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REGISTERED REPORT STAGE 1

Ecological Solutions and Evidence

BRITISH ECOLOGICAL SOCIETY

What is the effectiveness of methods for eradicating or controlling abundance and biomass of invasive aquatic plants in Canada? A systematic review protocol

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Abstract

1. Invasive freshwater aquatic plants can have adverse ecological effects on the systems to which they are introduced, changing ecosystem function, threatening native plant species and causing billions of dollars in damage to infrastructure. Additionally, once established, invasive aquatic plants are often difficult to eradicate or control.
2. Given the importance of managing invasive aquatic plants, and the high associated economic costs of doing so, it is essential to determine the relative effectiveness of different control methods. Here, we present a protocol for a systematic review that will estimate the effectiveness of various biological, chemical, habitat manipulations and/or manual/mechanical methods for eradicating or controlling invasive plant abundance and biomass.
3. This systematic review will use published and grey literature, without date restriction, that determines the effectiveness of invasive plant control methods. English-language searches will be performed using five bibliographic databases, Google Scholar, and networking tools to find relevant literature. Eligibility screening will be conducted at two stages: (1) title and abstract and (2) full text. Studies that evaluate the effectiveness of methods for controlling the abundance or biomass or eradicating invasive plants will be included. A list of plant species currently, or potentially, in Canadian freshwater systems and of management concern will be considered.
4. Included studies will undergo critical appraisal of internal study validity. We will extract information on study characteristics, intervention and comparator details, measured outcomes (abundance and biomass, broadly defined) and effect modifiers (e.g., plant growth pattern or timing of treatments). A narrative synthesis will be used to describe the quantity and characteristics of the evidence base, while quantitative synthesis (i.e., meta-analysis) will be conducted to estimate an overall mean and variance of effect when sufficient numbers of similar studies are available.

KEYWORDS
alien species, environmental management, evidence synthesis, macrophyte, non-native species

1 | INTRODUCTION

Humans are widely regarded as dominant forces on the planet, responsible for extensive changes in ecosystems and the loss of biodiversity (Vitousek et al., 1997). Although there are many ways in which humans have altered the planet, the facilitated movement of species, whether accidental or intentional, has led to ever increasing numbers of new species' introductions and establishment (Seebens et al., 2017) and even the creation of a bespoke research field devoted to the topic (i.e., Invasion Science—Richardson, 2011 or Invasion Biology—Davis, 2006; Reichard & White, 2003) that continues to develop (Stevenson et al., 2023).

Freshwater ecosystems are currently experiencing a biodiversity crisis (Albert et al., 2021; Harrison et al., 2018; Tickner et al., 2020). The impact of non-native species is one of the many continuing threats that freshwater ecosystems face (Reid et al., 2019). Globally, freshwater species have high levels of endemism. For example, the majority of aquatic macrophytes have narrow global distributions (Murphy et al., 2019). Unfortunately, many of these species are under threat; in Canada alone, nearly 20% of assessed aquatic plants have been designated endangered or threatened (Desforges et al., 2022). Due to this unique biodiversity, their potentially high invasibility, and because new invasions are often difficult to detect (Moorhouse & Macdonald, 2015), preventing and controlling non-native species invasions has been identified as a component of an 'Emergency Recovery Plan' for freshwater systems to reverse the current downward trend in freshwater biodiversity (Tickner et al., 2020).

Invasions by non-native plant species can result in a wide range of ecological effects from changes in nutrient cycling to alterations to plant and animal community diversity and fitness (Vilà et al., 2011). Invasive aquatic plants can cause many changes in an ecosystem's physiochemical components, such as by increasing turbidity and organic matter (Gallardo et al., 2016) and can alter a system's greenhouse gas emissions (Bezabih Beyene et al., 2022). They have also been found to decrease overall taxonomic diversity, and especially impact the diversity of native macrophytes (Tasker et al., 2022). Invasions in freshwater systems can even led to the elimination of sensitive or endangered native species (Zedler & Kercher, 2004).

In addition to causing significant and potentially long-lasting ecological change, species invasions also cause billions of dollars of damages yearly, with recent cost estimates being in the same magnitude of natural disasters (Turbelin et al., 2023). Invasive plants, including invasive aquatic plants, are no exception, with damages incurred across many parts of the economy (Cuthbert et al., 2021; Fantle-Lepczyk et al., 2022; Hoffman & Broadhurst, 2016). This is especially true when the costs of management and control are also considered (Jardine & Sanchirico, 2018). Managing invasive aquatic plants is therefore an essential component of ecosystem management and conservation in freshwater systems.

While preventing the establishment of potentially invasive species is more effective in the long term (Mack et al., 2000), in many cases, species become established prior to managers and practitioners being aware of their presence (e.g., through cryptic invasion, Morais & Reichard, 2018). Plant species have been accidentally or purposefully introduced prior to determination of impact, often resulting in well-established populations that are nearly impossible to completely eradicate. Options for managing invasive aquatic plants include no action, controlling or suppressing the species or complete eradication (Simberloff, 2021). Controlling or eradicating invasive aquatic plants can be extremely difficult, making it important to determine which control method(s) is most likely to achieve the desired results.

The types of aquatic plant control methods available to resource managers to decrease populations of invasive plants vary widely. They can include biological, chemical or manual/mechanical methods (Hussner et al., 2017), among others. The effectiveness of each largely depends on the species under consideration and environmental conditions. Selecting appropriate control methods is also required to balance the likelihood of effective control (i.e., sufficient decreases in the invasive population) and potential negative off-target impacts such as secondary invasion (Robichaud & Rooney, 2021). Decisions surrounding the selection of control methods requires knowing what management strategies are available, what the likelihood of success will be and what adverse effects are likely to occur.

