Management in Practice

Identifying research gaps related to control of high priority freshwater invasive aquatic plant species in the Great Lakes

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Abstract

The impacts of invasive aquatic plants (IAPs) are well documented and extensive relative to other functional groups of invasive species. Operational control of IAPs has evolved from a limited range of general biocides and physical control methods to the development of more targeted methods that offer more selective control measures. Despite the increase in IAP control strategies, several studies have identified the need to better serve IAP managers through identification and implementation of control-related research needs. Successfully aligning research needs and management products requires consulting with all interested parties to develop research questions and engagement of managers interested in adaptive management in the research programs. To this end, it is vital to use a process in which ecologists, practitioners, and decision-makers work collaboratively to develop scientific research, a process known as translational ecology. We identify IAP control-related research needs through a combination of species-specific literature reviews and an expert elicitation workshop for 20 priority IAP. Based on the literature reviews and workshop, generalized research needs, species-specific research needs, and an analysis of factors related to tool availability were developed. While the scope of this case study is the Great Lakes region, the IAPs and associated research needs discussed in this study are relevant to researchers studying these globally invasive species anywhere within their invasive range and should be used to inform research wherever it is undertaken. These findings will help agencies and academic institutions to plan future research activities and project proposals and serve as a reference document to inform funding agencies as they make decisions related to invasive aquatic plant control and research.

Key words: operational control, biocontrol, propagules, eradication, translational ecology, florpyrauxifen-benzyl, integrated control strategies

Introduction

The impacts of invasive aquatic plants (IAPs) are well documented and extensive relative to other functional groups of invasive species (Gallardo et al. 2016). Cumulative costs attributed to impacts and control of IAPs are estimated at US$32.8 billion (1975–2020; Macêdo et al. 2024). Given the wide variety and broad distribution of ecological and socioeconomic impacts, IAPs are a major focus of management efforts globally (Hussner et al. 2017).

The current number of IAPs already established and the ongoing presence of IAPs in various pathways necessitates control efforts to limit impacts (McGeoch et al. 2010). Numerous agencies, nongovernment organizations, and private interests implement control measures for IAPs that impede recreation, navigation, and hydroelectric facilities; degrade habitat for native species; and disrupt natural ecosystems. These entities work with research institutions and the private sector to develop new tools for management and to improve the efficiency and effectiveness of control efforts.

Control efforts may focus on a goal of containment (spread prevention), population suppression, or eradication. Achieving these goals involves one or more operational control strategies: mechanical, physical, biological, and/or chemical (summarized in Hussner et al. 2017). Identifying which management goal and control strategies to invoke depends on several factors, including characteristics of the invaded system, life history of the IAP, community opinion, funding, and strategy availability. This review focuses on the last factor, availability of operational control strategies.

Operational control of IAPs has evolved from a limited range of general biocides (e.g. copper and arsenic) and physical control methods, to the development of more targeted methods that offer more selective control measures. Despite the increase in IAP control strategies, several studies have identified the need to better serve IAP managers through identification and implementation of control-related research needs. A study of perceptions toward general invasive species research found stakeholders (researchers, practitioners, and policy makers/advisors) believed invasive species research is not sufficiently focused on practical considerations and therefore not useful to their on-the-ground efforts (Bayliss et al. 2013). This belief may in part be driven by the lack of management-related literature; over 25% of priorities identified were related to management, yet a review of published invasive species literature found that only 10% of journal articles were related to management (Bayliss et al. 2013). Matzek et al. (2015) analyzed general research trends and manager needs for invasive terrestrial plants in California and also found wide gaps between the priorities identified by managers and what is published, i.e., managers want more applied research. While many publications do include some discussion of "management implications", research on invasive plants is heavily dominated by basic research (research to gain knowledge in and of itself), rather than applied research (research to solve a problem) (Matzek et al. 2015). When managers in South Africa were asked to identify knowledge gaps that prevented effective management of invasive species, 40% of knowledge gaps were categorized as control/management related. Of published papers related to invasive species globally and in South Africa, only 26% mentioned an applied (management/control) component (Esler et al. 2010). These outcomes support calls for increased research related to control of invasive species (Kühn et al. 2011; Hofstra et al. 2020; Ortiz et al. 2020).

Many reviews summarizing IAP control strategies exist, both in the published and grey literature. For example, Hussner et al. (2017) provides a comprehensive general overview of available control strategies for IAP management, focusing on temperate and subtropical freshwater systems. These reviews of available IAP control strategies, while invaluable, do not generally include explicit analyses of research needs related to these control strategies. Several studies have looked at control-related research needs for individual species, either in peer-reviewed literature (e.g., *Ludwigia* spp., Grewell et al. 2016; *Cabomba caroliniana* A. Gray, Roberts and Florentine 2022) or in grey literature (e.g., *Pistia stratiotes* L., EGLE 2018), but these only cover a subset of high impact IAPs. The only existing literature focused on identifying control-related research needs for a broad range of IAP is related to control under a changing climate. Climate change adds an extra layer of complexity to IAP management and several publications have highlighted the need for research related to control under future climate change scenarios (Hellmann et al. 2008; Beaury et al. 2020; Mishra et al. 2023). Range expansion, increased biomass, and enhanced spread have already occurred for several IAPs, and are expected to continue with climate change (e.g., the northward spread of *Eichhornia crassipes* (Mart.) Solms).

This need for more control-related research, combined with the absence of efforts to identify IAP control-related research needs, highlights the need for a gap analysis to help understand the research questions that reflect on-the-ground management needs. Successfully aligning research needs and management products requires consulting with all interested parties to develop research questions and engagement of managers interested in adaptive management in the research programs, a process often facilitated by organizations that partner science and decision-making, a process known as boundary spanning (Matzek et al. 2015; Newcomb et al. 2021). To this end, it is vital to use a process in which ecologists, practitioners, and decision-makers work collaboratively to develop scientific research, a process known as translational ecology (Enquist et al. 2017). The value of this collaborative process and knowledge sharing in improving outcomes has been echoed in the invasive species literature. Practically, the first step entails engaging managers to identify research questions that will alleviate barriers to successful management (Esler et al. 2010; Piria et al. 2017; Beaury et al. 2020).

In this study, we provide an overview of a process designed to identify operational control research needs for priority established IAPs in the Laurentian Great Lakes region using the principles of translational ecology. The Great Lakes are one of the most heavily invaded aquatic systems globally, and invasive plants are a major management focus, given that they account for over 30% of established non-native species in the region and nearly half of a surveillance list of potentially high impact species (Sturtevant et al. 2019; Davidson et al. 2021). Yet, there has been no regional approach to coordinate engaged entities, identify needs, and share outcomes and lessons learned. While the scope of this case study is the Great Lakes region, the IAPs and associated research needs discussed in this study are relevant to researchers studying these globally-invasive species anywhere within their invasive range and should be used to inform research wherever it is undertaken. Understanding these research needs should help inform future investments towards the highest priorities and facilitate improved control and more efficient and effective management of IAPs. To this end, the research needs identified here contribute both to invasion biology theory globally, and also address local knowledge gaps within the Great Lakes region.

