Invasive Aquatic Plant Control Needs: Research Agenda

Ceci Weibert[1], Alisha Davidson[1], Lindsay Chadderton[2], Andrew Tucker[2]

[1]Great Lakes Commission,
[2]The Nature Conservancy

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Executive Summary

The Great Lakes Panel on Aquatic Nuisance Species (Great Lakes Panel) identified the need to improve coordination of invasive aquatic plant control method research and to identify and prioritize needs related to this research. This research agenda details key research questions that need to be addressed to improve operational control efficacy for a set of 20 priority invasive aquatic plant species, and outlines capacity needs and obstacles to implementation that also need to be addressed. Funding for this work was provided through the U.S. Fish and Wildlife Service via the Great Lakes Restoration Initiative under funding agreement F21AP00426. The priority species were selected based on a set of criteria developed via the Great Lakes Panel. The goal of this research agenda is to facilitate more efficient and effective control and management of invasive aquatic plants in the Great Lakes basin. The research needs identified in this agenda are related to operational control strategies. Additional research needs for each plant are included in the supplementary material to this research agenda, titled "Non-Operational Control Research Needs."

The research agenda presents both general needs, which serve to improve the management of many invasive aquatic plants, and species-specific needs tailored to each of the 20 priority species. Research needs were identified via a series of species-specific literature reviews and an expert elicitation workshop, in which 12 of the 20 species were discussed in-depth (indicated by * in the species list). The priority species are: Carolina fanwort, didymo*, Brazilian elodea, water hyacinth*, hydrilla* (including both monoecious and dioecious hydrilla), European frog-bit*, yellow flag iris*, purple loosestrife*, parrot feather, Eurasian watermilfoil* (including hybrid milfoil), brittle naiad, starry stonewort*, yellow floating heart*, reed canarygrass, water lettuce*, curly-leafed pondweed*, water soldier*, water chestnut, narrow-leaved cattail (including hybrid cattail), and graceful cattail.

The highest priority general research needs identified for most invasive aquatic plant species included in this process are listed below, in no particular order:

- 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
- 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

The information outlined in this research agenda is intended to inform the development of proposals and work plans for future funding opportunities. It is the intent of the Great Lakes Panel that not only will agencies and academic institutions utilize this document to plan future research activities and project proposals, but that funding agencies will also use this as a reference document when making decisions related to these invasive aquatic plants.

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Introduction

Great Lakes biodiversity and ecosystem services continue to be compromised and threatened by the introduction, establishment, and spread of invasive aquatic plants (IAP). For the purposes of this research agenda, two nuisance macroalgae species (*Didymosphenia geminata* and *Nitellopsis obtusa*) are included in the use of the acronym IAP throughout this document, given their similar environmental and social impacts and their management within government agencies by plant staff. Numerous agencies, nongovernment organizations, and private interests are implementing control measures for those IAP that impede recreation and navigation, degrade habitat for native species, and disrupt natural ecosystems. These entities are also working with research institutions and the private sector to develop new tools for management and improve the efficiency and effectiveness of control efforts. These activities cost millions of dollars and are widespread throughout the Great Lakes region and across the United States; however, there has been no regional approach to coordinate engaged entities, identify needs, share outcomes and lessons learned, and ensure future investments are directed towards the highest priorities. Recognizing that this lack of coordination is a hindrance to effective implementation for cross-boundary IAP prevention and control, jurisdictions in the Great Lakes region endorsed a collaborative project to develop an IAP research agenda to improve coordination of IAP control method research and prioritize research needs. The Great Lakes Commission (GLC), with support from the Great Lakes Panel Research Coordination Committee (GLP RCC) was tasked with developing the research agenda.

Purpose

This research agenda will detail key research questions that need to be addressed to improve operational control efficacy for priority IAP species. The information outlined in this research agenda is intended to inform the development of proposals and work plans to submit under future funding opportunities.

Audience

Funding institutions as well as research teams should reference this research agenda when planning and/or funding research activities related to operational control of these species.

Background

The research agenda was developed with input from the GLP RCC and based on feedback received at the "Great Lakes Regional Invasive Aquatic Plant Control Prioritization and Needs Assessment Workshop," convened by the GLC in January 2023. A final list of 20 IAP species were selected from an initial list of 23 established plant species in the Great Lakes region, prioritized through an objective process utilizing criteria that considered impacts and management interest. For each priority species, a literature review was completed that identified gaps in management methods, focusing on operational control needs (see below, "Definitions" and "Assumptions"). For six of these species (*Cabomba caroliniana*, *Hydrocharis morsus-ranae*, *Myriophyllum spicatum*, *Nitellopsis obtusa*, *Pistia stratiotes*, and *Potamogeton crispus*), the state of Michigan's status and strategy management reports were used as the basis of knowledge, with the literature reviews serving to fill any additional gaps or provide updates to the content of the management report in the years since they had been published. Literature reviews were reviewed by species experts and utilized to plan the workshop with management agencies, industry partners, and research agencies and institutions to discuss research needs and identify additional needs not yet recorded in published literature.

The supplementary material to this research agenda describes additional research needs that are not directly related to the operational control of these species. Many research needs were identified through literature reviews and the expert elicitation workshop that may inform improved operational control of these species, but are more specific to ecological traits, early detection and rapid responses, and other factors. Of note, lessons learned from research needs that are identified herein could be applied for containment and response scenarios, but the focus of this document is identifying research needs that improve operational control for established IAP populations.

Definitions

Several terms are used throughout this document that may have multiple, distinct definitions depending on the context in which they are used. For the purposes of this research agenda, the following terms have been defined and used in a consistent manner and are adapted from Section 3.1 A Manager's Definition of Aquatic Plant Control in *Biology and Control of Aquatic Plants: A Best Management Practices Handbook* (AERF, 2020). 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 research agenda.

Management: Plant management is the process of first establishing realistic expectations for the amount and duration of plant control (endpoints) prior to the initiation of a control activity, then implementing an operational strategy to meet these management endpoints (control) and concluding with the measurement of how well the control strategy met those endpoints (efficacy).

The management endpoints can include change in percent cover or biomass (small reduction through to eradication), duration of change (several weeks through to permanent), species diversity, reproductive capacity of target plant, or nutrient availability in the system. Achievable endpoints can be influenced by species traits, water body uses, environmental conditions, financial resources, and available management tools. Endpoints can also include considerations of acceptable non-target impacts.

Control: Techniques used alone or in combination that result in a reduction/alteration of a target plant population to a desired state (endpoint).

Efficacy: Effectiveness of a control strategy can be determined by how well the results of control efforts meet the pre-determined management endpoints associated with plant control activity.

Assumptions

Several assumptions were used throughout the planning and development of this research agenda, including during the workshop held to inform this document. Those assumptions are defined below and form the basis for the research needs identified in this document.

1. The focus is on research needs that address knowledge gaps in operational control strategies.
2. Within the Great Lakes region, stakeholders are interested in actively managing the species included in this research agenda. That is, the discussion is not whether a species *should* be managed, but rather, how it *could* be managed to meet desired management endpoint(s).
3. Managers are legally able to apply, and interested in, utilizing herbicides that are approved for use in aquatic environments in the United States, or herbicides for which legal approval is possible if desired.
4. Chemical, physical, biological (including genetic), and other control methods are equally of interest to managers (i.e., preference is not given for one type of control over another but are each considered for use based on several factors when making management decisions).
5. Research needs remain focused on operational control efforts and roadblocks to those efforts, not personnel/resource restrictions or limitations.
6. Researchers are interested in shared agreement that a treatment method, novel or otherwise, is worth exploring for a given species, rather than philosophical or technical debates about the method itself.
7. Just because a non-target impact isn't mentioned doesn't mean that there isn't one – every control method has its limitations.
    a. Managers and decision-makers are interested in understanding non-target impacts associated with a specific method where that information is not known, but where that data might be important information when determining whether they may want to adopt a specific method.