Successful management of invasive aquatic plant species greatly depends on project objectives (i.e., whether to suppress or eradicate the species population). Success can therefore be difficult to determine, especially when faced with multiple potentially invasive aquatic plant species in the same ecosystem (Pearson et al., 2016). Failure to meet project goals can result from a number of factors such as ineffective application of control methods (i.e., late vs. early seasonal application, Adams & Galatowitsch, 2006), species-specific factors (i.e., stem fragmentation may increase submerged plant populations—Coetzee & Hill, 2009 or herbicide resistance—Richardson, 2008) and physical properties of the environment (i.e., stagnant or flowing water, large or small water bodies, water depth, Hussner et al., 2017). Additional complications arise when it is unclear whether management activities will result in the desired effect of decreasing or eradicating the population, or whether management activities could result in no change or the spread of the invasive plant species. Determining which control methods are most effective typically requires long-term evaluation and assessment of past management activities at meeting objectives.

Previous reviews on invasive plant management have been conducted to determine the use of different control methods (Hussner et al., 2017), the effectiveness of control methods for a specific species (e.g., Kabat et al., 2006; Roberts & Pullin, 2006), the influence of control methods on off-target species, environmental or ecosystem impacts (Breckels & Kilgour, 2018; Martin et al., 2020; Thiemer et al., 2021) and restoration initiatives (Kettenring & Reinhardt Adams, 2011). However, at time of writing, we know of no systematic review considering the effectiveness of invasive aquatic plant control methods specifically for the Canadian context that uses the Collaboration for Environmental *Evidence* (CEE) guidelines for systematic review (CEE, 2022). Our review will focus on plants of particular interest to Parks Canada, a federal government agency responsible for the preservation, control and management of Canada's national park system, including the protection of flora, fauna and waters within the parks (Government of Canada, 2022). This review will help identify gaps in the available evidence on the species of interest. Where overlap does exist with previous reviews on specific species (i.e., Spartina species, Roberts & Pullin, 2006), our review will act as an update. Additionally, for several of the species considered in this review, we are not aware of any systematic reviews with meta-analysis that comprehensively quantify the effectiveness of different control methods (e.g., *Iris pseudocharis* or *Eichhornia crassipes*). This review will provide the first systematic review of the literature for these species and will aim to quantify effectiveness of control methods through meta-analysis whenever possible. A systematic review of the effectiveness of invasive plant control methods in the Canadian context would yield valuable information to inform ecosystem management.

1.1 | Topic identification and stakeholder involvement

Given the potentially high negative impacts of invasive aquatic plants and the number of potentially problematic species in Canada (e.g., over 64 species of aquatic plants have been identified in a single surveillance list for the Great Lakes region alone, Dahlstrom Davidson et al., 2021), managing invasive aquatic plants is an important aspect of conserving and maintaining ecosystem health. However, for conservation managers, decisions on selecting methods for controlling invasive aquatic plant species are difficult because of uncertainties in our understanding of control method effectiveness. A review of the effectiveness of invasive aquatic plant control methods has been identified by Canadian stakeholders (i.e., Parks Canada) as a priority question for land managers and practitioners responsible for protecting and maintaining the natural heritage of Canadian parks. Staff from Parks Canada and the Canadian Centre for Evidence-Based Conservation (CEBC) collaborated to develop this question in the context of the non-native invasive aquatic freshwater macrophytes in Canada that are of concern to their agency. Although Parks Canada initiated the collaboration, this question has also been identified by other Canadian natural resource management agencies (e.g., various conservation authorities in Ontario) and is of broader relevance to other governments and non-governmental organizations, both within Canada and beyond its borders, who are tasked with making conservation decisions related to the invasive aquatic plants included in this review (see Table 1 for a list of included species).

During the formulation of the systematic review question, evidence synthesis specialists from the CEBC (i.e., review team) established and consulted an Advisory Team made up of stakeholders and experts including academic scientists in Canada (6 members) and staff from Parks Canada (2 members). The Advisory Team was consulted in the development of the plant species list and the inclusion criteria for article screening and will continue to participate in this systematic review through to completion.

2 | OBJECTIVE OF THE PROTOCOL

The objective of the proposed systematic review is to clarify, from the existing literature, the effectiveness of methods for eradicating or controlling invasive aquatic plant abundance and biomass to better inform decisions in invasive aquatic plant management.

2.1 | Primary question

What is the effectiveness of methods for eradicating or controlling abundance and biomass of invasive freshwater aquatic plants in Canada?

2.2 | Components of the primary question

Subject (population): Non-native invasive aquatic macrophytes in Canada that are of concern to Canadian stakeholders such as Parks Canada (see Table 1 for a list of included species).

Intervention: Application of control methods including biological, chemical, habitat manipulation and/or manual/mechanical.

Comparators: No intervention or alternative levels of intervention, or lack of comparator.

Outcomes: Measures of change in invasive aquatic plant populations (broadly defined to include measures of abundance, density, biomass, extent, cover and presence/absence).

2.3 | Secondary questions

To what extent do factors (e.g., stage of invasion, number, timing and duration of treatments, spatial scale and growth habit) influence the effectiveness of invasive aquatic plant control methods?

TABLE 1 Eligible list of plants identified through consultation with Advisory Team and Canadian stakeholders with alternative scientific and common names used during searches.