Materials and methods

While the terms "aquatic plant control" and "aquatic plant management" are often considered synonymous, many resource managers consider control efforts as being operational in nature, and management as a process more aligned with program goals and objectives. We use this distinction for purposes of this study, with "control" defined as techniques used alone or in combination that result in a reduction/alteration of a target plant population to a desired state (endpoint) (Gettys et al. 2020). Effectiveness of a control strategy is defined by how well the results of control efforts meet the pre-determined management endpoints associated with plant control activity.

The priority IAPs were chosen based on a set of criteria determined by the Research Coordination Committee (RCC) within the Great Lakes Panel on Aquatic Nuisance Species (GLP). The GLP was first convened in 1991 by the Great Lakes Commission in response to the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990. Duties of the GLP include coordinating aquatic nonindigenous species program activities in the Great Lakes region and advising public and private interests on prevention and control efforts.

For the purposes of this research agenda, two nuisance macroalgae species (*Didymosphenia geminata* (Lyngb.) M. Schmidt and *Nitellopsis obtusa* (Desv.) J. Groves are included in the use of the acronym IAP given their similar environmental and social impacts and their management within government agencies by plant staff. There is uncertainty whether *D. geminata* is native to the Great Lakes (Lavery et al. 2014) and whether the predominant strain of *Phalaris arundincea* L. is a North American native (Anderson et al. 2021). But given the intent of this study is to examine control tools for species considered desirable to manage, we include them and leave the decision of whether to manage to practitioners. Criteria and definitions for selection of the priority IAPs are provided below.

1. Total impact score: impact scores were obtained from the Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS), a regional node of the United States Geological Survey (USGS) database on Nonindigenous Aquatic Species (NAS). Species with a transformed

total impact score of 4, 5, or 6 (transformed total impact score is determined by summing environmental plus social/cultural impacts, possible maximum total of 6), and/or a 3 in either environmental or social/cultural category were considered for inclusion (for more detail on impact categories, see Davidson et al. 2016). If a species did not meet the impact threshold but was under review by GLANSIS or was considered high priority by members of the GLP RCC, it was included. Due to their unique status in the invasion timeline and the likelihood that full impacts have not been realized, watchlist species with known, recent populations in the Great Lakes as confirmed by RCC members were considered for inclusion regardless of impact score. Watchlist species are those not officially established per GLANSIS protocols or only established in inland waters of the Great Lakes that have recent, reported populations in the Great Lakes basin.

2. Distribution: species were considered for inclusion if they were (as defined by NOAA 2022):
    a) nonindigenous;
    b) range expander species; or
    c) watchlist species.
3. Conflict of interest: species that provide a significant beneficial value (e.g., species part of recreational or commercial fisheries) and would therefore not be the focus of control efforts were excluded.
4. Existing control effort: species with existing significant regional control efforts were excluded (i.e., *Phragmites australis* (Cav.) Trin. ex Steud.), as these would already be the focus of research-based gap analysis.

IAP control-related research needs were identified through a combination of species-specific literature reviews and an expert elicitation workshop. Literature reviews summarized existing control strategies and related gaps in understanding related to operational control. Literature reviews included peer-reviewed literature found using a standard set of search terms (e.g, “control”, “management”, “action plans”, along with species name). Given that managers most frequently communicate their work informally (Matzek et al. 2014), also focused on contacting managers individually to request unpublished case studies related to the priority IAPs. Managers for each jurisdiction were contacted individually; other managers were included based on GLP recommendations. Each literature review was reviewed by a subject-matter expert with experience in operational control of that species. Workshops in which scientists, managers, and/or policymakers are expressly asked to exchange information or set priorities together is a best practice to communicate management information (Matzek et al. 2014). As such, the “Great Lakes Regional Invasive Aquatic Plant Control Prioritization and

Needs Assessment Workshop," convened by the Great Lakes Commission on January 24–25, 2023, included management agencies, industry partners, and research agencies and institutions. Participants discussed research needs listed in the literature reviews and identified additional needs not yet recorded in published literature. Based on the literature reviews and workshop, generalized research needs, species-specific research needs, and an analysis of factors related to tool availability were developed.

To determine general research needs, research needs for specific species from the literature review and workshop were scored using a thematic analysis. Thematic analysis is a qualitative research method used to identify, analyze, and interpret patterns, themes, and meanings within data (Clarke and Braun 2016). By examining the text of the literature reviews, reports, discussion notes, and workshop transcripts, we were able to identify recurring themes that emerged from the data. Any research need highlighted for at least one-quarter of species was categorized as a "general research need". Species-specific research needs were summarized for each species. For the analysis of the availability of effective tools (see "tool availability", below), tool availability for each species was compared to the following factors that may explain the differences in availability of effective tools:

- Total, environmental, and social/cultural impact (using GLANSIS data from original criteria setting);
- regulatory status (number of jurisdictions in the Great Lakes regulating the respective species, e.g., any jurisdiction with laws regulating any aspect of species trade, sale, transport, etc., including prohibited and restricted species);
- regional distribution in the Great Lakes;
- global distribution;
- growth form (submerged, floating, emergent, or semi-aquatic based on Hussner et al. (2017), Macêdo et al. (2024), and/or expert consultation); and
- years since introduction in the Great Lakes.

Several of these factors were grouped into categories to aid analysis:

Tool availability. Given the variety of spatial scale and endpoints against which control strategies are measured (e.g., reduction in abundance, and duration of population suppression), it was not possible to quantitatively describe the availability of effective tools across all species. Tool availability was categorized as "low" (no demonstrably effective tool available; containment often a primary control strategy); "moderate" (one or more existing strategies that alone or in combination can reduce population abundance at least 70% over a season (Gettys et al. 2020)); or "high" (no research/knowledge gaps identified in this process; may have had successful eradication efforts).

- Great Lakes and global distribution. For Great Lakes distribution, species were categorized as "limited" (present in < 5 of the 10 Great Lakes jurisdictions, often in isolated populations); "moderate" (< 10 jurisdictions, populations are generally controlled, still have many uninvaded lakes in the jurisdiction); and "widespread" (in all 10 jurisdictions, in many waterbodies in each jurisdiction). For global distribution, species were categorized based on number of countries with introduced populations (GBIF 2024) with categories based on natural inflection points. I.e., "limited" (present in < 13 countries); "moderate" (13–36 countries); and "widespread" (> 37 countries).
- Years since introduction. Regular use of selective herbicides (e.g., 2,4-D, endothall, glyphosate, and triclopyr) in the Great Lakes began in the 1970s (WI DNR 2019). As such, "years since introduction" was categorized into the following time periods: > 50 years (before selective herbicides were available, i.e. predominantly copper and arsenic), 10–50 years (selective herbicides and the start of mechanical, physical, and biocontrol methods), and < 10 years (representing recent introductions for which managers may have not had time to develop effective tools).