Species and Geographic Scope

The geographic scope of this research agenda is limited to the eight U.S. Great Lakes states (i.e., Indiana, Illinois, Michigan, Minnesota, New York, Ohio, Pennsylvania, Wisconsin) and Indigenous Nations that fall within the Great Lakes basin. However, the research needs discussed in this document are relevant to researchers studying these species anywhere within their invasive range and should be used to inform research no matter where it is being undertaken.

The species selected for inclusion in this document were chosen based on a set of criteria determined by the GLP RCC. Literature reviews were conducted to identify species that fit the criteria. Species that fit the criteria are included in Table 1, and Figure 1 shows the ecological and socioeconomic impact scores of each species from NOAA Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS) risk assessments. Criteria and definitions are provided below:

- Total impact score: established and/or range expander species with a transformed total impact score of four, five, or six (transformed total impact score is determined by summing environmental plus social/cultural impacts, possible maximum total of six), and/or a three in either environmental or social/cultural category (see below) were considered for inclusion. If a species did not meet the impact threshold but was considered high-priority by members of the GLP RCC, it was also included. The only species included in this manner is *Nyphoides peltata*. 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 (see

"Distribution", below) were included regardless of impact score. The only watchlist species included that did not meet other impact score criteria is *Typha laxmanii*.

    - Environmental impact: Environmental impact was determined by summing the following six components, as scored and defined by NOAA-GLANSIS: (1) threat to health of native species (e.g., toxic/poisonous, parasite); (2) out-competes native species for resources (e.g., food, light); (3) alters predator-prey relationships; (4) genetic impacts on native species (e.g., hybridization); (5) water quality impacts (e.g., increased turbidity or clarity); and (6) alters physical components of ecosystem (e.g., facilitated erosion/siltation, altered hydrology, altered macrophyte/phytoplankton communities, physical or chemical changes to substrate). The total score of 0-36 was transformed to 0-3 using methods developed by GLANSIS.
    - Social/cultural impact: Social/cultural impact was determined by summing the following six components, as scored and defined by GLANSIS: (1) threat to human health; (2) damage to industrial or recreational infrastructure (e.g., water intakes, pipes); (3) impact on water quality as it relates to human use; (4) impact on markets or economic sectors (e.g., commercial fisheries, aquaculture); (5) inhibition of recreational activities and/or associated tourism; and (6) reduction of perceived aesthetic or natural value. The total score of 0-36 was transformed to 0-3 using methods developed by GLANSIS.
- Distribution: species were considered for inclusion if they are:
    - (1) nonindigenous;
    - (2) range expander species with limited native distribution in Great Lakes (given those with extensive Great Lakes native distribution will have natural expansion due to climate change); or
    - (3) watchlist species (species 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, as confirmed by RCC members.
- Conflict of interest: species that provide a significant beneficial value (e.g., recreational or commercial fisheries) and would therefore not be the focus of control efforts were excluded.
- Existing control effort: species with existing significant regional control efforts were excluded.

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

Scientific name	**Common name**
Cabomba caroliniana	Carolina fanwort
*Didymosphenia geminata**[1]	Didymo*
Egeria densa	Brazilian elodea
*Eichhornia crassipes**	Water hyacinth*
*Hydrilla verticillata** • Monoecious hydrilla • Dioecious hydrilla	Hydrilla*
*Hydrocharis morsus-ranae**	European frog-bit*
*Iris pseudacorus**	Yellow flag iris*

[1] For the purposes of this research agenda, nuisance macroalgae 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.

*Lythrum salicaria**	Purple loosestrife*
Myriophyllum aquaticum	Parrot feather
*Myriophyllum spicatum** • *Myriophyllum × spicatum*	Eurasian watermilfoil* • Hybrid milfoil
Najas minor	Brittle naiad
*Nitellopsis obtusa**[1]	Starry stonewort*
*Nymphoides peltata**	Yellow floating heart*
Phalaris arundinacea	Reed canarygrass
*Pistia stratiotes**	Water lettuce*
*Potamogeton crispus**	Curly-leafed pondweed*
*Stratiotes aloides**	Water soldier*
*Trapa natans**	Water chestnut
Typha angustifolia • *Typha × glauca*	Narrow-leaved cattail • Hybrid cattail
Typha laxmanii	Graceful cattail

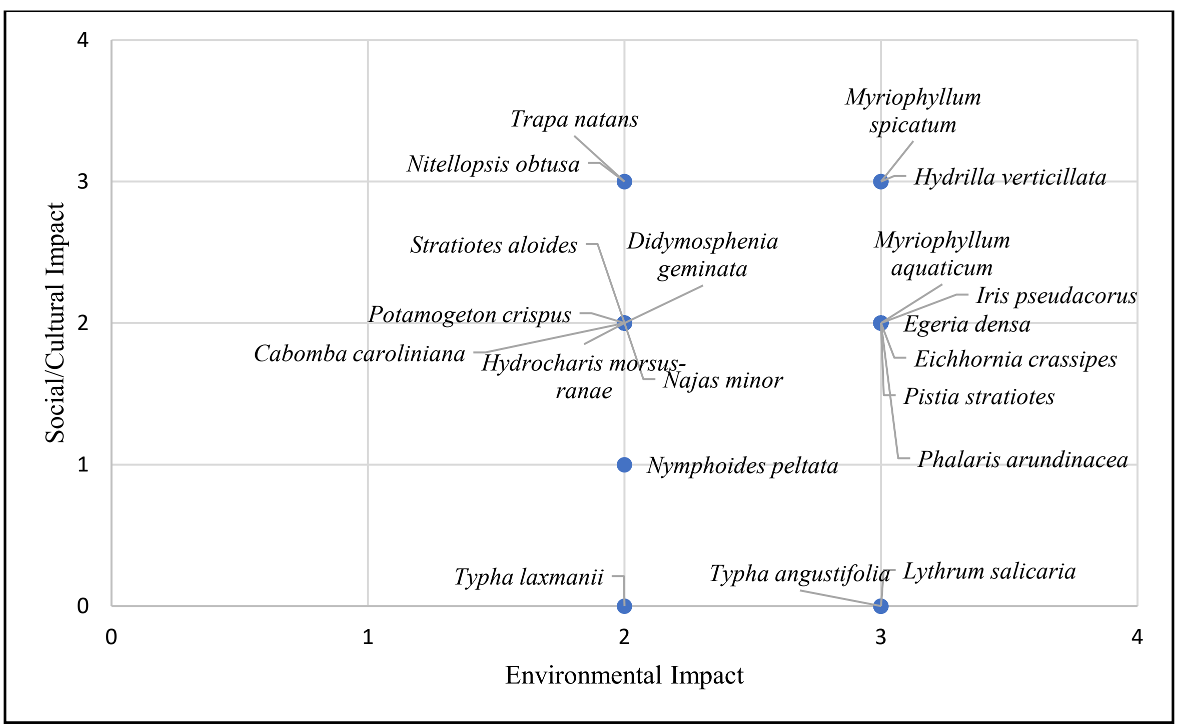

Figure 1. Species impact scores (transformed) from NOAA-GLANSIS risk assessments. 0/1=low or unknown; 2=moderate; 3=high impact.