Species	Alternative scientific and common names
Butomus umbellatus	Flowering-rush
Cabomba caroliniana	Carolina fanwort; Carolina water shield; green cabomba; Washington grass
Egeria densa	Elodea densa; Brazilian waterweed; Brazilian elodea; Large-flowered waterweed
Hydrilla verticillata	Waterthyme
Hydrocharis morsus-ranae	European frog-bit; European frogbit; European frog's-bit
Iris pseudacorus	Yellow iris; Pale Yellow Iris; Yellow Flag Iris
Lythrum salicaria	Purple-loosestrife; Spiked loosestrife; Purple lythrum
Myriophyllum aquaticum	Parrotfeather; Parrots-Feather; parrot feather milfoil; Parrot feather watermilfoil
Myriophyllum heterophyllum	Broadleaf Water-Milfoil; Broadleaf watermilfoil; Twoleaf watermilfoil
Myriophyllum spicatum	Myriophyllum verticillatum; Eurasian water-milfoil; Eurasian Milfoil; Eurasian watermilfoil; Spiked water-milfoil
Nasturtium officinale	Rorippa officinalis
Nitellopsis obtusa	Starry Stonewort
Nymphaea alba	European White Waterlily; White nenuphar
Nymphaea odorata	Fragrant waterlily; American white waterlily; Fragrant water-lily; Beaver root; Fragrant white water lily; Sweet-scented white water lily
Nymphoides peltata	Yellow floating heart; Fringed water lily; Floating heart; Water fringe
Phalaris arundinacea	Phalaroides arundinace; Reed canarygrass; Reed canary grass; Ribbon grass; Gardener's-garters
Phragmites australis	European common reed; Common reed
Pistia stratiotes	Water lettuce; Water cabbage; Nile cabbage; Shellflower
Pontederia crassipes	Eichhornia crassipes; Water Hyacinth
Potamogeton crispus	Potemogeton crispus; Curly-pondweed; Curly pondweed; Curled pondweed
Sparganium erectum	Exotic Bur-reed; Simplestem bur-reed; Branched bur-reed
Spartina alterniflora	Sporobolus alterniflorus; Smooth cordgrass; saltmarsh cordgrass; salt-water cordgrass
Spartina densiflora	Sporobolus montevidensis; dense- flower cordgrass denseflower cordgrass
Spartina patens	Sporobolus pumilus; Salt hay; Salt meadow cordgrass; Saltmeadow cordgrass; salt hay
Sporobolus anglica	Sporobolus anglicus; Spartina anglica; Common cordgrass; English Cordgrass
Trapa natans	European water chestnut; Water nut; Water caltrop; Bat nut; Devil pod
Typha angustifolia	Narrow- leaved cattail; Narrow leaf cattail
Typha × glauca	Hybrid cattail

2.4 | Hypotheses and predictions

Primary question: Selecting control methods for managing invasive aquatic plants is dependent on the tools available (e.g., availability could be influenced by a lack of a biological control vector or due to a lack of resources or financial capacity to use a particular method), the species under consideration and other local context (e.g., presence of imperilled species, human drinking water sources). It is expected that the direction of change in population abundance and biomass, and the magnitude of that change (i.e., measurable changes in population) depends on the type of control method being applied. Although it is anticipated that populations will respond by decreasing in abundance and biomass in response to any applied control method aiming to eradicate or control a population, the level to which each method changes the population size often varies widely (see Figure 1 for a conceptual model). As such, it is difficult to predict which method will be the most effective and to what level the invasive plant population is likely to respond. With the application of any control method, it is anticipated that the population should decrease, but in some cases, the application of a control method may result in no significant change or even the spread of the invasive plant species (e.g., using mechanical cutting treatments alone, can cause the spread of *Spartina* species, Roberts & Pullin, 2006). It is unclear whether there will be differences among various control methods or whether one broad method, such as chemical treatments, will always be more effective than other methods, such as biological or mechanical methods.

Secondary question: Methods to control aquatic invasive plants are expected to vary in effectiveness depending on secondary factors, such as number or duration of treatments, or timing of treatments. For example, a later treatment of *Phragmites australis* was found to be less effective at decreasing the population size than those conducted earlier in the growing seasons (Mozdzer et al., 2008). We may also expect that changes in abundance and biomass are not necessarily the same at different stages of invasion, with newly established invasive