Results

The priority species review process identified 20 priority IAPs that met the criteria: significant impacts, established (or in the process of establishing) in the region, no beneficial impacts that would preclude control, and lacking extensive, control efforts. The workshop included 67 participants from 29 agencies. Workshop discussion focused on 12 of the 20 priority IAPs for which significant research needs were identified based on the literature reviews (Table 1). Thematic analysis identified research gaps for 17 of the 20 species; these gaps fell within the range of chemical, mechanical, physical, and biological strategies (Table 2).

Species-specific research needs related to operational control were numerous and varied, and as such are provided in Supplementary material Appendix 1 as part of the final research agenda. The workshop also generated non-operational control research needs, including key questions related to species ecology and life history that would have implications to inform operational control. These basic research questions are an important complement to applied research questions (Matzek et al. 2014) and are provided in the research agenda (Appendix 1). Full literature reviews for each IAP are provided in Appendix 2.

Though the difference was slight, higher total impact scores had greater tool availability (i.e., all species with high tool availability had higher impact scores (score of 5), and no species with the highest score (score of 6) had low tool availability) (Figure 1a, Table 3). We observed a moderate relationship between environmental impact score and tool availability; all species with

Table 1. Species included in the research agenda. *denotes species discussed at IAP workshop

Scientific name	Common name
Cabomba caroliniana	Carolina fanwort
*Didymosphenia geminata**	Didymo*
Egeria densa	Brazilian elodea
*Eichhornia crassipes**	Water hyacinth*
*Hydrilla verticillata**	Hydrilla*
Monoecious hydrilla	
Dioecious hydrilla	
*Hydrocharis morsus-ranae**	European frog-bit*
*Iris pseudacorus** L.	Yellow flag iris*
*Lythrum salicaria**	Purple loosestrife*
Myriophyllum aquaticum	Parrot feather
*Myriophyllum spicatum**	Eurasian watermilfoil*
Myriophyllum × spicatum	Hybrid milfoil
Najas minor	Brittle naiad
*Nitellopsis obtusa**	Starry stonewort*
*Nymphoides peltata**	Yellow floating heart*
Phalaris arundinacea	Reed canarygrass
*Pistia stratiotes**	Water lettuce*
*Potamogeton crispus**	Curly-leafed pondweed*
*Stratiotes aloides** L.	Water soldier*
Trapa natans	Water chestnut
Typha angustifolia	Narrow-leaved cattail
Typha × glauca Godr.	Hybrid cattail
Typha laxmanii	Graceful cattail

high environmental impact score had moderate or high tool availability (Figure 1b, Table 3). Several species with moderate or high social/cultural impact had low tool availability (Figure 1c, Table 3). Those species with low tool availability tended to be regulated by fewer jurisdictions (Figure 2, Table 3). All species regulated by nine (out of ten total) jurisdictions had high tool availability (and all species regulated by more than 6 jurisdictions had at least moderate tool availability). Distribution in the Great Lakes basin as measured by the number of jurisdictions with the species present did not seem related to the availability of effective tools (Figure 3, Table 3). However, there were proportionally more species that had high tool availability with widespread global distribution than with limited or moderate global distribution (Figure 4, Table 3). Floating and emergent growth forms had proportionally more species with high tool availability; submerged was the only growth form with low tool availability (Figure 5, Table 3). There was no observable difference between time since introduction in the Great Lakes and tool availability (Figure 6, Table 3).

Discussion

Through consulting experts, facilitating a workshop, and compiling literature reviews, we identified general and species-specific research needs for 20 high priority IAPs. Status of the 20 IAPs identified as high priority by this study aligns with other designations of priority status (e.g., Hussner et al. 2017; Gettys et al. 2020). For example, of the 16 species from this list assessed by the U.S. Fish and Wildlife Service Ecological Risk Screening Summary (ERSS) process, 14 are scored as high risk, which provides support for the

Table 2. General research needs identified as a result of the literature reviews and workshop.

Species	General Research Need						
	Investigate effect of, and where necessary refine, current treatment methods for **propagules** (e.g., bulbils, seeds, turions)	Investigate **biocontrol** options, including genetic biocontrol	Investigate the efficacy of the herbicide **florpyrauxifen-benzyl**	Refine optimal **treatment timings** for known effective herbicides based on plant phenology knowledge to reduce non-target impacts and improve treatment efficacy	Determine the efficacy of **integrated control strategies**	Establish quantitative, standardized pre- and post- treatment **efficacy data** relative to each control method	Develop **decision-support tools** to determine treatment methods and approaches for different populations and environments
C. caroliniana	x	x				x	
D. geminata							x
E. densa							
E. crassipes	x	x	x	x		x	
H. vertillata	x	x	x	x			
H. morsus-ranae	x	x			x	x	
I. pseudacorus						x	x
L. salicaria							
M. aquaticum			x				
M. spicatum		x	x	x	x		x
N. minor							
N. obtusa	x	x		x	x	x	x
N. peltata	x		x				
P. arundinacea					x		
P. stratiotes	x	x		x		x	
P. crispus	x			x			
S. aloides			x				x
T. natans							
T. angustifolia					x		
T. laxmanii					x		
Total	8	7	6	6	6	6	5

priority status of these species. Historically, only a few species (i.e., *Myriophyllum spicatum* L., *Hydrilla verticillata* (L.f.) Royle, *P. australis* and *E. crassipes*) receive most of the attention in IAP studies (Evangelista et al. 2014). This trend is similar in terrestrial ecosystems (e.g., in Matzek et al. (2015) where only four terrestrial plant species accounted for nearly half of publications and several high priority invasive plants were absent). The use of quantitative criteria (e.g., impact) to identify priority species was an important element that ensured a comprehensive list of species for this study. This study revealed key findings in several areas, which we explore in detail below: 1) the importance of more investment in control-related research (including consideration of a broader suite of potentially high-risk species), 2) research gaps and emergent themes that should help to inform IAP control-related research and improve IAP management generally, and 3) trends in the availability of control tools as they relate to species' distribution, impacts, and regulatory status (and the implications thereof, especially for regulatory policy).