Species considered for inclusion but ultimately excluded are listed below with explanation for exclusion:

Butomus umbellatus (flowering rush)

Risk criteria: GLANSIS overall risk (3); moderate environmental impact; low social/cultural impacts. While this species met the general criteria for inclusion (except impact), the GLP RCC determined that there were sufficient control tools available for this species and very few barriers to management.

Marsilea quadrifolia (European water clover)

Risk criteria: GLANSIS overall risk (0); no U.S. Fish and Wildlife Service Ecological Risk Screening Summary (ERSS) or U.S. Department of Agriculture Animal & Plant Health Inspection Service (APHIS) weed risk assessment found. This species is on Michigan's watchlist but was excluded from this species list due to lack of documented impacts.

Phragmites australis subsp. australis

Risk criteria: GLANSIS overall risk (5); high environmental impact; moderate social/cultural impacts. The Great Lakes *Phragmites* Collaborative has already identified research needs for this species and is coordinating research efforts to address those needs.

Funding and Timeline

Initially, this research agenda intended to include recommendations regarding funding requirements for each research need and a prioritized implementation timeline for all research needs. However, while developing literature reviews and hosting the expert elicitation workshop, it became apparent that the diversity and complexity of research needs precludes any sort of formal, generalized recommendation. Funding agencies and research teams should ensure that they are allocating sufficient time and resources to answer these questions through to management implementation completion.

Generalized Research Needs

Here, generalized research needs are those that are shared across species and can be applied to (almost) every species in this document. Research on these questions will likely still 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 the major research gaps that may be undertaken by nearly any aquatic plant management research effort. Additional species-specific research needs related to these general research needs are included in the species-specific section of this research agenda to further clarify any unique needs or species traits that may influence how research is conducted.

- Investigate effect of, and where necessary refine, current treatment methods for propagules (e.g., bulbils, seeds, turions). While control of individual plants may reduce seasonal biomass, regrowth of a population from propagule within a treatment area is a significant barrier to true eradication. Effective treatment of these propagules can be difficult based on where and how they are shed by a plant (e.g., within substrate).
- Investigate biocontrol options, including genetic biocontrol. Biological control is the reduction of an organism's population density through use of its natural enemies (United States Department of Agriculture-Forest Service). Genetic biocontrol may refer to any method of genetic modification of a target invasive species where the end goal is reduction of the species population (e.g., sterilization tools, increased susceptibility to chemical herbicides). Biocontrol may be a useful control method for IAP without other effective control tools, or in habitats or sensitive areas where other forms of control may be too disruptive. However, any development or planned use of any type of biocontrol must be done in an ethical manner that considers all potential non-target impacts and the anthropogenic values of the system.
- Investigate the efficacy of the herbicide florpyrauxifen-benzyl. This herbicide was recently approved by the U.S. Environmental Protection Agency (2018), and as such, detailed information on field applications is very limited. Initial results suggest it is nearly non-toxic to fish and birds, and it has no drinking, fishing or swimming restrictions. The success of laboratory studies combined with the initial evidence of limited non-target impacts creates a strong need for further field studies of both efficacy on IAP and non-target impacts.
- Refine optimal treatment timings for known effective herbicides based on plant phenology knowledge to reduce non-target impacts. For example, water temperature is also an important component of herbicide control strategies for *Potamogeton crispus*, as this species grows earlier in the spring than other native submersed aquatic plants. This allows for certain herbicide treatments to be selective for *P. crispus* alone when other native plants are still dormant.
- Determine the efficacy of integrated control strategies. Integrated pest management (IPM) is a science-based decision-making process that combines diverse treatment approaches, frequent monitoring, and adaptive strategies. 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 (Wisconsin DNR, 2019). For example, integrated control strategies and repeated treatments are needed to decrease the competitive dominance of *Typha angustifolia* and *Typha* × *glauca*. These most commonly include a combination of cutting, herbicide, flooding, and burning; which combination is best will depend on site characteristics.
- Establish quantitative, standardized pre- and post-treatment efficacy data relative to each control method. For example, *Hydrocharis morsus-ranae* has a Standard Treatment Impact Monitoring Protocol to establish a consistent methodology for evaluating the impact that selected treatments have on this species.

- Develop decision-support tools to determine treatment methods and approaches for different populations and environments. The most appropriate treatment strategy depends on a variety of factors including size of population, water flow, accessibility, and ecological value of the proposed site. A tool to suggest a treatment strategy based on site characteristics would aid management efforts.

Species-Specific Research Needs

Research needs specific to the species included in this research agenda are organized into three categories:

Biology/life cycle: Species traits and/or biological structures that may influence the short-term and/or long-term success of control efforts. Research into these traits is intended to improve the efficacy of known/existing control tools.

Control tools: Specific techniques used alone or in combination that result in a reduction/alteration of a target plant population to a desired state (endpoint). General research into control tools is intended to improve knowledge about the use of control tools to improve efficacy of their use in the field.

Chemical: The use of registered aquatic herbicides, algaecides, or other chemical compounds as control tools. *Adapted from AERF (2020).*

Biological: The exploitation of biological traits as control tools. This may include but is not limited to herbivory (i.e., consumption of plants as a food source to an organism, preventing the plant from growing and/or spreading) and genetic tools (i.e., the manipulation of genetic material that may reduce a plant's competitiveness, ability to reproduce, susceptibility to other control tools, etc.). *Adapted from AERF (2020).*

Physical/mechanical: The application of techniques that physically reduce a species' access to resources and/or ability to compete. This may include but is not limited to hand removal of plants, cutting/pruning of plants, smothering, water drawdown, etc. *Adapted from AERF (2020).*

Other: Research needs that may not fit within the definition of the above categories, or additional research needs identified by other experts/prior research efforts.

Table 2 indicates which research need(s) have been identified for each species. Click on any checkmark to navigate directly to that section.

Table 2. Research need(s) identified for each species included in the research agenda.

Species	Biology/ life cycle	Control: *General*	Control: *Chemical*	Control: *Biological*	Control: *Physical*	Other
C. caroliniana			✔	✔	✔	✔
D. geminata						✔
E. densa						✔
E. crassipes		✔		✔	✔	
H. verticillata	✔	✔	✔	✔		

Species	Biology/ life cycle	Control: *General*	Control: *Chemical*	Control: *Biological*	Control: *Physical*	Other
H. morsus-ranae	✔	✔	✔	✔	✔	✔
I. pseudacorus					✔	
L. salicaria						✔
M. aquaticum						✔
M. spicatum		✔	✔	✔		✔
N. minor	✔		✔			✔
N. obtusa	✔	✔		✔	✔	✔
N. peltata		✔	✔		✔	
P. arundinacea						✔
P. stratiotes	✔	✔		✔	✔	✔
P. crispus			✔		✔	✔
S. aloides		✔	✔			
T. natans						✔
T. angustifolia						✔
T. laxmanii						✔

Cabomba caroliniana (Carolina fanwort)

Native to South America and southern and eastern USA, *Cabomba caroliniana* is present with a limited number of populations in six Great Lakes jurisdictions. Previous and current management efforts have been largely focused on biological control, drawdown methods, herbicide application, manual removal, shading and the use of a concentrated urea solution. However, no single method has shown consistent success in long-term control (for review of previous management effort, see Roberts and Florentin 2022 and Hackett et al. 2017). Part of the challenge is lack of understanding of varying phenotypes, ecotypes, and reproductive strategies (including seed set viability).