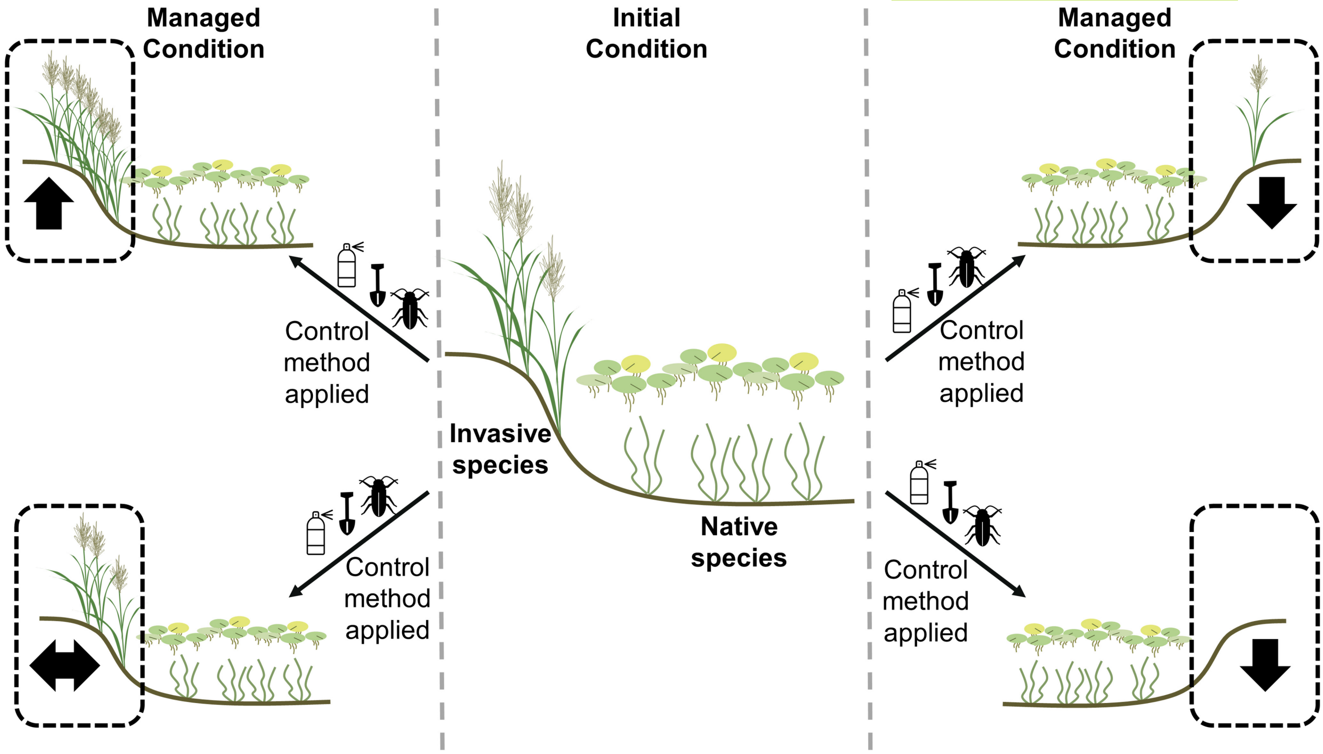

FIGURE 1 Conceptual model linking the application of a control method (e.g., biological, chemical and manual/mechanical) to potential changes in abundance or biomass of freshwater invasive plant species. Down arrow (↓): a significant reduction in abundance/biomass (top right), or complete eradication of (bottom right) the invasive aquatic plant population, indicating a positive effect of the application of a control method. Up arrow (↑): a significant increase in invasive plant population size, indicating a negative effect of the application of a control method (top left). Horizontal arrow (↔): a lack of a statistically significant change in the invasive plant population (relative) size or biomass (bottom left), indicating no effect of the application of a control method. Note: Dashed boxes indicate species of interest (freshwater invasive plant species); impacts of invasive aquatic plant management on native aquatic plant species are not considered.

aquatic plants potentially more likely to be fully controlled than more established populations (Hussner et al., 2017). Further, different control methods may be more effective for plant taxa with specific ecologies and morphologies. For instance, fully submerged species might potentially be effectively controlled by water drawdown while emergent species may not be as effectively managed by the same method.

3 | MATERIALS AND METHODS

The review will follow, as closely as possible, the CEE guidelines and standards for systematic reviews (CEE, 2022) and conform to ROSES reporting standards (Haddaway et al., 2018) (Appendix S1). The methods for this review were informed by Taylor et al. (2017), Harper et al. (2020) and Birnie-Gauvin et al. (2021).

3.1 | Searching for articles

3.1.1 | Search terms and language

Search for articles will involve sourcing both traditional academic literature and grey literature. A list of potentially relevant search terms was developed in consultation with the Advisory Team and based on the previous literature and systematic reviews on the subject of invasive plant management (Hussner et al., 2017; Kettenring & Reinhardt Adams, 2011; Prior et al., 2018; Rejmánek & Pitcairn, 2002; Roberts & Pullin, 2006; Thiemer et al., 2021). We conducted a scoping exercise using Web of Science Core Collections in February–June 2023 to assess search terms related to this review topic and evaluated the sensitivity of the search terms and associated wildcards. The three components of the search are population, intervention, and outcome and will be combined with Boolean operators 'AND' and/or 'OR'. The operator 'NOT' will be used to decrease the number of non-relevant studies found by the search. The asterisk (*) is a 'wildcard' representing any group of characters (including no characters) and the dollar sign ($) includes zero or no character. In some databases, the dollar sign ($) may be replaced by the question mark (?) but the meaning does not differ. Quotation marks are used to search exact phrases (e.g., "control program" includes the exact phrase control program as well as the hyphenated control-program).

No date or document type restrictions will be applied during the search. English search terms will be used to conduct all searches in all databases and search engines, but no language restrictions will be applied during the search. All bibliographic databases will be accessed using Carleton University's institutional subscription

(Appendix S2) when possible or will be accessed directly through the database organization's web portal. When complex search strings are not accepted, search strings will be customized and included in the final report (Appendix S3).

3.1.2 | Publication databases

The following online bibliographic databases will be searched:

1. ISI Web of Science core collection—multidisciplinary research topics including journals, books, proceedings, published data sets and patents.
2. ProQuest Dissertations and Theses Global—international depository of graduate dissertations and theses.
3. Scopus—abstract and citation database of peer-reviewed literature including journals, books and conference proceedings.
4. Federal Science Library—Canadian government books, reports, government documents, theses, conference proceedings and journal titles.
5. USDA National Agricultural Library (SEARCH)—searches the Catalogue and Articles Database (AGRICOLA), PubAG (USDA's public access repository) and the NAL Digital Collections (NALDC).