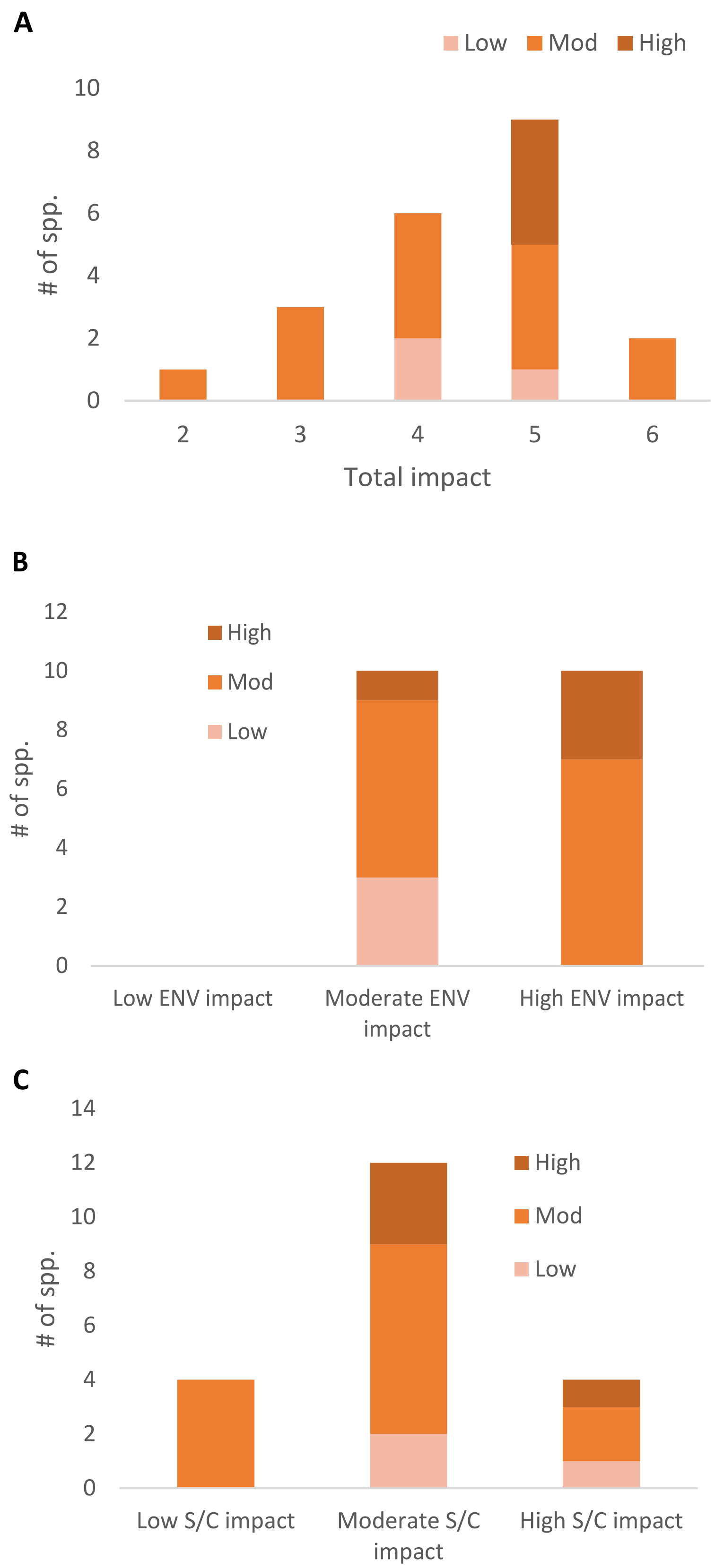

Figure 1. Relationship between total impact of IAPs (scored 1–6) and number of species with low, moderate, or high tool availability (A), relationship between environmental (ENV) impact of IAPs and number of species with low, moderate, or high tool availability (B), relationship between social/cultural (S/C) impact of IAPs and number of species with low, moderate, or high tool availability (C).

Table 3. Factors related to tool availability. See Methods for explanation of categorical thresholds for global distribution, Great Lakes distribution, years since introduction, and tool availability.

Species name	Total impact score	No. of jurisdictions regulating	Great Lakes distribution	Global distribution	Growth form	Years in Great Lakes basin	Tool availability
E. densa	5	9	1	3	Submerged	1	3
M. aquaticum	5	9	1	3	Submerged	3	3
T. natans	5	9	2	1	Floating	3	3
I. pseudacorus	5	5	3	2	Emergent	3	3
C. caroliniana	4	4	1	2	Submerged	3	2
P. crispus	4	6	3	1	Submerged	3	2
M. spicatum	6	8	3	2	Submerged	3	2
H. morsus-ranae	4	8	2	1	Floating	2	2
T. laxmanii	2	1	1	2	Emergent	1	2
H. verticillata	6	8	1	3	Submerged	2	2
T. angustifolia	3	3	3	2	Emergent	3	2
L. salicaria	3	8	3	1	Semi-aquatic	3	2
P. arundinacea	5	1	3	2	Semi-aquatic	3	2
E. crassipes	5	2	1	3	Floating	2	2
P. stratiotes	5	1	1	3	Floating	2	2
S. aloides	4	6	1	1	Submerged	2	2
N. peltata	3	6	2	1	Floating	3	2
N. minor	4	4	3	1	Submerged	3	1
D. geminata	4	2	1	1	Submerged	2	1
N. obtusa	5	4	2	1	Submerged	2	1

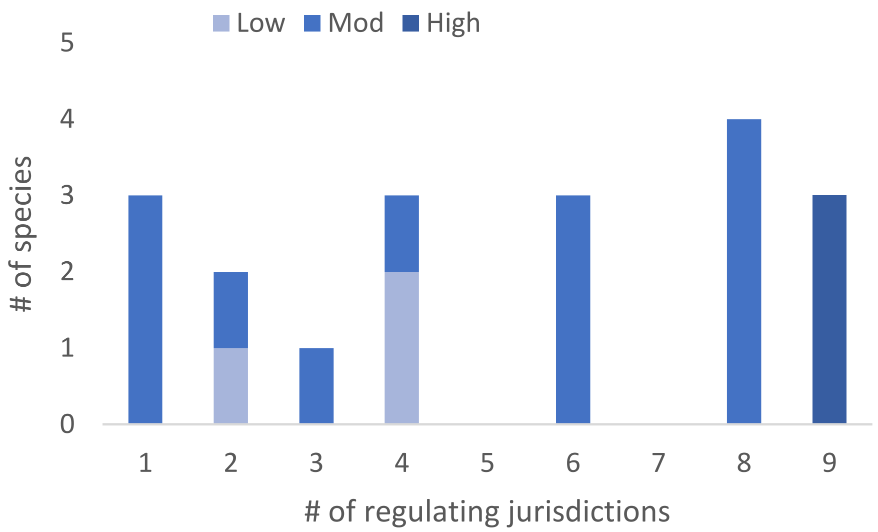

Figure 2. Relationship between number of jurisdictions regulating an IAP and number of species with low, moderate, or high tool availability.