<u>Other</u>

- Please consult "Research Needs" and Table 2 in [State of Michigan's Status and Strategy for Carolina Fanwort Management report]() (Hackett et al., 2017a) for additional research need details. These include:
  - Efficacy of Endothall amine salt and lime in the field;
  - Short and long-term efficacy of other chemical treatments, as well as the impact these treatments have on native macrophyte, fish, and invertebrate communities;
  - Potential for mechanical harvesting to proliferate fragment dispersal;
  - Long-term efficacy of shading and benthic barriers for control and the recolonization of native macrophytes post-treatment;
  - Potential for water level drawdown to promote seed germination; and
  - *Hydrotimetes natans*, an aquatic weevil, and *Parapoynx diminutalis*, a pyralid moth, as potential biological control agents.

Didymosphenia geminata (didymo)*

The management of *Didymosphenia geminata* in the Great Lakes has been hindered by uncertainty surrounding its native range, i.e., whether the blooms are caused by a new introduction, or rather a change in environmental conditions that triggered the formation of thick mats from existing populations. However, Elwell et al. (2014) suggest the substantive issue of concern with *D. geminata* is the formation of thick mats of stalk material in streams and rivers, regardless of whether it is native or non-native. This presence as a nuisance species, and the increasing frequency of blooms in the Great Lakes, makes it a priority species of concern. Eradication is considered impossible, though some work has investigated methods to reduce bloom severity.

- In the absence of any effective treatment systems, the only management options available are containment and slowing the spread of this species to other locations. Additional research needs not directly related to operation control of this species are included in supplementary material.

Egeria densa (Brazilian elodea)

Egeria densa is native to South America and there are a small number of isolated and generally managed populations present across six Great Lakes jurisdictions. It has been effectively controlled with two herbicides (fluridone and diquat), particularly if this treatment is followed by manual methods (e.g., hand pulling or benthic barriers) to remove remaining stands. Use of fluridone vs. diquat will depend on water flow and turbidity.

- Strategies to control this species are available. No additional significant management gaps/challenges have been identified beyond the shared generalized research needs presented earlier in this document.

Eichhornia crassipes (water hyacinth)*

Eichhornia crassipes is native to South America and has traditionally been assumed unable to establish in the Great Lakes, though that assumption is shifting with climate change and the discovery of persistent populations. This species may be acting as an annual, with persistent populations sustained through seed production, although evidence of successful sexual reproduction has not been documented in the Great Lakes. As such, understanding effective control methods for *E. crassipes* is a priority. Recent developments in management of *E. crassipes* have highlighted the effectiveness of integrated control strategies (e.g., biological combined with chemical control, and chemical control followed by manual removal). These integrated management approaches have reduced the amount of herbicide applied and led to longer-term population suppression. In addition, research trials of herbicides florpyrauxifen-benzyl, penoxsulam, and imazamox have shown better selectivity (fewer non-target impacts) and increased efficacy at lower concentrations than the more traditionally-used 2,4-D and glyphosate.

<u>Control tools</u>

- Conduct Great Lakes-specific case studies of control strategies used elsewhere for this species to determine effectiveness in Great Lakes ecosystem and/or on Great Lakes populations.

Biological

- Determine the over-wintering ability of known biological agents.

Physical/mechanical

- Establish best practices for removal efforts, including timing of when removal of plants is not needed and where to spend resources.

Hydrilla verticillata (hydrilla)*

The monoecious strain of *Hydrilla verticillata* is found in the Great Lakes. Thought to be native to Korea, found in six Great Lakes jurisdictions, there are a small number of generally managed populations within the Great Lakes basin, whereas it is relatively widespread in southern parts of New York, Pennsylvania and Ohio. Due to the presence of tubers that can survive up to 10 years, eradication is a multi-year effort. Years 1-2 are critical to decrease overall *H. verticillata* biomass and reduce the number of fragments. Years 3-8 are designed to control the last 1-5% of the tuber bank. In later years, it becomes increasingly difficult to eliminate the final 1 to 2 percent of the tuber bank, as detection becomes difficult. Endothall (contact herbicide) and fluridone (systemic herbicide) have been highly effective on monoecious *H. verticillata*. Initial results of florpyrauxifen-benzyl suggest this may also be an effective herbicide, but additional research is needed. In 2016, a new biotype of *H. verticillata* was detected in the Connecticut River. This strain appears to outperform monoecious *H. verticillata* in cooler water and could present a new threat to the Great Lakes if containment is not successful.

Hydrilla (general)

<u>Biology/life cycle</u>

- Identify/develop methods to facilitate sprouting to aid in herbicide application.

<u>Control tools</u>

- Develop effective tools or methods for containing populations.
- Develop tools that are effective in flowing habitats and for small populations.

Chemical

- Develop an effective systemic herbicide with a relatively short exposure time requirement.

Biological

- Continue exploration and testing for selective and effective biocontrol agent for both monoecious and dioecious strains of hydrilla.

Monoecious hydrilla

<u>Biology/life cycle</u>

- Study hydrilla reproductive propagules (tubers, turions, and seeds) and investigate effective treatment methods for propagules, including:
    - Susceptibility of tubers and turions to freezing.
    - Viability of tubers in dredged material, methods of inactivation, and implications for disposal of dredged material.
    - Environmental factors that influence sprouting and the timing of tuber sprouting in the North.
    - Exploration of methods to “trigger sprouting.”

Hydrocharis morsus-ranae (European frog-bit)*

Native to Europe and Asia, *Hydrocharis morsus-ranae* is present in seven Great Lakes jurisdictions, and is widespread in the coastal and inland waters of the three lower Great Lakes (Huron, Erie and Ontario).

Management agencies are especially concerned about its westward expansion into Lakes Michigan and Superior and impacts upon coastal wetlands and river estuaries. A better understanding of the production of seeds and turions will aid control efforts, particularly with respect to timing and how chemical options effect seed and turion viability. Manual removal has been effective for small populations.

Biology/life cycle

- Determine viability of turions and plants out of water and define desiccation rates.

Control tools

- Determine what level of control/effort is needed for eradication of this species at varying population sizes, densities, and habitats.
    - It may be helpful to examine other eradication frameworks, and understand how that applies to a leafed, floating AIS
- Develop integrated management strategies of emergent vegetation and European frog-bit.
    - Including investigation of overlapping herbicides that are effective for European frog-bit and emergent vegetation.
- Determine how current control methods affect turions.
- Conduct further research on the efficacy of control methods in use, particularly for sprouting plants.

Chemical

- Test the efficacy of the herbicide penoxsulam.
    - Penoxsulam is similar to fluoridone, and maintains concentration and residuals in the system

Biological

- Investigate possible herbivory/biocontrol options.
    - Weevils, aphids, and aquatic lepidoptera have been identified on leaves

Physical/mechanical

- Investigate water drawdowns as a potential control measure.
- Evaluate mechanical control methods used for other free-floating plants (like water lettuce and water hyacinth) to understand if these methods may be effective for European frog-bit.

