g., water gardens in Marson et al. 2009, bait trade in Nathan et al. 2014). The ongoing push to better document species composition within each of the live trades is therefore critical to reducing uncertainty.

The surveillance species list also has potential to inform prevention efforts within the pathways of introduction, recognizing this is the most cost-effective approach (Leung et al. 2002). For example, the list and underpinning assessments can be used to inform efforts to regulate the live trades and to develop state, provincial and federal prohibited species lists by identifying species of concern within those pathways. The prevalence of high-risk species in the recreational boating (hitchhiker) pathway highlights the need for more comprehensive and regional management of this pathway – consistent with recognized best practice (Otts and Nanjappa 2014). And the presence of high-risk invertebrates and plants within the canal pathway (Chicago and Erie Canals) underscores the importance of implementing comprehensive solutions to prevent the bi-directional movement of AIS through these artificial connections, especially since current proposals, like the Great Lakes and Mississippi River Interbasin Study report, continue to emphasize the prevention of fish alone (US Army Corps of Engineers 2018).

Priority surveillance locations

Broad monitoring of multiple species or taxa should target those areas where the highest risk species are most likely to invade, based on our best understanding of propagule pressure and habitat suitability (Vander Zanden and Olden 2008). Our surveillance species list can be used to inform our understanding of both of these risk factors for invasion, in that propagule pressure is a function of the number and kinds of species within all relevant pathways and site suitability can only be determined once the most likely and damaging invaders have been identified.

Tucker et al. (2020) recently used an approach based on this surveillance list to develop an index of invasion pressure for management units within the U.S. waters of the Great Lakes. Estimates of invasion pressure within each management unit were based on the cumulative propagule pressure from a set of spatial surrogates for each pathway weighted by the prevalence of surveillance list species within each pathway. The Index results suggested that plant and fish surveillance should be directed to locations with the highest densities of natural and artificial connections (dispersal), boat launches/marinas (hitchhiking/fouling), and large population centers (intentional release from water gardens or aquaria), whereas surveillance efforts for most invertebrates (except crayfish) should target locations with heavy shipping traffic.

Conclusion

With a surface water area of 245,759 km^2 and shoreline length of 17,017 km, the Great Lakes represent a daunting challenge for aquatic invasive species management (Trebitz et al. 2017). Management resources are finite, hence it is important that monitoring efforts are informed by objective assessments of species' risk (Lodge et al. 2006). By identifying the potential for introduction, establishment and impact, this surveillance species list assessment provides a foundation for objective decision making. The surveillance species list identifies the nexus between pathways and species and highlights the evolving threat of new introductions (e.g., from shipping to live trade). The list can be used as a guide to prioritize monitoring for species or taxonomic targets, inform survey design, and identify priority sites for surveillance. Because the list is based on a single framework that can assess probability of introduction and impact for species across all taxonomic groups, the list can be efficiently updated to include new species. The surveillance species list will be a useful resource for states, provinces and federal agencies with responsibility for the management of the shared and interconnected Great Lakes water, as well as in other regions where agencies aim to develop comparable surveillance programs.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Sources used to compile a candidate inventory of surveillance list species.
Table S2. Results of species screen for 447 species.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2021/Supplements/MBI_2021_Davidson_etal_SupplementaryTables.xlsx