Value of control-related research

The costs of IAPs are well documented. Floating plants have had economic costs (which includes negative impacts and control costs) of $4.7 billion, submerged plants $8.4 billion, emergent plants $684 million and semi-aquatic $306 million (Macêdo et al. 2024). *E. crassipes* (floating), *H. verticillata* (submerged), and *Lythrum salicaria* L. (semi-aquatic) are three of the costliest freshwater IAPs globally (Macêdo et al. 2024). Several studies have found that control of these IAPs yields net benefits. Wainger et al. (2018) found research into control of *E. crassipes* yielded a cost-benefit ratio of 34:1. Weber

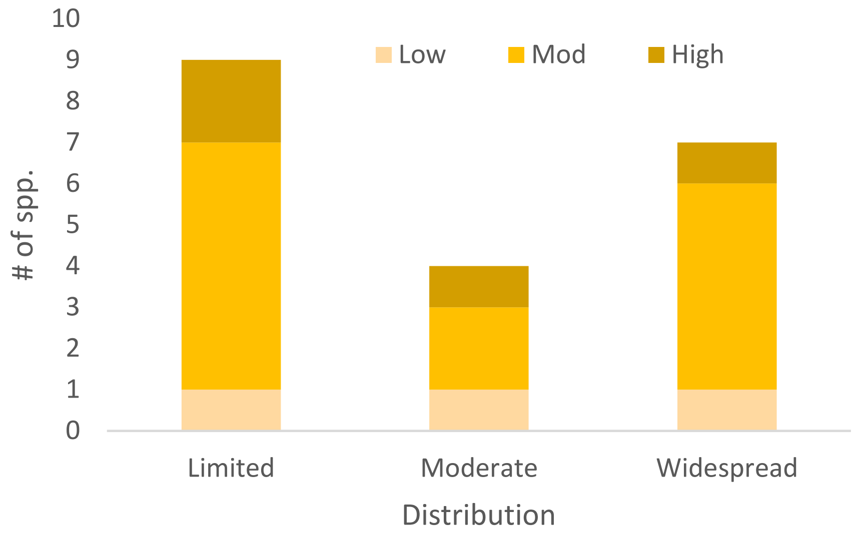

Figure 3. Relationship between Great Lakes distribution of IAP and number of species with low, moderate, or high tool availability.

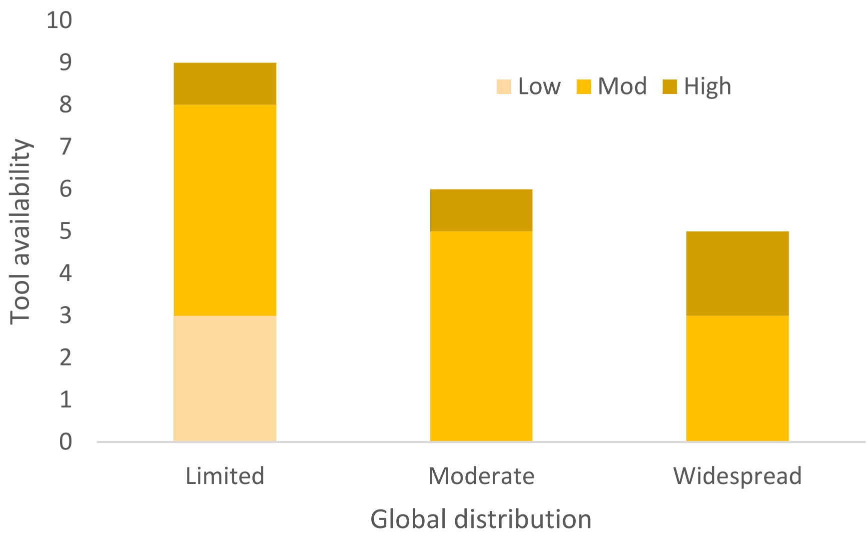

Figure 4. Relationship between global distribution of IAP and number of species with low, moderate, or high tool availability.

et al. (2020) found research into control of *H. verticillata* yielded a benefit-benefit ratio of 3.8, which is likely an underestimate given conservative methods of the study. Despite these finds, expenditures on IAP management to maintain ecosystem services are estimated as too low (Rockwell 2003) and constitute a fraction of the negative economic costs caused by IAPs (Macêdo et al. 2024).

These studies use the costs of on-the-ground control efforts to calculate the benefits of control. Support for research on control strategies has also been found to yield significant benefits (e.g., Weber et al. 2020) but is evenless well-funded than on-the-ground efforts. For example, from 1999 to 2009, local and federal research on hydrilla control that included improved

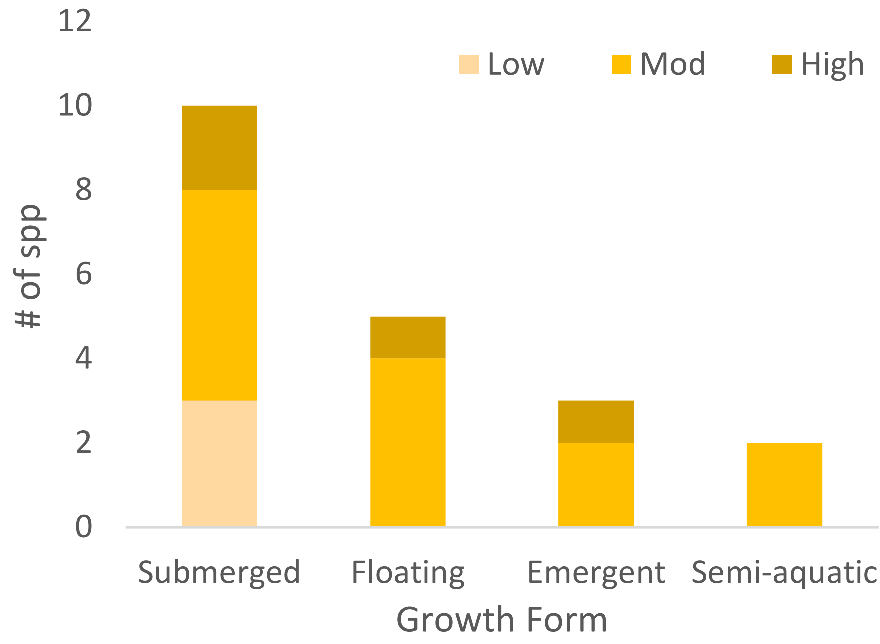

Figure 5. Locations Relationship between growth form of IAPs and number of species with low, moderate, or high tool availability.

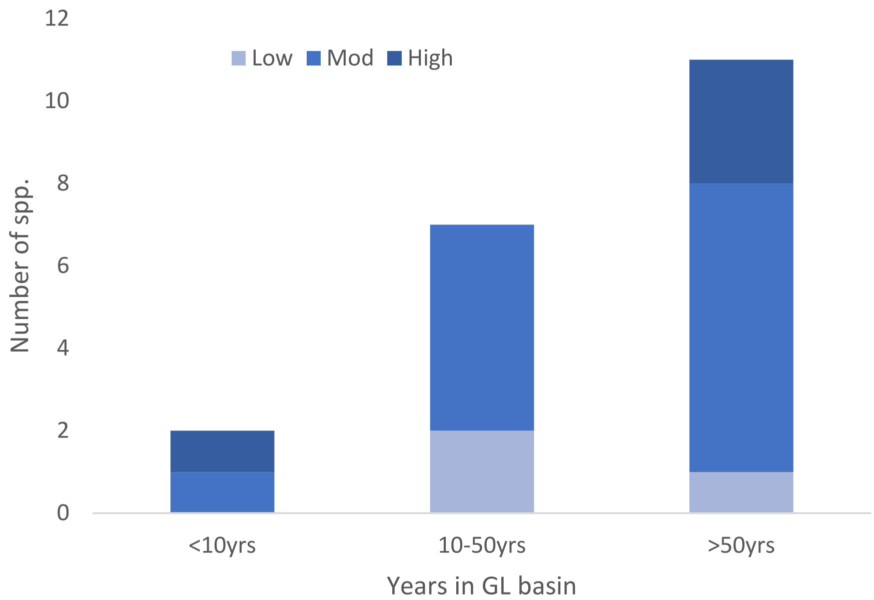

Figure 6. Relationship between years an IAP has been in the Great Lakes basin and number of species with low, moderate, or high tool availability.