Other

- Please consult "Research Needs" and Table 3 in State of Michigan's Status and Strategy for European frog-bit Management report (Cahill et al., 2018a) for additional research need details. These include:
    - Effectiveness of herbicide treatments used on the closely related *Limnobium spongia*, (e.g., triclopyr, diquat, imazamox) for *H. morsus-ranae* control;
    - Understanding how ramet, turion, and seed production are impacted by chemical treatment;
    - Efficacy of physical and mechanical management techniques;
    - Efficacy of the potential biocontrol agent the waterlily leafcutter moth (*Elophila obliteralis*), a semi-aquatic moth, in the field as well as its nontarget impacts; and
    - Exploring potential biological control agents, particularly in this species' native range

Iris pseudacorus (yellow flag iris)*

Iris pseudacorus is native to Europe, northern Africa, and temperate Asia, and is a widespread invasive of wetlands and riparian communities across of all 10 Great Lakes states and provinces. Control of *I.*

pseudacorus has been successful with several strategies. For large populations, imazapyr or glyphosate, repeated cutting/mowing, and hand digging have worked. For small populations, benthic barriers and hand-digging are options. One of the main impediments to control of this species is absence of regulation in several jurisdictions.

<u>Control tools</u>
Physical

- Further evaluation of mechanical harvesting to determine if there is a phenological marker to visually indicate when to cut plant off at base.

Lythrum salicaria (purple loosestrife)*

Lythrum salicaria is native to Europe and Asia, and widespread throughout all 10 Great Lakes states and provinces. Biological control of *L. salicaria* is the most widely known management option. The most common biocontrol species (*Galerucella calmariensis*) exhibits long-term biomass reduction (not eradication), but with variable results. Other options include herbicide or mowing. In areas <1 acre, and <50% purple loosestrife cover, mechanical/chemical methods are recommended. Infestations greater than that should be treated with biological control methods.

- Although biocontrol does not eradicate *L. salicaria*, it provides moderate long-term control. No additional significant management gaps or challenges were identified beyond the shared generalized research needs presented earlier in this document.

Myriophyllum aquaticum (parrot feather)

Native to South America, *Myriophyllum aquaticum* has only a small number of isolated populations present in seven Great Lakes states (with the exception of southern New York and Pennsylvania). Chemical control for this species appears to be less effective, both in short-term percent cover and long-term recovery, than for other species. Many studies report "efficacy" at rates around 60% reduction. Studies that report successful control may have higher proportions of emergent vegetation, which is more susceptible to many of the herbicides; the submerged vegetation often remains and can lead to recovery. However, the Michigan Department of Environment, Great Lakes, and Energy has reported success in multiple case studies using florpyrauxifen-benzyl. A biocontrol agent (*Lysathia* sp.) has been effective in South Africa, reducing percent cover to 30%; this species is currently being trialed for use in Canada and northwest US. A second biocontrol agent (*Phytobius vestitus*) is the subject of initial research in the southeast U.S.

- No additional operational control research needs were identified for this species beyond the shared generalized research needs presented earlier in this document.

Myriophyllum spicatum (Eurasian watermilfoil)*

Myriophyllum spicatum is native to Europe, Asia, and North Africa, and is widespread and the most commonly managed IAP found throughout all ten Great Lakes states and provinces. Effective control of *M. spicatum* is difficult to achieve. Part of the challenge is the hybridization of *M. spicatum* with native *M. sibiricum* to get *M. spicatum* × *sibiricum*. While many hybrid strains are more aggressive than native strains, and more resistant to control efforts such as chemical control, overlap in control tools exists. Few herbicides provide consistent control, although fluridone has been the most effective and the recently-approved florpyrauxifen-benzyl has initially promising results, with fewer non-target impacts as compared to other herbicides. Benthic mats and hand-pulling have also been tried in areas where herbicide use is restricted, with mixed results. Given the inconsistent results of herbicides on *M. spicatum*, and non-target effects on wildlife, any *M. spicatum* control effort should be carefully considered as part of a lake management plan.

Including M. spicatum × *sibiricum* (hybrid milfoil)

<u>Control tools</u>

- Determine most effective tool for lakewide treatment, including low dose formulations/applications of known effective methods (e.g., florpyrauxifen-benzyl)
- Develop a model/process to work with public stakeholders, lakefront managers, etc. to determine mutually acceptable population levels and agree on management endpoints/goals
    - Public stakeholders may prefer a small or non-monoculture *M. spicatum* population rather than no aquatic plants in their local lakes and/or other non-target impacts
- Examine/trial alternate control tools that are not frequently utilized, including weevils and other herbivory/biocontrol options

Chemical

- Determine if there are differences in efficacy of florpyrauxifen-benzyl between "pure" and hybrid strains of this species.
    - Resistance to herbicides is a result of "resistance alleles" that may be present in hybrid strains
- Develop technology and tools to screen *M. spicatum* for resistance alleles and known herbicide resistances.
    - Similar technology is widely available to screen agricultural pests for known resistance mutations
    - Similar technology has already been developed to screen *H. verticillata* populations for fluoridone resistance
- Evaluate whether costs (non-target impacts and economic) and lack of long-term efficacy of currently used herbicides warrants their continued application (described in detail in "Summary of Control Options for Invasive Aquatic Plants" document).
    - Particularly for lake associations and other organizations that undertake private *M. spicatum* control.
- Investigate the efficacy of fungicides as a control tool.

Biological

- Investigate the potential for gene silencing to make plants more susceptible to control methods

<u>Other</u>

- Develop mutual public/private partnerships to identify common goals and areas of public support for further management and research
- Please consult "Research Needs" and Table 2 in [State of Michigan's Status and Strategy for Eurasian Watermilfoil Management report] (Michigan DEQ, 2018) for additional research need details. These include:
    - Optimize chemical treatment methods;
    - Establish biocontrol strategies that will sustain *M. spicatum* populations below control and minimize negative impacts;
    - Better understand the effects of mechanical management techniques on native and nonnative macrophytes; and

  - Increased scientific understanding of the impact of indirect management (e.g., shoreline buffers, native macrophyte beds, laminar flow aeration, etc.).

Najas minor (brittle naiad)

Native to Europe, western Asia, and northern Africa, *Najas minor* is present in all Great Lakes states and provinces, but is especially widespread in the eastern lower Great Lake states of Ohio, Pennsylvania and New York. *Najas minor* prefers stagnant or slow-moving waters, such as ponds, lakes, reservoirs, and canals.

- There is an absence of literature or reports on control strategies and efforts for this species. Investigate plant phenology, invasion ecology, and the efficacy of various herbicides.

Nitellopsis obtusa (starry stonewort)*

Native to Eurasia, *Nitellopsis obtusa* (hereafter, "starry stonewort") is found in the four lower Great Lakes, and is widespread in New York and Michigan. While present across nine Great Lakes jurisdictions, management is concerned about its westward and southern range expansion and impacts in invaded inland lakes. The exact reproductive mechanism(s) of *N. obtusa* in the Great Lakes are unknown. Asexual reproduction via star-shaped bulbils is likely and it may reproduce and spread through vegetative fragmentation. Few in situ experiments have been conducted to evaluate control methods for *N. obtusa* and many management recommendations are based on qualitative observations and are lacking untreated controls or pre- and post-treatment monitoring for effectiveness. Work in Wisconsin that did use quantitative pre- and post-treatment monitoring for a variety of control strategies did not result in any control or eradication of *N. obtusa*. Chemicals such as copper and diquat provide short-term nuisance control but no long-term population control. Invasive aquatic plant managers surveyed by the Great Lakes Commission identified this species as particularly lacking in available and feasible control tools.

<u>Biology/life cycle</u>

- Further study of invasion ecology and plant phenology including dispersal, establishment, growth, and competition to inform control strategies and predictive modeling.
- Determine bulbil viability and resting period; identify best practices to manage the bank of propagules.