3.1.3 | Search engines

Internet searches will be performed using the search engine Google Scholar to identify additional published literature and grey literature. Due to search string limitations, two simplified search strings will be used: (1) ~Aquatic AND ~Plant AND ~Invasive AND (Biological OR Biocontrol OR Herbivory OR Physical OR Manual OR Mechanical OR Remove OR Weeding OR Rake OR Mow OR Cut OR Dredge OR Chemical OR Herbicide OR Management OR Control OR Drawdown OR Dewater OR Harvest OR Barrier) and (2) ~Aquatic AND ~Plant AND ~Invasive AND (Restore OR Remove OR Eradicate OR Control OR Reduce OR Eliminate OR Contain OR Prevent OR Exclude OR Suppress). Searches will look 'anywhere in the article' to increase the likelihood of finding relevant articles. Results will be sorted by relevance and a reasonably sized subset (i.e., the first 150 articles) will be screened for appropriate fit with the review question. If the reviewer determines that the level of relevance of each article significantly declines (i.e., no new inclusions for 50 consecutive titles) before reaching that point, the reviewer will stop (Livoreil et al., 2017).

3.1.4 | Specialist websites

Specialist organizational websites (listed below) will be searched to ensure inclusion of grey literature that might otherwise be missed by databases and search engines. Websites and portals will be searched using built-in search facilities and simplified English search terms. For each site, the top 30 results for each search string, sorted by relevance, will be screened. In cases where built-in search facilities are not available, the sites will be searched 'by hand' (i.e., focussing on any 'Publications' pages and examining site maps where available). After consulting with the Advisory Team, a list of 22 websites and institutional databases was selected, including:

- Canadian Council on Invasive Species (https://canadainvasives.ca/research/).
- Conservation Evidence (https://www.conservationevidence.com/).
- Ducks Unlimited—Institute of Wetland and Waterfowl Research (https://iwwr.ducks.ca/our-research/library/).
- Fisheries and Oceans Canada (https://www.dfo-mpo.gc.ca/).
- Great Lakes Commission (https://www.glc.org/).
- Great Lakes Phragmites Collaborative (https://www.greatlakesphragmites.net/).
- Invasive Species Centre (https://www.invasivespeciescentre.ca/).
- Invasive Species Council of BC (https://bcinvasives.ca/).
- Midwest Invasive Plant Network (https://www.mipn.org/).
- Minnesota Aquatic Invasive Species Research Centre (https://maisrc.umn.edu/).
- National Park Service (https://www.nps.gov/subjects/invasive/index.htm).
- North American Invasive Species Management Association (https://naisma.org/).
- Ontario Invasive Plants Council (https://www.ontarioinvasiveplants.ca/).
- Ontario Ministry of Natural Resources and Forestry (https://www.ontario.ca/page/invasive-species-ontario).
- Parks Canada (https://parks.canada.ca/).
- Province of British Columbia (https://www2.gov.bc.ca/gov/content/home).
- Province of Manitoba (https://www.gov.mb.ca/).
- Sea to Sky Invasive Species Council (https://ssisc.ca/invasives/invasive-plants/).
- The Nature Conservancy of Canada (https://www.natureconservancy.ca/en/).
- US Fish and Wildlife Service (https://www.fws.gov/).
- US Forest Service (https://www.fs.usda.gov/).
- US National Invasive Species Information Centre (https://www.invasivespeciesinfo.gov/).

3.1.5 | Supplementary searches

In addition to the searches listed above, the reference sections of relevant reviews identified during searching will be hand searched for articles that are within the scope of the review and not captured by the searches. We will also use social media, relevant email list serves and professional contacts to inform the community of this ongoing systematic review. We will request submissions of potentially relevant articles, reports or other forms of grey literature. Additionally, as it is anticipated that much of the literature on this topic may be available from sources other than commercial publishers, we will conduct targeted outreach to relevant government and non-government organizations, such as Parks Canada, to specifically request access to unpublished reports and other publications not readily accessible online. Additional unpublished information for projects not yet summarized will be targeted for inclusion by requesting managers and practitioners complete a fill-able form (Appendix S4). Stakeholders will be consulted for additional sources of information. No date restrictions will be applied to any submission found through supplementary searches. All submissions will be screened using the same strategy (see Section 3.3.1) as those found in searches. Relevant submissions will be included in the database.

3.1.6 | Estimating comprehensiveness

To test the comprehensiveness of the search, the results of database search were checked against a benchmark list of 32 articles during scoping. The list of benchmark articles was provided by the Advisory Team. The final list of the 32 benchmark articles can be found in Appendix S5.

3.2 | Search record database

Results from database literature searches will be exported into separate Zotero databases. Individual databases will be exported into EPPI-reviewer as one database. Duplicate results will be identified using 'fuzzy logic' and removed (EPPI Centre, 2018). Articles found through search engines will be kept separate and screened in MS Excel with duplicates between databases and search engines removed prior to screening. Further duplicates may be removed at subsequent stages of the review. The final search record database will serve as an archive of all included search results, regardless of relevance. This database will act as a direct product of the search strategy and will not be changed during the review process.