monitoring technology, registering additional herbicides, testing of a large-scale treatment protocol for endothall or penoxsulam, testing for the continuance and spatial extent of fluridone resistant *H. verticillata*, improved mechanical control, and biological control options were estimated at $7 million (Weber et al. 2020). The total global impact cost of *H. verticillata* (including management and damage costs) has been estimated at $626.6 million (Macêdo et al. 2024). While the research expenditures for *H. verticillata* are for 10 years and limited to the United States, and the total impact cost for *H. verticillata* is for 47 years and calculated globally, the gross inequality is still informative, particularly given the United States reports the highest economic costs for all IAPs of any country and would therefore form a large, if not majority, portion of the global costs for *H. vertillata* (Macêdo et al. 2024). This emphasizes the need for more investment in control-related research (Kettenring and Adams 2011).

General research themes

There were a number of research themes or areas of common need identified across multiple species. Research to fill these operational control knowledge gaps that were common to a number of species will likely need to be carried out within the context of individual species to be useful – there is no "one size fits all" approach to aquatic plant control and management. However, by providing these general needs here in the absence of individual species connections, we illustrate some major research areas that require greater investment and capacity development given their relevance to many aquatic plant management efforts.

1. Investigate effect of, and where necessary refine, current treatment methods for overwintering propagules (e.g., bulbils, seeds, turions). The presence of overwintering seeds, turions, or bulbils can undermine and greatly extend control efforts into multi-year programs that can be difficult to sustain (Hussner et al. 2017). Effective operational control therefore requires a solid understanding of vegetative and sexual reproduction strategies including (a) the regeneration capacity of plant fragments; (b) the timing of development and potential dispersal of overwintering or storage organs (e.g. turions, winter buds, root crowns, rhizomes); and (c) the timing and development of seed production and requirements for seed germination (Hussner et al. 2017). In a study of invasive terrestrial plants, Matzek et al. (2015) also found managers desired more information related to the seedbank (longevity and viability). The difficulty in controlling propagules was identified in the workshop as one of the most significant challenges in *H. verticillata* and *N. obtusa* control. Another knowledge gap identified in the workshop was how treatment of adult plants impacted viability/production of propagules.
2. Investigate biocontrol options. Development of biocontrol tools fell out of favor in 1990's following a series of papers documenting some of the drawbacks, in particular the non-target impacts of biocontrol agents (Simberloff 2014). Biocontrol can take a range of forms (Hussner et al. 2017) and when developed properly, however, can result in long-lasting and cost-effective management (Simberloff 2014). For example, the intrinsic growth rate of *E. crassipes* in Louisiana declined by 84% between 1976 and 2013 (biocontrol program initiated in 1974), despite higher winter temperatures over time (Nesslage et al. 2016). This biocontrol has led to a benefit:cost ratio of 34:1 (Wainger et al. 2018).

Increased biocontrol research has previously been identified as an important endeavor, particularly as a tool in integrated and adapted management strategies (DiTomaso et al. 2017). In the workshop, gene silencing was mentioned as a potential option for species which are not vulnerable to other knowns methods of control. While this has been proposed for plant crops (Zulfiqar et al. 2023), we are not aware of any successful genetic control tools that have been developed for IAPs. Finally, several of the species (e.g., *P. stratiotes*, *E. crassipes*) have biocontrol organisms that are partially effective on invasive populations in warmer climates, but their effectiveness in colder climates is unclear given uncertainty around their ability to overwinter. Initial work in how to adapt tropical biocontrol agents to temperate climates is discussed in Harms et al. (2021).

3. Investigate the efficacy of the herbicide florpyrauxifen-benzyl. This herbicide was approved by the U.S. Environmental Protection Agency in 2018, and as such, detailed information on field applications is limited. Initial mesocosm experiments suggests this herbicide has a short exposure time and good efficacy for *H. verticillata*, *M. spicatum*, and *E. crassipes* (Beets and Netherland 2018; Mudge et al. 2021). Initial field trials are also promising, e.g., 100% control of *Nymphoides peltata* (S.G.Gmel.) Kuntze in a large reservoir (Lamb 2020), 94% reduction of *M. heterophyllum* Michx. (Howell et al. 2023), and 90–100% reduction of *M. spicatum* in a small lake (Davidson 2023). Understanding the full suite of species that can be effectively controlled by this herbicide and the long term efficacy of florpyrauxifen-benzyl treatment were priority needs identified by the Great Lakes management community.
4. Refine treatment timing. Treatment timing can influence the success of control efforts. For example, *Potamogeton crispus* L. grows earlier in the spring than native submersed aquatic plants. This allows for certain herbicide treatments to be selective for *P. crispus* when other native plants are still dormant, reducing non-target impacts (Johnson et al. 2012). Another consideration from the workshop included a question of whether there becomes a time period when removal is no longer needed (with subsequent cost savings) due to upcoming winter die-off for *P. stratiotes* and *E. crassipes* (this assumes no seed production). The understanding of treatment timing is also a concern for managers with respect to climate change (Beaury et al. 2020).
5. Integrated management strategies. Integrated pest management (IPM) is a science-based decision-making process that combines diverse treatment approaches, frequent monitoring, and adaptive strategies to increase the likelihood of attaining the desired level of control, often with reduced impact on non-target species and risks to human health and the environment. IPM is intended to ensure the efficacy of management over the long-term while ensuring the lowest-possible risk

to beneficial ecological functions. Decisions are informed by thorough planning and monitoring efforts, during which all permissible plant management techniques are considered based on their potential to control target plant species while reducing non-target impacts and risks to human health and the environment (WI DNR 2019). For example, integrated control strategies and repeated treatments are needed to decrease the competitive dominance of *Typha angustifolia* L. and *T.* ×*glauca* Godr. These most commonly include a combination of cutting, herbicide, flooding, and burning; which combination is best will depend on site characteristics. The value of integrated management strategies are oft cited, both in general and for specific species (e.g., *P. australis* in Blizzard 2023).