<u>Control tools</u>

- Determine whether herbicide management for other nuisance species, such as *Myriophyllum spicatum* and *Potamogeton crispus*, exacerbate *N. obtusa* spread, abundance, or density, particularly if it is already present in a system.
- Leverage information on "failed" introductions (i.e., where the species has been introduced but failed to establish) to better predict when and where to intervene, and to inform development of decision-support tools.
- Investigate feasibility of simultaneous management of *N. obtusa* and other aquatic invasive species.
  - Observational reports suggest *N. obtusa* is occurring more frequently in areas currently experiencing infestations of other aquatic invasive species.
- Develop tools that can keep growth at a manageable level, and that managers feel comfortable recommending to stakeholders for local control.

- Investigate if phenology cues can help to optimize treatment timing.
    - Biomass and bulbils tend to peak in September and be at their lowest in mid-summer.

Biological

- Investigate the potential of gene silencing to limit bulbil production.
    - There may be regulatory and public relations issues related to genetic manipulations, but this could be a key for a species with limited control tools.
    - The best case scenario for successful management would be the development of highly selective techniques that disrupt bulbil formation.

Physical

- Determine if hand pulling is a viable control method (and under what conditions), if hand pulling and herbicide use is more effective than herbicide use only, and why.

<u>Other</u>

- Develop decision-support tools to determine when management goals/endpoints should shift focus from eradication to maintenance.
- Explore the public perception of the 'do nothing' approach as another management option.
    - There can be an emotional response from the public related to desire for management – there can be the short-term view that any aquatic plants (including native) are "bad" and thus a hesitation to development a management plan for that lake, instead favoring a lakewide herbicide approach to "kill everything."
- Please consult "Research Needs" and Table 1 in State of Michigan's Status and Strategy for Starry Stonewort Management report (Hackett et al., 2017b) for additional research need details. These include:
    - Short and long-term efficacy of chemical treatments, as well as the impact these treatments have on native macrophyte, fish, and invertebrate communities;
    - Understanding how bulbil or oospore production is impacted by chemical treatment;
    - Investigate the potential for physical and mechanical control methods to proliferate fragment and bulbil dispersal; and
    - Understanding how bulbil and oospore viability are impacted by shading from benthic barriers.

Nymphoides peltata (yellow floating heart)*

Native to east Asia and the Mediterranean, *Nymphoides peltata* is present in nine Great Lakes states and provinces, but is only locally widespread in south/central Michigan, northern Ohio and southern portions of New York and Pennsylvania. Observations in Michigan in 2018 and 2019 demonstrated the presence of viable seeds at three locations, although the role seeds play in reproduction of *N. peltata* remains unclear in the Great Lakes. The most effective control strategies include herbicide (florpyrauxifen-benzyl and endothall), benthic mats and potentially flooding/drawdown (yet to be demonstrated in the Great Lakes). Timing is an essential component of treatment; a study using the same treatments in spring and late summer/early fall found no control in spring, but good control in late summer/early fall.

<u>Control tools</u>

- Evaluate additional possible control methods based on tools used to control other species in the genus.

Chemical

- Utilize BACI-designed studies to determine optimal application methods for the herbicide florpyrauxifen-benzyl in the Great Lakes and effects on seed viability.

Physical

- Investigate effectiveness of flooding/drawdown as an alternative to herbicide use

Phalaris arundinacea (reed canarygrass)

The non-native status of *Phalaris arundinacea* (hereafter, "reed canarygrass") is uncertain, with recent genetic research determining most populations in Minnesota are native, rather than introduced from Europe. This species is widespread across the region and these findings suggest additional research on native vs. non-native genotypes should occur to determine its status across the other nine Great Lakes states and provinces, to better inform management efforts. If management is attempted, successful reversal and restoration of a system dominated by *P. arundinacea* requires not only properly implementing effective control techniques, but also disrupting feedbacks that maintain the invaded state using a "system dynamics approach". It is widely accepted that integrated control methods and repeated treatments are needed to decrease the competitive dominance of established *P. arundinacea*, and thereby promote the establishment of less-competitive native plants. If resources are limited, it may be better to focus management on mixed stands of *P. arundinacea* and native species. Once re-established, the native plant community will compete for sunlight, suppressing the *P. arundinacea* seed bank and re-growth from its dormant bud bank.

- Determine the status of *P. arundinacea* populations in the Great Lakes (i.e., which jurisdictions have native populations, and where those occur)

Pistia stratiotes (water lettuce)*

Pistia stratiotes is a pantropical species that has been detected in all eight Great Lakes states. *Pistia stratiotes* has traditionally been assumed to be unable to establish in the Great Lakes, though that assumption is shifting with climate change. The discovery of persistent populations suggest this species may be acting as an annual that is sustained in the wild through seed production, although evidence to support this contention remains elusive. As such, understanding effective control strategies for *P. stratiotes* is a priority. Early detection and rapid response to a *P. stratiotes* introduction prior to seed set could prevent the establishment of a persistent population. The rapid vegetative reproduction of *P. stratiotes* and persistence in the seed bank make it exceedingly difficult to manage once it becomes established. Globally, *P. stratiotes* has been managed with chemical, physical, mechanical, and biological control techniques. In North America, biological control agents (e.g., *Neohydronomus affinis*), chemical treatments (e.g., diquat, 2,4-D, glyphosate), water level manipulations, manual removal, and mechanical removal have been used.

<u>Biology/life cycle</u>

- Determine the value of treating populations in fall months if the vegetation will die back in winter.
- Establish best practices for removal efforts.
    - Including timing of when removal of plants is not needed and where to spend resources.

<u>Control tools</u>

- Conduct Great Lakes-specific case studies of known control strategies to determine effectiveness.

Biological

- Determine the over-wintering ability of known biological control agents.

Physical/mechanical

- Establish best practices for removal efforts, including timing of when removal of plants is not needed and where to spend resources

<u>Other</u>

- Please consult "Research Needs" and Table 3 in State of Michigan's Status and Strategy for Water Lettuce Management report (Cahill et al., 2018b) for additional research need details. These include:
  - Short and long-term efficacy of chemical treatments, as well as the impact these treatments have on native aquatic plants, fish, and invertebrate communities;
  - Efficacy of manual and mechanical removal as well as their potential to enhance the spread of plants and seeds;
  - Efficacy of water level manipulation and impact to native flora and fauna;
  - Potential biological control agents that would be effective in temperate climates; and
  - Understanding how ramet and seed production is impacted by treatment.

Potamogeton crispus (curly-leafed pondweed)*

Native to Eurasia, Africa and Australia, *Potamogeton crispus* is widespread and abundant in all ten Great Lakes states and provinces. Several herbicides (diquat, endothall, and fluridone in particular), as well as drawdown, have been shown to be effective at long-term control of *P. crispus*, but eradication is highly unlikely after establishment due to the presence of the turions or reproductive propagules that persists in the sediment. Considerations of its unique growth cycle is important for control as the plant has both a spring and an overwintering form. Water temperature is also an important component of herbicide control strategies as *P. crispus* grows earlier in the spring than other native submersed aquatic plants. This allows for certain herbicide treatments to be selective for *P. crispus* alone when other native plants are still dormant.