3.3 | Article screening and study eligibility criteria

3.3.1 | Screening process

Articles will be screened at two stages: (1) title and abstract and (2) full text. Articles from databases, and search engines will be screened at title and abstract. Before screening begins, a random subset of 10% or 100 abstracts (whichever is larger) from database searches will be screened by two or more reviewers. This subset will be independently screened as a consistency check to ensure consistent and repeatable application of the eligibility criteria before articles are moved to the next stage of the review. The results of the consistency check will be compared between reviewers, and all discrepancies will be discussed to understand why an inclusion/exclusion decision was made. Revisions to the inclusion criteria will be made as necessary to ensure consistent application of criteria. If the level of agreement is low (i.e., below 90% agreement), further consistency checking will be performed on an additional set of articles and discussed. Following consistency checking (i.e., when agreement is ≥90%), each article will be screened by one reviewer. All articles included at title and abstract will also be screened at full text. An additional consistency check at that stage (using 10% of the articles included at title and abstract) will be conducted in the same manner as for title and abstract screening. Articles from websites, calls for evidence or reference lists of accepted articles and relevant reviews will be screened at full text but will not be included in consistency checks.

If a reviewer is uncertain whether to include an article at any screening stage, they will tend towards inclusion to the next stage. If there is further doubt, the Review Team will discuss those articles as a group and come to a decision. The random screening function will be used to allocate articles, with all articles included being screened at title and abstract (i.e., decreasing relevance will not be used as a stop-criteria to abort title and abstract screening). Justification of inclusion/exclusion at title and abstract will be recorded using EPPI-reviewer and a list of studies rejected at full text will be provided in an additional file, together with reasons for exclusion, for the final report.

Digital media will be screened, when available, without having to purchase media or using specialized pay-for-use software to view. The InterLibrary Loans program at Carleton University will be used to acquire hard or digital, full-text copies of any article included at title and abstract. Authors will be contacted for articles not in print or unavailable through Carleton subscriptions. Reviewers will not screen studies (at title and abstract or full text) for which they are an author.

3.3.2 | Eligibility criteria

The following predefined criteria will be used when assessing relevance and deciding on inclusion or exclusion of articles. Any alteration to criteria made during the review process will be recorded and included in the final report.

Eligible populations

A list of eligible invasive aquatic plant species was developed in consultation with Parks Canada and the Advisory Team (Table 1). These species include those that are found within park lands or are of concern and present in North America. Invasive aquatic plant species include floating, emergent and submergent growth habits. Studies must consider at least one of the species of concern and occur within the species' non-native range to be included. For example, if studies occur outside North America and the species considered is on the eligible list, these studies will be included, as long as the species is considered non-native to the area of study (i.e., species on the eligible list within their native range will be excluded). Populations may be newly or firmly established, in freshwater systems or estuaries (i.e., brackish water) and may be within lotic (e.g., rivers, streams) or lentic (e.g., lakes, ponds and wetlands) systems. Populations found within man-made structures such as canals, reservoirs or in-land harbours will also be included. Wastewater treatment ponds using invasive plants as part of water treatment will not be considered.

Eligible interventions

Articles that describe the application of a control method or management activity on invasive aquatic plants will be included. Relevant control methods can include any biological (i.e., herbivory), chemical (e.g., herbicide, salt), habitat manipulation (e.g., water drawdown, flooding and shading) or manual/mechanical (e.g., pulling and cutting mowing) method, or any combination of methods that are applied by land managers. Relevant control methods may also include restoration activities after other control methods are applied. Studies considering native species herbivory or invasive species control due to natural events (i.e., natural flooding events) will not be considered as they are not active control methods applied by practitioners or researchers. However, at the request of stakeholders, articles with natural events controlling invasive plant species will be identified during screening. Studies that do not specify the type of control method but indicate that aquatic invasive plants were managed in some way, will be included but the effect of inclusion will be tested using sensitivity analysis if quantitative synthesis is possible.

Eligible comparators

Relevant comparators include: (1) invaded stands on the same waterbody with no intervention; (2) invaded separate but similar waterbodies with no intervention; (3) before intervention data within the same waterbody (i.e., post-invasion but pre-intervention); (4) an alternative level of intervention on the same or different waterbody (e.g., two herbicide treatments compared); (5) randomized control trials (RCTs); or (6) time-series data within the same waterbody or spatial trends across waterbodies with different levels of the same intervention (with or without a comparator i.e., pre-intervention time period or a waterbody with no intervention comparison). However, no study will be excluded based on comparators.

Eligible outcomes

Studies must report measured effects that indicate a change in invasive aquatic plant population size after application of a control method. These can include studies where the goal is (1) complete eradication (within a spatial extent, as defined by authors), or (2) changes in aquatic invasive plant metrics (i.e., reduction or suppression). Relevant outcomes include those related to abundance, density, biomass, extent, percent cover, frequency or presence/absence. Studies only considering individual outcomes (i.e., surrogates of population-level responses such as fitness metrics) or ecosystem responses (i.e., native plant recovery and water quality) will not be considered. Studies that look at off-target effects of invasive plant control on native species will not be considered if they do not also include a measure of change in the invasive aquatic plant population. For example, if an author considers changes in native plant biomass after application of an herbicide for treating an invasive aquatic plant but does not also measure a change in the biomass of the invasive plant species, this study will not be included for further reviewing. Studies considering the impacts of the invasive aquatic plant species itself on the ecosystem or other species will be excluded from this review, as will studies using invasive aquatic plants for remediation efforts or wastewater treatment.

Eligible study designs

Primary field-based, mesocosm or laboratory studies including quantification of invasive aquatic plant outcomes, and using Before/After (BA), Control/Impact (CI) including a gradient of intervention intensity that include a 'zero-control' site (CI-gradient), Before/After/Control/Impact (BACI), or RCT (e.g., laboratory, mesocosm or small in-field manipulations) study designs will be included. It was recognized that study designs included in this review will likely not all fit these typical structures. As such, other study designs that will be considered include temporal (i.e., time series) or spatial trend designs. Studies that use Impact-only (I-only) designs where a single impact site is assessed without a control site or other impacted sites for comparison, or After-only designs where a single point in time with no comparison to another site or a before-treatment time period will not be considered. Theoretical modelling, reviews and policy discussions will be excluded, although relevant reviews will be used to find potentially relevant primary studies.