6. Treatment efficacy data. The desire for more data on the relative efficacy of different treatment approaches was unsurprising, given this is critical to refining invasive species control strategies (Esler et al. 2010; Matzek et al. 2014). Improved understanding of the efficacy of control strategies can lead to more cost-effective control (D'Evelyn et al. 2007). A better understanding of efficacy can also help avoid the use of a control strategy simply because it has low labor or financial costs despite being ineffective (Kettenring and Adams 2011), and potential non-target impacts to native species. For example, 2,4-D is an herbicide commonly used for *M. spicatum* treatment, despite its high variability in successful control and significant non-target impacts (Kujawa et al. 2017; Nault et al. 2018). Mikulyuk et al. (2020) found that lake-wide 2,4-D treatments aimed at controlling *M. spicatum* led to larger decreases in number of native plant species and abundance of native plant populations, than decrease in *M. spicatum* itself. Given the variety of non-target impacts resulting from some IAP control strategies (e.g., Schuler et al. 2008; Jin et al. 2018; Breinlinger et al. 2021; Dehnert et al. 2021), understanding the efficacy of a particular control strategy relative to its non-target impacts is essential (Kujawa et al. 2017). The importance of long-term pre- and post-treatment monitoring was highlighted in the workshop as an essential component of assessing control efficacy.
7. Decision support tools. The need for decision support tools that are regionally-specific and can assist practitioners in optimal control method(s) was a common topic of discussion during the workshop. The value of such tools is well established. They have been used to assess the probability of successful eradication of invasive species (Drolet et al. 2015); to assist decisions in location-specific control programs (e.g., Cape Town; Gaertner et al. 2017); and to assist decisions with species-specific control programs (e.g., *Spartina alterniflora* Loisel. in Hastings et al. 2006, Gobio lozanoi (Doadrio & Madeira, 2004) in Muñoz-Mas et al. 2016). Variables in an aquatic plant-based control decision tool could include differences in treating urban vs rural populations, varying densities, water flow, etc.

In addition to the above general research needs, several themes from the literature reviews and workshop discussion are relevant for control-related research, including a systems approach to management, a shift from suppression to eradication mindset, and the understanding of climate change-related impacts to control.

System dynamics approach. A system dynamics approach (as opposed to a plant community structure approach) to invasive species management takes a broad-scale view of the target ecosystem, and includes mitigating disturbances, disrupting facilitating feedbacks that reinforce invasions, strengthening feedbacks that augment community recovery and invasion resistance, and reestablishing natural disturbance regimes (Annen 2011). Many habitats contain multiple invasive species, yet most studies focus on a single invasive species; Kuebbing et al. (2013) found that while two-thirds of reviewed conservation projects had multiple invaders, only one-third of conservation projects mentioned multiple invaders. Yet, management strategies for a single species may be less effective when the species occurs in a system with multiple invasive species, especially if there are facilitative or competitive interactions where control of one could result in increased impacts of another IAP (Kuebbing et al. 2013). In addition, interactions between native and non-native species may vary between populations, emphasizing the need to approach control from a population level (Reichard et al. 2015). This understanding will also assist in effectively allocating limited funding in a habitat with multiple species. For example, a system dynamics approach for *P. arundinacea* involved removal of hydrological disturbances, litter removal, reseeding after herbicide applications, and reestablishing fire regimes (Annen 2011).

Suppression to eradication. Population containment/suppression is the most common approach to management (61% of control efforts for freshwater species; Green and Grosholz 2021). This is generally due to logistical and ecological constraints that make eradication unfeasible, e.g., widespread populations, ongoing propagule and reinvasion pressure, long lived seedbank, potential non-target impacts of intense control, and/or insufficient funding (Green and Grosholz 2021). For species with no available control tools, containment (spread prevention) may be the only option (Hussner et al. 2017). Where eradication is not feasible, research to determine optimal quantitative target endpoints for biomass reduction ("functional eradication") will lead to decreased environmental and social/cultural impacts (Green and Grosholz 2021). Nevertheless, eradication can be the preferred management outcome especially where a site, and/or species are characterized by features that improve the chance of eradication (Simberloff 2008; Dodd et al. 2015; Phillips et al. 2018) and the cultural and regulatory frameworks enable prompt action and access to a full range of management approaches (Hofstra et al. 2020). In addition, eradication is more expensive than alternative responses in the short-term but less expensive than no action or ongoing control in the long-term (Muller et al. 2021). Examples of successful plant eradications are not well represented in the literature and views on eradication often focus on the failures rather than total (or near total) eradications (Mack and Foster 2009). Large scale eradication attempts are dogged by the difficulty of sustaining long term management programs and uncertainty about declaring success when faced with persistent seed banks (Panetta 2007), whereas eradication or extirpation of small discrete populations are often poorly documented or are at best located in gray literature (Simberloff 2008). The successful eradication of over 200 discrete populations of IAPs in New Zealand (Champion 2018) is one exception. But examination of aquatic plant management across the Great Lakes region over the last 20 years also finds numerous examples of small (and even large scale) eradication success stories that at best are reported in internal state agency documents. There are multiple examples of successful *H. verticillata* eradications across basin including the high-profile success story in Lake Manitou (755 acres) to various small artificial ponds in Indiana (Eric Fischer, Indiana DNR *pers. comm.*) and Ohio (Mark Warman, Cleveland Metroparks *pers. comm.*). Other examples of IAP eradications include the successful eradication of *Egeria densa* Planch. from Griffy Lake (109 acres) (Indiana Department of Natural Resources 2017) and *E. densa* from Powderhorn Lake (12 acres) (Wendy Crowell, Minnesota Department of Natural Resources *pers. comm.*) Populations of *Myriophyllum aquaticum* (Vell.) Verdc. have been eradicated in Michigan (Bill Keiper, Michigan EGLE *pers. comm.*) and in Indiana (Indiana Department of Natural Resources 2012). Even one of the species with the fewest available control strategies (*N. obtusa*) has potentially been eradicated from 605-acre Webster Lake (Eric Fischer, Indiana DNR *pers. comm.*) These successes are characterized by an aggressive approach to eradication that has been shown to be particularly effective in the early phase of an introduction where populations are still small and eradication feasible. The methods employed in these efforts are diverse and range from elegant science to excessive biological control (grass carp), to just overwhelming physical labor. To the latter point, the use of hundreds of volunteers from 1999–2004 to hand-pull over 260,000 pounds of *Trapa natans* L. from approximately 6 acres of invaded waterways in Maryland was successful in its eradication (Naylor 2003).

Climate change will necessitate adaptive control strategies and increased control efforts for these IAPs. Invasive species are generally more resilient to environmental shifts due to faster growth rates and shorter germination times, allowing them to outcompete native species (Mishra et al. 2023). Invasive species also respond quickly to increasing temperatures and are spreading into areas historically too cold for them to survive over the winter (You et al. 2013), which suggests increasing populations in cooler regions in the future (Hellmann et al. 2008; U.S. Environmental Protection Agency (EPA) 2008; Beaury et al. 2020). Plant species intolerant to freezing such as *Alternanthera philoxeroides* (Mart.) Griseb. have spread into higher latitudes in China and South America (Wu et al. 2017; Mishra et al. 2023). In the Great Lakes, several of the IAPs (notably, *P. stratiotes* and *E. crassipes*) are repeatedly found in the same locations despite uncertainty as to their ability to produce seeds or overwinter, which suggests they are overwintering or being released in the same location each year. In addition to establishment of new IAPs, climate change will increase the growing season, allowing plants more time to establish biomass that leads to greater environmental and social/cultural impacts and therefore warrants additional control efforts and cost (Mishra et al. 2023). This has recently occurred in the Great Lakes with *Hydrocharis morsus-ranae* L. found earlier in the year after a mild winter/spring (Bill Keiper *pers. comm.*). Research on the efficacy of existing control methods under climate change scenarios will also be necessary to maintain effective IAP management (Hellmann et al. 2008; Beaury et al. 2020).