<u>Other</u>

- Please consult "Research Needs" and Table 2 in State of Michigan's Status and Strategy for Curly-leafed Pondweed Management report (Hackett et al., 2014) for additional research need details. These include:
  - Effects of herbicide temperature on treatment;
  - Relationship between biofilms (i.e., communities of bacteria, algae, fungi, and protozoan that accumulate on surfaces in aquatic environments) and herbicide effectiveness;
  - Field tests of the application of the plant hormones 6-benzyladenine (6-BA) and gibberilic acid in controlling the production of turions; and
  - Overall effectiveness of benthic barriers, timing of mat placement (e.g. spring, summer after die back, etc.), length of time for optimal treatment, and efficacy of biodegradable bottom barriers of jute or hemp.

Stratiotes aloides (water soldier)*

Native to Eurasia, the only populations of *Stratiotes aloides* in North America and the Great Lakes are found within the province of Ontario. The two most effective management strategies include hand-pulling (populations <25m2) and application of diquat herbicide (populations >25m2). Herbicides with the active ingredient florpyrauxifen-benzyl have also shown potential. Management approaches are informed by the biology of the plant; it is an evergreen perennial, with two key morphologies (submergent and emergent life forms) that undergo a seasonal transition within the water column. *Stratiotes aloides* propagates primarily by vegetative reproduction (offsets and turions). In its native range, *S. aloides* also reproduces by seed, however that occurs rarely, and has not been observed in Ontario. *Stratiotes aloides* does not regenerate from stem/leaf fragments which makes it more suitable for manual/mechanical control than other aquatic plants that can reproduce by fragmentation (e.g. milfoil species).

<u>Control tools</u>

- Develop effective management strategies to inform the transition from large scale to small scale control.
    - As large-scale control of high density plants is successful, the transition to a small scale, low density approach.

Chemical

- Test the efficacy of herbicides not currently used to manage this species (e.g., florpyrauxifen-benzyl).
    - Diquat is limited in effectiveness.
- Establish viability and risks of using drone application of herbicide in areas airboats can't access.
    - Note that there may be regulatory concerns with using drones to apply aerial herbicides.
- Develop methods to improve residency time of herbicides in a flowing system.

Trapa natans (water chestnut)

Native to western Europe and Africa and northeast Asia, *Trapa natans* (hereafter, “water chestnut”) is restricted to the eastern Great Lakes basin (relatively widespread in Pennsylvania and New York, and spreading into neighboring waters of Ontario and Quebec). Unlike many invasive aquatic plants, it has been effectively controlled and perhaps even eradicated in some bodies of water, but only after persistent effort. Seeds are viable for up to 12 years; to be successful, control methods must be in place for the same amount of time. The herbicide imazamox has become the preferred control method for large infestations that cannot be controlled by hand-pulling. While increased flow is effective in reducing *T. natans*, data suggest that lake drawdowns alone do not significantly reduce the germination of the nuts buried in the sediment.

- Given that this species does not reproduce by fragmentation, hand-pulling (or similar) has been a successful control strategy. No management gaps/challenges were identified at this time beyond the shared generalized research needs presented earlier in this document.

Typha angustifolia (narrow-leaved cattail)

Native to northern Africa and Eurasia, *Typha angustifolia* is present and widespread in all eight Great Lakes states and appears to have a foot hold in Ontario. Integrated control strategies and repeated treatments are needed to decrease the competitive dominance of this cattail species, including its hybrid

Typha × *glauca*. These strategies most commonly include a combination of cutting, herbicide, flooding, and burning; which combination is best will depend on site characteristics. In addition to integrated control strategies, taking a "system dynamics approach" (as opposed to a plant community structure approach) improves restoration outcomes. Eradication is rarely the goal of *Typha* management, as Typha provide food and habitat for wildlife when limited in distribution. Management goals may include 1) controlling the spread and domination of potential habitat by narrow-leaved cattail in and perhaps adjacent to natural areas, 2) preventing declines in other plant species, and 3) preventing development of monotypic cattail growth and loss of habitat heterogeneity.

Including Typha × *glauca* (hybrid cattail)
<u>Other</u>

- See "Section 6: Future Research Needs" in Bansal et al. (2019) for a description of additional research and management gaps and challenges. These include:
    - Develop an interdisciplinary, systems approach for managing *Typha*

Typha laxmanii (graceful cattail)

Native to southeastern Europe and temperature Asia, *Typha laxmanii* is only thought to be present at a small number of sites in the basin in Wisconsin, and is also established in at least one site in Illinois and lower New York state. It spreads by creeping rhizomes to form dense colonies in shallow water. It grows 3-5 feet tall, often with a submerged base.

- There is an absence of literature or reports on control strategies and efforts for this species. Broad research in this area is warranted.
    - Given the potential similarity in effective management strategies for the congener *T. angustifolia*, please see the Literature Review for *T. angustifolia.*

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- Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS)
- Great Lakes Panel on Aquatic Nuisance Species
- Illinois Department of Natural Resources
- Illinois Natural History Survey
- Illinois-Indiana Sea Grant
- Indiana Department of Natural Resources
- Invasive Species Centre
- Lake County (IL) Health Department
- Michigan Department of Environment Great Lakes, and Energy
- Michigan Sea Grant – GLANSIS
- Michigan State University
- Minnesota Department of Natural Resources
- Montana State University
- National Oceanic and Atmospheric Administration
- New York State Department of Environmental Conservation
- Ohio Department of Natural Resources
- Ontario Federation of Anglers and Hunters
- Ontario Ministry of Natural Resources and Forestry
- Pennsylvania Department of Agriculture
- Parks Canada
- Québec Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs
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- Wisconsin Department of Natural Resources
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References

AERF (2020) Biology and Control of Aquatic Plants: A Best Management Practices Handbook. Aquatic Ecosystem Restoration Foundation, Marietta, Georgia.

Annen, C. A. (2011). Manipulating internal system feedbacks to accelerate reed canarygrass (*Phalaris arundinacea*) control: From theory to practice. Ecological Restoration 29(3): 222-224.

Cahill BC, Hackett RA, and Monfils AK (2018a) 2018 Status and Strategy for European Frog-bit (*Hydrocharis morsus-ranae L*.) Management. Michigan Department of Environmental Quality, Lansing, Michigan.

Cahill BC, Hackett RA, and Monfils AK (2018b) 2018 Status and Strategy for Water Lettuce (*Pistia stratiotes L*.) Management. Michigan Department of Environmental Quality, Lansing, Michigan.

Hackett RA, Richards CM, and Monfils AK (2014) Status and Strategy for Curly-leafed Pondweed (*Potamogeton crispus L*.) Management. Michigan Department of Environmental Quality, Lansing, Michigan.

Hackett RA, Cahill BC, and Monfils AK (2017a) 2017 Status and Strategy for Carolina Fanwort (*Cabomba caroliniana A. Gray*) Management. Michigan Department of Environmental Quality, Lansing, Michigan

Hackett RA, Cahill BC, and Monfils AK (2017b) 2017 Status and Strategy for Starry Stonewort (*Nitellopsis obtusa* (Desv. in Loisel.) J. Groves) Management. Michigan Department of Environmental Quality, Lansing, Michigan.

Michigan DEQ (2018) State of Michigan's Status and Strategy for Eurasian Watermilfoil Management. Michigan Department of Environmental Quality, Lansing, Michigan.

Thum RA, Parks S, McNair JN, Tyning P, Hausler P, Chadderton L, Tucker A, and Monfils A (2017) Survival and vegetative regrowth of Eurasian and hybrid watermilfoil following operational treatment with auxinic herbicides in Gun Lake, Michigan. Journal of Aquatic Plant Management 55:103-107.

Wisconsin DNR (2019) Strategic analysis of aquatic plant management in Wisconsin. Wisconsin Department of Natural Resources, Madison, Wisconsin.