Language

English-language literature will be included during the screening stage. French-language studies will be identified and binned, but no French-language searches will be conducted for this review. This limitation is due to resource restraints of the Review Team. If French-language studies are found opportunistically through searches or shared during calls for evidence, efforts will be made to identify these studies and provide them in a separate list for stakeholders, although it may not be possible to incorporate them formally into the final review.

3.4 | Study validity assessment

Articles that are found to be relevant to this review at full-text screening will then undergo a study validity assessment. This critical appraisal will be carried out on a study-by-study basis rather than article-by-article. If a single article has multiple studies (i.e., experiment/observation with different designs or experimental set-ups), these will be regarded as separate studies. The focus of the assessment will be on internal validity (i.e., susceptibility of each study to bias) and study clarity. External validity (study generalizability) will be captured during screening or otherwise noted as a comment in the critical appraisal tool.

Data will be extracted from each relevant study in a detailed and transparent manner and entered in a MS-Excel worksheet. The information from assessments will be used to describe general patterns of critical appraisal across studies during narrative synthesis and will be used to assess studies during the quantitative synthesis (if performed). Critical appraisal will be done by at least two reviewers on a subset of 10 articles to ensure consistency in assessments. When uncertainties arise, the reviewers will come together to discuss. Final decisions regarding doubtful cases will be taken by the Review Team as a whole. No study will be rejected based on validity assessment. Reviewers will not assess studies for validity for which they are an author.

Critical appraisal will incorporate FEAT (focused, extensive, applied and transparent) principles as recommended by Frampton et al. (2022) and the recommended guidelines from the CEE (2022). A modified critical appraisal tool based on the Critical Appraisal Tool version 0.3 (prototype) (CEE, 2022; Konno et al., 2021) and previous critical appraisal tools from other reviews (Birnie-Gauvin et al., 2021; Harper et al., 2020) will be developed for this review to capture risk of bias unique to this topic. A draft of the critical appraisal tool can be found in Appendix S6. Studies will be classified on three levels of overall risk of bias: (1) low risk of bias, (2) medium risk of bias or (3) high risk of bias. To meet these criteria, articles will be assessed on seven criteria including: (1) study design, (2) risk of confounding biases prior to the occurrence of the intervention (i.e., baseline imbalances in explanatory factors within the study system), (3) risk of bias in post-intervention selection (i.e., non-random sampling), (4) risk of performance bias (i.e., deviations from the intended treatment), (5) risk of detection bias (i.e., use of inappropriate sampling methods for the outcome of interest), (6) risk of outcome reporting bias (i.e., missing data) and (7) risk of outcome assessment bias (i.e., inappropriate statistical methods). Questions within each criterion will be answered as 'Yes', 'No', 'Unclear' or 'Not applicable', and the combined influence of these questions will be used to determine whether each criterion has high, medium or low risk of bias. To determine overall risk of bias, if any of the seven criteria are identified as having a high risk of bias, the overall risk of bias for the study will be *high*. If no criteria are at high risk of bias, but at least one criterion is identified as having medium risk of bias, the overall risk of bias for the study will be *medium*. Studies with *low* risk of bias will therefore have no criteria with high or medium risk of bias (Konno et al., 2021).

Based on stakeholder input, it was determined that most studies on this topic investigate the effectiveness of invasive aquatic plant control methods using comparators (i.e., control sites or before data). However, some studies may not have comparators, for example, comparisons among different treatments with no reference conditions, or plant population responses over time but no before-treatment outcome data. These studies would therefore be characterized as low validity (i.e., high risk of bias) but may have important insights into the overall effectiveness of management activities, especially over time. Therefore, no studies will be excluded based on study validity assessments. If the evidence base does not allow for quantitative assessments of study validity, results will be used to provide a general understanding of the robustness of the evidence and will be used to provide recommendations for future research needs and considerations.

3.5 | Data coding and extraction strategy

Meta-data from studies included at full text will be extracted by the Review Team and recorded in a MS-Excel spreadsheet that includes pre-defined coding. The extraction data will be used to assess the overall effectiveness of invasive plant control methods in terms of changes in population outcomes (i.e., abundance, density, biomass, extent, cover, frequency or presence/absence). When sufficient, good quality data exist, the information will be used in meta-analysis. We will extract data on: (1) bibliographical information, (2) study location and characteristics (i.e., geographic location, waterbody name and type), (3) study design details (e.g., study dates, study design), (4) intervention and comparator details (i.e., control methods and intensity, comparator type and magnitude), (5) outcome (i.e., abundance, density, biomass, extent, cover, frequency, or presence/absence), (6) sampling method(s) (e.g., type, size, and number of sampling units), (7) species (e.g., species names), (8) effect modifiers (see below), (9) study validity assessment results, (10) the goal of the methods applied (i.e., eradication or control/suppression) and (11) study findings (effectiveness) as reported by authors. This list may be expanded depending on the type and variety of included studies. Coding options within these key variables will be compiled as a partly iterative process as the range of options is encountered during extraction.