Trends in tool availability

While the relatively small number of priority IAPs precluded a statistical analysis of explanatory variables for the relative availability of control tools, some general relationships can be observed. An important assumption is that availability of control tools is related to effort/investment into developing tools for each species.

Total impact score highlights the need for better tools for several species, including *H. verticillata* and *M. spicatum* (the two highest-scoring species that only had moderate tool availability), as well as *N. obtusa* (second-highest scoring species that had low tool availability). Treatment of *M. spicatum* is variable, *H. verticillata* control is confounded by the presence of a persistent tuber bank, and *N. obtusa* control has no reliable options. Specific research needs for these high priority IAPs can be found in Appendix 2. That several species had moderate or high social/cultural impact yet low tool availability was surprising. Generally, species with higher social/cultural impact would be expected to have at least moderate availability of control tools (e.g., *M. spicatum*, *E. crassipes/P. stratiotes*) because reducing the impediments to recreation is an objective of many management agencies. These three species with moderate or high social/cultural impact yet low tool availability (i.e., *D. geminata*, *Najas minor* All., *N. obtusa*) were also less regulated than most species on the list. While it is generally viewed as beneficial to regulate all high-impact IAPs, it may be particularly beneficial to regulate those with an absence of effective control tools. Regulation not only provides impetus to control the species (and therefore develop control tools for those species without any), but regulation can also provide a “stop gap” ability to slow the spread of species for which agencies have no other methods to control. While the cryptogenic status of *D. geminata* poses regulatory challenges (agencies do not want to regulate a native species), increased regulation of a species such as *N. obtusa* that has high impact but few control tools will not only help limit its spread but may also provide support for researchers to develop control tools. Other species for which increased regulation would be beneficial (despite a moderate availability of tools) are those species that are in relatively early stages of invasion (in this case study, *P. stratiotes*, *Typha laxmanii* Lephech., *E. crassipes*, and *C. caroliniana*).

As might be expected, tool availability appears to be more related to a species' global versus Great Lakes distribution. A number of globally important IAPs still have relatively limited Great Lakes distributions. For example, there are a limited number of *M. aquaticum* populations in the Great Lakes basin proper (many of which are under management), whereas it has the third-highest non-native distribution globally. The distribution trend may also explain why length of time since its introduction in the Great Lakes did not seem to relate to tool availability. That is, species that are recent to the Great Lakes may have a long history of invasion elsewhere (and thus more time to develop control tools), and vice versa. In addition, the Great Lakes may be at the northern climate limits for some important common IAPs which explains the lack of regional tools. So, despite *E. crassipes* being introduced worldwide as early as the 17th century (Parolin et al. 2010), it appears to be winter limited in the basin, and even under a warming climate is uncertain as to whether it can fully establish in the Great Lakes (Adebayo et al. 2011).

Despite the expectation that species with a submerged growth form would have a greater impetus for control tools given they have resulted in significantly more economic costs (Macêdo et al. 2024), this did not seem to be true. This may be due to several factors, including relative difficulty in accessing/treating submerged populations (e.g., difficulty maintaining contact times and concentrations) and less perceived nuisance ("out of sight, out of mind"), or market acceptance of the current levels of control. Since the 1990s, there has been a major decline in patent applications for new herbicide ingredients, and only a small number of companies remain actively engaged in the development of herbicides (Kraehmer et al. 2014). The commercial development of a new herbicide for smaller niche treatments like control efforts for *N. obtusa* and other submersed IAPs with belowground asexual reproductive structures that are not as susceptible to chemical or mechanical control methods (Glisson et al. 2018) is likely to remain unfavorable without some form of government research investment.

Conclusion

Better information related to management of invasive species forms the main set of priorities for practitioners working to manage invasive species, followed by information sharing, communication, and collaboration (Bayliss et al. 2013). The methods and focus of this study (a set of literature reviews and workshop focused on enhancing regional collaboration to identify control-related research needs) addresses each of these priorities. The research needs identified in the expert workshop were supported by the literature reviews; as such they are not the result of a lack of familiarity with available information but rather represent real gaps in knowledge. As mentioned earlier, the scope of this study was operational control methods; there also remain research needs related to the human and social components of IAP management.

While identification of these research needs is a crucial first step, this type of exercise will not benefit IAP control until these research needs are addressed. There are two facets to this: completing the research and delivering the findings to managers in a meaningful way. There are several barriers to completing the research, e.g., the gap between applied and basic research (which would be alleviated by expanding rewards to applied research; Esler et al. 2010), the tendency for scientists to work on only a few well-known species (Matzek et al. 2015) that are also often favored by government funding models. The explicit identification of applied research needs for lesser known, but still priority, species in this study should help alleviate this gap. The information outlined in this research agenda is intended to inform the development of proposals and work plans to submit under future funding opportunities. These findings will help agencies and academic institutions to plan future research activities and project proposals and serve as a reference document to inform funding agencies as they make decisions related to invasive aquatic plant control and research.

Delivery of research findings to managers is an important aim of aquatic plant management societies. Yet, the integration of research into on-the-ground application could be augmented via several approaches. Publications on invasive species management often have limited usefulness to managers as management uptake of research is hindered by insufficient time and library access (Matzek et al. 2014), though the increase in open access publications reduces this barrier. Alternative forms of communication could take the form of workshop presentations, communication with extension specialists, or contribution to a relevant newsletter or listserv (Matzek et al. 2014). Boundary spanning organizations, like Land and Sea Grant extension programs, have experience in the two-way communication of research ideas and knowledge, and have helped fund needed AIS research in the past (Campbell and Otts 2024). In addition to existing forums within aquatic plant management societies, these communications could be facilitated by regional aquatic invasive species panels (such as the regional Panels that report to the U.S. Aquatic Nuisance Species Task Force, which coordinates AIS efforts on a federal level). Finally, while this study provided insights into operational control methods, a more comprehensive understanding of IAP management requires additional research into the human and social aspects. By addressing research needs, bridging knowledge gaps, and enhancing communication channels, stakeholders can better equip themselves to effectively manage invasive species and pave the way for informed decision-making and practical application in the field.

Authors' contribution

CW contributed to research conceptualization, data interpretation, funding provision, and writing; WLC contributed to research conceptualization, data interpretation, and writing; ADD contributed to research conceptualization, data interpretation, and writing; AJT contributed to research conceptualization, data interpretation, and writing.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. Invasive Aquatic Plant Control Needs: Research Agenda.
http://www.reabic.net/journals/mbi/2024/Supplements/MBI_2024_Weibert_etal_Appendix_1.pdf

Appendix 2. Plant species literature reviews.
http://www.reabic.net/journals/mbi/2024/Supplements/MBI_2024_Weibert_etal_Appendix_2.pdf