Supplementary Material: Non-Operational Control Research Needs

Introduction

Throughout the course of the literature reviews and expert elicitation workshop hosted to inform the development of this IAP operational control research agenda, a number of additional research needs were identified and discussed that are relevant to IAP management and control. While these research needs are not strictly operational control needs, they are still valuable to record and consider in future research and funding opportunities. Thus, those additional research needs are presented here, as supplementary material to the primary IAP research agenda.

Generalized Research Needs

As in the primary AIS research agenda, generalized research needs are those that are shared across species and can be applied to (almost) every species in this document. Research on these questions will likely still 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 the major research gaps that may be undertaken by nearly any aquatic plant management research effort.

- Develop enhanced U.S. Fish and Wildlife Ecological Risk Screening Summaries incorporating climate change data and models.
- Develop decision support tools to determine the efficiency trade-offs between amount of effort and time spent surveying population extent vs treatment of known populations. Tools should be developed to support a variety of surveillance needs, including:
    - Delimitation of a population at landscape scale to determine the extent of an infestation, if any rapid response action is warranted, and if so, at what scale.
    - Surveillance during and towards the end of the application of control tool(s) for the goal of eradication of the species to locate any individual plants that have survived the control regimen and may repopulate a water body.
    - Surveillance within a site to improve control efficacy by finding satellite populations to treat alongside/beyond the primary population to lower the risk of reintroduction.

Species-Specific Research Needs

Additional research needs specific to an individual species are presented below. It may be valuable to research programs and funders to consider these needs alongside opportunities for research on the operational control needs presented in the primary IAP research agenda.

Didymosphenia geminata (didymo)

Biology/life cycle

- Identify ways to disrupt or break the polysaccharide stalk to enable/accelerate removal of mats/blooms.
- Identify the environmental factors that trigger nuisance blooms.
    - May be a stress response to low phosphorous (<0.5ppm, often below detection limits)

Environmental impacts

- Determine if blooms impact early life cycle stages of other species.
- In areas of water upwelling, determine if mats negatively impact dissolved oxygen levels within beds where fish eggs are present in redd/nests.
- In areas of water upwelling, determine if mats impede emergence of fish eggs in redd/nests.

<u>Early detection, surveillance, response actions</u>

- Develop a decision process to determine whether (and in what form) management/control actions will be taken if a population of didymo is found.
    - Incorporate size of this species (microscopic diatom) and cryptogenic nature
- Determine efficacy of felt wader bans in preventing spread of this species.
- Define the value of containment measures and critical locations/habitat for containment efforts.
- Conduct extensive surveillance to delineate extent of populations beyond locations of nuisance blooms.
    - It is possible that didymo is already widespread, but sparse, and low levels of detection until it forms nuisance blooms.
- Determine if there is a need to conduct more sensitive regional delimitation surveys for didymo using RNA and drift net sampling approaches adopted by Biosecurity New Zealand (BNZ).

<u>Other</u>

- Better accessibility to and awareness of existing grey literature, particularly from outside the United States/Canada
    - Unpublished studies from BNZ response work, etc.

Eichhornia crassipes (water hyacinth)

One of the most significant uncertainties related to *E. crassipes* control is whether populations are overwintering in the Great Lakes. As such, the following research needs have been identified to answer this question

<u>Biology/life cycle</u>

- Establish definitive knowledge of overwintering seed set and viability.
- Understand, via genetic analysis, if some populations are more cold-adapted than others.
    - Genetics may determine if recurring populations are repeat introductions or from seed production.
- Repeat prior overwintering and seed viabilities studies (e.g., MacIsaac et al., 2016) and over a longer duration.
- Establish how climate change may impact suitability for seed germination/viability.
    - Primarily for the genera *Eichhornia*, *Nymphoides, Pistia*
- Determine factors that influence seed production; identify rates of seed production and germination.
- Conduct genetic studies to determine how often a plant will reproduce by seed vs. clonally.
- Identify viable options for managing a seed bank.
- Determine the value of treating populations in fall months if the vegetation will die back in winter.

<u>Early detection, surveillance, response actions</u>

- Document all introductions across the Great Lakes basin, whether populations are persisting, and what management actions are underway or were taken to synthesize knowledge of the species in the region.
- Determine ability and likelihood for hitchhikers to be present in nursery stock of this species.

Hydrilla verticillata (hydrilla)

Hydrilla (general)

Biology/life cycle

- Confirm biological characteristics of the Connecticut River strain.
    - The strain does not seem to be producing viable seeds. It is believed to be monecious and there are still many traits that need to be investigated.

Early detection, surveillance, response actions

- Develop eDNA surveillance/detection tools.
- Develop monitoring tools that are effective at detecting low density populations.

Monoecious hydrilla

Environmental impacts

- Further study of invasion ecology and plant phenology including dispersal, establishment, growth, and competition to inform control strategies and predictive modeling.

Hydrocharis morsus-ranae (European frog-bit)

Biology/life cycle

- Determine why there is less flowering in sparse population and more flowering in dense populations, and what implications this may have for control, seed production, etc.
- Determine factors that influence seed viability and identify germination requirements.

Early detection, surveillance, response actions

- Determine significance of waterfowl as a pathway of spread and identify possible management actions for this pathway.

Iris pseudacorus (yellow flag iris)

Biology/life cycle

- Identify environmental factors that determine why some populations form monocultures and others do not.

Other

- Determine which control strategies are allowable given regulations.

Myriophyllum spicatum (Eurasian watermilfoil)

Including Myriophyllum x spicatum (hybrid milfoil)

Early detection, surveillance, response actions

- Establish landscape scale models to identify the lakes that might be a key vector and prioritize management/eradication of those populations

Other

- Keeping public access sites clean of invasive plants as a form of a management is an important strategy to eliminate a vector of spread

Nitellopsis obtusa (starry stonewort)

Biology/life cycle

- Determine precipitating factors for explosive growth, including boom and bust cycles.
- Understand variation of growth patterns within lakes between years.

Environmental impacts

- Investigate if starry stonewort beds are utilized in any way by wildlife.
- Determine if starry stonewort is allopathic.

Early detection, surveillance, response actions

- Investigate distribution and movement, especially in the Great Lakes basin.

Nymphoides peltata (yellow floating heart)

Early detection, surveillance, response actions

- Determine potential for spread via seeds.
    - Seeds are sticky and Velcro-like.

Pistia stratiotes (water lettuce)

Early detection, surveillance, response actions

- Determine ability and likelihood for hitchhikers to be present in nursery stock of this species.

Stratiotes aloides (water soldier)

Biology/life cycle

- Determine if water soldier seeds may become viable with enough genetic diversity.

Early detection, surveillance, response actions

- Determine spread methods, including spread potential in a serious wind event or flood.
- Develop planning tools to respond to a new population as efficiently as possible.
- Develop a species identification algorithm/software for remote sensing, imaging, etc.

Typha angustifolia (narrow-leaved cattail)

Including Typha x glauca (hybrid cattail)

Management gaps/challenges

- Determine the efficacy of integrated control strategies to shift to a system dynamics approach in management.
- See "Section 6: Future Research Needs" in Bansal et al. (2019) for a description of additional research and management gaps and challenges. These include:
    - Develop an interdisciplinary, systems approach for managing Typha; and
    - Determine optimal combinations and sequencing of integrated control tools.

Typha laxmanii (graceful cattail)

- There is an absence of literature or reports on control strategies and efforts for this species. Broad research in this area is warranted.