Some outcome data that will be recorded include sample size, outcome means and/or percent change and measures of variation (e.g., standard deviation, standard error, confidence intervals). When information is present in tables or graphs, all information will be extracted; if it is not possible to interpret the information from graphs, the corresponding author will be contacted (via email) if time permits, or imaging software (i.e., WebPlotDigitizer, Rohatgi, 2022) will be used. Comparisons will only be made within individual figures/tables but not between figures/tables. For example, if studies were done in two or more areas and these results are reported separately, we will assume that comparisons cannot be made across figures/tables unless specifically indicated by the authors. Where data are presented for multiple years or sites, we will work to maximize the information extracted. When only raw data are included in the article, the Review Team will calculate summary statistics and will record how the calculations were conducted and what information was used. All extracted data will be made available with the final report. Reviewers will not extract data from studies for which they are an author.

Two reviewers will extract information from 10 of the same articles prior to beginning the data extraction process. This will ensure that data are extracted in a consistent and repeatable manner. Information will be compared, and any inconsistencies will be discussed. If any disagreements occur, the entire Review Team will discuss them to reach consensus. Modifications will be made to the extraction code book where needed to ensure that reviewers extract data and interpret studies in the same manner.

3.6 | Potential effect modifiers and reasons for heterogeneity

Potential reasons for heterogeneity will be identified and extracted from articles included at full-text screening if reported in primary studies or available from the authors. Effect modifiers were selected after consultation with stakeholders and will be used to test how these modifiers are expected to influence the effectiveness of different control methods. The following potential effect-modifying factors will be considered and recorded:

- Biological factors (i.e., plant taxa or growth patterns: floating, emergent, submerged).
- Outcome metric (i.e., abundance, density, biomass, extent, cover, frequency, or presence/absence).
- Stage of invasion (i.e., new, established, well established) or time since invasion recognized.
- Number or duration of treatments (i.e., single treatment vs. multiple treatments).
- Timing of treatments (i.e., season).
- Spatial scale measured (i.e., stand size, aerial extent).
- Herbicide formulation (including surfactant type).

Additional effect modifiers and reasons for heterogeneity may be identified and extracted from studies as the review proceeds. Additions will be included with stakeholder consultation.

3.7 | Data synthesis

A narrative synthesis of all eligible articles in the systematic review will be generated. The synthesis will aim to be as visual as possible, describe the validity of results and summarize findings in figures and tables. The goal of this review was to determine the overall effectiveness of different types of invasive plant control methods. As such, we will aim to conduct quantitative synthesis through meta-analysis. All efforts will be made to conduct formal meta-analysis of studies with comparators included in the review when study designs and evidence-base allows. Separate subgroup analyses will be conducted for plant outcomes: (1) abundance (combining e.g., abundance, density) and (2) biomass. In the case that meta-analysis is possible (given sufficient sample size of studies), study effect sizes will be standardized and weighted appropriately, and analysis will take the form of random-effects models. Meta-regression or subgroup analysis of studies will also be performed where sufficient studies report common sources of heterogeneity. Risk of publication bias will be assessed through funnel plots and sensitivity analysis using study validity categories will be carried out when possible. We will produce forest plots to visualize effect sizes and 95% confidence intervals from individual studies. Analyses will be conducted in R (R Core Team, 2022) using the rma.mv function in the metafor package (Viechtbauer, 2010).

4 | DISCUSSION

The proposed systematic review will examine the effectiveness of methods (i.e., biological, chemical or mechanical methods) for eradicating or controlling invasive aquatic plant abundance and biomass in a Canadian freshwater context. Results from this review can serve to support new and ongoing research examining effectively managing invasive aquatic macrophytes. In particular, this review will help better predict the potential response of invasive aquatic plants to control methods, helping to support management and conservation decision-making and efforts.

Additionally, the results of this systematic review, conducted following the standards established by CEE (2022), will form the basis of an upcoming comparative analysis of different evidence synthesis techniques on the same topic (i.e., systematic reviews, rapid reviews and expert knowledge reviews). The goal of the proposed methodological comparison is to quantify how decisions made within evidence syntheses influence results, and how the type of evidence synthesis influences conservation decisions and recommended courses of action. To enable this methodological comparison, additional data will be recorded during the systematic review process to facilitate the retrospective analysis of methodological short cuts in rapid reviews and allow for comparability of the systematic review to rapid reviews and expert knowledge syntheses. No short-cuts will be taken during the conduct of the systematic review, but information obtained about the process, such as screening time and the allocation order of articles, will be recorded. To our knowledge, this comparison will be the first of its kind in the environmental management/conservation field.

AUTHOR CONTRIBUTIONS

The manuscript was drafted by Meagan Harper and Trina Rytwinski. Robyn Irvine and Steven J. Cooke read and provided critical revisions to the draft, and all authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

Ecological Solutions and Evidence BRITISH ECOLOGICAL SOCIETY

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.12350.

DATA AVAILABILITY STATEMENT

There are no data associated with this protocol. Once the systematic review is completed following the protocol outlined here, data will be made publicly available via an online repository, such as Dryad or Figshare.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. ROSES form for systematic review protocols.

Appendix S2. Institutional subscriptions. Includes details of institutional subscriptions for databases to be used in searches.

Appendix S3. Search strategy. Includes a description of the search strategy for literature searches within databases.

Appendix S4. Supplementary searches—fillable form. Includes a fillable form that can be used to summarize currently unpublished or ongoing projects.

Appendix S5. Benchmark list. Includes the list of benchmark articles used to test search comprehensiveness.

Appendix S6. Draft critical appraisal form. Includes a draft of the critical appraisal tool for internal study validity assessment.

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